The Role of Serial and Discrete Processing in Rapid Naming and Reading Fluency Development

by

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Abstract

This dissertation includes three papers that investigate the distinction between serial and discrete processing in rapid naming and word reading tasks, across three elementary grades (1, 3, and 5) and two languages (English and Greek). Rapid naming and word reading tasks were utilized in two presentation formats: multiple stimulus displays (i.e., serial naming or reading) and isolated stimulus displays (i.e., discrete naming or reading). The first study examined the correlational patterns between serial and discrete versions of digit naming and word reading tasks across grades in English, using serial and discrete digit naming to index word reading processes. Results showed that serial and discrete digit naming reflect not only shared but also distinct processes related to word reading. Evidence also advanced the idea that serial digit naming can be used as an index of sequential multi-element processing both within individual words and across multiple words. Children from different grades were clustered into two classes, namely beginning, and advanced readers. Between the two classes of readers, discrete and serial word reading tasks started off as rather similar but grew further apart with age and reading proficiency. This finding supported the idea that fluent reading of words sequences requires additional skills beyond the ability to recognize individual words.

The second study examined the interrelations among individual word recognition, word list reading, and text reading across grades and orthographies. It also examined the unique role of sequential multi-item processing (indexed by serial digit naming) in reading multiple words in lists and in text. Results showed that the correlation between individual word recognition and both word list and text reading gradually decreased across grades, irrespective of contextual processing requirements. Moreover, serial digit naming (indexing multi-item processing) uniquely predicted both word-list and text reading fluency in Grades 3 and 5, beyond single word recognition speed. The same pattern of results was observed across languages. These findings suggest that an additional component of processing multi-item sequences appears to emerge by Grade 3, after a basic level of both accuracy and speed in word recognition has been achieved, offering a potential mechanism underlying the transition from dealing with one word at a time to efficient processing of word sequences.

The third study examined the development of the serial advantage, defined as the gain in naming rate in the serial over the discrete task of the same content, between grades and different types of content in English and Greek. Serial tasks yielded faster naming rates across grades, irrespective of task content. This finding suggested that there is some form of temporal overlap during processing of multiple stimulus displays. It also supported the idea that the ability to coordinate multiple successive items at different overlapping processing stages (i.e., *cascading*) may be a critical element in the development of efficient serial naming and multiword reading. However, content-specific characteristics influenced the changes of the serial advantage between grades, suggesting that practice and familiarity with the content on the naming or reading task may impact the development of serial advantage.

Overall, this dissertation provides evidence for an additional component skill involved in word reading and text reading fluency, over and above efficient word recognition and single item identification. This component skill – indexed by serial naming tasks – relates to the efficiency of processing multiple successive items and may be a critical and missing element towards understanding reading fluency and its development.

Preface

This thesis is an original work by Angeliki Altani. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "How is reading fluency achieved?", No. Pro00047805, April 28, 2014.

The research work presented in this dissertation forms part of an international research collaboration with Dr. Athanassios Protopapas (University of Oslo), and Dr. George Georgiou (University of Alberta).

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I was responsible for the concept formation, development of experimental tasks, data collection and data processing, as well as the writing composition of each manuscript. Dr. Athanassios Protopapas was involved in the concept formation, writing composition and editing, and assisted with data analysis and interpretation. Katerina Katopodi assisted with the development of experimental tasks in Greek, as well as with the Greek data collection and processing. Dr. George Georgiou was the dissertation supervisor and assisted with the concept formation, manuscript revision and editing.

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Chapter 1: General Introduction

The development of fluent word reading is very important in our fast-changing and information-rich society. Learning to recognize words (converting print to meaningful sounds) with accuracy, speed, and without conscious effort is not only a gateway towards gaining further knowledge (reading to learn), but it is also a fundamental skill in everyday life: it is difficult to imagine spending even a day without being able to access printed information from websites, emails, text messages, or even road signs on the way to school or work, and product labels in groceries and pharmacies. However, although most children acquire these skills successfully, there is still high prevalence of reading difficulties reported in literate societies (about 3-20% of school-aged children; Parrila & Protopapas, 2017). Therefore, it is of crucial importance to understand how word reading fluency develops and examine individual differences in key processes that underpin reading fluency attainment.

Although there is no consensus on the definition of reading fluency, there is agreement among researchers that reading fluency incorporates the ability to accurately and quickly recognize words—whether in isolation or in connected sentences—without effortful attention to the mechanics of decoding (e.g., Meyer & Felton, 1999; Schwanenflugel et al., 2006), which subsequently facilitates meaning construction (Jenkins, Fuchs, van den Broek, Espin, & Deno, 2003; LaBerge & Samuels, 1974; Perfetti, 1986; Rasinski, Reutzel, Chard, & Linan-Thompson, 2012; Stafura & Perfetti, 2017). Thus, relevant research has mainly focused on (a) efficient single word recognition development (i.e., from effortful serial decoding to parallel sight-word reading) and the connection between single word and connected text reading, and (b) understanding the processing skills that explain individual differences in reading fluency, such as rapid automatized naming (RAN). Yet, reading fluency is typically measured by reading aloud quickly and rapidly multiple words presented either in unconnected lists (i.e., word list reading fluency) or in connected text (i.e., text reading fluency) as opposed to reading a single word in isolation. This implies that reading fluency (either in word-lists or text) involves dealing with multiple words in sequences. At the same time, the predictive value of RAN seems to largely rely on the serial format of the task, with evidence showing that rapid naming measures are much more strongly correlated with reading fluency when the stimuli are presented simultaneously, in series (i.e., *serial naming*) compared to one-by-one, in isolation (i.e., *discrete naming*; Georgiou, Parrila, Cui, & Papadopoulos, 2013). Although this further implies that the way stimuli are being presented in both rapid naming and reading fluency measures may influence how they are actually being processed, this aspect of sequential processing has been largely neglected in previous work and theories of reading fluency or rapid naming.

The three studies in the current dissertation address this gap in research by examining the sequential nature in both serial naming and reading fluency. The main objective was not to explain the serial naming and reading fluency connection as such. Instead, this work aimed to better understand whether the ability to deal with multi-item sequences (indexed by serial naming tasks) plays a distinct role in fluency development, potentially offering a link for the developmental transition from efficient identification of individual words (i.e., intraword processing) to fluent multiword reading in lists or text (i.e., interword processing).

The RAN Task

Rapid naming speed operationalized by rapid automatized naming (RAN) tasks has been largely used as a fluency-related predictor of reading skills (e.g., Bowey, 2005; Breznitz, 2006; Norton & Wolf, 2012). Rapid naming refers to the time required to name accurately and rapidly a set of well-known visual stimuli, such as letters, digits, objects, and colors displayed in a grid format (Wolf & Bowers, 1999). RAN tasks can be divided into two different types based on their content: alphanumeric, including letters or digits, and nonalphanumeric, including objects or colors. In the standard form of the rapid naming task, namely *serial naming*, arrays of stimuli need to be named as quickly and accurately as possible in sequential order as they are displayed in a matrix of 5 items repeated 10 times in 5 rows or in a similar gridded structure (see Figure 1.1). In a common variation of the task, namely *discrete naming*, stimuli are presented individually (one-by-one) in the middle of a computer screen and individuals are asked to name them as fast and as accurately as possible (see Figure 1.1).

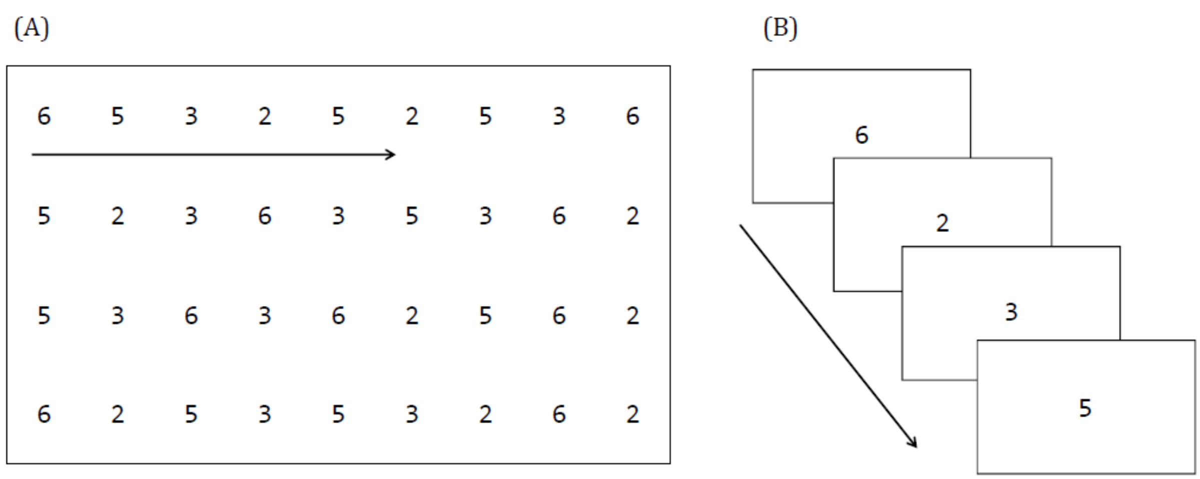

Figure 1.1. Example of serial-trial and discrete-trial format in rapid naming of digits.

RAN became popular based on the plethora of evidence suggesting that it is one of the strongest predictors of both concurrent and future reading ability across ages (Aarnoutse, van Leeuwe, & Verhoeven, 2005; Georgiou, Papadopoulos, & Kaizer, 2014; Kirby, Parrila, & Pfeiffer, 2003; Landerl & Wimmer, 2008; van den Bos, Zijlstra, & Spelberg, 2002), and languages (de Jong & van der Leij, 1999; Georgiou, Aro, Liao, & Parrila, 2015; Georgiou, Parrila, & Liao, 2008; Georgiou, Parrila, & Papadopoulos, 2008; Moll et al., 2014;), which can also distinguish readers with dyslexia from normally developing readers (e.g., Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000; Yan, Pan, Laubrock, Kliegl, & Shu, 2013). However, although RAN's predictive value on reading skills has been extensively examined, there is little consensus as to the cognitive process(es) or skill(s) that rapid naming measures which could account for its strong relationship with reading. Most of the proposals concern single processing skills involved in RAN and reading, including but not limited to phonological processing, orthographic processing, visual-verbal association, and speed of processing (see Kirby, Georgiou, Martinussen, & Parrila, 2010). In their seminal paper, Wolf and Bowers (1999) entertained a more holistic approach for the RAN-reading association. They described a theoretical model of rapid letter naming, identifying several cognitive processes underlying RAN that largely coincide with processes underlying fluent reading. According to their model, RAN requires the following subcomponents:

(a) attention to the visual stimuli, (b) visual processing, responsible for initial feature detection, visual discrimination, and letter/letter pattern recognition, (c) integration of visual information with stored orthographic and phonological representations, (d) lexical processing, including access and retrieval of phonological labels, (e) integration of activated conceptual and semantic information, and (f) motoric processing, including articulatory output.

Wolf and Bower's model (1999) further indicated that efficient performance in RAN relies on the coordination of the several subcomponents in a rapid manner. Based on this earlier account, Norton and Wolf (2012) argued that RAN entails several cognitive components closely related to those involved in word reading, and therefore it should be conceptualized as "a microcosm or mini-circuit of the later-developing reading circuitry" (p. 430). Furthermore, more recent evidence suggests that what is critical for RAN and reading that also influences the strength of their relation is the task format (i.e., whether symbols or words are presented simultaneously in serial format vs. isolated, in discrete format), the level of reading proficiency (whether beginning or advanced readers are examined), and the task content (i.e., alphanumeric or nonalphanumeric stimuli).

In what follows, I will present empirical evidence and theoretical accounts from earlier and more recent studies examining the serial versus discrete component in naming and reading that has provided new insights on the RAN-reading association. Most importantly, I will focus on the interrelations between serial and discrete tasks in both rapid naming and reading and on the idea that distinct format-specific associations can unravel word reading processes across development, concerning both single-word and multi-word (i.e., word list or text) reading (e.g., Altani, Georgiou, et al., 2017; de Jong, 2011; Protopapas, Altani, & Georgiou, 2013a; Protopapas, Katopodi, Altani, & Georgiou, 2018; van den Boer, Georgiou, & de Jong, 2016).

Serial vs. Discrete Naming

An important distinction in rapid naming tasks appears to lie on the serial vs. discrete format of the tasks: In discrete naming, the stimuli are presented one-by-one for the participant to name them as quickly and accurately as possible, and then wait for the next stimulus to be presented. The time required to name each stimulus is typically measured (i.e., onset latency), and the response time is averaged across trials. In serial naming, all stimuli are presented simultaneously in a grid format, and the participants are required to name the arrays of stimuli in sequential order. The final score is based on the total time required to name all the stimuli in the grid (i.e., response time corresponds to the entire trial), often expressed as the number of stimuli named per second (i.e., naming rate).

The serial format of the naming tasks (i.e., serial naming) has been long known to be a stronger correlate of reading than the discrete format of the task (i.e., discrete naming; e.g., Bowers & Swanson, 1991; Georgiou et al., 2013; Jones, Branigan, & Kelly, 2009; Logan, Schatschneider, & Wagner, 2011; Stanovich, 1981; Stanovich, Feeman, & Cunningham, 1983), indicating that processes specific to its serial format, that are not shared with discrete naming, must be critical for its strong association with reading. Thus, the sequential nature of the serial naming task has been claimed to be a crucial component towards understanding the task itself and its connection to reading fluency.

At the same time, more recent work has suggested that if serial and discrete naming reflect at least partially different processes, examining the relative magnitude of their association with word reading can provide useful information about word reading processes (de Jong, 2011; Logan & Schatschneider, 2014; Logan et al., 2011). For example, it has been claimed that discrete naming, measuring response latency of isolated items, is a more precise measure for speed of lexical access or individual item recognition, as it removes more complex processes (e.g., scanning or tracking multiple items) involved in the serial naming task (Bowers & Swanson, 1991; Logan et al., 2011). Thus, it has been hypothesized that a stronger association between individual word reading and discrete naming compared to its association with serial naming should reflect similar demands of rapid access to the phonological representations of visual stimuli. Based on this notion, Logan et al. (2011) examined the performance of both serial and discrete naming tasks in early reading development with English-speaking children from Kindergarten to Grades 1 and 2. Their results showed that not only discrete naming did not contribute to reading after controlling for serial naming, but also the contribution of serial naming to reading was significant and even increased after accounting for variation in performance on discrete naming. The results of this study were particularly important, as they showed not only that serial naming is a better predictor of reading compared to discrete naming, but also that discrete naming acted as a suppressor variable (see Friedman & Wall, 2005), indicating that serial naming reflects one or more cognitive components not shared with discrete naming, that seems to boost its relationship with reading. The authors rejected the "lexical access" hypothesis, according to which the relationship between RAN and reading relies mainly on the shared requirement of rapid access to phonological codes. Instead, they proposed that task demands specific to the serial format of the task, such as visual scanning, may account for the unique contribution of rapid naming to reading.

Another study included both younger Grade 2 and older Grade 6 children in a different language (Greek; Protopapas et al., 2013a). The results confirmed that among the group of younger Grade 2 readers, discrete naming contributed negatively to word list reading and acted as a suppressor variable, enhancing the contribution of serial naming to word list fluency (i.e., suppressive effect; Protopapas et al., 2013a). Notably, the task of discrete naming in this study included both response latency and production (articulation). Based on this finding, the authors argued that the nature of the association between serial naming and word reading fluency could not be solely attributed to processes involved in discrete naming—from visual identification to word production of individual stimuli. Similarly, other evidence with Greek-speaking children also attending Grades 2 and 6 showed that discrete naming (either with or without articulation) was not a significant predictor of word-list reading after controlling for serial naming (Georgiou, Papadopoulos, Fella, & Parrila, 2012). Thus, the serial component of the RAN task seems to be critical for its association with reading fluency, beyond factors associated with processing of discrete items―from visual pattern recognition to lexical access and all the way to articulatory planning and execution, as described in the letter naming model by Wolf and Bowers (1999).

Moreover, earlier studies have reported that serial naming better distinguishes between poor and good readers (e.g., Perfetti, Finger, & Hogaboam, 1978; Stanovich, 1981; Wolf & Bowers, 1999), while more recent studies have found that difficulties in both naming and reading are significantly amplified in the serial versions of the tasks (e.g., Gasperini, Brizzolara, Cristofani, Casalini, & Chilosi, 2014; Georgiou, Ghazyani, & Parrila, 2018; Zoccolotti et al., 2013; Zoccolotti, De Luca, & Spinelli, 2015). Specifically, Zoccolotti et al. (2013) examined performance on single- vs. multiple-stimulus displays in both naming and reading tasks between a group of older children with dyslexia and a group of peers of typical reading development and reported disproportionate severity of the deficit for the children with dyslexia during naming and reading tasks of multiple-stimulus displays (particularly in serial word reading). These findings suggest that sequential processing of multiple items may be a bottleneck in individuals with dyslexia, beyond a core deficit in word decoding or the speed of single item identification and retrieval (e.g., Gasperini et al., 2014; Zoccolotti et al., 2013; Zoccolotti et al., 2015).

Finally, the serial format of the naming (or word reading) tasks has been found to produce faster naming times compared to the discrete format of the tasks among older children or adults of typical reading development (Jones et al., 2009; Protopapas et al., 2013a; Protopapas et al., 2018; Zoccolotti et al., 2013; Zoccolotti et al., 2015). This evidence provides support for a facilitation effect, expressed as a gain in naming rate, in the serial over the discrete format of naming and reading tasks, at least among advanced (typically developing) readers. This facilitation effect has been termed *serial advantage* (Protopapas et al., 2013a; Protopapas et al., 2018). Moreover, recent evidence has shown that among more advanced readers, naming and reading tasks of the same format are more strongly associated, that is, discrete naming with discrete reading and serial naming with serial word reading (e.g., de Jong, 2011; Protopapas et al., 2013a). This stronger association between serial naming and serial word reading, termed *serial superiority effect* (Altani, Protopapas, & Georgiou, 2017), seems to be strong across development (with both beginning and more advanced readers; de Jong, 2011). Yet, how the serial advantage (gain in serial over discrete naming and reading) is associated with this serial superiority effect (the strong link between serial naming and serial word reading) across development is far from straightforward and requires further investigation.

The Serial Superiority Effect

The idea that *seriality* is crucial in both RAN and reading fluency mainly comes from (a) evidence showing that when stimuli are presented in isolation (discrete naming) the relation between naming and reading is weaker compared to serial naming tasks (e.g., Bowers & Swanson, 1991; Chiappe, Stringer, Siegel, & Stanovich, 2002; Jones et al., 2009; Logan et al., 2011; Stanovich, 1981), (b) evidence suggesting that among readers with dyslexia, difficulties in rapid naming and/or reading are significantly amplified when stimuli are presented simultaneously vs. in isolation (Jones et al., 2009; Zoccolotti et al., 2013; Zoccolotti et al., 2015), and (c) the fact that both standard RAN tasks and reading fluency measures (typically assessed with passages or word lists) include simultaneous presentation of the stimuli (in matrices, lists, or sentences), and thus share the requirement of processing multiple item (symbols or words) in a serial order (e.g., Georgiou et al., 2013).

Some researchers have proposed that the aspect of seriality in RAN and reading may reflect a common requirement for efficient visual scanning, that is the ability to program rapid and accurate eye movements, with a right-side parafoveal advantage (or the other way around for readers in languages like Hebrew; Rayner, 1998), termed visual scanning hypothesis (e.g., Clark, Hulme, & Snowling, 2005; Jones, Ashby, & Branigan, 2013; Jones, Branigan, Hatzidaki, & Obregón, 2010; Kuperman & Van Dyke, 2011). This hypothesis was tested in Protopapas, Altani, and Georgiou (2013b) with Grade 6 children performing a standard-forward RAN task, where stimuli were processed in the reading direction (left-to-right, then downward), and a backward RAN task, where the same stimuli were processed in the opposite direction (right-to-left, then up with a rightward sweep). Results showed that both forward and backward RAN correlated equally well with text and word-list reading fluency, indicating that the key element in the serial superiority effect cannot be attributed to any asymmetry in the perceptual span (resulting from reading practice) or direction-specific visual scanning. A more recent study (Kuperman, Van Dyke, & Henry, 2016) replicated the finding of a strong association between backward RAN tasks and text reading fluency in English, and further advanced a non-directional visual scanning hypothesis.

Other researchers examining eye movements in adult (skilled) readers, proposed that multi-item sequencing and/or oculomotor control may be the crucial component in RAN-type tasks (e.g., Jones et al., 2009; Kuperman et al., 2016). More specifically, Jones et al. (2009) administered a standard task of serial naming, in which multiple stimuli were simultaneously available in a matrix presentation (continuous-matrix), as well as a novel "serial" naming task. In this new "serial" naming task, multiple stimuli were presented serially (one at a time) within a matrix presentation, without being simultaneously visible (i.e., discrete-matrix). The study used this task manipulation to examine the role of oculomotor control vs. multi-item sequencing in RAN: both tasks of continuous-matrix and discrete-matrix required oculomotor control, such as saccadic efficiency from one stimulus to the next one in line. Yet, only the continuous-matrix—where all stimuli were simultaneously available—required participants to manage and coordinate multi-item sequences; because in the version of discrete-matrix, the presentation of the next item and sequencing was externally controlled. A standard discrete naming task was also included as a baseline condition, in which isolated items were presented in a single location (discrete-static). Their results showed that skilled readers and readers with dyslexia differed equally on their performance on the discrete-static and the discrete-matrix task. Instead, the difference between the skilled and impaired readers was significantly greater in the continuous-matrix task. Thus, the ability to coordinate and monitor multiple stimuli (i.e., more than one item at the same time), in order to minimize interference was argued to be the key component in RAN and by extension, in fluent reading (Jones et al., 2013; Jones et al., 2009).

Altani, Protopapas et al. (2017) further examined this idea, hypothesizing that the serial component in RAN and reading may reflect shared demands of executive control, that is, the ability to inhibit previously activated stimuli in the array, update and monitor current and upcoming stimuli, and shift the attention successfully by disengaging from the previous and engaging to the next stimulus in line. The study included executive function tasks (i.e., measuring updating/monitoring, inhibition, and shifting control; see Miyake, Friedman, Emerson, Witzki, & Howerter, 2000), as well as serial and discrete versions of rapid naming and word reading tasks, hypothesizing that if serial naming/reading tasks reflect greater requirement for executive control compared to discrete naming/reading, then executive functions should correlate much more strongly with the serial than the discrete version of naming and reading tasks. Findings showed the opposite pattern, suggesting that the executive functions along with tasks of simple reaction time correlated much more strongly with discrete naming/reading than with serial naming/reading tasks. Importantly, in the executive function (and simple reaction) tasks, stimuli were presented one-by-one on the screen and were processed individually, in a manner that was *exogenously* controlled by the display software, similarly to the way stimuli in discrete naming and discrete reading were displayed and processed. In contrast, in the serial naming/reading tasks, stimuli were simultaneously available and processed by the reader in a self-generated sequential procedure. Based on these findings, Altani, Protopapas et al. (2017) argued that the critical component of serial naming and serial reading lies in the *endogenously* controlled sequential processing of multiple items that are simultaneously available.

More specifically, Protopapas et al. (2013a, 2018) have proposed that the crucial aspect of this sequential—endogenously controlled—procedure in serial naming concerns the ability to simultaneously deal with more than one item at different processing stages: While one item is processed, the previous one is articulated, the next one is viewed, and one further down is previewed, "resulting in an effectively parallel processing pipeline termed *cascaded processing*" (Protopapas et al., 2018, p. 249). That is, efficient serial naming largely lies in the ability to overlap different processing stages across successive stimuli, thus executing different processes (e.g., visual, articulatory, phonological) in parallel or with great overlap to adjacent (previous and following) items, while buffering information and maintaining a tightly packed pipeline of sequential (cascaded) processing. Therefore, the cascaded processing hypothesis implies some temporal overlap between different processing stages of multiple items, potentially accounting for the advantage in naming rate reported in the serial over the discrete versions of the naming and reading tasks. This novel claim that sequential multi-item processing may be a critical component not only in RAN but also in reading fluency will be further examined in this dissertation.

Influence of Task Format and Reading Proficiency

The serial superiority effect—which refers to the well documented finding that serial naming is much more strongly associated with serial word reading compared to discrete naming—implies that RAN and reading measures share the same presentation format, in which all stimuli (words or symbols) are presented simultaneously. However, the distinction between serial vs. discrete task format took a different spin when researchers suggested that we should examine the relation between the two formats not only in rapid naming but also in word reading, by including reading tasks where words are presented simultaneously vs. in isolation (see de Jong, 2011; Protopapas et al., 2013a; van den Boer et al., 2016).

de Jong (2011) was the first to propose that by a closer examination of the two formats of the reading tasks and their distinctive association with serial vs. discrete naming, we could gain important information about word reading processes across development. This idea was based on two main notions: (a) throughout reading development, word recognition undergoes a gradual shift from serial decoding of letter strings to parallel identification of whole word forms (Ehri, 2005), and (b) serial naming is partially distinct from discrete naming, reflecting not only similar, but also different processes (Bowers & Swanson, 1991; Wolf, Bally, & Morris, 1986).

