Cascaded Processing in Serial RAN and Reading Fluency:

A Study with University Students

by

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Abstract

The current study investigates the hypothesis that rapid automatized naming (RAN) is related to reading fluency because both tasks rely on the ability to simultaneously process multiple items presented in serial fashion (termed cascaded processing). One hundred undergraduate students (67 females, 33 males, M_{age} = 22.63 years, *SD* = 5.16) from the University of Alberta were assessed on RAN Digits (discrete and serial) as well as on word- and text-reading fluency. In addition, they performed a RAN Letters task in an eye tracking session. The results indicated that whereas performance in serial RAN accounted for unique variance in word- and text-reading fluency when discrete RAN performance was controlled for, the opposite was not true. Furthermore, eye movement parameters (fixation count, fixation duration, and regression count) in RAN Letters accounted for unique variance in text-reading fluency even after controlling for the effects of word reading fluency. Taken together, these findings extend those of previous studies with children and suggest that simultaneous processing of serial items is critical in understanding the RAN-reading relationship as well as how reading fluency develops.

Preface

The research conducted for this thesis is part of a larger project on RAN and reading with university students led by Dr. George Georgiou at the University of Alberta. The literature review, analysis, and discussion are the original work of Pamela Eberharter.

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Chapter 1: Introduction

Rapid Automatized Naming (RAN), defined as the ability of an individual to name highly familiar visual stimuli such as letters, digits, colors, and objects has been found to be a strong concurrent and longitudinal predictor of reading ability in different languages and ages (see Kirby, Georgiou, Martinussen, & Parrila, 2010; Norton & Wolf, 2012, for reviews). RAN tasks typically require children to name an array of stimuli (see Appendix A and B) and the score is the total time to name the stimuli. Despite the acknowledged importance of RAN as a predictor of reading, researchers concur that we still do not know what mechanism is responsible for their relationship (Norton & Wolf, 2012).

Although many aspects of the RAN-reading relationship remain a subject of debate, researchers agree on a few others. First, RAN is a stronger predictor of reading fluency than reading accuracy (e.g., Georgiou, Parrila, Kirby, & Stephenson, 2008). Second, alphanumeric RAN (letters and digits) is more closely related to reading ability than non-alphanumeric RAN (colors and objects) (e.g., Wolf, Bally, & Morris, 1986). Finally, RAN in its serial format (i.e., when all stimuli are presented at once) is more closely related to reading than in its discrete format (i.e., when the stimuli are presented one at a time) (e.g., Logan, Schatschneider, & Wagner, 2011). The latter is very important for the discussion around the mechanism that is driving the RAN-reading relationship. Specifically, given that access to phonological representations in long-term memory, motor programming, and articulation are also involved in discrete naming, and serial RAN continues to predict reading after controlling for discrete naming (see e.g., Georgiou et al., 2013), then the aforementioned processes cannot be the (only) reason RAN predicts reading. Because of this, researchers turned their interest to the role of seriality (i.e., that RAN and reading involve naming stimuli presented in serial format) in the

RAN-reading relationship and further proposed the cascaded processing hypothesis according to which the serial format of RAN and reading allows individuals to simultaneously process multiple stimuli (e.g., Altani, Protopapas, Katopodi, & Georgiou, 2018, Protopapas, Altani, & Georgiou, 2018). Currently, there are only a few studies that have addressed the importance of seriality in understanding the RAN-reading relationship and they have all been conducted with young children (e.g., Altani et al., 2018; de Jong, 2011; Protopapas et al., 2013b; van den Boer, Georgiou, & de Jong, 2016). Thus, the current study aimed to examine the role of seriality in the RAN-reading relationship in a group of university students. In doing so, we employed not only behavioral measures, but also eye-tracking methodology.

Examining eye movements allows for real-time monitoring of readers' perception and processing of visual stimuli. Eye movements have been studied for years and the findings of eye tracking studies have increased our knowledge regarding normal versus abnormal oculomotor patterns in reading (see e.g., Al Dahhan et al., 2014; De Luca, Di Pace, Judica, Spinelli, & Zoccolotti, 1999; Kuperman, Van Dyke, & Henry, 2016**;** see also Rayner 1998, for a review). Furthermore, the use of eye tracking technology allows researchers to examine the role of parafoveal preview, the oculomotor preview that increases the speed in naming tasks such as RAN (e.g., Huang, 2018; Kuperman et al., 2016; Yan, Pan, Laubrock, Kliegl, & Shu, 2013).

This thesis is expected to contribute to the literature in two important ways: first, it examines the extent to which the serial format of RAN contributes to the RAN-reading relationship in young adults who are fluent readers. This, in turn, allows us to test directional hypotheses regarding the role of serial processing in RAN and reading fluency. Second, none of the existing studies have used eye movements to examine the role of seriality in the RAN-reading relationship.

Chapter 2: Literature Review

Rapid Automatized Naming (RAN), defined as the ability of an individual to name as fast as possible highly familiar visual stimuli (e.g., letters, digits, color, and objects) is a strong predictor of reading ability across languages (e.g., Georgiou, Aro, Liao, & Parrila, 2016; Georgiou, Parrila, & Papadopoulos, 2008), ages (e.g., Altani, Protopapas, & Georgiou, 2018; Georgiou, Papadopoulos, & Kaizer, 2014; van den Bos, Zjilstra, & Spelberg, 2002), and ability levels (e.g., McBride-Chang & Manis, 1996; McIlraith & Language and Reading Research Consortium, 2018). The interest in the use of RAN tasks in reading research started in the early 1970's when Denckla and Rudel (1974) showed that individuals with dyslexia were slower (but not less accurate) than typical readers in color naming. Since that time, several studies have established that fast performance in RAN is related to better reading ability and conversely that slow performance in RAN is associated with the presence of reading difficulties (see Araújo, Reis, Petersson, & Faísca, 2015; Song, Georgiou, Su, & Shu, 2016, for meta-analyses). RAN has also been found to distinguish average from poor readers during childhood (e.g., Badian, Duffy, Als, & McAnulty, 1991; Bowers & Swanson, 1991; Wolf et al., 1986) and into adulthood (e.g., Felton, Naylor, & Wood, 1990; Georgiou, Ghazyani, & Parrila, 2018; Korhonen, 1995).

Importantly, RAN continues to predict reading even after statistically controlling for verbal and nonverbal IQ (e.g., Badian, 1993), letter knowledge (e.g., Kirby, Parrila, & Pfeiffer, 2003), articulation rate (Parrila, Kirby, & McQuarrie, 2004), phonological awareness (e.g., Bowers & Swanson, 1991; Manis, Doi, & Bhadha, 2000; Parrila et al., 2004), short-term memory (e.g., Bowers, Steffy, & Tate, 1988; Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007), orthographic knowledge (e.g., Georgiou, Parrila, & Kirby, 2009), and speed of processing (e.g., Georgiou et al., 2016; Liao et al., 2015). Because of the strong connection between RAN and reading, Norton and Wolf (2012) described RAN as a “microcosm of the reading circuitry” (p. 430) that develops as children mature, tapping into the same cognitive demands as fluent reading.

Theoretical Accounts Explaining the RAN-Reading Relationship

Various researchers have proposed competing theoretical accounts to explain the RAN-reading relationship (see Georgiou & Parrila, 2013, for a list of theoretical accounts). Initially, researchers hypothesized that RAN and reading are related because proficiency in both tasks relies on quick access to stored phonological information in long-term memory (e.g., Torgesen, Wagner, & Rashotte, 1994; Wagner & Torgesen, 1987). For this reason, RAN tasks were also included in psychometric batteries of phonological processing (e.g., Comprehensive Test of Phonological Processing; Wagner, Torgesen, & Rashotte, 2012). However, several studies have established that RAN accounts for variance in reading beyond the effects of other measures of phonological processing, such as phonological awareness (e.g., Kirby et al., 2003; Manis et al., 2000), phonological short-term memory (e.g., Bowers et al., 1988), or both (e.g., Parrila et al., 2004; Powell et al., 2007). In addition, children with a double deficit in RAN and phonological awareness perform more poorly in reading tasks than children with a single deficit in either RAN or phonological awareness (e.g., Kirby et al., 2003; Papadopoulos, Georgiou, & Kendeou, 2009).

In turn, Bowers and her colleagues (e.g., Bowers, Golden, Kennedy, & Young, 1994; Bowers & Newby-Clark, 2002; Bowers, Sunseth, & Golden, 1999; Bowers & Wolf, 1993) proposed that RAN is related to reading via orthographic processing. If letter identification proceeds too slowly, letter representations in words are not activated quickly enough to induce sensitivity to commonly occurring orthographic patterns. Manis et al. (2000) provided preliminary evidence in support of this hypothesis by showing that RAN Letters and RAN Digits accounted for more variance in orthographic processing tasks than in phonological processing tasks. However, there is also evidence showing that RAN performance is not strongly related to measures of orthographic processing (e.g., Conrad & Levy, 2007; Cutting & Denckla, 2001; Georgiou et al., 2009; Moll, Fussenegger, Willburger, & Landerl, 2009).

Finally, Kail and colleagues (e.g., Kail & Hall, 1994; Kail, Hall, & Caskey, 1999) attributed the relationship between RAN and reading to a global speed of processing factor. Specifically, Kail et al. (1999) argued that "naming and reading are linked because skilled performance in both naming and reading depends, in part, on the rapid execution of the underlying processes" (p. 312). However, as is the case for the phonological and the orthographic processing accounts, there is also evidence contradicting the speed of processing hypothesis (e.g., Bowey, McGuigan, & Ruschena, 2005; Georgiou et al., 2016; Liao et al., 2015).

The Role of Serial Processing in RAN and Reading

The above theoretical accounts highlight the complexity of the RAN-reading relationship, but none of them alone sufficiently explains the association of RAN with reading. Orthographic processing, phonological processing, and speed of processing demands are all involved in both discrete and serial presentations of RAN (see Appendix C for an example of each) and yet, serial RAN predicts reading more strongly than discrete RAN (e.g., Altani, Protopapas, & Georgiou, 2018; Georgiou et al., 2013). While discrete RAN has been recognized as a measure of lexical retrieval of a single stimulus from long-term memory (e.g., Naslund & Schneider, 1996), the additional demands of RAN in the serial format (e.g., shifting of attention, visual scanning, and coordination) are essential skills in fluent reading (e.g., de Jong, 2011; Jones, Branigan, & Kelly, 2009; Kuperman et al., 2016). Researchers have only recently begun to recognize the importance of seriality in the RAN-reading relationship (Altani et al., 2018; de Jong, 2011; Jones et al., 2009; Kuperman et al., 2016; Protopapas et al., 2013a; Protopapas et al., 2013b). Jones et al. (2009), for example, tested both adults with dyslexia and their typical reading peers on continuous matrix, discrete matrix, and discrete static presentations of RAN Letters, and found that the best predictor of reading ability was the continuous matrix presentation. They concluded that this may be due to the fact that continuous RAN and reading both allow parallel processing of stimuli when these stimuli are presented in serial format.