More specifically, according to Ehri's (1995; 2005) theory of sight-word reading development, readers in early development rely predominantly on a serial decoding strategy, sounding out individual graphemes into phonemes (or larger chunks of syllabic units) and blending them into words. As they become increasingly aware— through exposure and practice—of the systematic letter-sound mappings and how smaller units of sounds (syllables, rimes, phonemes) are combined to form words, children build more specific orthographic representations in their memory, and they become able to retrieve letter patterns as whole entities and read words rapidly, by sight. Sight-word reading development is, therefore, described as a connection-forming process, in which the link between the orthographic representation of the word and its phonological code (the link between spellings and pronunciations) is reinforced in memory (Ehri, 2005). In other words, upon seeing the word, its pronunciation and meaning can be immediately or automatically retrieved from memory in a single step, without any sounding out or blending required (i.e., sight word reading; Ehri, 1995). Thus, although children start with slow and effortful serial word decoding, sounding out letters one-by-one, later in development—once this connection-forming process from print-to-sound is established— they become able to recognize words automatically as whole entities.

Turning to the RAN literature, discrete naming has been proposed to be a more precise measure of the speed of lexical access or single item identification and retrieval compared to the more complex serial naming (Bowers & Swanson, 1991; Logan et al., 2011). On the other hand, serial naming is assumed to share all component processes with discrete naming (e.g., visual stimulus recognition, speed of lexical access and name retrieval) except for the requirement of serial processing of multi-elements (Jones et al., 2009; Logan et al., 2011). Thus, it has been proposed that discrete naming can be used as an index of rapid single-item recognition and retrieval (i.e., speed of lexical access), while serial naming can be used as an index of serial processing of multiple elements, beyond the processes involved in discrete naming (e.g., de Jong, 2011; Logan et al., 2011).

Based on this idea, de Jong (2011) hypothesized that the magnitude of the relationship between serial vs. discrete naming and word reading should be influenced by reading proficiency or grade level, based on the reading strategy that readers across development predominantly rely on: If beginning readers deal with individual words by sounding out individual letters and blending them to assemble the word, then discrete word reading should correlate more strongly with serial naming reflecting a serial processing of multiple elements, referring to letter-by-letter (or syllable-by-syllable) internal processing of the letter string. In contrast, if older more advanced readers are able to chunk letter strings into larger units and read single words by sight, then discrete word reading should correlate more strongly with discrete naming, reflecting parallel processing of the letter string and immediate retrieval of the word as a single unit. This hypothesis has been known as *intraword processing hypothesis*.

Based on the intraword processing hypothesis, de Jong (2011) used short, high-frequency words and digit naming tasks in both serial and discrete formats, and examined the magnitude of their relationship among Dutch children attending Grades 1, 2, and 4. Results showed that among beginning Grade 1 readers, discrete (isolated) word reading correlated more strongly with serial naming, consistent with the hypothesis of a serial multi-element internal assembly of the letter string. In contrast, among older readers from Grades 2 and 4, discrete word reading was associated more strongly with discrete naming, suggesting that children in these grades process short, high-frequency words in parallel, as unitized symbols. The serial format of the word reading task (i.e., serial word reading) was associated more strongly with serial naming across grade levels, consistent with the serial superiority effect.

Since then, other studies in consistent orthographies (Dutch: van den Boer & de Jong, 2015; Greek: Protopapas et al., 2013a) have confirmed the intraword processing hypothesis, reporting that serial naming is a stronger correlate of discrete words among beginning readers, while discrete words correlate more strongly with discrete naming (and serial words with serial naming) among advanced readers. Based on this evidence, researchers (Altani, Georgiou, et al., 2017; de Jong, 2011; Protopapas et al., 2013a) have argued that the relation between serial naming and word reading may reflect serial (or sequential) processing of multiple elements within individual words (i.e., *intraword processing*) or across multiple words (i.e., *interword processing*) depending on the format of the word reading task and the level of reading proficiency. In terms of the intraword processing, it has been claimed that the association between serial vs. discrete naming and word reading can provide useful information about the developmental transition from serial, subword decoding to parallel, lexical processing of single words (de Jong, 2011; van den Boer & de Jong, 2015). In terms of the interword processing, the association between serial vs. discrete naming and word reading may provide a link for the shift throughout reading fluency development, from dealing with single words one at a time to managing multiple word sequences in lists or text (i.e., interword processing) (Altani, Georgiou, et al., 2017; Protopapas et al., 2018).

Intraword Processing and Word Recognition

Following de Jong's (2011) work, van den Boer and colleagues (van den Boer et al., 2016; van den Boer & de Jong, 2015) have argued that the relationship between discrete word reading and serial vs. discrete naming can shed light into *intraword* processes, pointing toward an early serial/sublexical vs. a later parallel/lexical processing of words. The idea of a binary serial vs. parallel distinction, in which single words can be processed via either a sublexical or a lexical way, stems from the dual-route theory of the word recognition system (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). The word recognition model (dual-route cascaded model; Coltheart et al., 2001) was developed based on this framework to model how skilled adult readers read aloud single words and specify processes involved in the reading system to achieve the translation from print to sound (from orthographic to phonological unit). According to the model, skilled word recognition—involving the selection of the lexical unit (and pronunciation) that corresponds to the orthographic unit—can be achieved in two ways: either via a lexical or a sublexical route. The former is assumed to be faster and refers to direct connections between orthographic representations and phonological output from the mental lexicon, by converting whole printed words to whole phonological units (direct/lexical activation). The latter refers to a slower more analytic approach, where individual graphemes are mapped to the corresponding phonemes through applying grapheme-to-phoneme conversion rules (indirect/sublexical activation).

One of the main differences between the two ways or routes of word recognition concerns whether parallel or serial processing is involved: In the lexical route, the letter string is processed in parallel. In the sublexical route, the letter string is processed and converted into sound by processing the letters serially, from left to right. van den Boer and de Jong (2015) proposed that a connection between the dual-route assumptions for word recognition and evidence from the serial vs. discrete naming and reading can be used to unravel the internal processing of individual words across development. More specifically, they hypothesized that if word recognition undergoes a developmental shift from slower sequential decoding (sounding out) of words to faster (more) parallel processing of orthographic word forms as whole units (Ehri, 1995; 2005; Vaessen & Blomert, 2010), and if individual words can be processed via a serial/sublexical or a parallel/lexical route (Coltheart et al., 2001), then readers from different grades can be divided into two main groups: novice readers or “serial processors” vs. more advanced readers or “parallel processors”. Based on this idea, van den Boer and de Jong (2015) examined the intraword hypothesis with serial vs. discrete naming and reading tasks and tested whether Dutch readers from Grades 2, 3, and 5 can be classified into these two groups based on the size of the relationship between discrete reading and serial vs. discrete naming. The results confirmed their hypothesis. When clustering the children from the three grades, two classes emerged representing beginning and more advanced readers. In the first class of readers (including mostly younger children), discrete reading was correlated more strongly with serial naming, reflecting serial intraword processing strategies. In the second class of (older, more advanced) readers, discrete reading correlated more strongly with discrete naming, reflecting parallel word reading processes.

Moreover, the way words are processed can be further influenced by word-specific factors (i.e., factors associated with the word itself, such as frequency, length, or lexicality). Theories of reading development (Ehri, 2005; Seymour, 2005) and dual-route models (e.g., Coltheart et al., 2001; Perry, Ziegler, & Zorzi, 2007) assume that familiar words that have been previously encountered and decoded successfully, can be processed in parallel and then rapidly retrieved from the lexicon as whole entities. In contrast, serial/sublexical processing is required for successful reading of unfamiliar words or nonwords. In the case of serial/sublexical processing, the speed of word recognition also depends on its length: If individual letters are processed one after the other, the time to decode the entire letter string increases with every additional letter (Coltheart, 2001).

At the same time, word recognition processes are assumed to be further influenced by orthographic transparency. The degree of correspondence between orthographic and phonological mappings varies across different languages (see Seymour, Aro, & Erskine, 2003). For example, English is considered an orthographically opaque language, as graphemes may correspond to more than one phoneme within different spelling patterns (Seymour et al., 2003). Readers in less transparent orthographies are assumed to rely on larger orthographic units (e.g., letter clusters, rimes) than individual graphemes to reliably recognize words (Ziegler & Goswami, 2005; Ziegler et al., 2010). Thus, it is generally assumed that sublexical analytic processes are more useful in transparent orthographies than in opaque orthographies (where larger orthographic units may be more reliable).

A cross-linguistic study (van den Boer et al., 2016) examined the intraword processing hypothesis across two languages varying in orthographic consistency (Dutch being relatively consistent and English being opaque), including older Grade 5 children and reading tasks of both words and nonwords varying in length (i.e., monosyllabic vs. multisyllabic). van de Boer and colleagues (2016) found that discrete word reading of short and longer words (and short nonwords) correlated more strongly with discrete naming across languages. This finding suggested that more advanced (Grade 5) readers were able to recognize real words of different length or short nonwords as more unitized symbols in both relatively transparent and opaque orthographies. However, longer nonword reading was found to correlate more strongly with serial naming than discrete naming in Dutch, but the association was equally strong with both serial and discrete naming in English. This finding was interpreted as follows: Older readers in English relying on partially different reading strategies from their peers in Dutch when reading multisyllabic nonwords. More specifically, Dutch readers used serial decoding for long nonword reading, while English-speaking readers relied on larger orthographic units to successfully read longer nonwords, consistent with the notion that individual graphemes are not very reliable units in less transparent orthographies (Ziegler et al., 2010).

However, the intraword processing hypothesis (de Jong, 2011; van den Boer & de Jong, 2015) has not been examined across different grade levels in less transparent orthographies like English. Existing studies in English have included mostly intermediate or older (more advanced) readers from a single grade level (Grade 3: Altani, Georgiou, et al., 2017; Grade 5: van den Boer et al., 2016). Previous studies from orthographically transparent languages (Dutch: de Jong, 2011; van den Boer & de Jong, 2015; Greek: Protopapas et al., 2013a) point toward an early serial vs. later parallel processing of individual words. However, these results may not generalize to less transparent orthographies, as a serial/sublexical strategy has been claimed to be less efficient for children who learn to read in an opaque orthography such as English. There is some evidence suggesting that discrete naming, reflecting whole-item processing, is more strongly correlated with discrete (monosyllabic word) reading among Grade 2 children in English (Bowers & Swanson, 1991). Thus, further examination is required towards understanding intraword reading processes across different grade levels within an opaque orthography, using serial vs. discrete naming as indexes of word reading processes.

Interword Processing and Reading Fluency

The ability to read individual words rapidly and accurately is considered an integral component of reading fluency development (e.g., Ehri, 2005; Hudson, Pullen, Lane, & Torgesen, 2008; Stanovich, 1980), and one of the primary educational goals during the elementary school grades. When children become able to process individual words in parallel (by sight; Ehri, 2005) without effortful attention to the mechanics of serial word decoding, higher text-level functions are allowed to take place when reading connected texts (Jenkins et al., 2003; LaBerge & Samuels, 1974; Rasinski et al., 2012; Stafura & Perfetti, 2017). Thus, reading fluency is viewed as comprising component processes within two main aspects: a lower word-level aspect, concerning intraword processes involved in word recognition (i.e., the ability to identify and retrieve single words including lexical and/or sublexical processes), and a higher text-level aspect, concerning supralexical processes (e.g., semantic integration, syntactic processing) involved in connected text reading (e.g., Fuchs, Fuchs, Hosp, & Jenkins, 2001; Hudson et al., 2008; Kuhn, Schwanenflugel, & Meisinger, 2010; Rasinski, Rikli, & Johnston, 2009; Wolf &

Katzir-Cohen, 2001). However, reading fluency is typically assessed by reading quickly and accurately either unconnected word lists (i.e., word-list reading fluency) or connected texts (i.e., text reading fluency). One main characteristic of both word-list and text reading fluency tasks is the requirement of processing multiple words, whether surrounded by other unrelated words or by meaningfully related words forming sentences, which are presented simultaneously―as opposed to reading individual words presented in isolation.

This aspect of multiword vs. isolated word reading (i.e., interword vs. intraword processing) has been recently introduced in the RAN-reading research, with studies using serial and discrete formats of both naming and word reading tasks (Altani, Georgiou, et al., 2017; de Jong, 2011; Protopapas et al., 2013a; Protopapas et al., 2018; van de Boer et al., 2016). Results have shown format-specific associations among tasks of naming and reading in advanced readers, that is, tasks of similar format correlate much more strongly than tasks of different format (i.e., serial reading with serial naming, and discrete reading with discrete naming). This evidence suggests that naming and reading tasks are carried out differently, at least among more advanced readers, based on their presentation format (Altani, Protopapas, et al., 2017).

Notably, Protopapas et al. (2013a, 2018) found that among younger Greek children in Grades 1 and 2, serial word reading was mainly predicted by discrete word reading. Among older Grade 5 and 6 readers, however, the dominance shifted, with serial naming accounting for most of the variability in serial word reading―beyond the effects of discrete naming or discrete word reading. These findings suggested that beginning readers process sequences of multiple words like arrays of isolated words, with intraword reading processes (word recognition efficiency), mainly influencing word list reading fluency. In contrast, advanced readers appeared to process sequences of multiple unconnected words as series of overlearned items (such as digits), with serial digit naming explaining the majority of variance in word list reading fluency, after the efficiency of discrete (intra)word processing was controlled. Moreover, a recent cross-linguistic study with intermediate Grade 3 students (Altani, Georgiou, et al., 2017) replicated the format-specific associations between naming and reading tasks (serial naming with serial reading and discrete naming with discrete reading), and reported that serial digit naming predicts serial word reading beyond the contribution of discrete words equally across a wide range of different orthographies (Korean, Chinese, English, and Greek).

Taken together, these findings suggest that when individual words can be perceived in parallel as unitized symbols (indicated by the strong association between discrete words and discrete naming), sequential multi-item processing skill (indexed by serial digit naming) seems to largely predict individual differences in word list reading fluency. This sequential processing across multiple items has been proposed to be an important component in reading fluency and a missing link in its development (Altani, Protopapas, et al., 2017; Protopapas et al., 2018), potentially accounting for the developmental shift from dealing with one word at a time (i.e., intraword processing) to managing multiword sequences (i.e., interword processing), whether in unconnected lists or connected text. However, much of the previous work on the role of multi-item sequencing in reading fluency included only unconnected word-lists as a reading fluency measure and/or data from orthographically transparent languages (Altani, Georgiou, et al., 2017; de Jong, 2011; Protopapas et al., 2013a; Protopapas et al., 2018; Zoccolotti, De Luca, Marinelli, & Spinelli, 2014). The only existing study conducted in English included only older Grade 5 children (van den Boer et al., 2016). Thus, more research is required using both unconnected word-lists and connected text as reading fluency measures, as well as data from different grade levels, across orthographies to better understand the role of multi-item sequencing in reading fluency development.

Influence of Task Content

Although RAN is typically measured with digits, letters, objects, and colors, there is considerable variability on RAN performance and its relationship with reading based on the different types of stimuli. RAN tasks with nonalphanumeric stimuli, such as colors and pictured objects, are typically used in preschool when students have limited exposure to letters and numbers, or among individuals who have not yet mastered letters and digits for them to be highly familiar (e.g., Lervåg & Hulme, 2009). After the initial exposure to letters and numbers and with increasing literacy development, alphanumeric RAN tends to show higher correlations with reading performance than nonalphanumeric RAN (e.g., Kuperman & Van Dyke, 2011; Lervåg & Hulme, 2009; Misra, Katzir, Wolf, & Poldrack, 2004; Savage & Frederickson, 2005; van den Bos, Zijlstra, & van den Broeck, 2003; see Wolf et al., 1986, for earlier findings). For example, when van den Bos and colleagues (2003) examined an unusually wide age range of Dutch-speaking children attending Grades 2, 4, 6, and 7, adolescents (15-17 years old), and adults (36-65 years old), they found that the increasing correlation between naming and reading across ages was specific to the alphanumeric type of stimuli and did not extend to color or object naming. Furthermore, alphanumeric naming has been found to be a unique predictor of reading even after controlling for non-alphanumeric naming, suggesting that there is something specific to the processing of letters and digits that is strongly associated with word reading (Bowey, Storey, & Ferguson, 2004).

It has been argued that the alphanumeric and nonalphanumeric stimuli differ not only in when and where they are learned, but also in the nature of the sets from which they are derived, and therefore on their inherent properties (Georgiou, 2010; Kirby et al., 2010). In the (letter) naming model developed by Wolf and Bowers (1999), there are no differentiated subcomponents accounting for the distinction between alphanumeric and nonalphanumeric naming; instead, the initial visual feature detection (i.e., letter-pattern identification) is followed by integration of the visual information with stored orthographic and phonological representations, and access to the mental lexicon (semantic access). Nevertheless, because alphanumeric digit naming has been found to correlate equally well with reading as letter naming (e.g., Bowey, McGuigan, & Ruschena, 2005), the strong and increasing relation between reading and alphanumeric naming should not be limited to processing letters, but it should also extend to digit processing.

Researchers have argued that alphanumeric and nonalphanumeric stimuli differ in that both letters and digits can be directly mapped onto arbitrary phonological outputs (through direct nonsemantic visual-verbal mappings), whereas nonalphanumeric stimuli require semantic mediation (through access to the concept of the visual input; Poulsen & Elbro, 2013; Roelofs, 2003; 2006). The WEAVER++ model (Levelt, Roelofs, & Meyer, 1999; Roelofs, 2006) describes in detail the processing stages involved in spoken word production for single digits, pictures/colors and words, which can be summarized in: (a) visual form perception, (b) conceptual identification of the stimulus, (c) lemma retrieval or response selection, (d) word form encoding and motor response programming, and (e) response execution/articulation. According to this model, digit and word naming can be accomplished via parallel activation, which involves a *shallow* direct mapping of the numeric form or orthographic code of the word onto the corresponding word-form output and articulatory program. In contrast, naming colors (or pictured objects) involves activation of the conceptual node, which, in turn, results to an additional planning stage not required in digit naming or word reading.

In a similar vein, Georgiou (2010) proposed that object naming involves access to the semantic lexicon, which corresponds to activation of the semantic information of the visual input (object) and subsequent retrieval of its corresponding label from the long-term memory and its phonological representation prior to articulation. In contrast, oral reading requires mapping of the visual input (word) to its phonological and orthographic code, without semantic processing prior to programming and articulation (see also Liu & Georgiou, 2017).

Therefore, if naming colors or objects requires conceptual mediation, then this additional planning stage should also be reflected on relatively prolonged naming times. Indeed, previous studies have reported that children, as well as adults of typical reading development, are faster in digit or letter naming than in object naming (see Fraisse, 1969; Georgiou et al., 2014; Protopapas et al., 2013a; Protopapas et al., 2018), a finding in line with the assumption that alphanumeric naming is inherently faster than nonalphanumeric naming (Georgiou et al., 2012; van den Bos et al., 2003).

However, serial naming shows an asymmetrical improvement in naming rate compared to discrete naming across development, regardless of task content (Logan et al., 2011; Protopapas et al., 2013a; Protopapas et al., 2018). In fact, it has been reported that among older or skilled readers, performance across various naming tasks is correlated based on the task format rather than the task content. That is, naming tasks of different content, but same presentation format, correlate more strongly with each other (i.e., serial with serial and discrete with discrete) than naming tasks of the same content, but of different presentation format (Protopapas et al., 2013a; Protopapas et al., 2018). Thus, the format-specific association (and the serial superiority effect) that has been reported between naming and reading tasks among older children (e.g., Altani, Protopapas et al., 2017) seems to apply across various naming tasks. Protopapas et al. (2018)

argued that differences between task content impact the degree of efficient sequential multi-item processing in serial naming/reading tasks, based on the level of individual (single-item) processing efficiency and their contextual availability.

Taken together, these findings suggest that there is a dissociation between naming tasks of different content (e.g., alphanumeric or nonalphanumeric). The fact that the way different types of material are processed largely depends on their presentation format, at least among skilled readers, invites a more nuanced perspective on content-specific vs. format-specific variation in naming and reading. Further investigation of the asymmetry in the improvement of serial vs. discrete naming tasks of various types of content is required across development to understand better how processes specific to sequential multi-item processing develop. Moreover, the connection between the format- vs. content-specific associations among different naming tasks and the corresponding serial advantage (i.e., faster naming rates in serial over discrete versions of tasks) across development remains unknown. Finally, it should be considered that the differences in the correlational patterns or overall performance previously observed among alphanumeric and nonalphanumeric stimuli, may reflect the different *materials* (words to be pronounced) rather than differences in the nature of the task content and the type of material *per se*. This aspect was addressed in the present work by carefully matching the items to be named in several linguistics aspects to create comparable measures across conditions, controlling to the extent possible for the word naming demands.

Current Dissertation

This dissertation aimed to address the gap between studies that examine the development of word recognition and intraword processes on the one hand, and studies that examine the development of word reading fluency and interword processing on the other hand, and thus, to provide a potential link between single-word and multi-word reading in the development of reading fluency. It consists of three studies that examine serial- and discrete-trial naming and/or reading tasks across grades, aiming to provide more information about the interaction between multi-element and single-element processes in reading fluency across development.

The first study (see Chapter 2) focused on the development of intraword processing, examining the correlational patterns between serial- and discrete-trial versions of word reading and digit naming tasks among children of different grade levels and reading proficiency in an orthographically opaque language (English). de Jong's (2011) intraword processing line of reasoning was followed, according to which the size of the relationship between serial- and discrete-trials of rapid naming and word reading can reveal whether words are processed via a parallel, automatic processing of orthographic word forms or via a serial, subword decoding strategy. Expanding on previous research initiated by de Jong (2011), the relation between discrete word reading and discrete digit naming, reflecting whole word parallel processing, was expected to increase across grades, based on the idea that word recognition becomes more automatic and words are perceived as unitized symbols. Instead, the relation between discrete word reading and serial digit naming, reflecting sequential intraword processing, was expected to decrease across grades, based on the idea that children in upper grades are expected to rely less on sequential decoding (sounding out) of words. Based on previous findings from orthographically transparent languages, serial digit naming should independently contribute to single word reading, after discrete naming is controlled, only among younger readers, who are expected to rely on sequential intraword processing. In contrast, among older readers, serial naming should not account for unique variance in discrete word reading after discrete digit naming is controlled, as direct lexical processing precludes partial, serial decoding (Coltheart et al., 2001). However, if readers in the orthographically opaque English rely on larger units than phonemes (e.g., rimes) to recognize words (Ziegler & Goswami, 2005) even in early phases of reading development, then discrete naming should be the main predictor of discrete word reading across grades. Serial digit naming was expected to significantly correlate with serial word reading, reflecting the ability to process sequentially multiple words (interword processing).

Chapter 2 also examined the proposal that children from different grades can be grouped into two classes of readers, based on their performance and interrelations patterns among serial vs. discrete digit naming and word reading. According to previous evidence (de Jong, 2011; van den Boer & de Jong, 2015), it was hypothesized that younger children from Grade 1 should be assigned to a "beginners" class of readers who process individual words via a serial manner, whereas older children from Grade 5 should be assigned to the "advanced" class of readers who process individual words in parallel; the majority of children from Grade 3 were expected to be grouped with the older, more advanced readers from Grade 5 since children have largely mastered word recognition skills by Grade 3 (e.g., Kuhn and Stahl, 2003).

The second study (see Chapter 3) focuses on the development of interword processing, as well as on the transition from intraword to interword processing in reading development. One of the main objectives of the second study was to examine the developing interrelations between isolated, discrete word reading and multiple word reading (either in lists or in text). Our hypothesis was that all reading tasks (i.e., discrete word reading, serial word reading, and text reading) would be strongly associated during early reading development, reflecting a general skill of word reading, but the link between discrete word reading and both word list and text reading would decrease across grades, confirming that performance in multiword reading is not exhausted by the efficiency of individual word recognition across languages.

A second objective of the study was to examine the contribution of sequential multi-item processing, indexed by serial digit naming, to reading multiple words (unrelated word lists or connected text). This was examined after controlling for the efficiency of individual word recognition among readers of English and Greek from multiple grades. For this purpose, a simple model with two predictors was tested, namely discrete word reading and serial digit naming. Any intraword (lexical/sublexical) processes required for the efficient recognition of isolated words should be captured by the discrete word reading task. In turn, any requirements specific to processing of multiword sequences involved in the reading fluency tasks of word list and text reading should be captured by the serial digit naming task beyond discrete word reading. Our hypothesis was that serial digit naming, indexing sequential multi-item processing efficiency, would account for unique variance in both word list and text reading fluency—beyond the effect of discrete word reading efficiency— among more advanced readers, confirming and expanding on previous evidence (Protopapas et al., 2013a; Zoccolotti et al., 2014).