De Jong (2011) further highlighted the important role that the format of both the reading and the RAN tasks may play in the RAN-reading relationship. First-, second-, and fourth-grade Dutch students were assessed on serial and discrete RAN, as well as on serial and discrete reading. Based on previous evidence that skilled readers process short, high frequency words as automatically as single letters or digits (Ehri & Wilce, 1985), de Jong (2011) hypothesized that in skilled readers, serial reading should be more strongly related to serial RAN than discrete RAN, because skilled readers should process each word with approximately the same speed as each RAN symbol. Furthermore, the serial format of both tasks allows participants to take advantage of a preview from the parafoveal visual field of upcoming stimuli, which allows readers to overlap processing of consecutive stimuli. In contrast, in beginner readers, performance on word reading (regardless of format) should be more strongly related to serial RAN, because every letter is processed as a single entity serially. The results were consistent with these hypotheses in that among advanced readers (Grade 4) RAN and reading correlated more strongly with each other when both tasks were presented in the same format (serial or discrete), whereas among beginner readers (Grades 1 and 2) serial RAN correlated more strongly with reading (regardless of the format of the reading task). de Jong further showed using cluster analysis that his participants could be classified into two groups: (a) those that rely solely on serial processing for reading, and (b) those that process words as a whole unit (i.e., those who could utilize a parafoveal preview to process items in parallel).

Van den Boer and de Jong (2015) expanded on de Jong's (2011) study by exploring if the length and complexity of words also impact the relation between serial/discrete RAN and reading. Increasingly complex or novel words should result in readers becoming less able to process the words as single units and this, in turn, should be reflected in the correlations between RAN and reading. If serial processing is responsible for the RAN-reading relationship, then serial RAN should be more strongly related to the reading of familiar words that can be easily processed as a whole. Results revealed very small differences in the correlations between RAN and reading when the reading task was pseudoword reading fluency rather than real word reading fluency. This draws attention to the fact that RAN explains variance approximately equally in short novel words (i.e., pseudowords) and sight words, suggesting that words can be read as unitized items, even if they are not highly familiar. The study also noted that readers could be classified into three general categories: (a) readers who utilize parallel processing for both words and pseudowords, (b) readers who process words in parallel, but pseudowords in serial fashion, and (c) readers who process words and pseudowords serially. The study provided further evidence to support the hypothesis that as readers become increasingly skilled, they can rely on parallel processing of words (and pseudowords), enabling them to read more fluently.

The aforementioned studies were all conducted in Dutch, which has a semi-transparent orthography (Seymour, Aro, & Erskine, 2003). Could similar results then be found in English, which has an opaque orthography? The first study to examine this in English was conducted by van den Boer, Georgiou, and de Jong (2016). More specifically, van den Boer et al. (2016) examined the RAN-reading relationship using both serial and discrete RAN and reading tasks in

Grade 5 children in Dutch and English. Results showed that serial RAN was a stronger predictor of serial reading in both English and Dutch, with little variance in serial reading being explained by discrete RAN. With increasing complexity (longer nonwords), serial RAN in both Dutch and English became a stronger predictor of reading fluency. It was also observed that in discrete tasks, performance in four letter words correlated strongly with discrete RAN, suggesting that both tasks measure the ability to quickly retrieve a single item from memory (either a short, highly familiar word, or a single stimulus from the RAN task). Van den Boer et al. suggested that regardless of the characteristics of the language, the ability to overlap processing of simultaneous stimuli is dependent on how efficiently an individual can process each stimulus. In skilled readers, words are often processed as a whole unit, allowing for overlapping processing of words. In contrast, a reader who processes letters within a word serially may overlap processing of letters in a word, but do not have the same capability to overlap processing of multiple words. This may be why the format of both the RAN and reading tasks is critical to the RAN-reading relationship in fluent readers and less so in beginning readers.

Altani and colleagues (2018) expanded on van den Boer et al.'s (2016) study by examining serial and discrete RAN and reading in English across development (Grades 1, 3, and 5). Results revealed that it becomes increasingly important for RAN and reading to be presented in similar formats as participants become more skilled readers. Across grades, serial RAN predicted serial reading even after controlling for the effects of discrete RAN. Discrete RAN and discrete reading were related because they both measure single item retrieval time (either of a familiar word or of a RAN symbol), while the strong relation between serial RAN and serial reading reflects the ability to simultaneously process items presented in serial fashion. Thus, if serial RAN is related to reading even when discrete RAN is controlled for, it can be concluded that the ability to overlap processing of multiple items in serial RAN (what is now called cascaded processing) plays a unique role in predicting reading fluency.

More recently, Altani, Protopapas, Katopodi, and Georgiou (2019) also included passage reading as a measure of serial reading. Passage reading not only requires lexical retrieval of words as in the word reading tasks, but also involves comprehension because the words in a passage have meaning connecting them. This comprehension feature of passage reading is recognized as an essential feature of fluent reading and should be utilized in skilled readers (see model of reading fluency by Hudson, Pullen, Lane, & Torgesen., 2009). Altani et al. (2019) found that as participants age, serial digit naming becomes increasingly predictive of passage reading fluency. Furthermore, serial RAN predicted passage reading beyond what can be explained by discrete word reading, supporting the idea that seriality is a critical aspect of the RAN-reading relationship. The study attributed the stronger relationship between serial RAN and serial reading in the fifth graders to cascaded processing, the ability to simultaneously process multiple stimuli. Cascaded processing suggests that ability to name either RAN symbols or words in serial format more efficiently than in discrete format is due to the reader being able to manage multiple stimuli at once by engaging in different stages of processing at the same time. Altani et al. (2019) also noted that as participants age, serial word reading fluency and passage reading become increasingly alike and decreasingly like discrete word reading. The similarities between word reading and passage reading performance suggests that reading fluency is determined by more than just text-related skills (such as comprehension monitoring or syntactic skills). Unfortunately, the passage used in Altani et al.'s study was designed to be similar in its naming demands to the RAN and word reading tasks (i.e., use highly familiar and short words).