Moreover, based on Altani et al.'s (2017) findings, the effects from the two predictors to word list and text reading, as well as the patterns of interrelations among reading tasks were expected to be similar across languages, despite differences in the processing of individual words (intraword processing) due to orthographic consistency. Alternatively, based on evidence pointing toward differences across alphabetic orthographies in the pace of master decoding (e.g., Seymour, Aro, & Erskine, 2003), one might expect that children who are learning to read in the orthographically opaque English may achieve efficiency in intraword processing later compared to their peers in Greek. In this case, the effect from discrete word reading to word list and text reading fluency tasks should differ between languages. Yet, if processes specific to multi-item processing are important for reading fluency, then the effect from serial digit naming to word list and text reading should be similar across languages, despite differences (if any) in individual word (intraword) processing during early reading acquisition.

The third study (see Chapter 4) focused on the development of multi-item processing efficiency (and the corresponding development of single-item processing efficiency) in naming and reading, by tracking the serial advantage (i.e., the gain in naming rate in the serial over the discrete task of the same content), across Grades 1, 3, and 5, and different types of content in English and Greek. The first hypothesis was that serial advantage would increase significantly in higher grades, confirming the asymmetry in the increase of the serial naming rate compared to the discrete naming rate across material types and languages (Logan et al., 2011; Protopapas et al., 2013a; Protopapas et al., 2018). The second hypothesis was that if the serial advantage is content-specific, then different trajectories of serial advantage should be observed across grades for different naming material. Alternatively, if serial advantage is not influenced by content-specific characteristics, similar trajectories of serial advantage development should be observed across naming tasks irrespective of their content.

Another objective of the study (Chapter 4) was to examine how the correlation between naming tasks of different format (but same content) might be associated with their corresponding serial advantage and, subsequently, with the extent to which the serial advantage is associated with improvement in discrete naming (i.e., single-item processing) or processes specific to serial naming, both in group (grade) and in individual analyses level. Specifically, the following hypotheses were tested: If serial advantage depends on the increasing naming rate of individual stimuli (i.e., on the efficiency of single item processing), then a positive association between serial advantage and discrete naming rate should be detected across grades. Alternatively, if the serial advantage is determined by a specific sequential processing skill, then a stronger association between serial advantage and serial naming rate should be observed. Moreover, similar patterns of results in two languages differing in the level of orthographic transparency (English and Greek) would indicate that findings concerning the development of the serial advantage in word reading and rapid naming cannot be attributed to language-specific aspects related to the consistency of the orthography.

The main findings from the three studies are summarized in Chapter 5. Implications and future directions are discussed with reference to the existing literature on (a) word recognition and intraword processing, (b) reading fluency and interword processing, and (c) how these processes develop.

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Chapter 2: Using Serial and Discrete Digit Naming to Unravel Word Reading Processes

Introduction

Rapid, automatic word recognition is viewed as a crucial component of fluent reading (LaBerge & Samuels, 1974; Perfetti, 1985; Wolf & Katzir-Cohen, 2001). In their seminal paper, LaBerge and Samuels (1974) highlighted the importance of automaticity in word reading, arguing that after practice and exposure, letters in words are consolidated in memory and, thus, multi-letter patterns become unitized and are perceived as a single unit. Similarly, when describing the phases of reading development, Ehri (2005) essentially equated fluency with "sight word" reading. Reading by sight means that seeing a word automatically activates its pronunciation and meaning in long-term memory in a single step. As such, in skilled reading (or sight-word reading), individual words are recognized as unitized, whole entities. In contrast, reading speed is slower during the initial phases of reading development, or when the number of letters increases (in multisyllabic words). This is thought to be indicative of serial processing for computing the pronunciations of words, in which graphemes are mapped into their corresponding phonemes one after the other (Ans, Carbonnel, & Valdois, 1998; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Ziegler et al., 2003). As beginning readers become more skilled, word naming speed increases even for longer words, consistent with the idea that word reading becomes less serial and more parallel, at least for familiar words (e.g., Di Filippo, De Luca, Judica, Spinelli, & Zoccolotti, 2006). Thus, the speed with which a printed word is identified and named has been assumed to reflect the way the stimulus is processed and, subsequently, the level of automaticity in word reading (Bowers & Swanson, 1991). In line with this view, Ehri and Wilce (1983) proposed that we can determine whether familiar words are recognized automatically, as completely unitized symbols, when their naming times have reached the same response rate as the naming of single digits.

In a similar vein, response latency to individually presented digits (or other familiar stimuli presented in isolation) has been used as a measure of the speed of lexical access (e.g., Jones, Branigan, & Kelly, 2009; Logan, Schatschneider, & Wagner, 2011; Näslund & Schneider, 1994). In fact, the discrete-trial naming task (where individual items are presented in isolation) has been proposed as a much "purer" measure of name retrieval time or item identification speed compared to the serial naming task (where items are presented simultaneously on a grid), because it eliminates more complex processes, such as sequential response, rapid scanning, and motor-production planning involved in the serial format of the task (Stanovich, Feeman, & Cunningham, 1983; Wolf, 1991). For example, Bowers and Swanson (1991) examined the relationship between serial and discrete versions of digit naming and a discrete version of reading regular and exception words among Grade 2 readers, and reported that discrete naming was a unique predictor of single word reading. Instead, serial naming did not account for any unique variance in single word reading after discrete naming was controlled. Bowers and Swanson claimed that both digit naming and word reading reflect common lexical retrieval processes.

However, several studies have shown that serial naming is a strong predictor of reading fluency (e.g., Georgiou, Parrila, & Liao, 2008; Juul, Poulsen, & Elbro, 2014; Lervåg & Hulme, 2009; Moll et al., 2014; Vaessen & Blomert, 2010; van den Bos, Zijlstra, & Spelberg, 2002; Xue, Shu, Li, Li, & Tian, 2013). In particular, studies that have used both serial and discrete versions of the naming task to predict performance in reading tasks have found that serial naming is a better predictor of reading (e.g., de Jong, 2008; Georgiou, Parrila, Cui, Papadopoulos, 2013;

Pennington, Cardoso-Martins, Green, & Lefly, 2001; Stanovich et al., 1983; Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993). In light of this evidence, researchers have claimed that serial naming involves processes specific to the sequential nature of the task (e.g., rapid eye movement control and efficient scheduling of multiple items) which drive its relationship with reading (e.g., Georgiou et al., 2013; Gordon & Hoedemaker, 2016; Kuperman, van Dyke, & Henry, 2016), beyond the automaticity of name retrieval (e.g., Logan et al., 2011; Stanovich et al., 1983). Recent studies examining this serial superiority effect in the relationship between naming and reading have shown that the way items are presented and processed in both word reading and digit naming can influence the size of their relationship (e.g., Altani, Protopapas, & Georgiou, 2017; de Jong, 2011; Protopapas, Altani, & Georgiou, 2013).

In particular, de Jong (2011) argued that measures of serial and discrete naming of digits can provide insight into the processes involved in word reading. Individual word reading (henceforth, discrete reading) and discrete naming share the demand of rapid lexical access and retrieval from long-term memory. As such, a strong correlation between the two tasks could be indicative of a sight-word reading process. In contrast, the serial version of the naming task—where items are presented simultaneously in a grid format—taps additional processes specific to its sequential nature. Thus, serial naming reflects serial processing demands beyond its shared processes with discrete naming. That is, serial naming and discrete naming presumably involve the same cognitive processes (e.g., identification of visual information, print-to-sound mapping, articulatory demands) except for the component of sequential processing (e.g., Logan et al., 2011). Hence, it has been argued that a strong relationship between serial naming and reading arrays or lists of words (henceforth, serial reading) reflects similar task demands of sequential processing over series of items. By analogy, a strong relationship between serial naming and discrete word reading reflects a serial decoding strategy in word recognition, because in this case, sequential processing concerns series of items (i.e., letters, graphemes, or syllables) within individual words.

Evidence from Dutch (de Jong, 2011; van den Boer & de Jong, 2015), a relatively transparent orthography, suggests that the pattern of relationships is in favor of a more serial decoding strategy in the early phases of reading development (Grades 1 and 2), in which stronger correlations between discrete word reading and serial naming were observed. In contrast, in later phases of reading development (Grades 4 and 5), or amongst groups of more advanced readers, discrete word reading is more strongly associated with discrete naming, reflecting sight-word reading. Protopapas et al. (2013) found similar results in Greek, which is also a relatively transparent orthography. More specifically, they reported format-specific relationships between naming and reading tasks among a group of older children (Grade 6), that is, a stronger association between discrete naming and discrete reading, and between serial naming and serial reading. In contrast, a strong association was found between serial naming and both discrete and serial reading among a group of younger children (Grade 2). Thus, although serial naming is strongly associated with serial reading throughout development, its relationship with discrete reading can be indicative of word reading processes when compared to discrete naming across different ages.

Expanding on this rationale, van den Boer and de Jong (2015) proposed that readers can be divided into two groups (or classes), namely serial and parallel processors, based on the size of the relationship between discrete word reading and serial vs. discrete naming. In their study, they found that when clustering Grade 2, 3, and 5 readers using factor mixture analysis, two classes emerged, representing beginning and more advanced readers. Within the first class of (mostly younger) readers, serial naming correlated more strongly with discrete reading, reflecting serial word processing strategies. In contrast, among the (more advanced) readers in the second class, discrete naming correlated more strongly with discrete reading, reflecting sight-word processing.

Additional findings from a cross-linguistic study have confirmed the strong relationship between discrete naming and discrete word reading among Grade 5 Dutch- and English-speaking children (van den Boer, Georgiou, & de Jong, 2016). Van den Boer et al. used both real words and nonwords varying in length and found that discrete naming correlated more highly with discrete reading of short words and nonwords, as well as with longer words, in both languages. This suggests that advanced readers recognize words as whole entities in both relatively transparent and opaque orthographies. Yet a stronger correlation was reported between serial naming and multisyllabic nonword reading in Dutch, whereas in English the relationship of longer nonwords with serial naming and discrete naming was equally strong. Van den Boer et al. argued that long nonwords required a more serial within-word processing strategy in Dutch. In contrast, Grade 5 readers in English had to rely on larger orthographic units to reliably recognize longer nonwords, because individual graphemes are not very reliable units in opaque orthographies (Ziegler & Goswami, 2005).

The studies examining the relationship between serial/discrete naming and serial/discrete reading across ages have so far been conducted in relatively consistent orthographies (Dutch and Greek). Studies in English (an opaque orthography) have examined only advanced readers (van den Boer et al., 2016) or only discrete reading (Bowers & Swanson, 1991). Even though serial naming appears to predict discrete reading in younger readers (Grades 1 and 2) in transparent orthographies, there is some evidence (Bowers & Swanson, 1991) to the effect that discrete naming, reflecting unitized item processing, is more strongly associated with discrete reading among younger readers (Grade 2) in English. It has thus been claimed that a serial decoding strategy is less efficient in opaque orthographies, where grapheme-to-phoneme mappings are not reliable (Ziegler et al., 2010). To address this matter, the present study examined the association between digit naming and word reading, in both serial and discrete formats and over a wide range of grade levels (1, 3, and 5) in English, in order to understand the role of serial and discrete naming as indexes of word reading processes across development in an opaque orthography. To our knowledge, this is the first study to systematically examine the relationship between serial and discrete naming and serial and discrete reading in English, including beginning, intermediate, and advanced readers.

Based on de Jong's (2011) findings, we would expect the following: (a) Serial naming will strongly correlate with serial reading across grades, reflecting sequential processing across multiple items in both tasks, that is, sequences of digits and sequences of words. (b) The relationship between discrete naming and discrete word reading will increase across grades, reflecting attainment of efficient whole-word processing (i.e., "sight word" reading) rendering words effectively equivalent to unitary symbols. In conjunction with that, (c) the relationship between serial naming and discrete word reading will decrease across grades, reflecting diminishing within-word sequential processing (e.g. serial letter-by-letter or grapheme-by-grapheme) as words are increasingly read "by sight". Moreover, we would expect serial naming to independently contribute to single word reading, after discrete naming is controlled, only among younger readers, who are expected to still employ sequential within-word processing. In contrast, among older readers, serial naming should not account for additional variance in discrete word reading when discrete naming is controlled, because sight word reading specifically precludes partial, serial processing. However, if readers in English rely on larger units than phonemes to efficiently recognize words from early stages of reading, then discrete naming should be the main predictor of discrete word reading across grade levels.

In addition, we examined whether children from different grades can be grouped into two classes of readers. Based on previous findings in Dutch (de Jong, 2011), most Grade 1 children should be assigned to a "beginner" class of readers, purportedly processing individual words in a serial manner; therefore serial naming should be the main predictor of discrete word reading in this class. In contrast, most Grade 5 children should be assigned to the "advanced" class of readers, purportedly processing words in a parallel manner; therefore discrete naming should be the main predictor of discrete word reading in this class. Finally, because by Grade 3 children have largely mastered word recognition skills (e.g., Kuhn & Stahl, 2003), we expected that the majority of children from this grade level would be grouped together with the more advanced Grade 5 readers.

Method

Participants

Four hundred twenty-nine English-speaking Canadian children from Grades 1, 3, and 5 (Grade 1: N = 167, 87 girls, age M = 81.41 months, SD = 4.22; Grade 3: N = 137, 64 girls, age M = 105.75, SD = 3.94; Grade 5: N = 125, 70 girls, age M = 129.70, SD = 4.17) participated in the study. All children were recruited on a voluntary basis from eight public elementary schools located in different parts of Edmonton (to represent as much as possible different demographics in our study). The schools can be characterized as average-performing (based on Provincial Achievement Tests) serving primarily middle-class families (based on parents' education and teachers' reports). Based on the schools included in our study and the demographics of the students they have traditionally been serving, our sample could be considered representative of the general student population of Alberta. All children were native speakers of English (English language learners who did not have at least three years of schooling were excluded to avoid confounding the effects of learning English at the same time as learning to read) and had no formal diagnosis of intellectual, behavioral, or sensory difficulties. Parental and school consent, as well as research ethics approval, were obtained prior to testing.

Materials

Materials consisted of digits and words. The naming tasks included nine repetitions of four digits (2, 3, 5, and 6). The reading tasks included two sets of 36 high frequency words. All items in the naming and reading tasks were monosyllabic words, varying in length between three to five letters. Also, items were matched between the naming and reading tasks in several variables, including frequency, number of phonemes, number of graphemes, and syllabic structure, in order to keep naming demands constant across naming and reading conditions to the extent possible. Word frequencies were derived from the Children's Printed Word Database, which includes words that appear in books for children in Grades 1–4 (Masterson, Stuart, Dixon, & Lovejoy, 2010).

Procedure

Digit naming and word reading tasks were presented in both serial and discrete format. In the serial format, all 36 digits were presented in a matrix of four rows by nine items. All 36 words of the serial reading task were also arranged in a 4 rows × 9 items format to match the presentation of the serial naming task. In the discrete format, all items of the naming and reading tasks were presented one-by-one in the middle of the screen in a fixed quasi random order precluding immediate repetitions (Figure 2.1). For both serial and discrete tasks, children were asked to name out loud the items or read the words as quickly as possible. Instructions and practice items were provided prior to each trial to ensure compliance with task demands.

Item presentation and response recording was controlled by the DMDX experimental display software (Forster & Forster, 2003). Items were presented in black 20-pt Consolas font on a white background and remained on the screen until the experimenter pressed a key to proceed to the next item, as soon as complete production of a response was registered. Individual responses were recorded in audio files through a head-mounted microphone.

Testing took place in April-June (near the end of the academic year). The naming and reading tasks were administered in random order during a 40-minute session within a larger testing battery. Children were tested individually in their school during school hours by trained assistants.

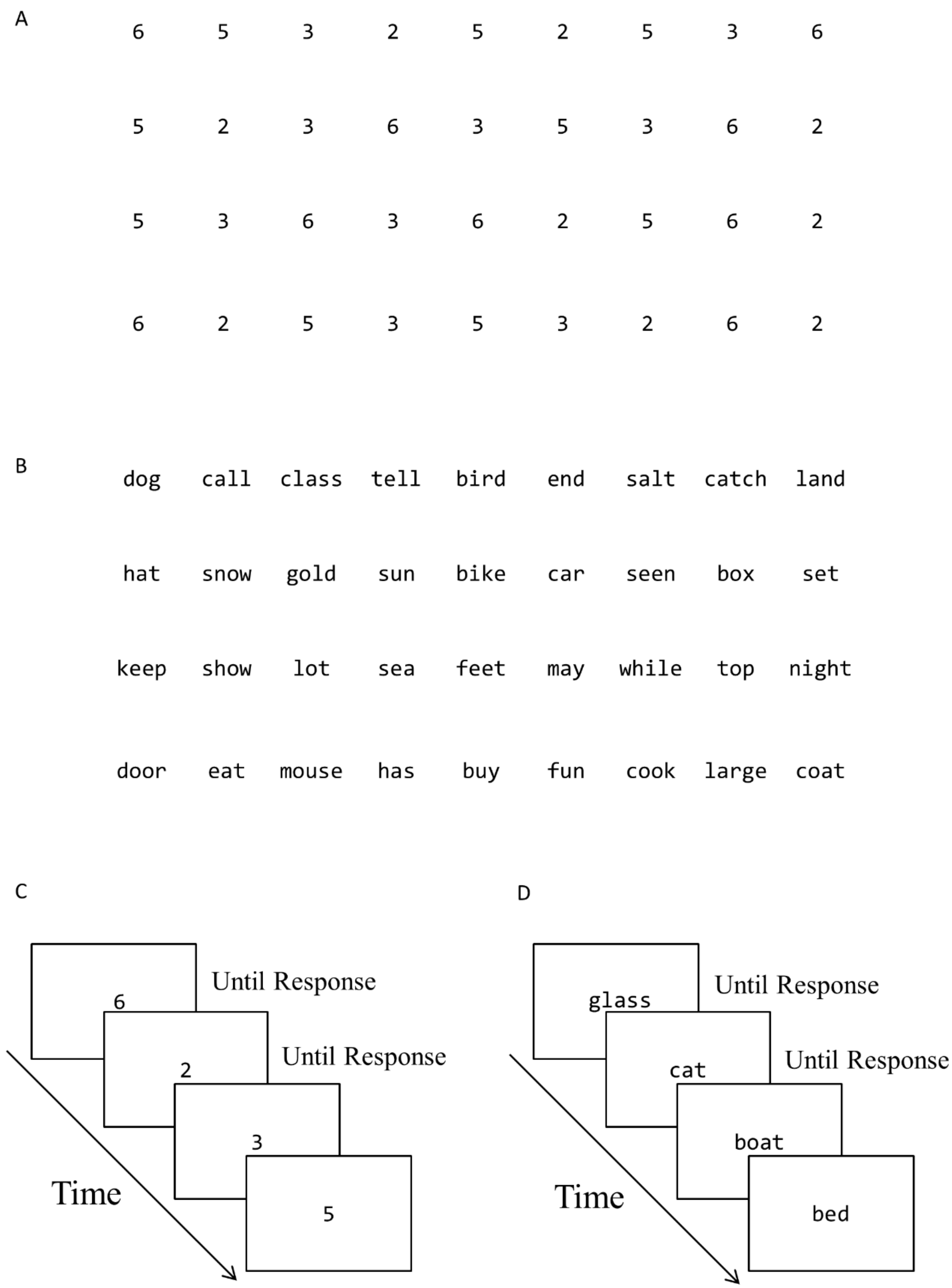

Figure 2.1. Examples of task presentation and trial sequence. (A) Serial digit naming. (B) Serial word reading. (C) Discrete digit naming. (D) Discrete word reading.

Results

Data Preparation

Total naming or reading time was determined off-line using CheckVocal (Protopapas, 2007). For serial tasks, total naming or reading times of the entire array were processed; for discrete tasks, naming or reading times of individual items were processed. All recorded response times (RTs) analyzed below included both onset latency and articulation time, to be fully comparable across formats. RTs were subsequently transformed to a scale of “items per second”. For discrete tasks, a single score for each participant was computed by averaging RTs across correctly named or read items. Intraclass correlation coefficient (ICC) for a two-way mixed model was computed to estimate inter-rater reliability (IRR) for a sub-sample of mean response times (across 22 subjects and 2 raters) using icc function from irr package in R (McGraw & Wong, 1996). The ICC can range from 0 to 1, with higher ICC (close to 1) indicating smaller-magnitude disagreements (Hallgren, 2012). The resulting ICC was high (0.99; 95%CI: 0.98 – 0.99), indicating excellent IRR in coding response times and suggesting that a minimum amount of measurement error was introduced in data processing by independent coders.

Errors in serial digit naming were ignored. Errors in serial word reading were analyzed and an accuracy level of 70% correct was used as a cut-off score. This criterion was selected based on previous evidence showing that speed of word recognition begins to develop only when this basic accuracy level of 70% correct is achieved among children in early elementary school grades (Juul et al., 2014). Table 2.1 shows the descriptive statistics on each measure excluding data points associated with outliers (three children in Grade 3 and three in Grade 5), accuracy below 70% in both discrete and serial reading tasks (65 children in Grade 1 and one child in

Grade 3), overall accuracy <67% (three children in Grade 1), or technical problems (two children in Grade 1 and five children in Grade 3). This cleaning procedure left us with 99 complete cases in Grade 1, 129 in Grade 3, and 122 in Grade 5. Examination of Q-Q plots and Shapiro-Wilk tests indicated no significant deviations from normality. All analyses were conducted using R (R Core Team, 2016) with the cleaned-up dataset. Results from previous studies reporting concurrent correlations (or regressions) are included in the supplementary material (Tables S2.1-S2.4; S2.7) for comparison. Results for the hierarchical regression analyses (Table S2.4) of the sample reported in Protopapas et al. (2018) were derived from a re-analysis of the original dataset.

Table 2.1

Descriptive Statistics with the Final Dataset in Each Grade

Grade 1		*N*	*M*	*SD*	Skew	Kurt
Serial	digits	99	1.23	0.3	0.12	−0.05
	words	97	0.94	0.38	−0.04	−0.93
Discrete	digits	99	0.85	0.14	0.25	−0.55
	words	99	0.72	0.16	0.01	0.09
Grade 3		*N*	*M*	*SD*	Skew	Kurt
Serial	digits	129	1.69	0.39	0.27	−0.20
	words	129	1.57	0.38	−0.14	−0.57
Discrete	digits	129	1.03	0.14	0.04	−0.17
	words	129	0.98	0.13	0.09	0.66
Grade 5		*N*	*M*	*SD*	Skew	Kurt
Serial	digits	122	1.92	0.38	0.29	−0.38
	words	122	1.8	0.37	0.11	−0.40
Discrete	digits	122	1.17	0.13	0.01	0.38
	words	122	1.09	0.12	−0.30	−0.03

Note. Skew = skewness; Kurt = kurtosis. The scores are presented in items per second (words or digits).

Correlation Analyses by Grade

Table 2.2 presents the correlation coefficients among discrete and serial versions of digit naming and word reading in each grade. Correlations between serial words and serial digits were moderate to strong (r = .30 – .61) across the three grades. Correlations between discrete digits and discrete words were strong already by Grade 1 (r = .51) and remained strong across grades (Grade 3: r = .64; Grade 5: r = .78); whereas correlations between serial naming and discrete words remained relatively weaker across grades (Grade 1: r = .36; Grade 3: r = .18; Grade 5: r = .42). The correlation between serial and discrete versions of words or digits was strong in Grade 1 (words: r = .78; digits: r = .57), yet moderate in Grade 5 (words: r = .49; digits: r = .39). A set of scatterplots among serial and discrete tasks for each grade is also provided in the Supplementary Material (Supplementary Figures S2.1–S2.3)

Table 2.2

Correlations (Pearson's r) Among Discrete and Serial Digit Naming and Word Reading Across Grades

	s_Words		d_Words		s-d correlations	
	d_Digits	s_Digits	d_Digits	s_Digits	Words	Digits
Grade 1	.24	.30	.51	.36	.78	.57
Grade 3	.26	.56	.65	.18	.52	.33
Grade 5	.34	.61	.78	.42	.49	.39

Note. d = discrete; s = serial.

Regression Analyses by Grade

Because serial and discrete naming share several important components (e.g., mapping from print to sound, rapid retrieval of the lexical code, articulatory demands), we performed hierarchical regression analyses to examine the unique contribution of the serial and discrete dimension of the naming task to word reading in each grade. Serial and discrete naming tasks were entered into the regression equation either in the first or in the second step in order to examine their effects on serial and discrete word reading separately, after the variable in the first step was controlled. The unique variance accounted for by each task entered in the second step is reported in Table 2.3.

Table 2. 3

R^2 Changes in Hierarchical Regression Analyses Using Serial and Discrete Digit Naming to Predict Serial and Discrete Word Reading Across Grades

	Grade 1		Grade 3		Grade 5	
Digit Naming	Serial Words	Discrete Words	Serial Words	Discrete Words	Serial Words	Discrete Words
1. Serial	.08*	.12**	.33**	.03*	.37**	.17**
2. Discrete	.01	.16**	.02	.37**	.01	.45**
1. Discrete	.05*	.28**	.10*	.40**	.11*	.61**
2. Serial	.04*	.01	.25**	.00	.27**	.01

Note. * $p < .05$; ** $p < .0005$.