To my knowledge, no studies have examined the role of discrete and serial RAN in text reading fluency with a more difficult passage.

Eye Movement Studies of RAN

Although some of the above studies have suggested that a parafoveal preview benefit may be partially responsible for the stronger relation between serial RAN and reading in fluent readers (e.g., Protopapas, Altani, & Georgiou, 2013a; van den Boer et al., 2016), none of these studies have used eye movements as a means to measure this preview benefit. Several studies using eye movements have noted the importance of an overlap in processing during serial reading through a parafoveal preview (e.g., McConkie & Rayner, 1975; Rayner & Duffy, 1986; Rayner, 1998, 2009). Furthermore, it has been documented that struggling readers have a weaker parafoveal preview (e.g., Al Dahhan et al., 2014; Yan et al., 2013), which, in turn, impairs their ability to read fluently. The parafovea is the area directly to the outside of the fovea (the central 2 degrees of visual field) that aids in processing of information anywhere within the central 5 degrees of the visual field (e.g., Engbert, Longtin, & Kliegl, 2002).

Yan et al. (2013) examined the parafoveal benefit on RAN and reading tasks in a group of Chinese fifth graders with and without dyslexia. Researchers impaired the participants' ability to process parafoveally by implementing a moving window paradigm in which only the fixated item could be seen. By eliminating the ability to preview upcoming items, both typical readers and those with dyslexia took longer to complete the RAN task, had longer fixations, and were more likely to fixate on a single stimulus more than once. Furthermore, Yan et al. found that children with dyslexia, who typically perform worse than chronological-age controls in both RAN and reading tasks, had a weaker parafoveal preview. The study provided evidence that the ability to process items simultaneously in the continuous RAN matrix plays a crucial role in the ability to complete the task efficiently and may also be critical in the RAN-reading relationship. Two studies with typical readers have further highlighted the role of parafoveal preview in the RAN-reading relationship (Huang, 2018; Kuperman et al., 2016). Huang (2018) compared the reading processes at work in novice readers (a sample of 6-year-olds) and skilled readers (a sample of young adults) when performing RAN and reading tasks in an eye tracker. He found that both children and adult readers engaged in parafoveal preview, especially when presented with well-practiced RAN symbols (e.g., numbers). In turn, Kuperman, van Dyke, and Henry (2016) used eye movements to investigate the role of oculomotor control in the RAN-reading relationship in young adults. They measured eye movements (regression rate, skipping rate) on increasingly complex RAN and RAN-like tasks in order to examine the importance of oculomotor control. They found that both eye movement parameters predicted passage reading and concluded that the ability to efficiently program the eyes to move from one fixation to the next is a critical skill in the RAN-reading relationship. Unfortunately, neither Huang (2018) nor Kuperman et al. (2016) examined the role of serial processing using eye movements.

The Present Study

The purpose of this study was to examine the role of seriality in the RAN-reading relationship. The research questions were as follows:

1. What is the relationship of serial and discrete RAN with reading fluency in university students? On the basis of previous studies with relatively fluent readers (e.g., Altani et al., 2019; Jones et al., 2009; van den Boer et al., 2016), we expected that serial reading would correlate more strongly with serial RAN than with discrete RAN. In addition, we expected that serial RAN would predict reading fluency even after controlling for the effects of discrete RAN.

2. To what extent can performance on eye movement parameters (fixation count, average fixation duration, and regression count) predict reading fluency over and above performance on discrete RAN? On the basis of existing studies that highlighted the role of eye movements in RAN and reading (e.g., Huang, 2018; Jones et al., 2009; Yan et al., 2013), we expected that all three eye movement parameters during serial RAN would account for unique variance in word- and text-reading fluency over and above discrete RAN.

Chapter 3: Methodology

Participants

One hundred undergraduate students (67 females, 33 males, M_{age} = 22.63 years, *SD* = 5.16) from the Faculty of Education at the University of Alberta participated in this study. Participants were recruited through the subject pool program offered through the Department of Educational Psychology and received credit towards one of their introductory education courses for their participation in the study. All participants reported English as a first language and had normal to corrected-normal vision. Written consent was obtained prior to testing.

Materials

Rapid automatized naming (RAN). Two RAN tasks were administered: RAN Digits and RAN Letters. Both RAN tasks were adopted from the RAN/RAS battery (Wolf & Denckla, 2005). RAN Digits was administered in both discrete and serial format. In the discrete format, participants were asked to name as fast as possible individually-presented digits (2, 6, 4, 9, 7) that were repeated in random order 10 times each. Voice onset reaction time for each digit was recorded through a head-mounted microphone. In the serial format, the same digits were presented in a 50-item matrix (5 rows of 10) and the participants were asked to name the items as fast as possible from left to right and from top to bottom. Total response time for the matrix was recorded. Finally, RAN Letters was used to measure eye movements. Participants were asked to name as fast as possible five letters (o, a, s, d, p) that were presented in a 50-item matrix (5 rows of 10). The task was administered on a computer, with the eye movement parameters being collected while the participants named the items (see below for details). Prior to timed testing, participants were given a practice trial to ensure familiarity with the task demands. Wolf and

Denckla (2005) reported test-retest reliability for RAN Digits and Letters across ages to be .92 and .87, respectively.