Following de Jong (2011), serial naming reflecting letter-by-letter serial processing should be the main predictor of word reading (both serial and discrete) in early grades, while discrete naming reflecting sight-word reading should become the dominant predictor of word recognition (i.e., discrete reading) in upper elementary school grades. The results in Table 2.3 show that when discrete naming was entered first, serial naming accounted for unique variance (4–27%) in serial word reading across grades, whereas discrete naming did not account for unique variance in serial word reading after the effects of serial naming were controlled for. In contrast, no unique variance in discrete word reading was left to be explained by serial naming after discrete naming was entered first in the regression equation—not even in Grade 1.[1] When serial naming was entered first, the contribution of discrete naming to discrete word reading remained significant across grades (explaining 16–45% of unique variance). Overall, the contribution of discrete naming to discrete word reading increased across grade levels (from 16% of unique variance in Grade 1, to 37% in Grade 3, and 45% in Grade 5), after partialling out the effects of serial naming (see also Table S2.6 for results from commonality analyses performed across grades).

Analyses by Performance-Based Groups

Following de Jong's (2011) suggestion that, because of unequal rates of reading skill development, the division of children into grades might not reflect their true classification as readers, but alternatively a classification based on their performance profiles should be preferred, we performed factor mixture modeling analysis to cluster our sample into groups based on task performance patterns. Factor mixture modeling can be used to distinguish latent classes from unobserved sources of heterogeneity of the sample based on mean performances and interrelations of the observed variables (Cagnone & Virolli, 2012). Four variables were used in the current analysis, including serial and discrete digit naming and serial and discrete word reading. Factor mixture modeling was performed using R package OpenMx 2.0 (see Boker et al., 2016, pp. 86–89). Following de Jong (2011; van den Boer & de Jong, 2015; as clarified by de Jong, personal communication, August 2017), we fit a two-class mixture model to cluster

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[1] Hierarchical regression analyses including the entire Grade 1 sample (excluding only those students who scored below 30% correct in the serial and discrete word reading) showed that the pattern of results did not differ between Grade 1 children who scored above 70% correct versus Grade 1 children who scored above 30% correct in both serial and discrete reading tasks (see Table S3.5 in supplementary material).

participants into two unobserved latent classes reflecting the hypothesized two groups of readers, namely, readers with different patterns of correlations among naming and reading tasks, reflecting different word processing strategies. Because we were interested in modeling the performance levels and their interrelations among the four individual tasks, rather than their shared variance as captured by latent factors, the model included four dummy latent factors with variance fixed at one and freely estimated mean. Each latent was indicated by a single task with residual variance fixed at zero, mean fixed at the observed value, and freely estimated loading. Class probabilities based on Bayes rule (Estabrook, 2010) were used to classify children into the two groups.

Table 2.4 shows the allocation of children to classes for each grade. The correlations between discrete and serial reading and naming tasks in the final two-class solution are shown in Table 2.5. In both classes, serial word reading correlated more strongly with serial naming (r = .26 in Class 1 and .65 in Class 2) than with discrete naming (–.08 and .39, respectively). The two formats of word reading were more strongly correlated in the first class (.86) than in the second class of readers (.53). Discrete word reading correlated more strongly with discrete naming (.79) than with serial naming (.44) in Class 2, but not in Class 1 (.15 and .28, respectively). In fact, the correlations between discrete naming and both formats of word reading were not significant in Class 1. Thus, only serial naming correlated significantly with discrete word reading among the first group of readers.

Table 2.4

Number of Children in Each Class

Subgroup	Total	Grade 1	Grade 3	Grade 5
Class 1	83	70	11	2
Class 2	265	27	118	120

Comparisons of correlation coefficients between the two classes via z transformation (Cohen & Cohen, 1983) as implemented in the multilevel package (Bliese, 2016), showed that the serial and discrete versions of word reading were more strongly correlated in the first class than in the second class. Moreover, the relationship between discrete reading and discrete naming was higher in the second class than in the first class of readers, whereas the relationship between discrete reading and serial naming did not differ significantly between the two classes of readers.

Table 2.5

Correlations (Pearson's r) Among Discrete and Serial Digit Naming and Word Reading in Each Class.

	s_Words		d_Words		s-d correlations	
	d_Digits	s_Digits	d_Digits	s_Digits	Words	Digits
Class 1	–.08	.26	.15	.28	.86	.52
Class 2	.39	.65	.79	.44	.53	.47
Z	3.85*	3.99*	7.21*	1.44	5.51*	0.52

Note. d = discrete; s = serial; Z = *z*-score value to estimate the size of the difference between the two correlation coefficients.

Finally, hierarchical regression analysis was performed using serial and discrete naming to predict serial reading and discrete reading in each class separately (Table 2.6). In the first class, serial naming was the main predictor of both formats of word reading. In the second class of readers a different pattern emerged, with serial naming being the main predictor of serial reading and discrete naming the main predictor of discrete reading. In fact, the contribution of discrete naming to discrete word reading was significant only in Class 2. In contrast, serial naming was consistently a unique predictor of serial word reading across classes. Notably, the coefficient of discrete naming predicting serial word reading was negative in the first class of readers, while serial naming not only was a unique predictor of serial reading, but also its contribution increased with discrete naming controlled for, signaling the presence of a suppressive effect (see Logan et al., 2011).

Table 2.6

R^2 Changes in Hierarchical Regression Analyses Using Serial and Discrete Digit Naming to Predict Serial and Discrete Word Reading in Each Class

	Class 1		Class 2	
Digit Naming	Serial Words	Discrete Words	Serial Words	Discrete Words
1. Serial	.06*	.07*	.42**	.19**
2. Discrete	.06*	.00	.01	.44**
1. Discrete	–.01	.01	.15**	.63**
2. Serial	.12*	.06*	.28**	.00

Note. * $p < .05$; ** $p < .0005$.

Discussion

The purpose of this study was to examine the relationship between serial and discrete naming and reading across three separate grade levels in English, using naming tasks to index word reading processes. Our results showed that (a) the contribution of serial and discrete naming to word reading is distinct beyond any shared variance, and (b) the serial and discrete naming and—especially—reading tasks start off as rather similar, yet their relationship gradually decreases with age and reading proficiency.

Serial vs. Discrete Dimension in Naming and Reading

One of our main hypotheses was that the relationship between discrete reading and discrete naming should increase with age, as word recognition becomes more automatic and words are perceived as whole units ("sight words"). In contrast, the relationship between discrete reading and serial naming, reflecting serial processing within the word (letter-by-letter), should decrease with age. In line with our hypotheses, the correlation between discrete words and discrete naming increased across grades, consistent with the idea that individual words are recognized as whole units—similarly to single digits—among more advanced readers. In contrast, the relationship between serial naming and discrete reading remained rather stable across grade levels, a finding which is at odds with the idea that serial naming indexes serial within-word processing. This could mean either that Grade 5 readers of English are not sight-word readers, even of short, familiar, and frequent words; or that a correlation with serial naming does not in fact imply within-word serial processing (hence precluding sight-word reading). But is this finding truly novel and discrepant? In fact, a similar pattern of associations between serial naming and discrete reading has been observed in previous studies in transparent orthographies (see Table S2.1), suggesting that the link between the two domains may not strictly reflect a serial item-by-item processing per se. Additionally, our results showed that the correlation between serial naming and serial reading increases with age; a finding consistent with previous evidence in other languages (see Table S2.2), suggesting that reading series of words gradually becomes more similar to naming series of overlearned symbols.

To address this conundrum, we examined the unique contribution of serial vs. discrete naming to word reading beyond any shared variance. Serial naming was found to be a unique predictor of serial reading across grades, consistent with previous findings in transparent orthographies indicating a serial superiority effect (see Table S2.4). Notably, serial naming did not account for any unique variance in discrete word reading in our study, not even among younger readers. This finding contradicts previous studies in transparent orthographies (see

Table S2.4), in which serial naming was a unique predictor of discrete word reading among novice readers (de Jong, 2011; Protopapas et al., 2018). However, a closer look at the results of the re-analyzed data from Protopapas et al. (2018) suggests that serial naming is not a better predictor of discrete reading compared to discrete naming among Grade 1 Greek readers (see Table S2.4). Similarly, a previous study among Grade 2 English-speaking children found that serial digit naming did not contribute additional variance to individual word reading speed after discrete digit naming was controlled for (Bowers & Swanson, 1991), consistent with our findings.

One could interpret this pattern of results according to theories suggesting that readers in opaque orthographies like English rely mostly on larger orthographic units for efficient word recognition (e.g., Ziegler & Goswami, 2005). Indeed, the absence of a significant effect from serial naming to discrete word reading as early as Grade 1 in our study presumably reflects an increased requirement to proceed faster to unitization of items (i.e., chunking) for efficient word recognition in English. Moreover, the words in our study were chosen to be familiar to the children, and were short and easy enough to be read correctly by most first graders. Therefore, they were especially likely to have attained sight-word status among the better readers in our sample. However, the fact that similar patterns of results were evident in a relatively transparent orthography (Greek) with longer (two-syllable) words (see Table S2.4) suggests that differences based on orthographic transparency cannot entirely explain the observed pattern of results in our study.

From Binary Distinctions to Flexibly Adjustable Processing

Alternatively, a significant effect from serial naming to discrete reading may imply a more dynamic skill of processing multiple elements in a sequential manner. That is, the extent of sequential processing demands in discrete word reading – reflected by the size of its relationship with serial naming – may vary as a function of word length (within a language) or language-specific characteristics (across languages). In accord with this idea, van den Boer et al. (2016) found that serial digit naming uniquely predicted discrete reading of multisyllabic nonwords among Grade 5 Dutch-speaking children, whereas both serial and discrete digit naming predicted discrete reading of multisyllabic nonwords among Grade 5 English-speaking children, suggesting that within-word sequential processing requirements are affected by item-specific and general orthographic factors, and are therefore not entirely determined by individual differences in general reading skill.

In our study, high-frequency, short and highly familiar words were used, probably limiting the extent to which sequential processing was required for word recognition, even for less advanced readers. This might also explain previous findings in van den Boer and de Jong (2015) showing that serial naming was a better predictor of single word reading compared to discrete naming among Grade 2 readers (see Table S2.4): Their use of words varying in length and frequency may have increased the demand for sequential within-word processing among the younger children they studied. Similarly, evidence from Greek (see Table S2.4; Protopapas et al., 2018) showing that serial naming predicts discrete word reading among the younger Grade 1 and Grade 3 readers might be due to the fact that two-syllable words were used in that study, presumably resulting in at least some sequential within-word processing requirements (see also Altani, Georgiou, et al., 2017, for related discussion).

Thus, the magnitude of the relationship between serial naming and discrete word reading might be dynamically adjusted based not only on grade level or reading proficiency, but also on word-specific or orthographic system characteristics, indicating a sequential processing continuum rather than a binary distinction (i.e., serial vs. parallel processing) either among readers or among items. Notably, the binary theoretical distinction between a supposedly parallel lexical vs. a supposedly serial sublexical reading route has also been challenged by previous studies using serial and discrete naming to index word processes. Specifically, van den Boer and de Jong (2015) and van den Boer et al. (2016) found that naming single digits predicts discrete reading of not only short words but also nonwords among advanced readers, suggesting that reading processes for familiar words and nonwords are similar, in sharp distinction to fundamental dual-route assumptions.

Finally, the finding that discrete naming accounted for unique variance in discrete word reading after serial naming was entered in the regression equation across grades – a finding also observed in other studies (see Table S2.4) – indicates that what is shared between discrete naming and discrete word reading is not included in the shared variance between discrete and serial naming. This may seem contradictory to the notion that serial naming shares everything with discrete naming except for the demands involved in sequential processing, and that, therefore, when accounting for serial naming, no additional variance should be left in discrete reading to be explained by discrete naming. This apparent contradiction can be explained by considering that it is possible for two tasks depending on mostly overlapping processes to be only weakly correlated, if the variance in the nonshared element(s) dominates overall performance. In particular, serial naming seems to be dominated by the ability to sequentially process multiple items, rather than by single element naming processes (evidenced by the moderate correlations between discrete and serial naming). As such, individual differences in serial naming, to a large extent, reflect variability in skills associated with efficient scheduling of sequences, where multiple processes occur simultaneously, rather than with the total recognition time for each individual item within the series. Consistent with this explanation, it has been shown in both our results (see Table 2.6) and previous studies that the effect of serial naming to serial reading increases when discrete naming is entered in the regression equation, indicating suppression from discrete naming to serial reading (e.g., Logan & Schatschneider, 2014; Logan et al., 2011; Protopapas et al., 2013), and thus suggesting that the serial dimension in naming (and reading) is largely independent from the speed with which individual items are processed within the discrete dimension of the tasks.

Grouping Children into Classes

As hypothesized by de Jong (2011) and confirmed by van den Boer and de Jong (2015) for Dutch children, our latent class analysis showed that the assumption of equal development among all children within a grade group was not optimal, as about 30% of the children in Grade 1 were assigned to the second class of more advanced readers, along with most of Grade 3 and Grade 5 children, indicating that there is no substantial difference in the way serial and discrete reading and naming tasks are performed between these two grades, at least as can be determined by their patterns of performance and interrelations.

Interestingly, when one third of Grade 1 students were classified as Class 2 readers, the pattern of results for Class 1 (Tables 2.5 and 2.6) departed from that for the whole of Grade 1 (Tables 2.2 and 2.3). Specifically, the correlation between discrete naming and discrete reading became insignificant, while serial naming became a significant predictor of single word reading among this group of beginning readers. These findings are consistent with those of a previous study from an orthographically transparent language (Dutch), indicating that the class of novice readers process single words in a serial manner (de Jong, 2011; see Table S2.7). However, a more recent study in Dutch found that discrete reading correlated equally with discrete and serial naming among Class 1 readers (van den Boer & de Jong, 2015; see Table S2.7). These inconsistent findings could be explained by differences in the composition of the first class of readers by students from various grade levels. More specifically, in both our study and de Jong (2011), most of the children assigned to Class 1 were from Grade 1 (see Table S2.8). Instead, in van den Boer and de Jong (2015) most of the children assigned to Class 1 were from Grade 2 (because Grade 1 children were not included in that study; see Table S2.8). At the same time, a large proportion of Grade 2 children in the previous studies was classified into the second group of more advanced readers, where discrete naming was the main predictor of single word reading. Hence, it seems that by Grade 2 (and Grade 3), the majority of children are able to read short familiar words by sight.

In sum, this line of evidence suggests that the degree of sequential within-word processing in the first group of readers is dictated, at least partially, by the level of reading proficiency of the students assigned in the group. At the same time, previous evidence showing that not only serial but also discrete naming correlates significantly with single word reading among the first class of readers, can be indicative of an intermediate phase where readers may process (at least some) words in chunks larger than individual letters, without having fully mastered sight-word reading, thus suggesting that serial and parallel processing of words are not mutually exclusive. In addition, our finding that one third of Grade 1 students were assigned to the second class of readers indicates that a significant proportion of children from this grade level have already mastered sight-word reading, at least for high-frequency, short words.

One clear distinction that emerged between the two classes of readers was in terms of the size of the relationship between serial and discrete word reading. This correlation was very strong in the first class of readers but substantially weaker in the second class (Table 2.5), suggesting that for beginner readers, serial and discrete versions of word reading are almost identical, whereas for the second class of readers, word reading tasks become fairly different depending on their presentation format (serial vs. discrete). This finding is consistent with previous evidence showing a common underlying structure based on task content (reading vs. naming) early in development, whereas in later development a task format structure (serial vs. discrete) predominates (Protopapas et al., 2013). Thus, other skills associated with sequential processing of multiple items appear to be crucial for emerging serial word reading fluency (Gordon & Hoedemaker, 2016; Protopapas et al., 2018; Zoccolotti, De Luca, & Spinelli, 2015), beyond individual item properties or word name retrieval speed. Recent evidence is in line with this idea, suggesting that tasks in which individuals are asked to process strings of visual symbols, requiring rapid eye movement control and efficient simultaneous processing of multiple items, are strong predictors of early and later reading performance (Kuperman et al., 2016; Onochie-Quintanilla, Defior, & Simpson, 2017).

Limitations and Conclusions

Some limitations of the present study are worth mentioning. First, we included only high frequency short words and we do not know if similar results would have been observed with multisyllabic words or pseudowords. It is possible —in fact, likely, according to our interpretation—that serial naming would be a stronger, and possibly unique, predictor of discrete reading of longer words or pseudowords, at least during the initial phases of reading development in English. Second, we have not examined the role of other potentially relevant components of individual skill development, such as vocabulary, phonemic awareness, and morphological awareness, which may contribute to individual word reading efficiency (e.g., Desrochers, Manolitsis, Gaudreau, & Georgiou, 2018; Hudson, Torgesen, Lane, & Turner, 2012; Kim, 2015).

In conclusion, our results demonstrated that both serial naming and discrete naming reflect distinct skills important for word reading efficiency beyond any shared variance. We also found strong correlations between discrete word reading and discrete naming, already present in early development. This is consistent with the psycholinguistic grain size theory (Ziegler & Goswami, 2005), suggesting that children who learn to read in opaque orthographies, like English, may use larger units of information (e.g., rimes) to efficiently recognize words. However, word-specific characteristics, along with orthographic transparency and reading proficiency, may influence the extent to which sequential processing is required within words.

Although our results support the classification of readers into two groups based on whether sequential processing takes place also within words or only between words, our study goes beyond the previous literature by highlighting evidence through comparisons of current and previous datasets that challenge the hypothesis of a binary distinction between serial and parallel word processing. We propose that, instead of a dichotomy between two mutually exclusive opposites (i.e., serial/sublexical vs. parallel/lexical), the temporal sequencing of multi-element processing may occur on a continuum (from simultaneous to consecutive) across items differing in properties such as familiarity, length, and lexicality. This speculative hypothesis should be further examined, including stimuli differing in their psycholinguistic properties and samples from different grade levels and orthographies.

Finally, the distinction between the serial and discrete formats of both naming and reading that emerged in both groups of readers was interpreted as an indication that performance in serial naming (and serial reading, in more advanced readers) relies on additional skills associated with efficient processing and coordination of series of items, beyond the ability to process individual items efficiently. This further implies that processing arrays of simple symbols or unconnected words might reflect important skills, beyond name retrieval speed or knowledge of individual words. Thus, serial naming and its unique role in word reading can be used as an index of emerging sequential processing skills, which may be critical for word fluency development.

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Supplementary Material

Supplementary Tables S2.1–S2.4 and S2.7–S2.8 report the same analyses as in the main text together with results from previous studies for comparison. Tables S2.5 and S2.6 report complementary analyses to the results of the main text.

Table S2.1

Correlations (Pearson's r) among discrete words with discrete and serial digits across grades for each study

	Grade	Our study	de Jong (2011)	van den Boer & de Jong (2015)	van den Boer et al. (2016)	Protopapas et al. (2013)	Protopapas et al. (2018)
Discrete words-Discrete digits	1	.50	.28	–	–	–	.54
	2	–	.58	.47	–	.50	–
	3	.65	–	.50	–	–	.82
	4	–	.51	–	–	–	–
	5	.78	–	.64	.86	–	.78
	5b	–	–	–	.80	–	–
Discrete words-Serial digits	1	.36	.36	–	–	–	.47
	2	–	.29	.53	–	.42	–
	3	.18	–	.27	–	–	.60
	4	–	.33	–	–	–	–
	5	.42	–	.23	.46	–	.45
	5b	–	–	–	.55	–	–

Note. The upper part of the table displays the correlations between discrete word reading and discrete digit naming. The bottom part of the table displays the correlations between discrete word reading and serial digit naming. 5b is derived from van den Boer et al. (2016) who reported the correlation coefficients for both English-speaking and Dutch-speaking Grade 5 children (5b = correlation coefficients for Dutch-speaking children).

Table S2.2

Correlations (Pearson's r) among serial words with discrete and serial digits across grades for each study

	Grade	Our study	de Jong (2011)	van den Boer et al. (2016)	Protopapas et al. (2013)	Protopapas et al. (2018)
Serial words-Discrete digits	1	.24	.19	–	–	.32
	2	–	.30	–	.26	–
	3	.32	–	–	–	.48
	4	–	.09	–	–	–
	5	.34	–	.42	–	.42
	5b	–	–	.48	–	–
Serial words-Serial digits	1	.30	.34	–	–	.53
	2	–	.50	–	.61	–
	3	.58	–	–	–	.62
	4	–	.53	–	–	–
	5	.61	–	.70	–	.66
	5b	–	–	.80	–	–

Note. The upper part of the table displays the correlations between serial word reading and discrete digit naming. The bottom part of the table displays the correlations between serial word reading and serial digit naming. 5b is derived from van den Boer et al. (2016) who reported the correlation coefficients for both English-speaking and Dutch-speaking Grade 5 children (5b = correlation coefficients for Dutch-speaking children).

Table S2.3

Correlations (Pearson's r) among serial and discrete versions of words and digits across grades for each study

	Discrete digits – Serial digits			Discrete words - Serial words		
Grade	Our study	van den Boer et al. (2016)	Protopapas et al. (2018)	Our study	van den Boer et al. (2016)	Protopapas et al. (2018)
1	.57	–	.40	.78	–	.85
2	–	–	.38 [a]	–	–	.83 [a]
3	.33	–	.49	.52	–	.69
4	–	–	–	–	–	–
5	.39	.40	.42	.49	.53	.56
5b	–	.53	–	–	.57	–

Note. [a] Data from Protopapas et al. (2013); 5b is derived from van den Boer et al. (2016) who reported the correlation coefficients for both English-speaking and Dutch-speaking Grade 5 children (5b = correlation coefficients for Dutch-speaking children).

Table S2.4

R^2 changes in hierarchical regression analyses using serial and discrete digit naming to predict discrete word reading for each study

	Our Study			Protopapas et al. (2018)			van den Boer & de Jong (2015)		
Digit Naming	Grade 1	Grade 3	Grade 5	Grade 1	Grade 3	Grade 5	Grade 2	Grade 3	Grade 5
1. Serial	.12**	.03*	.17**	.21**	.33**	.20**	.28**	.08*	.04*
2. Discrete	.16**	.37**	.45**	.15**	.37**	.41**	.06**	.18**	.39**
1. Discrete	.28**	.40**	.61**	.28**	.65**	.59**	.22**	.26**	.42**
2. Serial	.01	.00	.01	.07*	.06*	.02	.13**	.00	.01

Note. Results reported for Protopapas et al. (2018) were derived from a re-analysis of the original dataset. * $p < .05$; ** $p < .0005$;

Table S2.5

R^2 changes in hierarchical regression analyses using serial and discrete digit naming to predict serial and discrete word reading for Grade 1 children scoring above 70% correct versus above 30% correct

	Grade 1 Acc > 70% *N* = 99		Grade 1 Acc > 30% *N* = 144	
Digit Naming	Serial Words	Discrete words	Serial Words	Discrete words
1. Serial	.09**	.12**	.08**	.11**
2. Discrete	.01	.16**	.01	.08**
1. Discrete	.01	.28**	.04*	.17**
2. Serial	.04*	.01	.05*	.02

Note. Acc = Accuracy; The second group (Acc > 30%) includes all Grade 1 children from our study who scored at least 30% correct in both serial and discrete word reading tasks, including those children from the first group (Acc > 70%) who scored above 70% correct on the same reading tasks. * $p < .05$; ** $p < .0005$

Table S2.6

Variance proportions predicting serial word reading and discrete word reading in each grade

Variable		Serial Words			Discrete Words		
		Unique	Common	Total	Unique	Common	Total
Grade 1							
Serial	Digits	.04	.05	.09	.01	.12	.13
Discrete	Digits	.01	.05	.06	.14	.12	.26
Grade 3							
Serial	Digits	.25	.09	.33	.00	.03	.03
Discrete	Digits	.02	.09	.10	.39	.03	.42
Grade 5							
Serial	Digits	.27	.10	.38	.01	.16	.17
Discrete	Digits	.01	.10	.12	.45	.16	.61

Table S2.7

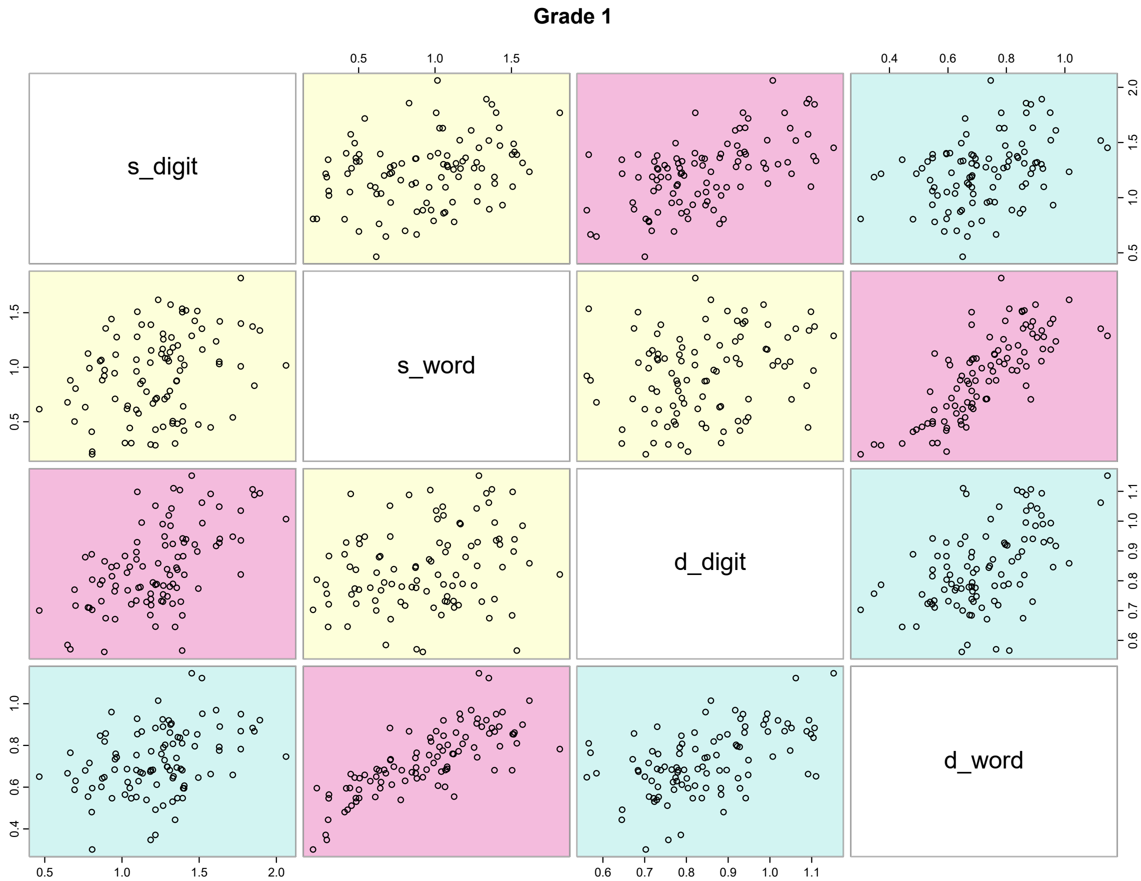
Correlations (Pearson's r) among discrete and serial versions of digit naming and word reading in each class and each study

		Serial words			Discrete words		
Variable	Class	Our study	de Jong (2011)	van den Boer & de Jong (2015)	Our study	de Jong (2011)	van den Boer & de Jong (2015)
Discrete digits	1	–.08	.06	–	.15	.16	.46
	2	.39	.17	–	.79	.56	.67
Serial digits	1	.26	.60	–	.28	.45	.55
	2	.65	.57	–	.44	.44	.44

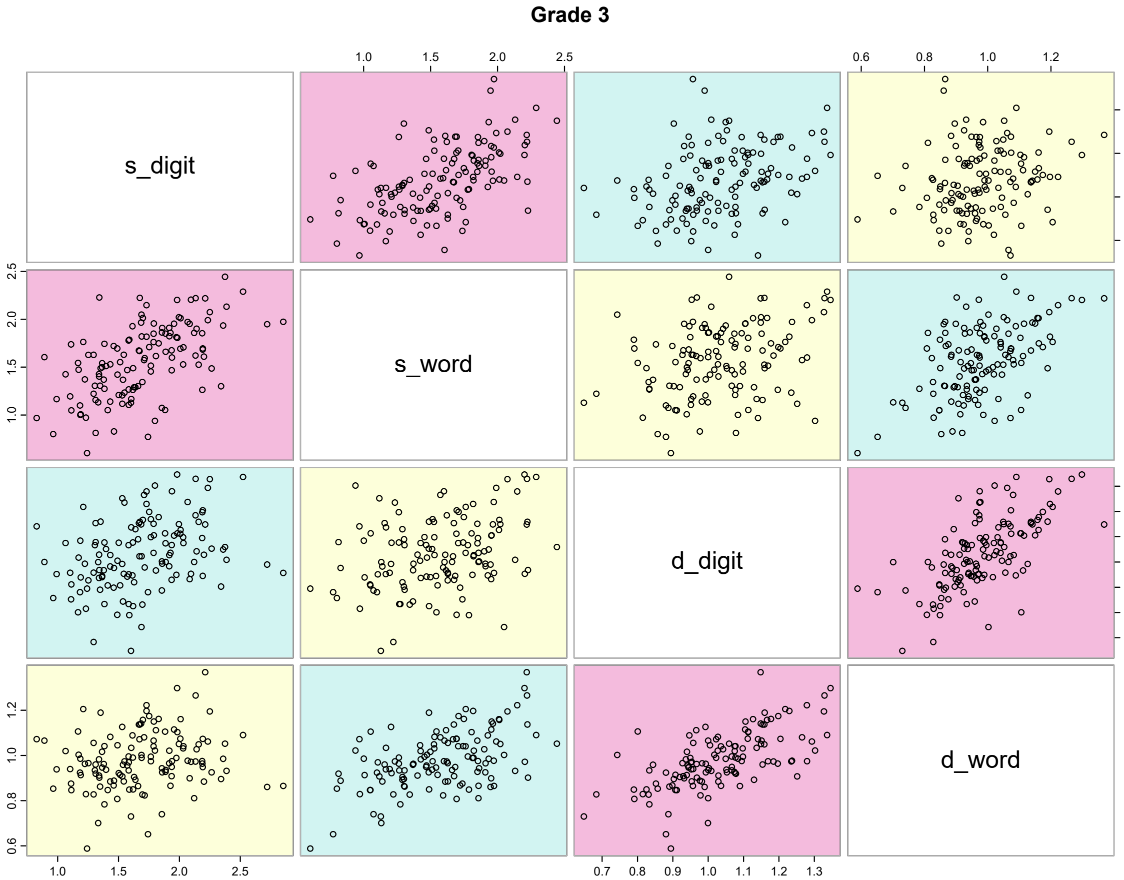
Table S2.8

Number of children per grade in each class and each study

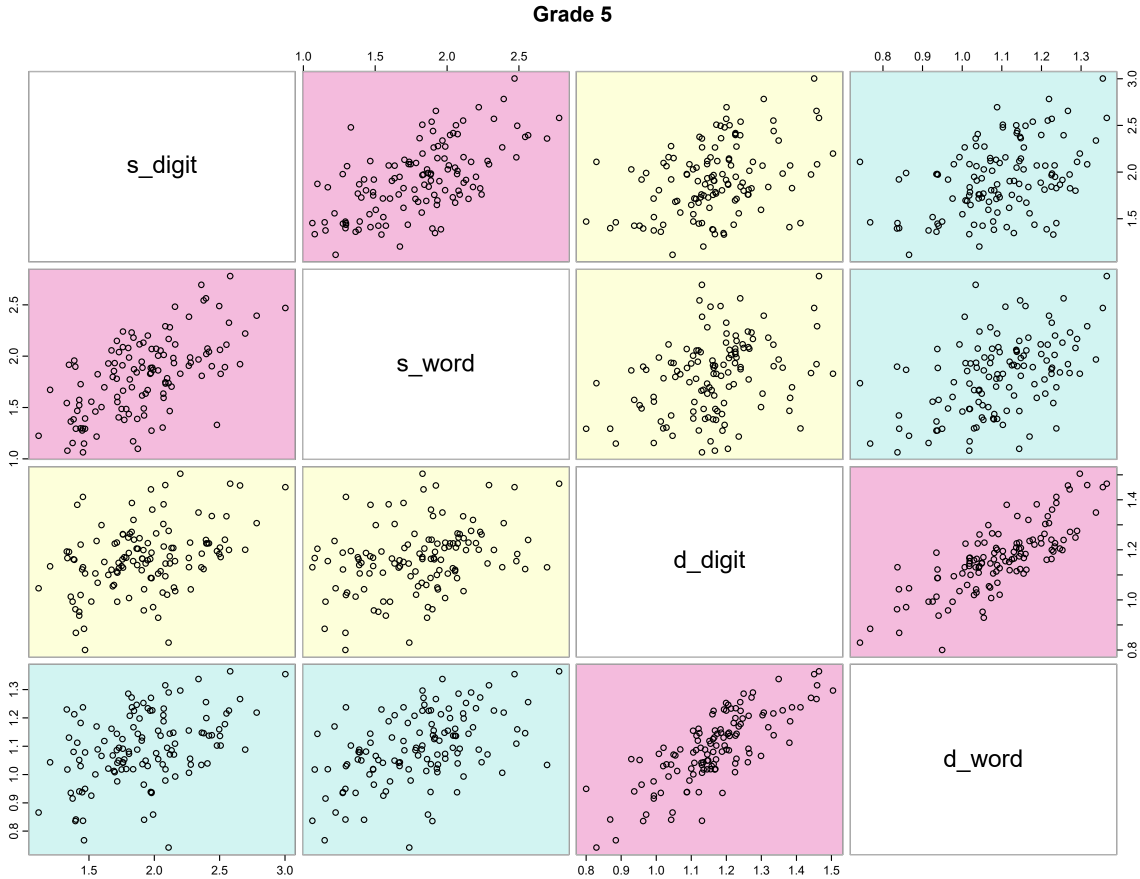
	Grade	Our study	de Jong (2011)	van den Boer & de Jong (2015)
Class 1	1	70	50	–
	2	–	20	34
	3	11	–	2
	4	–	4	–
	5	2	–	1
Class 2	1	27	21	–
	2	–	54	83
	3	118	–	84
	4	–	123	–
	5	120	–	110



Supplementary Figure 2.1. Bivariate scatterplots among serial and discrete digits and words in Grade 1. Darker colors indicate stronger correlations. (All data points in items per second).



Supplementary Figure 2.2. Bivariate scatterplots among serial and discrete digits and words in Grade 3. Darker colors indicate stronger correlations. (All data points in items per second).



Supplementary Figure 2.3. Bivariate scatterplots among serial and discrete digits and words in Grade 5. Darker colors indicate stronger correlations. (All data points in items per second).

Chapter 3: From Individual Word Recognition to Word List and Text Reading Fluency

Introduction

Although reading fluency is considered a hallmark of skilled reading and one of the primary educational goals for children in the elementary school grades (National Reading Panel, 2000), there is currently little consensus concerning its definition and underlying components. Recent frameworks concur that reading fluency is a complex construct, incorporating multiple skills both at—and conceivably divided between—a lexical level, concerning skills involved in word recognition, and a text level, concerning skills involved in understanding connected text (e.g., Fuchs, Fuchs, Hosp, & Jenkins, 2001; Hudson, Pullen, Lane, & Torgesen, 2009; Kuhn, Schwanenflugel, & Meisinger, 2010; Rasinski, Rikli, & Johnston, 2009; Wolf & Katzir-Cohen, 2001). Reading fluency is typically measured by quick and accurate reading of multiple words either in lists (*word list reading fluency*, often termed "word reading efficiency", see Test of Word Reading Efficiency; Torgesen, Wagner, & Rashotte, 1999) or in context (*text reading fluency*, often termed "oral reading fluency", see DIBELS; Good & Kaminski, 2002). Word list and text reading fluency are considered to be "superficially" identical (e.g., Fuchs et al., 2001; Hudson et al., 2009; Kim & Wagner, 2012) in that they both incorporate lower-level lexical skills (i.e., the ability to recognize individual words quickly and accurately without effortful attention to the mechanics of word decoding), but differ in the demand for higher-level supralexical processing skills, such as syntactic parsing and semantic integration, which are only involved in text reading and not in word lists[2] (Jenkins, Fuchs, van den Broek, Espin, & Deno,

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[2] Reading lists of unconnected words entails semantic encoding of individual words, but does not involve linking of words, phrases, or sentences to construct meaning. Thus, word list reading fluency is not considered a task of 'reading for understanding'.

2003; Kim, 2015; Rasinski, Reutzel, Chard, & Linan-Thompson, 2012; Stafura & Perfetti, 2017). However, both word list and text reading fluency share the requirement of dealing with multiple successive words in a sequential manner. This aspect has so far been overlooked in reading fluency theories and, thus, the potential involvement of sequential multi-item processing skill in the transition from *reading as a word recognition activity* to *efficient processing of multiple words in lists or text* is currently missing from theoretical accounts of fluency development.

In particular, in the absence of any requirements for meaning construction, word list reading fluency is typically viewed as a process similar to individual word recognition or word naming (Kuhn et al., 2010; Stanovich, 1986; or, derisively, “barking at print”; Samuels, 2007). Individual word recognition is a term commonly used to refer to one’s ability to read words in isolation, while investigations into word recognition have traditionally focused on measuring how word characteristics (e.g., frequency, length) influence response time to individually presented words (see Martinelli et al., 2014; Yap & Balota, 2015). On the other hand, word list reading fluency is typically used in reading research and practice to assess one’s ability to read aloud (accurately and quickly) multiple unrelated words that are presented simultaneously (typically in columns; e.g., Torgesen et al., 1999). Therefore, although the measures for word recognition vs. word list reading fluency differ in the format in which words are presented (individually vs. simultaneously) and processed (in a discrete vs. continuous manner, respectively), word list reading has been treated in theory as similar to individual word recognition, in that both are supposed to index one’s ability to identify single words rapidly and accurately without the benefit of contextual information from surrounding words (e.g., Berninger et al., 2010; Katzir et al., 2006; Martin-Chang & Levy, 2006; Schwanenflugel et al., 2006). According to this view, in the absence of higher-order comprehension requirements, reading fluency attainment should be fully determined by one's ability to recognize individual words efficiently, that is, with accuracy and speed (Ehri 1997; 2005; Schwanenflugel et al., 2006; Wolf & Katzir-Cohen, 2001).

However, recent studies have suggested that in the upper elementary grades, word list reading fluency has more in common with rapidly naming a series of highly familiar symbols, such as digits, than with one's ability to accurately and rapidly read individually presented words or name individually presented symbols (e.g., Altani, Georgiou, et al., 2017; de Jong, 2011; Georgiou, Parrila, Cui, & Papadopoulos, 2013; Protopapas, Katopodi, Altani, & Georgiou, 2018; Protopapas, Altani, & Georgiou, 2013; van den Boer, Georgiou, & de Jong, 2016; Zoccolotti et al., 2013). More specifically, Protopapas and colleagues (2013, 2018) used word reading tasks, in which words were presented individually (one-by-one) vs. simultaneously (in lists) and found that individual differences in the speed with which children in Grades 5 or 6 read aloud individually presented words contributed modestly to individual differences in word list reading fluency. In contrast, children's ability to rapidly name series of digits presented simultaneously was found to be a better predictor of their performance in word list reading, suggesting that word list reading for children in these grades is more similar to processing a series of overlearned symbols than to recognizing individual words. This evidence contradicts the notion that, in the absence of contextual processing demands, word list reading fluency is simply an expression of fast and accurate word recognition or lexical retrieval (see Logan, Schatschneider, & Wagner, 2011, for a similar argument).

As a clarification, in the remainder of this article we will be using the term "discrete word reading" to refer to tasks presenting individual words to be read out aloud, and the term "serial word reading" to refer to tasks presenting series of multiple words presented simultaneously, typically in rows or columns. Discrete word reading tasks produce measures of isolated word reading speed, whereas serial word reading tasks produce measures of word list reading fluency. When referring to task performance, the terms “discrete words” and “isolated word reading speed” are used interchangeably, as are the terms “serial words” and “word list fluency”. Text reading can be conceived of as a special kind of serial word reading task in that the word sequences are meaningfully connected, in which case a measure of text reading fluency is produced instead. However, when referring to text-based measures, we always use the term “text reading fluency”, to avoid ambiguity and misunderstanding.

Returning to the association between reading isolated words and reading lists of words, it has been recently demonstrated that it is not stable across development. Specifically, there is evidence showing that the correlation between discrete and serial word reading is initially very strong (in the range of 0.80–0.90 during the early phases of reading development, indicating that the two tasks are nearly identical for beginner readers), followed by a gradual decrease as children become more advanced in reading proficiency (Altani, Protopapas, & Georgiou, 2018; de Jong, 2011; Protopapas et al., 2013, 2018). The same studies have reported that while there is a decrease in the strength of the relationship between discrete and serial word reading, the link between serial word reading and serial rapid naming is characterized by stability—or even slight increase—across grade levels (e.g., de Jong, 2011; Protopapas et al., 2013, 2018). In addition, a recent study (Altani, Georgiou, et al., 2017) found that not only did serial digit naming predict serial word reading beyond the effects of discrete word reading, but also the effect of serial digit naming to serial word reading was equal across orthographies and writing systems (English, Greek, Korean, and Chinese) among children attending Grade 3.

Serial naming, typically measured with rapid automatized naming (RAN) tasks (Norton & Wolf, 2012), has been shown to be a strong concurrent and longitudinal predictor of reading fluency throughout development (e.g., Georgiou, Papadopoulos, Fella, & Parrila, 2012; Kirby, Parrila, & Pfeiffer, 2003; Lervåg, Bråten, & Hulme, 2009; van den Bos, Zijlstra, & Lutje Spelberg, 2002). In serial naming, individuals are asked to name as quickly as possible sequences of familiar items, such as digits, letters, colors, or objects (Denckla & Rudel, 1976; Wolf & Bowers, 1999). Although the reason why RAN predicts reading fluency is still a subject of debate, it is well established that naming individually presented stimuli predicts reading fluency less well than typical measures of RAN, where multiple stimuli are presented simultaneously in a grid (e.g., de Jong, 2011; Georgiou et al., 2013; Jones, Branigan, & Kelly, 2009; in fact long known, see Wolf & Bowers, 1999, p. 418). This suggests that processing sequences of multiple stimuli that are simultaneously available is a critical element of the association between RAN and reading fluency.

The ability to process multi-item sequences has recently been proposed to be critical also in understanding reading fluency acquisition (Altani et al., 2017; Jones et al., 2009; Protopapas et al., 2013; Protopapas et al., 2018; Zoccolotti, De Luca, & Spinelli, 2015; Zoccolotti et al., 2014). Protopapas, et al. (2013) argued that both (oral) fluent reading and serial rapid naming require that multiple successive items are processed simultaneously through processing *cascades*. That is, within the array of successive words or symbols, readers process one stimulus whilst articulating the previous one and concurrently viewing the next stimulus in line and previewing the one further down, effectively buffering (i.e., internally storing temporarily) information about items that have already been viewed but not yet pronounced. This procedure has been described as *endogenously controlled*, because it appears to be governed by the reader's own planning when dealing with and coordinating multiple items that are simultaneously available, and seems to be distinct from the ability to regulate one's response to stimuli that are individually presented (see e.g., Altani, Protopapas, et al., 2017; Jones et al., 2009). It has also been proposed that buffering may underlie *prosody*, which is considered essential in fluent text reading. That is, if readers buffer upcoming words and thus make them available for syntactic and semantic processing, forming meaningful units (Zoccolotti et al., 2014), this can provide the basis for planning to pronounce them with proper expression (Protopapas et al., 2018). This is consistent with evidence from eye-movement research, which has long revealed a lag between the viewed and the articulated item during oral reading tasks (known as *eye-voice span*; Buswell, 1921) and, importantly, that keeping an optimal distance between the viewed and the spoken word by coordinating item sequences seems to be crucial for efficient performance in both oral reading (e.g., De Luca, Pontillo, Primativo, Spinelli, & Zoccolotti, 2013; Laubrock & Kliegl, 2015) and rapid naming (e.g., Gordon & Hoedemaker, 2016). However, this aspect of efficient processing of *multiword* sequences in terms of word-level multi-item (but not supralexical) processing has so far been disregarded in theoretical accounts of reading fluency. A somewhat related notion found in the literature, namely "unitization", has only been used to refer to either processing of multiple words to form meaningful units (enabling understanding in connected text reading), or processing of multiple elements (e.g., letters, spelling patterns) within single words to form whole-word entities (unitized words; enabling rapid word recognition) (e.g., Fuchs et al., 2001; Stafura & Perfetti, 2017; Wolf & Katzir-Cohen, 2001).

It is indisputable that the ability to recognize individual words efficiently (i.e., accurately and rapidly) is of paramount importance for reading fluency (e.g., Ehri, 2005; Hudson et al., 2009; Kim, 2015; Stanovich, 1980), particularly during the early years of reading acquisition (e.g., National Institute of Child Health and Human Development [NICHD], 2000; Schwanenflugel, Hamilton, Kuhn, Wisenbaker, & Stahl, 2004). Indeed, research confirms that the ability to read individually presented words with accuracy and speed is the main predictor of word list reading fluency in early grades (e.g., Grade 2; Protopapas et al., 2013). However, accuracy and speed in word reading do not develop entirely in parallel. Juul et al. (2014) found that there is a basic accuracy level which needs to be achieved before children's reading speed can begin to develop. They followed a group of Danish readers from Kindergarten to Grade 2 and reported that when speed and accuracy in the same reading fluency task were plotted against each other, a banana-shaped distribution emerged. This indicated a qualitative shift from accuracy to speed, whereby children with low accuracy tended to be slow readers (varying primarily in the accuracy dimension), whereas once a basic level of 70% accuracy was achieved, word speed took off (with variation between children found almost exclusively in the speed dimension). This suggests that reading fluency scores can be considered to reflect speed only after accuracy has reached a basic level.

Therefore, accurate and fast word recognition are two necessary building blocks before more advanced skills specific to reading fluency can develop (e.g., Ehri, 1997; 2005; Perfetti, 1985; Wolf & Katzir-Cohen, 2001). However, word recognition is not enough: As noted above, serial word reading diverges from discrete word reading during the upper elementary grades, and begins to align more closely with serial digit naming (Altani, Protopapas, et al., 2017; Protopapas et al., 2013, 2018). This suggests that fluent reading of multiple words (as in word-lists or sentences) is not fully determined by individual word recognition. Instead, when individual word recognition becomes relatively proficient, so that words can be perceived by sight as unitized items, fluent reading of multiple words seems to be co-determined by the ability to process multi-item sequences, an ability that is indexed by serial naming tasks (Protopapas et al. 2013; Protopapas et al., 2018; Zoccolotti et al., 2014; Zoccolotti et al., 2015).

So far, very limited information is available regarding the nature and role of multi-item processing in word list and text reading fluency. Although some studies have shown that serial naming contributes unique variance to word list reading fluency beyond one's ability to recognize individual words (Protopapas et al., 2013, 2018; Zoccolotti et al., 2013), only one study has included (oral) text reading as a measure of reading fluency (Zoccolotti et al., 2014), possibly limiting the applicability of the findings to more realistic reading situations. Furthermore, most previous studies have been conducted in orthographically transparent languages (Greek and Italian). The only cross-linguistic study that examined the contribution of a serial digit naming task to serial word reading, beyond the efficiency of discrete word reading, included only Grade 3 children (Altani, Georgiou et al., 2017). To address these gaps, the present study examined the association between reading multiword sequences and reading individual words in isolation, as well as the potentially distinct role of serial naming in reading fluency development with respect to (a) both text and word list reading as fluency measures, (b) different phases of reading development, and (c) different orthographies. To our knowledge, this is also the first study to examine the component of speed after taking into consideration the concurrent accuracy in the word reading tasks across languages.

The Present Study

This study aimed to examine the role and nature of processing multiple words in reading fluency development and the associated transition from individual word recognition (word-by-word reading) to reading multiword sequences (presented either in lists or in sentences). For this purpose, we developed three experimental reading measures, including isolated word reading, word list reading, and text reading. These three reading tasks differ either in the format of presentation (isolated vs. multiple words) or in contextual demands (connected text vs. lists of unconnected words). We tested children in three elementary grade levels (Grades 1, 3, and 5) and in two languages that differ in orthographic consistency (Greek being relatively transparent and English being opaque).

First, we focused on the developing interrelations between the efficiency of reading individually presented, discrete words (i.e., isolated word reading speed, as an index of individual word recognition) and the efficiency of reading word sequences (i.e., word list and text reading speed, as indices of fluency) across grades and languages. We specifically hypothesized that all three reading tasks (i.e., discrete word reading, word list reading, and text reading) would be strongly correlated during initial reading development (i.e., in Grade 1), reflecting a general skill of word reading. In contrast, we expected that the link between discrete word reading and both word list reading and text reading would gradually decrease across grades, confirming that performance in reading word sequences (i.e., in a list or in a text) is not exhausted by the efficiency of individual word recognition, across languages.

Second, we aimed to examine whether serial digit naming,[3] as an index of multi-item sequence processing (e.g., Altani, Georgiou, et al., 2017; Protopapas et al., 2013, 2018), can indeed account for individual differences in both word list fluency and text fluency, beyond the

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[3] RAN tasks may include different types of stimuli, such as digits, letters, colors, or objects. In the current study, digits were chosen because digit (and letter) naming tasks are generally known to be more strongly related to reading compared to color or object naming tasks (e.g., Kirby, Georgiou, Martinussen, & Parilla, 2010; Norton & Wolf, 2012). We did not use a letter naming task to ensure that naming performance could not be attributed to letter knowledge (and thus perhaps reading experience) among the group of younger readers.

effects of discrete word reading, across grades and languages. Any processes (lexical/sublexical) required for the efficient recognition and retrieval of isolated words should be captured by the discrete word reading task, whereas any requirements specific to multiword processing are only involved in the serial reading tasks (i.e., word list and text reading). Therefore, we tested a simple model with two predictors, namely discrete word reading (as an index of isolated word recognition efficiency) and serial digit naming (as an index of sequential multi-item processing efficiency) to predict individual differences in word list and text reading fluency across grades and languages.