Reading Fluency. Reading fluency was assessed with two tasks: Word Reading Efficiency (WRE) and Gray Oral Reading Test. Sight Word Efficiency from the Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 1999) was used to assess participants' word reading fluency. Participants were asked to name as fast as possible a list of 104 words that were arranged in terms of increasing difficulty in four columns of 26. A participant's score was the number of words read correctly within a 45 seconds time limit. The test-retest reliability coefficient for adults has been reported to be .82 (Torgesen et al., 1999). In turn, passage 9 from the Gray Oral Reading Test-4 (GORT; Wiederholt & Bryant, 2001) was used to assess text reading fluency. Participants were asked to read passage 9 (148 words) as fast and as accurately as possible. The total reading time in seconds was recorded. There were very few naming errors (the average number of errors across participants was less than 2) and for this reason they were not considered further. The part of the task that includes multiple choice questions was not administered because it was not the purpose of this study to examine reading comprehension. The internal consistency reliability coefficient for reading rate on Form A of GORT-4 has been reported to be .96 (Wiederholt & Bryant, 2001).

Eye Tracking Methodology

Apparatus. Eye movement data were collected using the Eyelink II Eye tracking system (SR Research Ltd., Ontario, Canada), a video-based eye tracking system that uses two cameras that are mounted on the participant's head to allow both vertical and horizontal eye position tracking. Participants were asked to hold as still as possible to ensure the system remained properly calibrated to recognize the position of the participants' pupil and cornea. The high resolution of the apparatus (noise-limited at <0.01°) allows for accurate tracking despite inevitable small head movements.

Data Extraction. Data were extracted using the Eyelink Data Viewer program (SR Research Ltd). Any eye movements between the initial focal point and the first letter in the upper left corner of the RAN task were disregarded. A rectangular interest area was created around each letter in the matrix and any fixations that occurred in the areas of interest were attributed to the reading of that letter. The border of the areas of interest for each letter were defined by the halfway point to the adjacent items. Any fixations to the left or right of the matrix outside the interest areas were disregarded. If a small fixation (a fixation that was less than 50ms) occurred on the same letter along with a larger fixation, the sum of the two fixations was used as a single fixation duration.

In this study, three types of eye movement data were extracted and used in the analyses: average fixation duration, fixation count, and regression count. Saccade count and average saccade amplitude were also extracted but they were not considered further because the former correlated strongly with fixation count (r = .98) and the latter had minimal variability. Average fixation duration and fixation count included any fixations, including those resulting from a regression. Average fixation duration was the average length in milliseconds of all fixations in the task. Fixation count was the total number of fixations in the task. Finally, regression count was the total number of fixations resulting from backward movement in the matrix.

Procedure

The participants were individually tested by a trained graduate student during two separate sessions. Session 1 included RAN Digits (serial and discrete), Sight Word Efficiency, and GORT-4, while Session 2 (the eye tracking session) included the RAN Letters task. The two sessions were counterbalanced. Participants were informed of the study goals and signed a consent form prior to beginning either session.

Prior to testing the participants in RAN Letters, the eye tracker was calibrated to ensure valid measurements of eye movements. The RAN task was displayed on a 21" SONY CRT monitor and the participants were asked to sit as still as possible about 40-60cm from the display monitor. Right after calibration, a focal point (black dot) appeared in the centre of a blank screen for participants to focus on prior to performing the RAN Letters task.

Chapter 4: Results

Preliminary Analyses

Before conducting any analyses, we examined the distributional properties of the measures included in the study. Normality was determined by viewing the distributional curve on a histogram. Outliers were defined as those having a *z* score +/-3.00. Average fixation duration on the RAN Letters task as well as discrete RAN Digits response time had two outliers each. In addition, there was one outlier found each in Word Reading Efficiency (WRE), Gray Oral Reading Test (GORT), and serial RAN Digits response time. To normalize the distributions of these measures, we winsorized the scores of the outliers by adding or subtracting 1 from the highest non-outlier value (Tabachnick & Fidell, 2007). Table 1 presents the descriptive statistics for the winsorized measures.

Correlational Analysis

Table 2 presents the results of the correlational analysis. The results indicated first that discrete RAN Digits correlated consistently less well with all reading outcomes than serial RAN Digits. The strongest correlation was found between serial RAN Digits and WRE (r =-.57, $p <$ 0.01). In terms of the eye movement parameters, although fixation count and regression count correlated strongly with each other (r =.75), the correlations of average fixation duration with the other eye movement parameters were weak (.02 < r < -.03). Finally, with one exception (the weak correlation between regression count and WRE (r = -.19)), the three eye movement parameters correlated moderately with the reading measures (*r*s ranged from -.24 to -.40).