We hypothesized that for beginning readers, isolated word reading speed should be the main predictor of individual differences in both word list and text reading fluency. In contrast, among older (i.e., more advanced) readers, serial digit naming should account for unique variance in word list reading fluency beyond the effect of isolated word reading speed, reflecting individual differences in sequential processing skill. Moreover, to the extent that differences between reading lists of unconnected words and reading meaningful texts stem primarily from the comprehension demands in the latter, we hypothesized that the two-predictor model of serial digit naming and discrete word reading would account for similar amounts of variance in both word list reading fluency and text reading fluency, as long as the text poses no appreciable comprehension requirements. Alternatively, if semantic integration (rather than word-level sequence processing) dominates performance in text reading, serial digit naming and discrete word reading should account for a smaller portion of variance in text reading fluency compared to word list reading fluency.

The final goal of the present study was to examine the extent to which the transition from individual word recognition to connected text fluency follows a similar path across languages varying in orthographic transparency (Greek being relatively transparent and English being opaque). Based on Altani et al.'s (2017) findings, one would expect similar patterns of intercorrelations to emerge across languages, despite differences in the processing of individual words due to orthographic transparency. On the other hand, considering the volume of research demonstrating significant differences across alphabetic languages in the pace of mastering decoding (Aro & Wimmer, 2003; Caravolas, 2018; Seymour, Aro, & Erskine, 2003), one might expect that the pattern of intercorrelations could differ between languages, particularly during the early phases of reading development. That is, differences between orthographies in the rate of mastering decoding and achieving individual word recognition efficiency might affect the contribution of discrete word reading to word list and text reading fluency for beginners or more advanced readers, with important implications for understanding the development of reading fluency across languages. Thus, if individual word recognition is more challenging, requiring more complex internal "assembly" for readers in the opaque English orthography, then we should expect that discrete word reading would have a stronger effect on reading fluency among beginner (and perhaps intermediate and advanced) English-speaking readers. However, if other processes specific to multi-item processing are more crucial for reading fluency, than initial differences in individual word processing, we should observe a similar pattern of findings across languages.

Method

Participants

Our participants consisted of 408 English-speaking Canadian children from Edmonton and 302 Greek children from Athens. Information about the sample size, gender, and mean age of participants for each grade and language are available in Table 3.1. All children were recruited on a voluntary basis from the general population of children attending public schools (8 schools in Edmonton, 12 schools in Athens). The schools were located in different parts of each city in order to increase as much as possible the representation of different demographics in our study. All children were native speakers of English or Greek, respectively, and none was diagnosed with any intellectual, behavioral, or sensory difficulties. In both sites, children are formally taught how to read in Grade 1 and teachers use a synthetic phonics approach to teach reading, which emphasizes letter-sound correspondences and sound blending. Parental and school consent, as well as ethics approval from the corresponding institutions in each country were obtained prior to testing. The same sample of children has been used in previous studies (Altani, Georgiou, et al., 2017; Protopapas et al., 2018). However, both the questions asked, and the analyses performed in previous studies differ from the ones in the current study.

Table 3.1

Sample Information for Each Grade and Language

	Grade	*N*	Age (*SD*)	Gender F:M
Greek				
	1	100	82.8 (3.4)	53:45
	3	103	107.1 (3.5)	53:50
	5	99	130.0 (3.4)	54:45
English				
	1	157	81.4 (4.2)	87:70
	3	129	105.8 (3.9)	64:65
	5	122	129.7 (4.2)	70:52

Note. Age in months; F = female; M = male.

Materials

Three reading tasks (one in discrete and two in serial format) and one serial digit naming task were administered. The digit naming task included nine repetitions of each of four digits (2, 3, 5, and 6, the same in both languages). Each of the three word reading tasks included 36 high-frequency words. One set of 36 words was used in a *discrete word reading task* as a measure of word recognition skills. A second set of 36 words was used in a *serial word reading* task as a measure of word list fluency. Finally, a text made up of 36 words[4] was used in a *text reading* task as a measure of text fluency. The three sets of 36 words and the four number words corresponding to the digits were matched on several psycholinguistic variables (see Appendix A): Within each language, word sets were matched in frequency, number of phonemes, number of graphemes, and syllabic structure to the four number words used in the digit naming task, in order to keep naming demands constant across tasks to the extent possible. All items in English were monosyllabic words. Greek words were bisyllabic in order to match the four number words used in the serial digit naming task. Orthographic word length was the same in the two languages, varying between three and five letters in word lists and number words, and between two and five (in English) or six (in Greek) letters in texts (see Appendix B for details). Word frequencies in English were derived from the Children's Printed Word Database of words (Masterson, Stuart, Dixon, & Lovejoy, 2010). Word frequencies in Greek were derived from the ILSP PsychoLinguistic Resource (IPLR; Protopapas, Tzakosta, Chalamandaris, & Tsiakoulis, 2012).

Procedure

The 36 digits in the digit naming task were simultaneously presented in a matrix of four rows by nine items. In the discrete word reading task, words were presented one-by-one in the middle of the screen. Each word remained on the screen until a complete response was recorded

[4] In English, the text was adapted from the Gray Oral Reading Test-Edition 5, Passage 2 (Wiederholt & Bryant, 2001).

and was followed immediately by the appearance of the next word without any prompt. In serial word reading, all 36 words were arranged in a format of four rows by nine columns, to match the presentation of the digit naming task. In text reading, words were presented in sentences of five rows in Greek and four rows in English, each row consisting of one sentence. For all tasks, children were asked to name out loud the items or read aloud the words as quickly as possible. Instructions and practice items were provided prior to each task to ensure compliance with task demands.

Item presentation and response recording was controlled by the DMDX experimental display software (Forster & Forster, 2003). Items were presented in black 20-pt Consolas font on a white background and remained on the screen until the experimenter pressed a key to proceed to the next item or trial, as soon as complete production of a response was registered. Individual responses were recorded in audio files through a head-mounted microphone.

Testing took place in April–June (near the end of the academic year in each country). The naming and reading tasks were administered in random order during a 40-minute session within a larger testing battery. Children were tested individually by trained assistants and the testing protocol was the same across the two sites.

Data Preparation

Total naming or reading time was determined off-line using CheckVocal (Protopapas, 2007). This software facilitates processing of vocal responses by displaying each response audiovisually (waveform and spectrogram), along with the corresponding timing mark indicating its onset or offset and with the correct (expected) response, so that the experimenter need only confirm the accuracy and timing with minimal effort. For the tasks of serial word reading, text reading, and serial digit naming, the total time of reading or naming the entire array was recorded (yielding 2,130 individual recordings for 710 participants × 3 serial tasks); for the task of discrete word reading, reading times of individual items were recorded (yielding 25,560 individual recordings for 710 participants × 36 items/words from the discrete task). All recorded response times (RTs) analyzed below included both onset latency and articulation time, thus being directly comparable between discrete and serial tasks. To better approximate a normal distribution, RTs were converted to rates, that is, number of items (digits named, or words read) per second. For discrete reading, a single score for each participant and task was computed by averaging the reading rates across correctly read words. RTs in serial digit naming, serial word reading, and text reading included both correct and incorrect responses. [5]

Results

Accuracy and Speed in Word Reading

Because word reading efficiency, which refers to one's ability to successfully recognize context-free words, is co-determined by speed and accuracy—especially during primary school grades and mostly in orthographically opaque languages like English—we first sought to examine the speed and accuracy dimensions separately and disentangle their contribution—to the extent they are separable. This was done in three steps:

First, we inspected the accuracy and speed scores within word reading tasks (both discrete and serial words). Table 3.2 presents the mean accuracy (proportion correct) and rate

[5] Trials in discrete word reading corresponded to individual words/responses, and thus, the average RT was computed based on the correct responses. In contrast, in the serial reading tasks, there was only one continuous trial/response per task, and thus both correct and incorrect individual words were included in the total time. It has been previously demonstrated that taking errors into account in the serial tasks has a negligible effect on the intercorrelations among tasks (Protopapas et al., 2018, Table S13 and Figure S12).

(words per second) in discrete and serial word reading in each grade and language. When asked to read short, high-frequency words, the great majority of Greek children scored above 70% correct, even in Grade 1, with no child getting less than half correct. In contrast, Grade 1 English-speaking children showed large variation in reading accuracy, with children scoring as low as 11% (in discrete word reading) and 6% (in serial word reading; see Table 3.2).

Next, following Juul et al. (2014), we examined whether a minimum accuracy level is required before the dimension of speed can begin to develop. For this purpose, the accuracy and speed scores from the same word reading tasks were plotted together. Figures 3.1 and 3.2 present the distributions of accuracy and speed for discrete and serial word reading in each grade and language. Correlations between the accuracy and speed for serial and discrete versions of word reading in each grade and language are listed in Table S3.1 in the Supplementary Material. Based on the distributions of scores in speed and accuracy (Figures 3.1 and 3.2), we can see that variation in word reading speed was large when accuracy level was above 70–80% correct. However, for Grade 1 English-speaking children who scored below 70–80% correct, variation was mainly seen in the accuracy dimension (Figure 3.2). In fact, a banana-shaped distribution was observed among younger readers of English, showing that children who scored below a basic level of accuracy (i.e., not exceeding 70% correct) were also likely to be slow. Instead, for children whose accuracy scores exceeded about 70–80% correct, the speed dimension showed great variation. High accuracy scores were observed among children in Grades 3 and 5 in English, and across all three grades in Greek, which were further associated with variation in word reading speed. Notably, variability in the speed dimension was greater in serial word reading than in discrete word reading across grades in both languages, with the latter reaching a plateau by Grade 3 but the former still progressing by Grade 5.

Table 3.2

Mean Accuracy (proportion correct) and Rate (words per second) in Serial and Discrete Word Reading for Each Grade and Language

	Grade 1					Grade 3					Grade 5				
Task	*N*	*M*	*SD*	Min.	Max.	*N*	*M*	*SD*	Min.	Max.	*N*	*M*	*SD*	Min.	Max.
Greek															
Serial (s_word)															
Accuracy	98	0.87	0.09	0.61	1.00	100	0.95	0.04	0.78	1.00	92	0.97	0.04	0.83	1.00
Rate	100	0.67	0.26	0.24	1.38	101	1.42	0.38	0.48	2.42	98	1.67	0.35	0.82	2.39
Discrete (d_word)															
Accuracy	100	0.94	0.08	0.56	1.00	103	0.98	0.03	0.83	1.00	99	0.99	0.02	0.83	1.00
Rate	100	0.60	0.14	0.28	0.94	103	0.96	0.17	0.52	1.41	99	1.06	0.16	0.67	1.42
English															
Serial (s_word)															
Accuracy	157	0.76	0.25	0.06	1.00	129	0.98	0.05	0.72	1.00	122	0.99	0.02	0.92	1.00
Rate	157	0.74	0.42	0.20	1.82	129	1.57	0.38	0.60	2.44	122	1.80	0.37	1.06	2.78
Discrete (d_word)															
Accuracy	157	0.75	0.24	0.11	1.00	129	0.96	0.04	0.83	1.00	122	0.99	0.02	0.92	1.00
Rate	157	0.63	0.19	0.21	1.15	129	0.98	0.13	0.59	1.37	122	1.09	0.12	0.74	1.37

Note. Min. = minimum; Max. = maximum; s = serial; d = discrete.

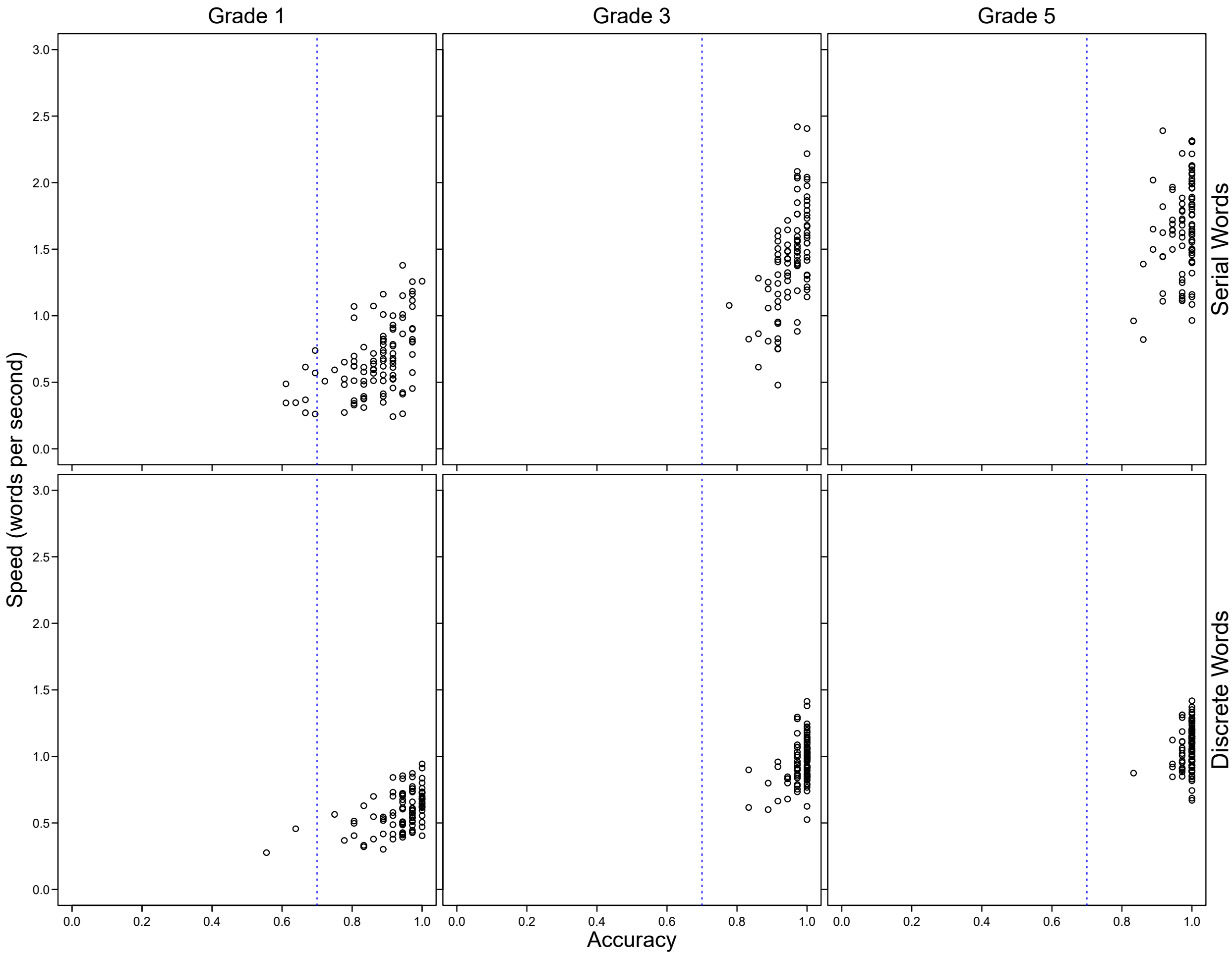

Figure 3.1. Scatterplots of accuracy (x-axis) and speed (y-axis) from the tests of serial and discrete word reading in each Grade in Greek. The blue dotted line indicates the threshold of 70% correct.

Finally, a threshold of 70% correct was applied, based on Juul et al. (2014) and visually confirmed by the distributions in Figures 3.1 and 3.2.[6] Examining the proportion of children who

[6] Additional analyses were conducted including only the children who scored at least 80% correct in both serial and discrete word reading, reported in the Supplementary Material. Using a higher threshold (80% correct) did not yield a different pattern of results (Tables S3.2–S3.5). Therefore, children who scored at least 70% correct were included in our main analyses, following the accuracy level proposed by Juul et al. (2014).

scored above vs. below this minimum level of word reading accuracy in Grade 1, we found that only few Greek children scored below 70% correct (6 children in serial word reading and 2 in discrete word reading). In contrast, the picture was quite different among English-speaking children, with about one third of first graders scoring below 70% correct (53 out of 157 children in discrete word reading and 50 out of 157 in serial word reading). Rate and accuracy scores for Grade 1 children who scored above vs. below the 70% accuracy threshold in each language are listed in Table S3.6.

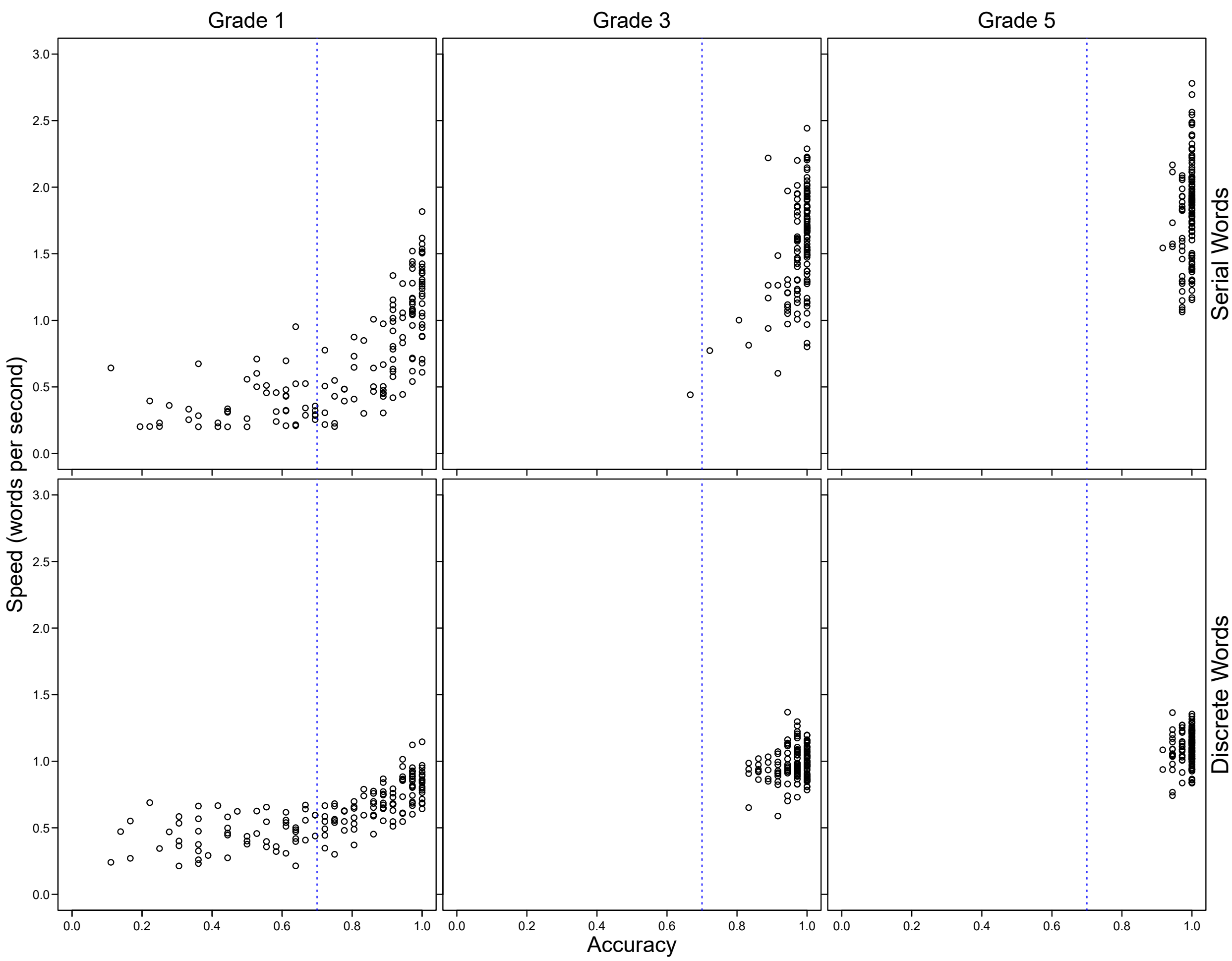

Figure 3.2. Scatterplots of accuracy (x-axis) and speed (y-axis) from the tests of serial and discrete word reading in each Grade in English. The blue dotted line indicates the threshold of 70% correct.

Following this extensive screening procedure, Table 3.3 shows the descriptive statistics for each measure across languages including only children who scored at least 70% correct in either serial or discrete word reading. This criterion left 99 complete cases in Grade 1, 129 in Grade 3, and 122 in Grade 5 in English; and 93 complete cases in Grade 1, 101 in Grade 3, and 99 in Grade 5 in Greek. Examination of Q-Q plots and Shapiro-Wilk tests indicated no significant deviations from normality. All further analyses were conducted using R (R Core Team, 2017) with the final dataset.

Interrelations Among Reading Measures Across Grades

Our first goal concerned the developmental patterns in the correlations among the naming and reading tasks. Table 3.4 shows the interrelations among all tasks across grades and languages. Overall, the relationship between discrete word reading and serial word reading or text reading gradually decreased across grades in both Greek and English. More specifically, discrete word reading and serial word reading correlated strongly among Grade 1 children in both languages (Greek: $r = .84$; English: $r = .78$), but only moderately among Grade 5 children (Greek: $r = .56$; English: $r = .49$; down by about .3 from Grade 1 in both languages). The same pattern was observed in the relationship between discrete words and text reading, with a strong correlation in Grade 1 (Greek: $r = .79$; English: $r = .81$), which decreased by Grade 5 in both Greek ($r = .50$) and English ($r = .54$). On the other hand, the correlation between text reading and serial word reading remained relatively strong across grades in both languages (ranging from .73 to .90 in Greek and from .63 to .84 in English).

Table 3.3

Descriptive Statistics for Naming and Reading Rates in Each Grade and Language with the Final Datasets

	Grade 1					Grade 3					Grade 5				
	N	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Greek															
d_word	92	0.61	0.14	−0.02	−0.53	101	0.96	0.17	0.06	0.20	99	1.06	0.16	0.01	−0.50
s_word	93	0.69	0.26	0.50	−0.37	101	1.42	0.38	0.06	0.05	98	1.67	0.35	−0.14	−0.49
s_text	93	0.84	0.35	0.69	−0.12	99	1.95	0.45	−0.35	−0.37	99	2.42	0.45	−0.25	−0.31
s_digit	94	1.39	0.28	−0.07	−0.39	101	1.93	0.32	−0.08	−0.59	99	2.13	0.38	−0.59	0.47
English															
d_word	99	0.72	0.16	0.01	0.09	129	0.98	0.13	0.09	0.66	122	1.09	0.12	−0.30	−0.03
s_word	97	0.94	0.38	−0.04	−0.93	129	1.57	0.38	−0.14	−0.57	122	1.80	0.37	0.11	−0.40
s_text	99	1.35	0.52	0.34	−0.44	129	2.35	0.57	−0.21	−0.39	122	2.86	0.62	0.14	−0.58
s_digit	99	1.23	0.30	0.12	−0.05	129	1.69	0.39	0.27	−0.20	122	1.92	0.38	0.29	−0.38

Note. d = discrete; s = serial; Skew = skewness; Kurt = kurtosis. The scores are presented in items (words or digits) per second. Final datasets (and subsequent results) include only the children who scored above 70% correct in serial or discrete word reading.

Comparisons of correlation coefficients between grade levels were performed via z transformation (Cohen & Cohen, 1983) as implemented in the multilevel package (Bliese, 2016). Results showed that discrete word reading correlated with both serial word reading and text reading to a significantly lesser degree in Grades 3 and 5 compared to Grade 1 in both languages (although correlations did not differ significantly between Grades 3 and 5). The correlation between serial word reading and text reading was significantly higher in Grade 1 compared to Grade 5, in both languages, but was not significantly different between successive grades (Grades 1 vs. 3 or 3 vs. 5).

Predicting Individual Differences in Serial Word and Text Reading Fluency

Our second goal was to examine whether serial naming can account for additional variance in reading sequences of multiple words (i.e., word list and text), beyond isolated word reading efficiency. To determine the unique contribution of discrete word reading and serial digit naming to serial word reading (i.e., word list fluency), we conducted two sets of analyses: (a) multiple regression analyses using discrete words and serial digits as predictors of serial word reading, followed up with (b) commonality analyses, using the R package yhat (Nimon, Lewis, Kane, & Haynes, 2008) in each grade and language. Table 3.5 shows the regression model coefficients with both measures entered simultaneously in the regression equation. Table 3.6 shows the unique and total contribution of each predictor to serial word reading and text reading in each grade and language.

Table 3.4

Interrelations Among Tasks in Each Grade and Language

Task	Grade 1				Grade 3				Grade 5			
	1.dWrd	2.sWrd	3.Text	4.sDig	1.dWrd	2.sWrd	3.Text	4.sDig	1.dWrd	2.sWrd	3.Text	4.sDig
Greek												
1 d_word		.85	.81	.44		.63	.60*	.53*		.54	.52	.42
2 s_word	.84		.89	.53*	.65		.80	.57	.56		.70	.62
3 s_text	.79	.90		.37	.65*	.83		.63	.50	.73		.41
4 s_digit	.44	.51	.37		.57*	.59	.65		.45	.65	.43	
English												
1 d_word		.80	.82	.37		.45	.39*	.22*		.47	.54	.37
2 s_word	.78		.86	.29*	.52		.73	.59	.49		.65	.57
3 s_text	.81	.84		.40	.43*	.75		.54	.54	.63		.48
4 s_digit	.36	.30	.42		.18*	.58	.50		.42	.61	.52	

Note. For each grade and language, Spearman's ρ is presented above the diagonal; Pearson's r is presented below the diagonal. d = discrete; s = serial; Wrd = word; Dig = digit.

*Correlation coefficients statistically significantly different between Greek and English, compared using Fisher's (1925) *Z* procedure and Zou's (2007) confidence interval as implemented in the cocor package for independent samples (Diedenhofen, 2016; Diedenhofen & Musch, 2015).

Table 3.5

Multiple Regression Coefficients for Models Predicting Serial Word Reading and Text Reading

	Grade 1		Grade 3		Grade 5	
	Serial Words	Text	Serial Words	Text	Serial Words	Text
Greek						
Discrete Words	1.41^{***}	1.98^{***}	1.09^{***}	1.19^{***}	0.74^{***}	1.10^{**}
Serial Digits	0.16^{*}	0.01	0.38^{***}	0.60^{***}	0.46^{***}	0.31^{**}
Total R^2	0.72	0.62	0.49	0.54	0.51	0.28
English						
Discrete Words	1.86^{***}	2.49^{***}	1.29^{***}	1.56^{***}	0.83^{**}	1.93^{***}
Serial Digits	0.03	0.25^{*}	0.48^{***}	0.64^{***}	0.49^{***}	0.59^{***}
Total R^2	0.59	0.66	0.50	0.36	0.43	0.39
Greek & English						
Discrete Words	1.64^{***}	2.23^{***}	1.19^{***}	1.38^{***}	0.78^{***}	1.51^{***}
Serial Digits	0.09	0.13	0.43^{***}	0.62^{***}	0.47^{***}	0.45^{***}
Language	0.06	0.37	0.16	0.09	−0.05	0.98^{*}
Language × Discrete Words	-0.45^{*}	−0.52	−0.20	−0.37	−0.09	−0.83
Language × Serial Digits	0.13	−0.23	−0.10	−0.04	−0.03	−0.28
Total R^2	0.68	0.74	0.51	0.49	0.48	0.44

Note. Unstandardized regression coefficients from simultaneous multiple regressions are presented. Top: regression models for each language and grade separately; bottom: cross-linguistic regression models for each grade. $^{*}p < .05$; $^{**}p < .005$; $^{***}p < .0005$

A similar pattern emerged using text reading as the outcome measure with both discrete word reading and serial digit naming as the model predictors. Discrete word reading was the main predictor of text reading among Grade 1 children in both Greek and English, accounting for larger proportions of unique and total variance compared to that accounted for by serial digit naming. In contrast, in Grades 3 and 5, serial digit naming also became a significant predictor of text reading, accounting for an almost equal proportion of total variance to that predicted by discrete word reading (see Table 3.6).

Regarding the total variance in serial word and text reading explained by the two-predictor model, we did not observe overall higher predictability for serial word reading compared to text reading. Specifically, in Grades 1 and 5 in Greek, and Grade 3 in English, serial digit naming and discrete word reading accounted for a smaller portion of variance in text reading than in serial word reading. However, in Grades 1 and 5 in English, and Grade 3 in Greek, the two-predictor model accounted for similar or even larger portion of variance in text reading compared to the explained variance in serial word reading (Table 3.5).

Table 3.6

Variance Proportions Predicting Serial Word Reading and Text Reading in Each Grade and Language

Variable		Grade 1				Grade 3				Grade 5			
		Serial Words		Text		Serial Words		Text		Serial Words		Text	
		Unique	Total	Unique	Total	Unique	Total	Unique	Total	Unique	Total	Unique	Total
Greek													
Discrete	Words	.47	.71	.50	.63	.15	.43	.12	.42	.09	.32	.11	.25
Serial	Digits	.02	.25	.01	.13	.07	.35	.13	.42	.20	.43	.05	.18
English													
Discrete	Words	.51	.60	.50	.63	.18	.27	.12	.18	.06	.24	.13	.29
Serial	Digits	.01	.09	.02	.18	.24	.33	.19	.25	.20	.38	.11	.27

Comparing Results Across Languages

With respect to our third goal, we found very similar patterns of interrelations across languages (see Table 3.4). In addition, we performed a set of regression analyses to predict serial word reading and text reading from discrete word reading and serial digit naming, with language (difference coded: −0.5 for English and +0.5 for Greek, using contr.sdif from the MASS package; Venables & Ripley, 2002) as an additional predictor, along with interaction terms of language with both discrete word reading and serial digit naming, aiming to examine whether language modulates the effects of these two predictors on reading fluency (see Table 3.5). The results of these regression analyses showed, first, that there was no main effect of language except for Grade 5 text reading (an effect at $p = .047$ that would not survive correction for multiple comparisons). Therefore, language was in general not a significant predictor of either serial word reading or text reading fluency for these materials. Second, a statistically significant Language × Discrete Word interaction was found only in the model predicting serial word reading in Grade 1, consistent with a larger effect of discrete words on word list reading fluency in English than in Greek at this grade level only. The interactions between Language and Serial Digit were not statistically significant in any grade level either for text or for serial word reading, consistent with a language-independent effect of serial digits on fluency for all grade levels examined (see Table 3.5). Interaction plots between language and the other two predictors are presented in Figure 3.3 (with serial word reading as outcome variable) and Figure 3.4 (with text reading as outcome variable). Notably, the lines representing the effect from Serial Digit to Serial Word or Text for the two languages are essentially parallel, consistent with the absence of a significant interaction.

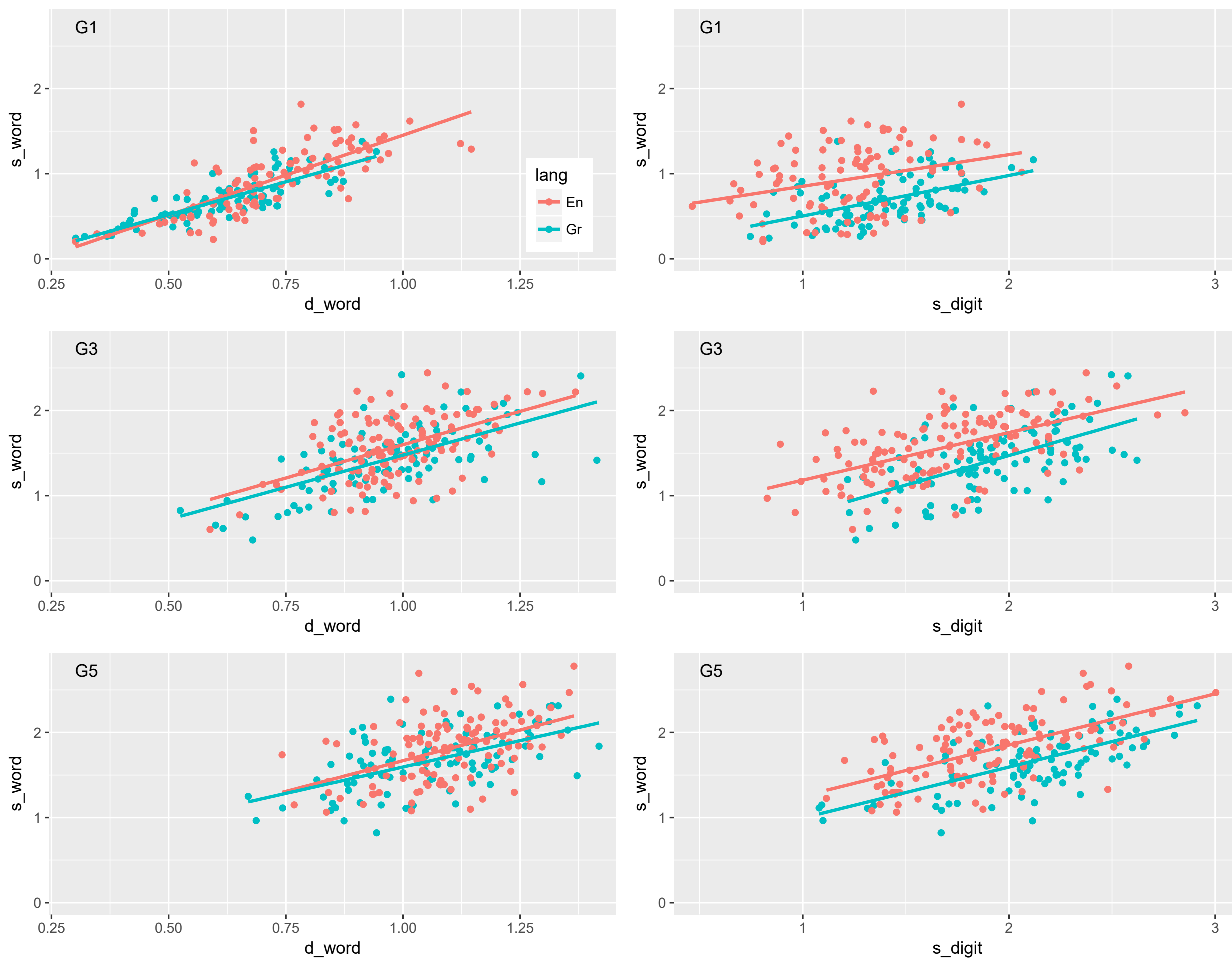

Figure 3.3. Interaction plots between language and discrete word reading (left) or language and serial digit naming (right) in the prediction of word list reading fluency. The regression lines represent the effects of the indicated predictor to serial words for each grade in Greek (Gr; blue) and English (En; red). Error bars show 95% confidence intervals. G = Grade; s = serial; d = discrete; lang = language.

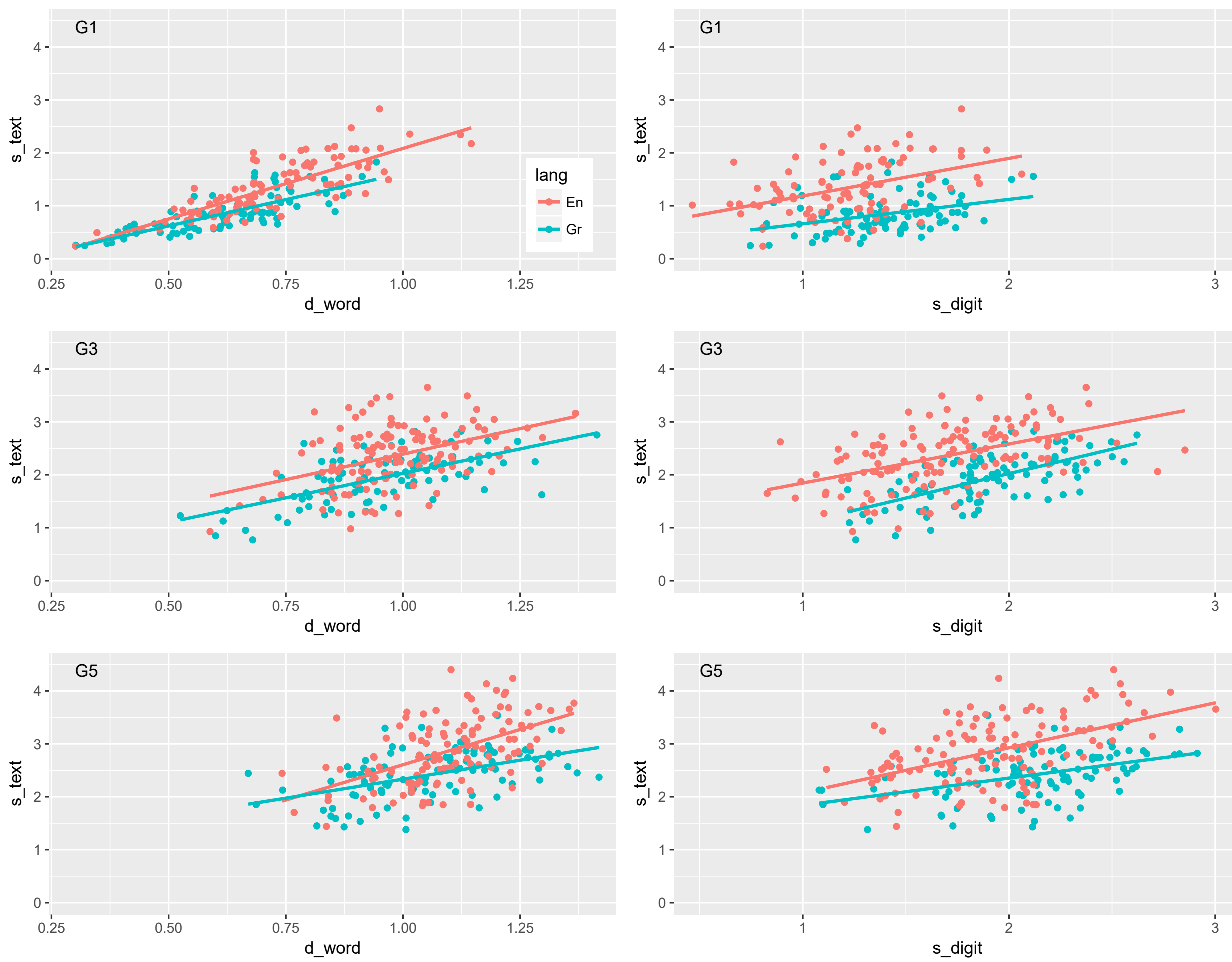

Figure 3.4. Interaction plots between language and discrete word reading (left) or language and serial digit naming (right) in the prediction of text reading fluency. The regression lines represent the effects of the indicated predictor to text for each grade in Greek (Gr; blue) and English (En; red). Error bars show 95% confidence intervals. G = Grade; s = serial; d = discrete; lang = language.

Discussion

In this study, we aimed to investigate the nature and role of processing multiple words in reading fluency development, focusing on the transition from individual word recognition (word-by-word reading) to fluent reading of word sequences in both unrelated word lists and connected text, across three grades in two languages that differ in orthographic transparency (English being opaque and Greek being relatively transparent). To meet our objectives, we examined: (a) the accuracy and speed of reading unconnected words (in isolation or in lists), in order to disentangle their contribution to word reading efficiency; (b) the developing interrelations among isolated word reading speed, word list reading fluency, and text reading fluency; (c) the extent to which individual differences in word list and text reading fluency can be explained by serial digit naming (an index of sequential item processing), beyond the effects of discrete word reading; (d) whether this two-predictor model accounts for similar amounts of variance in word list and text reading fluency; and (e) whether the observed developmental patterns and concurrent interrelations hold similarly across two languages differing considerably in orthographic transparency.

Our results showed that: (a) there is an interdependence between the accuracy and speed dimensions of word reading, with a minimum level of accuracy reached before speed develops; (b) the initially strong relationship between discrete word reading and both word list and text reading decreases across grade levels; (c) serial digit naming predicted word list and text reading fluency beyond the isolated word reading speed among readers of intermediate and upper elementary grades; (d) the two-predictor model of discrete word reading and serial digit naming predicted similar amounts of variance in text and word list reading fluency across grades; and (e) the interrelations among the tasks was similar across languages, consistent with a universal trajectory for reading fluency development beyond the efficiency of individual word recognition (cf. Altani et al., 2017).

Accuracy Before Speed

With respect to the accuracy and speed dimensions in word reading, our results differed between the two languages only among Grade 1 children. In particular, we found that accuracy was high among Greek children in all grade groups, including younger readers in Grade 1 (at least for this set of high frequency, short words), as expected based on previous studies showing that, in consistent orthographies, accuracy reaches ceiling by the end of Grade 1 (e.g., Aro & Wimmer, 2003; Seymour et al., 2003). In contrast, a significant number of Grade 1 children learning to read in English scored relatively low in word reading accuracy, consistent with previous evidence suggesting that children who learn to read in orthographically opaque languages lag behind in reading accuracy (Ellis et al., 2004; Seymour et al., 2003).

Notably, variability in speed was mostly evident among children who scored above 70% correct. In contrast, Grade 1 English-speaking readers who scored below 70% correct were generally slow in word reading, with little interindividual variability in word reading speed. This finding replicates the pattern previously reported for Danish-speaking children in primary school grades (Juul et al., 2014), described as a banana-shaped distribution. This distribution, which was also evident among our Grade 1 English sample, indicates that a minimum level of accuracy must be reached before speed can begin to develop. In addition, this finding is consistent with previous evidence showing that fluency scores in early reading development mainly reflect accuracy—at least among children who learn to read in orthographically opaque languages (e.g., Juul, et al., 2014). However, once a threshold of accuracy (at least 70% correct) is reached, there seems to be a shift from the accuracy dimension to the speed dimension in word reading (either in lists or in isolation), suggesting that speed can be examined relatively unaffected by accuracy above this performance threshold.

Variability in the speed of word reading was observed among readers with high accuracy in both orthographies. Notably, the range of word reading speed among Grade 1 English-speaking children who scored above 70% in accuracy included scores at the low end of the speed distribution from the readers who were less than 70% accurate (see Supplementary Table S3.6). That is, the slowest accurate word readers were about as slow as the slowest inaccurate word readers. Considered together with the fact that high variability in speed was observed among readers with high (> 70%) word reading accuracy (Figures 3.1 and 3.2), this finding suggests that the accuracy attainment alone is not *sufficient* for speed to emerge, even though it is *necessary*. This is also in accordance with evidence showing that in languages where word reading accuracy is achieved relatively early in reading development, large individual differences in reading ability are manifested in reading speed (e.g., Eklund, Torppa, Aro, Leppänen, & Lyytinen, 2015; Landerl & Wimmer, 2008; Mouzaki & Sideridis, 2007).

Finally, it is worth reiterating that although isolated word reading speed (at least for this set of short, high frequency words) apparently reached a plateau by Grade 3 in both languages, serial word reading speed increased further in Grade 5. This finding is important as it indicates that variability in word list reading fluency is not simply an expression of increasing speed and accuracy in reading isolated words. Similarly, the greater variation in serial than in discrete word reading, across grades and languages, further suggests that individual differences in reading isolated words and reading word lists reflect, at least to some extent, separable word-level reading skills, and it is to this point that we will now turn, focusing on the developing interrelations among reading isolated words and reading multiple words in lists and text across languages.

Isolated Word Reading Speed vs. Reading Fluency

Our results showed that reading isolated words and reading unconnected word lists or connected text correlate strongly among beginning readers. This is consistent with previous evidence showing that different reading task formats converge into a unified, simple reading fluency model in early development (Schwanenflugel et al., 2006). Thus, our findings confirm that during the early phases of reading acquisition, children appear to process words in a word-by-word manner (Kuhn & Stahl, 2013), irrespective of whether these words are presented in isolation or are surrounded by multiple unrelated words (Protopapas et al., 2013) or related words (Schwanenflugel et al., 2006). Evidence from eye movement research also supports this idea, showing that the time required to identify and name individually presented words is highly correlated with time spent viewing the word during normal (sentence) reading for young children in Grade 2 (but not for older, Grade 4 readers; Huestegge, Radach, Corbic, & Huestegge, 2009). This indicates that early in reading development, reading words within sentences (or lists) reflects the processing times of the words presented and read individually.

Indeed, in its beginner stages, reading has been described as a word recognition task (i.e., reading strings of individual words) rather than as a more complex task taking place in a phrase-by-phrase manner (e.g., Kuhn & Stahl, 2013; Rasinski et al., 2012). This idea also stems from theoretical accounts of reading fluency development, which assume that fluency emerges after decoding skills have been consolidated and word recognition is no longer laborious and effortful but, rather, automatic, freeing up cognitive resources for additional processes to take place (e.g., Ehri, 2005; Hudson et al., 2009; LaBerge & Samuels, 1974). Therefore, so far, our findings are in accordance with previous empirical evidence and theoretical accounts of reading fluency development.

Yet, our results also showed that the correlation of discrete word reading with both word list and text reading gradually decreased across grade levels. This pattern of results was found in both languages and is consistent with previous evidence in Greek showing that discrete and serial word reading become partially distinct in more advanced readers, loading on two separable (discrete vs. serial) factors (even though they are intertwined in early development, loading on a single factor; Protopapas et al., 2013, 2018).

This progressive decrease in the strength of the relationship between discrete and serial word reading across grades was evident in both serial reading tasks (irrespective of contextual processing demands, i.e., word list and text reading) across languages. In contrast, the association between the two reading fluency measures remained strong across grade levels and languages. In other words—and perhaps counterintuitively—word list reading fluency is increasingly more like text reading fluency than like isolated word reading speed. Therefore, what may distinguish isolated word reading, on the one hand, from reading fluency, on the other hand, cannot solely reflect text-level (e.g., oral reading expression, semantic, syntactic) processing skills. Rather, some additional processing skill(s) involved in the tasks measuring reading fluency—dissociating them from isolated word reading—must be applicable to multiword processing of both context-free word list fluency and connected text reading. The additional fluency-specific skill distinguishing isolated word reading speed from reading fluency goes beyond single word recognition skills but presumably precedes more complex supralexical processing involving, for example, syntactic, semantic, and discourse structures of text.

The Contribution of Serial Naming to Fluent Reading of Multiple Words

The second objective of this study was to examine the hypothesis that sequential multi-item processing skills may underlie the transition from isolated word reading to fluent reading of multiple words, presented either in lists or in sentences. Based on this hypothesis, we used a two-predictor model with discrete word reading (used as an index of individual word recognition) and serial digit naming (used as an index of sequential processing skills) to predict individual differences in word list and text reading fluency across grades and languages.

As expected, we found that both word list and text reading fluency were largely attributable to the ability to read isolated words for Grade 1 readers in both languages. This finding is consistent with previous evidence in Greek showing that, for Grade 2 children, serial word reading performance is mainly predicted by discrete word reading. Yet our results also showed that among the groups of intermediate (Grade 3) and more advanced (Grade 5) readers, serial digit naming became a significant and unique predictor not only for word list reading fluency, but also for text reading fluency – beyond isolated word reading speed. This pattern of results, observed across languages, is in agreement with previous studies with older children in orthographically consistent languages, showing that serial digit naming uniquely predicted word list reading fluency among Grade 6 Greek children (Protopapas et al., 2013) or text reading fluency among Italian children aged 11–13 (Zoccolotti et al., 2014), after accounting for individual word recognition or decoding skills. Thus, our finding confirms that variance related to sequential multiple item processing (indexed by serial digit naming) is shared with fluent reading of either connected or unconnected multiple words across different (alphabetic) orthographies.

Furthermore, our results indicated that this additional component skill concerning sequential multi-item processing emerges as early as Grade 3. This is most clearly seen in the context of the developmental course of other word reading performance indices. In particular, isolated word reading speed reached a plateau by Grade 3 in both languages, suggesting that by this time children have typically mastered word recognition, at least for high frequency, short words. (High accuracy was also presumably reached well before Grade 3 in both Greek and English, for this set of words). Thus, it seems that, across languages, once basic word recognition skills have been mastered (typically by Grade 3; Chall, 1983; Kuhn & Stahl, 2003), serial digit naming begins to capture a unique portion of variance in reading fluency (of both word lists and texts) beyond isolated word reading speed. This evidently occurs irrespective of language processing demands pertaining to orthographic depth or connected text understanding. This line of evidence is consistent with the idea that reading fluency develops in a similar fashion across languages (e.g., Caravolas et al., 2012; Vaessen e t al., 2010), as well as with the notion of a universal role of serial digit naming in accounting for reading fluency development (e.g., Altani, Georgiou et al., 2017; Georgiou, Aro, Liao, & Parrila, 2016). The present results further support the hypothesis that the emergent contribution of serial digit naming to reading fluency beyond discrete word reading in Grades 3 and 5 presumably reflects a developmental shift from dealing with words at a micro-level, which refers to individual word-by-word or *intraword* processing, to dealing with words at a macro-level, which refers to multiword or *interword* processing (see Altani, Georgiou, et al., 2017; de Jong, 2011, for similar arguments).

Finally, our results showed that the two-predictor model of serial digit naming and discrete word reading accounted for similar amounts of variance in word list reading fluency and text reading fluency. This can be attributed to the similar requirements of word list and text reading when it comes to efficient processing of word sequences. However, it may also be due in part to the special features of our tasks. In general, word list reading does not require any syntactic or semantic integration or other supralexical processing that may be involved in text reading: Text reading is indisputably much more complex, requiring additional linguistic and metacognitive processes (Breznitz, 2006; Hudson et al., 2009; Wolf & Katzir-Cohen, 2001). However, our text (used across grades to avoid confounding differences in material) included sentences that were very easy to read and comprehend, thereby intentionally minimizing supralexical requirements, especially for participants in Grades 3 and 5. The lack of appreciable syntactic and semantic processing difficulty minimized variance in task performance due to individual differences in the associated (syntactic and semantic) language processing skill, effectively rendering text processing similar to word list processing for these children. Therefore, our results suggest that variance in reading multiword sequences—either in lists or in text—is co-determined by a component skill of multi-item processing, as long as individual word recognition has become sufficiently proficient to allow uninterrupted sequential processing of adjacent items. This component skill concerning the ability to simultaneously deal with more than one item at different processing stages has been termed *cascading* and has been proposed to constitute a distinct domain of individual differences impacting the development of reading fluency (Protopapas et al., 2013, 2018).