Table 1

Descriptive Statistics on all Measures Used in the Study

	M	*SD*	min	max	skewness	kurtosis
RAN Digits						
D RT[a]	526.43	70.51	404.00	886.00	1.587	5.660
S RT[b]	16.49	2.54	10.81	23.67	.351	.360
RAN Letters						
RT[b]	18.62	2.82	12.83	30.24	.573	2.001
Fix Cnt	62.17	5.895	49.00	76.00	.31	-.174
Avg Fix Dur	270.98	37.48	194.80	372.32	.542	.210
Reg Cnt	5.35	3.006	.00	13.00	.588	-.328
WRE	96.58	7.00	77.00	104.00	-.72	-.312
GORT	47.19	5.54	37.44	64.23	.795	.810

Note. [a.] in milliseconds; [b]. in seconds. D RT, discrete RAN Digits response time per item; S RT, serial RAN Digits task response time, RT, serial RAN Letters task response time; Fix Cnt, RAN Letters fixation count; Avg Fix Dur, RAN Letters average fixation duration; reg cnt, RAN Letters regression count; WRE, TOWRE word reading efficiency words per 45 seconds; GORT, GORT-4 passage 9 response time.

Table 2

Pearson Correlations Between RAN and Reading Measures

	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Age	-								
2. D RAN Digits RT	-.01	-							
3. S RAN Digits RT	-.08	.38**	-						
4. RAN Letters RT	.11	.30**	.73**	-					
5. Fix. Count	.18	.28**	.51**	.60**	-				
6. Avg. Fix Dur	.02	.17	.51**	-.76**	-.03	-			
7. Reg. Count	.09	.27**	.41**	.46**	.75**	.02	-		
8. WRE	.02	-.32**	-.57**	-.46**	-.24*	-.40**	-.19	-	
9. GORT	-.15	.26*	.50**	.47**	.38**	.28**	.31**	-.56**	-

Note. D RT, discrete RAN Digits response time per item; S RT, serial RAN Digits task response time, RT, serial RAN Letters task response time; Fix Cnt, RAN Letters fixation count; Avg Fix Dur, RAN Letters average fixation duration; reg cnt, RAN Letters regression count; WRE, TOWRE word reading efficiency; GORT, GORT-4 passage 9 response time

*$p < 0.05$; **$p < 0.01$.

Hierarchical Regression Analyses

Three sets of hierarchical regression analyses were conducted. First, we examined the contribution of serial and discrete RAN Digits to word- and text-reading fluency. Second, we examined the contribution of serial RAN Digits on text-reading fluency after controlling for word reading fluency. The results of these analyses are presented in Table 3. Finally, we examined the contribution of the three eye movement parameters (entered interchangeably at step 2 of the regression equation) to word- and text-reading fluency, after controlling for discrete digit naming (entered at step 1 of the regression equation). The results of these analyses are presented in Table 4.

In line with our expectation, the results of the first regression analysis (see Table 3) indicated that serial RAN Digits continued to account for unique variance in both reading outcomes (19-23%), after controlling for the effects of discrete RAN Digits. Discrete RAN Digits did not account for unique variance in either reading outcome, after controlling for the effects of serial RAN Digits. In addition, we found that serial RAN Digits continued to predict text-reading fluency (accounting for 5% of unique variance) after controlling for the effects of word reading fluency.

In the final regression analysis, we found that after controlling for the effects of discrete RAN Digits, only average fixation duration continued to predict word-reading fluency. In contrast, all three eye movement parameters continued to predict text-reading fluency. Fixation count and regression count continued to predict text-reading fluency, even after controlling for the effects of word-reading fluency.

Table 3

Hierarchical Regression Using Serial and Discrete RAN to Predict Reading Performance

		WRE		GORT	
Step	Variable	*β*	ΔR^2	*β*	ΔR^2
1.	D RAN Digits RT	-.317	.10**	.257	.06**
2.	S RAN Digits RT	-.527	.24**	.477	.20**
1.	S RAN Digits RT	-.527	.33**	.506	.26**
2.	D RAN Digits RT	-.117	.01	.076	.01
1.	WRE			.559	.31**
2.	S RAN Digits RT			.270	.05**

Note. D RAN Digits RT, discrete RAN Digits response time; S RAN Digits RT, serial RAN Digits response time; SWE, TOWRE word reading efficiency score; GORT, GORT-4 passage 9 response time.

* $p < .05$; ** $p < .01$.

Table 4

Hierarchical Regression Using Eye Movements During RAN to Predict Reading Performance

		WRE		GORT	
Step	Variable	*β*	ΔR^2	*β*	ΔR^2
1.	D RAN Digits RT	-.317	.10**	.257	.07**
2.	FIX CNT	-.162	.02	.341	.11**
1.	D RAN Digits RT	-.317	.10**	.257	.07**
2.	AVG FIX DUR	-.359	.13**	.235	.05*
1.	D RAN Digits RT	-.317	.10**	.257	.07**
2.	REG CNT	-.113	.01	.263	.06**
1.	WRE			-.436	.31**
2.	FIX CNT			.266	.07*
1.	WRE			-.436	.31**
2.	AVG FIX DUR			.061	.00
1.	WRE			-.436	.31**
2.	REG CNT			.208	.04*

Note. D RAN Digits RT, discrete RAN Digits response time; Fix Cnt, fixation count; Avg Fix Dur, average fixation duration; reg cnt, regression count; RAN L RT, RAN Letters total response time; SWE, TOWRE SWE score; GORT, GORT-4 passage 9 response time.

*$p < 0.05$; **$p < 0.01$.

Chapter 5: Discussion

The first objective of this study was to examine the relation of serial and discrete RAN with word- and text-reading fluency. Results revealed that discrete RAN was not a significant predictor of either word- or text-reading fluency when serial RAN was controlled for. In contrast, serial RAN continued to predict both reading fluency outcomes after controlling for the effects of discrete RAN. This extends earlier findings with Grade 5 (van den Boer et al., 2016) and Grade 6 children (Protopapas et al., 2013b) supporting the superiority of serial naming tasks when predicting serial reading tasks. As children become more fluent readers, reading becomes so automatic that processing of single words becomes similar to processing single letters, which allows individuals to process multiple items simultaneously.

Our second research question was to determine the extent to which eye movements from a serial RAN task can predict word- and text-reading fluency over and above discrete RAN. In line with our expectation, we found that eye movements on serial RAN Letters (regression count, average fixation duration, and fixation count) predicted text-reading fluency over and above discrete RAN. Because discrete RAN performance was controlled for, the fact that eye movements continued to predict text-reading fluency is another piece of evidence supporting the critical role of seriality in the RAN-reading relationship (see below for an explanation why we did not find the same result when predicting word-reading fluency).

There might be two explanations for the significant contribution of the eye movements. First, it may be due to the role of oculomotor control and sequencing in both serial RAN and serial reading (see Kuperman et al., 2016, 2018). As proposed by Kuperman et al. (2016), serial RAN and serial reading may be related because both tasks require rapid coordination and sequencing of the eyes. The eyes need to rapidly engage and disengage to quickly uptake visual information about serially presented stimuli. How well a reader is able to do this will determine how fluently that individual will read. In Kuperman et al.'s studies, this was shown by examining how RAN tasks predict eye movements (regression and skipping rate) in reading. Regressions are representative of disruptions in processing during reading, either due to loss in comprehension or a misjudgement in landing position from the previous saccade. Because RAN does not have any comprehension demands (the items in RAN Letters do not form any words), it can be assumed that regressions made in RAN are a result of the eyes selecting an inappropriate landing position for information uptake. Effective and efficient oculomotor movements would result in quick and accurate selection of an ideal fixation location, therefore, fewer regressions during RAN. Furthermore, previous studies have suggested that a parafoveal preview can aid in the selection of ideal fixation locations and, therefore, should reduce the number of regressions (e.g., Acha, & Perea, 2008; Yan et al., 2013). We found here that the number of regressions during RAN Letters correlated significantly with performance in passage reading ($r = .31$), which further suggests that individuals who have better oculomotor control (i.e., fewer regressions) are more efficient readers.

An alternative explanation relates to cascaded processing (e.g., Altani et al., 2018; 2019; Protopapas et al., 2013b). Cascaded processing allows readers to simultaneously process multiple stimuli by engaging in many stages of processing at the same time. Overlapping processing of consecutive stimuli allows for fast and fluent reading in serial tasks (Altani et al., 2018). Furthermore, individuals can buffer information - holding information about stimuli in working memory to be processed while the eyes fixate on a new stimulus. Our results of average fixation duration and fixation count support this explanation. A decreased fixation count is evidence of greater time spent buffering information in between visual uptake. Fixations represent the time in which the reader is gathering new visual information to be processed, so an increase in fixation count is indicative of the reader stopping more frequently to gather visual stimuli. Phonological and orthographic processing that are involved in serial RAN should be occurring in between fixations, resulting in fewer fixations overall. Furthermore, if a skilled reader is truly benefitting from the parafoveal preview of items, this should increase the likelihood of observing less frequent fixations (Yan et al., 2013). In our study, we found a significant correlation between fixation count and reading fluency performance (r = -.24 with word-reading fluency and r =.38 with text-reading fluency) and fixation count explained unique variance in text-reading fluency. Thus, fixation count in serial RAN is reflective of the efficiency of cascaded processing.

Average fixation duration may also provide important information of the efficiency of cascaded processing. Average fixation duration is typically considered a good measure of how long it takes a reader to uptake visual information about the stimuli to be processed (Al Dahhan et al., 2014; Rayner, 1998). Overlapping processing of items implies that the phonological and orthographic processing of a visual stimulus occur after the visual uptake of the stimulus, when the eyes are already preparing a saccade to the next stimulus. If cascaded processing is occurring, then fixation duration is exclusively the amount of time for visual uptake, meaning that fixation durations should be shorter. Angele, Slattery, and Rayner (2016) found that an effective parafoveal preview can aid in the processing of the upcoming previewed items, therefore reducing the overall task completion time as well as the duration of the next item (see also Jones et al., 2009; Sereno & Rayner, 2000). Therefore, a reduced average fixation duration is indicative of a more effective parafoveal preview, as well as the ability to buffer between the uptake of visual stimuli. The average fixation duration in our study was correlated significantly with both reading fluency tasks, suggesting that more efficient readers are also more efficient on information uptake in serial RAN.

Although the correlations between the eye movement parameters and reading fluency in this study are slightly lower than the average correlations between RAN total times and reading reported in recent meta-analyses (e.g., Araújo et al., 2015; Song et al., 2016), they were similar to those of previous eye movement studies. Kuperman and colleagues (2016), for example, found that the eye movements in serial RAN correlated moderately with passage reading ($.16 < r < .26$) and Doyle (2005) reported weak to moderate correlations between regressions and fixations in RAN and text reading ($.04 < r < -.39$). The weaker correlations between the eye movement measures and reading are likely due to the limited variability of the former. In a sample of readers that are considered advanced (as in Kuperman et al., 2016, Doyle, 2005, and here), there is by nature less variability in these measures and, therefore, the correlations between these measures and reading are inevitably weaker.

Serial Word Reading versus Passage Reading

With the exception of average fixation duration, the relationship between eye movements in serial RAN and reading fluency was stronger with text-reading fluency than word-reading fluency. If regression counts are more closely associated with passage reading than with word reading, this may be indicative of two things. First, that the stronger relationship of regression count with passage reading is because of the additional semantic demands of passage reading (over word reading). As previously mentioned, this is unlikely to be the case, as the RAN Letters task has no semantic demands. A more plausible explanation is that the format of the RAN task (left to right and top to bottom) more closely resembles the layout of the passage reading than of the word reading task. Although researchers have found evidence against the role of directionality in the RAN-reading relationship (e.g., Protopapas et al., 2013a), it is because of directionality that the preview is larger on the right side of the foveal stimuli than on the left (see Rayner, 1998, for a review). If directionality of an orthography impacts the size of parafoveal preview, then a downward preview (as in word reading fluency) should be less beneficial than a preview to the right of the fixated stimulus (as in text reading). This is not surprising given that Kuperman et al. (2016) found that eye movements on various RAN-like tasks explained unique variance in passage reading in adults and noted the importance of directionality of oculomotor sequencing in their relationship.

The additional semantic demands in connected text reading may also explain the stronger contribution of fixation count to text reading fluency than word reading fluency. If fixation count is a measure of how often a reader must stop to uptake visual information, evidence in our study suggests that connected text helps to reduce the frequency that a reader must uptake new information. Less frequent fixations imply that less time is spent on visual processes and more time is spent on buffering information about the stimuli in between fixations. Thus, the stronger relationship of RAN with text-reading fluency, as opposed to word-reading fluency, suggests that fixation count during RAN is reflective of how well a reader can buffer information when reading connected text.

Interestingly, the eye movement parameters explained unique variance in text reading fluency, even after controlling for word reading fluency. Word reading should be closely related to passage reading, as they both involve the ability to recognize words as a unitized whole quickly and efficiently (Hudson et al., 2006). Why would then eye movement measures account for unique variance in text-reading fluency over and above word-reading fluency? The word reading task used in the current study (Word Reading Efficiency) requires naming words of increasing difficulty and the score is the total number correct (incorrect words or skipped items are excluded in the calculation of the total score). On the other hand, cascaded processing rests on the assumption that the words in a given reading task are highly familiar to allow simultaneous processing of multiple stimuli. Thus, by controlling for Word Reading Efficiency, we essentially controlled for word reading without cascaded processing. Given that RAN involves highly familiar stimuli that facilitate cascaded processing, controlling for word reading efficiency leaves room for RAN (and its eye movement parameters) to account for unique variance.

Limitations and Conclusion

Some limitations of the present study are worth mentioning. First, although we had a discrete digit naming task, we did not assess discrete reading. If RAN and reading are related primarily because of an overlap in processing between consecutive items, then there should be little or no relationship between serial RAN and discrete reading. Altani and colleagues (2018) found that when discrete RAN was controlled for, the relationship between serial RAN and discrete reading was almost nonexistent. Another limitation worth mentioning is that we did not calculate the eye-voice span (i.e., the distance between words being articulated and words being fixated). The inclusion of eye-voice span would provide a more comprehensive understanding of the parafoveal preview and the ability to overlap items presented in serial fashion. It can be assumed that the time between fixating a stimulus and articulating the name of that stimulus is spent on phonological and orthographic processing associated with that stimulus. Unfortunately, when the data was collected, we did not record the responses of the participants to be able to calculate the eye voice span. Finally, although we used a serial RAN Letters task in the eye tracker session, we did not assess discrete RAN Letters times (hence the use of discrete digit naming in the analyses) in the behavioral session. Nevertheless, previous studies have shown that discrete letter and digit naming correlate strongly with each other (*r*s > .60, see e.g., de Jong, 2011).

The current study extends the findings of previous studies with young children (e.g., Altani et al., 2018; de Jong, 2011; Protopapas et al., 2013b; van den Boer & de Jong, 2015; van den Boer et al., 2016) and provides support of the cascaded processing hypothesis (keeping always in mind that we did not measure discrete reading and, therefore, we have evidence supporting only one part of the hypothesis). Importantly, we have provided evidence in support of the cascaded processing hypothesis not only by using behavioral measures (this is a relatively established finding; see Altani et al., 2018; Protopapas et al., 2018), but also eye movement measures. We argue that eye movements should be explored further as they may reveal important aspects of the RAN-reading relationship that are difficult to capture with conventional measures. Finally, given that several studies have now supported the role of cascaded processing in RAN and reading fluency (e.g., Altani et al., 2017; 2018; Protopapas et al., 2018; van den Boer et al., 2016), it might be time to reconceptualize what reading fluency is and propose a new model where cascaded processing has its own place along with accuracy, automaticity, and prosody. This would have important implications for reading fluency intervention since most previous studies have exclusively focused on how to increase the speed of lexical processing in order to improve overall reading fluency.

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Appendix A

RAN Letters Task (Wolf & Denckla, 2005)

o	a	s	d	p	a	o	s	p	d
s	d	a	p	d	o	a	p	s	o
d	s	o	p	o	a	p	a	d	s
p	a	d	o	d	s	a	s	p	o
d	o	p	a	s	p	d	o	s	a

Appendix B

RAN Digits Task (Denckla & Rudel, 2005)

2	6	9	4	7	4	9	7	2	6
9	4	2	6	4	9	7	2	6	7
2	4	2	9	4	6	7	6	7	9
6	2	6	9	7	4	2	9	4	7
4	6	2	9	7	6	9	7	4	2

Appendix C

Example of Serial and Discrete RAN Formats