A Common Trajectory Across Languages Varying in Orthographic Transparency

With respect to the role of orthographic transparency, our results showed very similar patterns of intercorrelations across languages, consistent with previous cross-linguistic findings among Grade 3 children (Altani, Georgiou et al., 2017). Not everything was identical, however. Although isolated word reading speed dominated reading fluency among younger children in Grade 1, this effect was influenced by the language in which children learn to read. More specifically, the effect of discrete word reading on word list reading fluency was stronger for the English-speaking Grade 1 children (95% CI: –0.87, –0.02), evidenced in the somewhat steeper slope for the English than the Greek group in the top left panel of Figure 3.3, and indicating that orthographic transparency influences the relative contribution of isolated word reading speed to early reading fluency. In contrast, we did not find an interaction between language and serial digit naming in the prediction of either word list or text reading fluency across grade levels. This suggests that the role of multi-item processing (cascading) in reading fluency is not influenced by the orthographic depth or perhaps by any differences at the level of individual word recognition (i.e., reliance on different grain sizes of orthographic units) that may be imposed by different orthographies. In essence, this finding can be taken to point towards a separable skill domain within reading fluency (Protopapas et al., 2018), which concerns serial processing of multiple simultaneously presented items and is implemented by cognitive mechanisms not involved in the processing of individual items, whether digits or words.

Limitations

Some limitations of the present study are worth mentioning. First, our study is cross-sectional, and therefore any longitudinal interpretations, including claims pertaining to skill growth and causal developmental relations, can only be made with great caution and must remain tentative until specifically tested in future studies with appropriate longitudinal research designs. Second, all items in Greek consisted of two-syllable words, while items in English consisted of one-syllable words. Strictly matching items across and within these two languages was impossible, as most single-digit number words are bisyllabic in Greek, but monosyllabic in English (see Altani et al., 2017; Georgiou et al., 2016, for previous studies mentioning the same problem). Still, the great similarity in the pattern of results obtained across the two orthographies somewhat alleviates the concern that such differences in materials may have introduced consequential confounds. Third, our text reading measure consisted of short, simple sentences, made up of familiar, high-frequency words, thus substantially reducing its comprehension demands, particularly among older, more advanced readers. Therefore, our findings may not generalize to demanding texts (in terms of syntactic and semantic integration requirements), where reading performance may be dominated by text-level supralexical processing skills. Additionally, we did not test for comprehension during text reading. Future studies should investigate whether the importance of multi-item processing in text reading fluency is reduced in longer, more complex passages, where both reading speed and comprehension level are tested. Finally, our study was conducted in alphabetic orthographies, and we used only digits in the serial naming task. Future studies should examine if similar patterns of relationships can be obtained also in non-alphabetic orthographies (e.g., Chinese) and with serial naming tasks including different types of stimuli (but cf. Protopapas et al., 2018, on the differential alignment of different types of materials with the serial naming factor).

Conclusion

Our findings confirm that there is a qualitative developmental shift from the accuracy to the speed dimension of individual word recognition that takes place when a minimum level of word reading accuracy is achieved (also in agreement with Juul et al., 2014). Once this accuracy threshold is reached, variation in the accuracy dimension is not enough to account for the large variation observed in the speed dimension. Similarly, variation in isolated word reading speed cannot fully account for variability in word list reading fluency, across orthographies. Thus, there is not a direct transition from isolated word reading speed to serial word reading speed, as the former may be necessary, but not sufficient, for the latter to emerge. This evidence challenges the notion that in the absence of comprehension requirements word list reading fluency is merely an expression of single word reading efficiency (e.g., Hudson, Torgesen, Lane, & Turner, 2012; Kim & Wagner, 2012; Kuhn et al., 2010; Wolf & Katzir-Cohen, 2001). Instead, a separate component that is associated with sequential processing of multiple items appears to be crucial—across orthographies—for the emerging fluency skills that are involved in reading sequences of words (in lists or sentences), beyond the facility of individual word reading. This fluency-specific component, termed cascading, concerns the ability to overlap different processing stages across multiple successive items, over and above single word recognition but below more complex text-level (supralexical) processes (Protopapas et al., 2018). The emergence and gradual dominance of this component over reading fluency may offer a mechanism to account for the gradual developmental shift from individual word-by-word recognition to fluent reading of multiple words in lists or sentences.

There is little doubt that accurate and fast word identification is essential for reading fluency, or that multiple lexical and supralexical components (e.g., phonemic awareness, orthographic knowledge, semantic processing, syntactic parsing) contribute to the development of word recognition skills (e.g., Ehri, 2005) and more complex text reading (e.g., Kuhn et al., 2010; NICHD, 2000). Indeed, fast and accurate reading of single words is a prerequisite for fluency, as indicated by the contribution of isolated word reading speed to both word list and text reading fluency in early development. However, just as it is important to differentiate between accuracy and speed, as a reader may be accurate without being fast (e.g., Breznitz, 2006; Torgesen, 2005), it is also equally important to differentiate between isolated word reading speed and multiword reading fluency, as a reader may be able to recognize single words efficiently without being fluent in processing multiword sequences (either lists or texts).

Our findings highlight an important gap in the conceptualization of reading fluency, suggesting that a separate skill of sequential multi-item processing is involved in reading multiple words in lists or text, beyond isolated word reading efficiency. Evidence showing disproportionate difficulties in the serial over the discrete versions of word reading speed for children with dyslexia (Zoccolotti et al., 2013; Zoccolotti et al., 2015) is in line with this idea. Thus, accuracy and speed of isolated word reading will not likely suffice for the development of fluent multiword reading (cf. Torgesen, 2005), while, intervention at the more complex text level may need to be preceded by mastering serial multi-item fluency skills (see Vander Stappen & Van Reybroeck, 2018; Wolff, 2014, for some promising results concerning RAN interventions). Because efficiency in naming familiar stimuli, such as digits, is achieved relatively early in development, serial naming (RAN-type tasks) can be used as a proxy for sequential processing skills, beyond single-item accuracy and speed. Further research is required to examine similar serial tasks that differ in domain-specific and domain-global aspects (e.g., stimulus-specific characteristics, visual or articulatory/motor processes) and their contribution to reading fluency measures varying in level of syntactic and semantic complexity, towards a better understanding of multi-item processing (cascading) in reading fluency development.

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Supplementary Material

Supplementary Tables S3.1 and S3.6 report complementary analyses to the results of the main text. Supplementary Tables S3.2–S3.5 report the same analyses to the results presented in the main text using a higher (80% correct) threshold of word reading accuracy, for comparison.

Table S3.1

Correlations Between Accuracy and Rate on Discrete and Serial Word Reading for Each Grade and Language

Accuracy-Rate	Grade 1	Grade 3	Grade 5
Greek			
d_word	0.48	0.38	0.20
s_word	0.49	0.57	0.30
English			
d_word	0.72	0.22	0.12
s_word	0.71	0.49	0.22

Note. d = discrete; s = serial. Correlations (Pearson's *r*) are reported using the entire unselected sample of Grade 1 students in both languages.

Table S3.2

Descriptive Statistics in Each Grade and Language

	Grade 1					Grade 3					Grade 5				
	N	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Greek															
d_word	85	0.61	0.14	−0.07	−0.53	100	0.96	0.17	0.06	0.20	99	1.06	0.16	0.01	−0.50
s_word	86	0.70	0.26	0.43	−0.49	100	1.42	0.38	0.06	0.04	98	1.67	0.35	−0.14	−0.49
S_text	86	0.86	0.36	0.64	−0.26	98	1.95	0.45	−0.37	−0.31	99	2.42	0.45	−0.25	−0.31
s_digit	87	1.40	0.27	−0.08	−0.43	100	1.93	0.33	−0.09	−0.61	99	2.13	0.38	−0.59	0.47
English															
d_word	78	0.72	0.16	0.01	0.09	128	0.98	0.13	0.09	0.66	122	1.09	0.12	−0.30	−0.03
s_word	78	0.94	0.38	−0.04	−0.93	128	1.57	0.38	−0.14	−0.57	122	1.80	0.37	0.11	−0.40
s_text	78	1.35	0.52	0.34	−0.44	128	2.35	0.57	−0.21	−0.39	122	2.86	0.62	0.14	−0.58
s_digit	78	1.23	0.30	0.12	−0.05	128	1.69	0.39	0.27	−0.20	122	1.92	0.38	0.29	−0.38

Note. d = discrete; s = serial; Skew = skewness; Kurt = kurtosis. The scores are presented in items per second (words or digits). Results are reported using a higher threshold (80% correct) in word reading accuracy.

Table S3.3

Intrerrelations Among Tasks in Each Grade and Language

	Task	Grade 1				Grade 3				Grade 5			
		1.dWrd	2.sWrd	3.Text	4.sDig	1.dWrd	2.sWrd	3.Text	4.sDig	1.dWrd	2.sWrd	3.Text	4.sDig
Greek													
1	d_word		.85	.81	.45		.62	.59	.53		.54	.52	.42
2	s_word	.84		.89	.53	.65		.79	.57	.56		.70	.62
3	s_text	.78	.89		.37	.64	.82		.63	.50	.73		.41
4	s_digit	.44	.51	.36		.57	.59	.65		.45	.65	.43	
English													
1	d_word		.70	.73	.43		.44	.38	.23		.47	.54	.37
2	s_word	.68		.80	.35	.50		.72	.60	.49		.65	.57
3	s_text	.72	.77		.49	.41	.74		.55	.54	.63		.48
4	s_digit	.40	.33	.47		.19	.59	.51		.42	.61	.52	

Note. For each grade and language, Spearman's ρ is presented above the diagonal; Pearson's r is presented below the diagonal. d = discrete; s = serial; Wrd = word; Dig = digit. Results are reported using a higher threshold (80% correct) in word reading accuracy.

Table S3.4

Multiple Regressions Coefficients Predicting Serial Word Reading and Text Reading in Each Grade and Language

	Grade 1		Grade 3		Grade 5	
	Serial Words	Text	Serial Words	Text	Serial Words	Text
Greek						
Discrete Words	1.42***	1.97***	1.08***	1.16***	0.74***	1.10***
Serial Digits	0.17**	0.02	0.38***	0.61***	0.46***	0.31**
Total R^2	0.72	0.60	0.49	0.54	0.51	0.28
English						
Discrete Words	1.64***	2.23***	1.22***	1.48***	0.83**	1.93***
Serial Digits	0.08	0.32**	0.49***	0.65***	0.49***	0.59***
Total R^2	0.45	0.55	0.50	0.35	0.43	0.51

Note. Unstandardized regression coefficients from simultaneous multiple regressions are presented. Results are reported using a higher threshold (80% correct) in word reading accuracy.

$^{*}p < .05$; $^{**}p < .005$; $^{***}p < .0005$

Table S3.5

Variance Proportions Predicting Serial Word Reading and Text Reading in Each Grade and Language

		Grade 1				Grade 3				Grade 5			
		Serial Words		Text		Serial Words		Text		Serial Words		Text	
Variable		Unique	Total	Unique	Total	Unique	Total	Unique	Total	Unique	Total	Unique	Total
Greek													
Discrete	Words	.49	.70	.50	.61	.15	.42	.12	.42	.09	.32	.11	.25
Serial	Digits	.02	.24	.01	.11	.07	.35	.13	.43	.20	.43	.05	.18
English													
Discrete	Words	.35	.46	.34	.52	.16	.25	.10	.17	.06	.24	.13	.29
Serial	Digits	.01	.10	.04	.22	.25	.35	.20	.27	.20	.38	.11	.27

Note. Results are reported using a higher threshold (80% correct) in word reading accuracy.

Table S3.6

Mean Accuracy (proportion correct) and Rate (words per second) among Grade 1 Children Scoring Below versus Above 70% Correct in Serial and Discrete Word Reading for Each Language

	Accuracy ≥ 70%					*Accuracy <70%*				
Task	*N*	*M*	*SD*	Min.	Max.	*N*	*M*	*SD*	Min.	Max.
Greek										
Serial (s_word)										
Accuracy	92	0.88	0.07	0.70[a]	1.00	6	0.64	0.03	0.61	0.67
Rate	92	0.69	0.26	0.24	1.38	6	0.41	0.12	0.27	0.61
Discrete (d_word)										
Accuracy	98	0.95	0.06	0.75	1.00	2	0.60	0.06	0.56	0.64
Rate	98	0.60	0.14	0.30	0.94	2	0.37	0.13	0.28	0.46
English										
Serial (s_word)										
Accuracy	107	0.91	0.09	0.70	1.00	50	0.44	0.18	0.06	0.67
Rate	107	0.89	0.40	0.20	1.82	50	0.38	0.18	0.20	0.95
Discrete (d_word)										
Accuracy	104	0.89	0.09	0.70	1.00	53	0.46	0.16	0.11	0.67
Rate	104	0.71	0.16	0.30	1.15	53	0.45	0.13	0.21	0.69

Note. Min. = minimum; Max. = maximum; s = serial; d = discrete; [a] Three data points included in the group were only marginally below 0.70 correct (i.e., 0.69444).

Chapter 4: Tracking the Serial Advantage in the Naming Rate of Multiple over Isolated Stimulus Displays

Introduction

Rapid automatized naming (RAN) refers to the ability of an individual to name rapidly and accurately a matrix of a small set of familiar stimuli, such as letters, digits, objects, or colors (Kirby, Georgiou, Martinussen, & Parrila, 2010). Previous studies have shown that multiple stimulus displays (as in RAN tasks) yield faster naming rates compared to isolated stimulus displays (as in discrete naming tasks), at least among typically-developing children (Zoccolotti et al., 2013) or adults (Jones, Branigan, & Kelly, 2009). This has been termed *serial advantage* (see Altani, Georgiou, et al., 2017). To date, the serial advantage has been documented with alphanumeric (e.g., digits), nonalphanumeric (e.g., colors), and/or orthographic stimuli (words), mainly among older children (see Zoccolotti et al., 2013; Zoccolotti, De Luca, & Spinelli, 2015) or individuals with dyslexia (e.g., Gasperini, Brizzolara, Cristofani, Casalini, & Chilosi, 2014). It remains unknown how this serial advantage develops across different grade levels (including younger and older children), different naming material, and different languages. Thus, the purpose of this study was to examine the serial advantage in naming digits, dice, number words, objects, and words in a group of Grade 1, 3, and 5 Greek- and English-speaking children.

A few previous studies have reported an asymmetry in the improvement of performance in serial over discrete naming tasks—with serial naming showing a steeper growth—across elementary school grades (Logan, Schatschneider, & Wagner, 2011; Protopapas, Altani, & Georgiou, 2013; Protopapas, Katopodi, Altani, & Georgiou, 2018).

Our study focuses on quantifying this serial advantage (expressed as the concurrent difference between serial and discrete naming rate) and identifying the factors that are associated with its change.

Although it is well established that RAN is a strong predictor of reading (Kirby et al., 2010), researchers also concur that the RAN-reading relationship varies as a function of the presentation format of the reading and naming tasks (e.g., de Jong, 2011; Protopapas et al., 2013). For example, word list reading fluency correlates more strongly with serial naming (RAN) than with discrete naming (e.g., Altani, Protopapas, & Georgiou, 2017; de Jong, 2011). This format-specific association seems to apply across various naming tasks. That is, among older children or skilled readers, naming tasks of different content, but same presentation format, correlate more strongly with each other (i.e., serial with serial and discrete with discrete) than naming tasks of the same content, but of different presentation format (Protopapas et al., 2013; Protopapas et al., 2018).

In contrast, associations between serial- and discrete-trial versions of the same content are not necessarily stable across grades. For example, naming multiple word displays and naming isolated words are strongly associated among beginning readers, but only moderately so among advanced readers (Protopapas et al., 2013). In fact, the association between serial and discrete naming of either words or digits has been reported to decrease with increasing skill (Altani et al., 2018). These findings suggest that when a certain proficiency level is achieved, individual differences in serial naming are in part independent from individual differences in discrete naming of the same material (see also Bowey, McGuigan, & Ruschena, 2005). This evidence has led researchers to argue that there might be a distinct skill specific to the sequential processing component of the serial naming tasks (i.e., RAN), which is crucial for the development of fluent performance in multiple stimulus naming beyond the efficiency of naming the same stimuli in isolation (e.g., Altani, Protopapas, et al., 2017; Jones, Branigan, & Kelly, 2009; Protopapas et al., 2018).

It has also been claimed that not only the standard RAN tasks, but also word list reading (and presumably text reading) can be viewed as a serial rapid naming task, in the sense that both word recognition of individually-presented words and processing of sequences of multiple words need to become efficient for the successful reading of word lists or text (which is how reading fluency is typically assessed; see Altani et al., submitted; Protopapas et al., 2018).[7] This view originates from the idea that individuals need to be able to process multiple stimulus displays (words or other symbols) by performing both parallel and sequential processes. This coordination of multiple elements and processes both in parallel and serially has been termed *cascaded processing* (Protopapas et al., 2013) and is supported by evidence from eye movement studies showing that eyes are ahead of the voice, yet there is a very tight control between “looking” and “talking” during oral word reading or digit naming (see Gordon & Hoedemaker, 2016; Laubrock & Kliegl, 2015). Hence, different processing stages of adjacent words or symbols within a sequence may occur both in parallel and sequentially, resulting in a partial temporal overlap. This also implies that the processing stages (e.g., visual identification, name retrieval, articulation) of each stimulus within a sequence are not executed in a strictly serial manner

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[7] Notice that in some psychometric batteries (e.g., The Process Assessment of The Learner; Berninger, 2007) RAN is even assessed with word naming.

but can overlap in time for successive stimuli. As such, the processing of the next stimulus can begin before the processing and production of the previous one is completed.

The connection between the observed serial advantage and the aforementioned format-specific associations in naming tasks is far from being straightforward. The fact that performance is correlated across serial naming tasks, regardless of content, and that serial naming is faster than discrete naming can be thought to originate in cascaded (i.e., temporally overlapped) processing of successive stimuli (see Gordon & Hoedemaker, 2016; Protopapas et al., 2018). Cascaded processing efficiency is thought to constitute a distinct skill domain, which develops somewhat independently from discrete naming skills and governs performance in serial tasks. Nevertheless, serial and discrete naming tasks are correlated, obscuring the nature of the observed serial advantage, which is meant to express their difference rather than their common elements. In particular, the extent to which individual differences in the serial advantage in naming tasks might depend primarily on individual differences in the discrete or the serial dimension of the naming task remains unknown.

On the other hand, despite their format, naming tasks can be further divided into different categories based on their content, for example, into alphanumeric (digits, letters) and nonalphanumeric (objects, colors) naming tasks (Araújo, Reis, & Petersson, & Faísca, 2015). This distinction is supported by evidence showing that: (a) alphanumeric and nonalphanumeric tasks load on different factors (Donker, Kroesbergen, Slot, van Viersen, & de Bree, 2016; Rodríguez, van den Boer, Jiménez, & de Jong, 2015; van den Bos, Zijlstra, & Spelberg, 2002); (b) alphanumeric naming tasks correlate more strongly with reading tasks than nonalphanumeric naming tasks (Araújo et al., 2015); and (c) naming multiple stimulus displays is generally faster for alphanumeric than for nonalphanumeric material, at least in elementary school grades (Albuquerque & Simões, 2010; Bowey et al., 2005; van den Bos et al., 2002). It has thus been argued that the alphanumeric and nonalphanumeric stimuli differ not only in the time they are learned, but also in the nature of the sets from which they are derived (see Kirby et al., 2010). Protopapas et al. (2018) also claimed that differences between kinds of stimuli impact the degree of efficient sequential processing in multiple stimulus displays during RAN-type tasks, based on the level of individual processing efficiency and their contextual availability.

In a similar vein, when examining 10-year-old children with dyslexia vs. controls, Pan et al. (2013) found no significant differences between the groups in serial naming of number words depicted as dice surfaces. Instead, significant differences were detected between the groups during naming of the same number words depicted as digits. This suggests that—although the phonological representations were the same—dice were processed differently from digits, in a way that the former required semantic access prior to lexical retrieval, a property shared with nonalphanumeric stimuli such as objects (Jones, Branigan, Hatzidaki, & Obregón, 2010; Liu & Georgiou, 2017); whereas digit naming could proceed via direct (arbitrary) mapping from visual to phonological codes (Roelofs, 2006), a property that alphanumeric stimuli share with word naming. In other words, naming task content form different types that are hypothesized to be differentially processed with implications for serial naming efficiency that may impact the development and magnitude of the serial advantage. Thus, in the present study we included alphanumeric (digits), nonalphanumeric (images of objects or dice), and orthographic (number words and words) stimuli and anticipated that the trajectory of the serial advantage across grades would be influenced by the task content.

In summary, previous evidence shows that task content and task format matter as to how naming tasks are carried out. Yet, only recently was it pointed out that because of their differential processing requirements, serial- and discrete-trial naming tasks across grades offer a potential model for tracking multi-element vs. single-element processes in reading throughout development (de Jong, 2011; Protopapas et al., 2013; Protopapas et al., 2018). In particular, word list reading fluency can be modeled as a serial naming task to the extent it is dominated by the common processes of visual recognition, phonological mapping via lexical access, and articulatory planning and execution, rather than by an effort in graphophonemic decoding. That is, as soon as words are read "by sight", effectively treated as single items rather than complex sequences, going through a list of words and reading them aloud is very similar to going through a list of digits and naming them (see van den Bos, Zijlstra, & van den Broeck, 2003). As fluency emerges, the transfer of focus from intra-item (or intra-word) to inter-item (or inter-word) processing should be evident in the development of a serial advantage in word reading, in parallel with the overall development of the serial advantage across naming tasks indexing efficient sequential processing skill.

The Present Study

We aimed to examine the development of serial advantage, expressing the gain in naming rate when comparing multiple vs. isolated stimulus presentation, across five different kinds of naming material (digits, objects, dice, number words, and words) and three grade levels (Grades 1, 3, and 5). Serial advantage is defined as the benefit in performance during the serial-trial version of the task compared to the corresponding discrete-trial format. In the context of the present study, serial advantage refers to the difference between the serial and discrete naming rate of the same task content, as measured in items per second, that is, number of elements per unit time.

More specifically, we had two main objectives. First, we aimed to examine differences in serial advantage between different grades and different types of content. We specifically hypothesized that serial advantage would increase significantly in higher grades, confirming the asymmetry in the increase of the serial naming rate compared to the discrete naming rate across material types. Additionally, we examined the interaction between grade and task content to examine whether content-specific characteristics influence the trajectory of the serial advantage. If the serial advantage is content-specific, then we should observe different trajectories across grades for different naming material. Otherwise, similar trajectories of serial advantage development should be observed across naming tasks irrespective of their content.

Second, we sought to examine how the correlation between naming tasks of the same content, but of different format, might be associated with their corresponding serial advantage and, subsequently, whether the serial advantage is mainly determined by individual differences in the discrete or the serial component of the naming task. Specifically, we hypothesized that if serial advantage depends on the increasing naming rate of individual stimuli (displayed in isolation), then we should observe a positive association between serial advantage and discrete naming rate across grades. Alternatively, if the serial advantage is determined by a distinct skill concerning sequential processing of multiple stimulus displays, then we should observe a stronger association between serial advantage and serial naming rate.

Finally, we sought to examine these research questions in two languages differing in the level of orthographic transparency (English being opaque and Greek being relatively transparent; Seymour, Aro, & Erskine, 2003). If similar patterns of results are observed in these two languages, then we can reasonably assume that findings concerning the development of the serial advantage in word and symbol naming generalize to alphabetic orthographies and cannot be attributed to language specific aspects related to the consistency of the orthography.

Methods

Participants

Our participants were 720 children attending Grades, 1, 3, and 5, from two different sites: Canada and Greece. A sample of 409 English-speaking children was recruited in Edmonton (Alberta), and a sample of 311 Greek-speaking children in Athens. Age and gender information in each grade and site are presented in Table 4.1. All participants were native speakers of their respective language and were recruited from public schools typically serving middle-class families. Both parental and school consent was obtained in each research site prior to testing. Protocol approval was also obtained for each site prior to testing.

Materials

Ten tasks were administered: Five naming tasks of different content presented in two formats, namely serial (multiple stimulus displays) and discrete (isolated stimulus displays). Materials consisted of three types of stimuli: alphanumeric, nonalphanumeric, and orthographic stimuli (see Figure 4.1). Alphanumeric stimuli included four digits (2, 3, 5, 6). Nonalphanumeric stimuli included four images of objects and four images of dice.

Orthographic stimuli consisted of four number words and two sets of 36 high-frequency, short words. We used the same four words across the conditions of digit, dice, and number word naming. Object words and all words included in the word naming tasks were matched with the four number words in psycholinguistic variables (e.g., syllabic structure, word-length, frequency, and number of phonemes) to minimize differences in naming requirements (lexical access and articulatory planning) as a potential confounding variable across conditions (see Appendix B). Because of the matching requirements, dictated by the number words in each language, and the restriction to the range 1–6 for the dice, all English stimuli were monosyllabic whereas all Greek stimuli were bisyllabic. Object images were derived from a corpus of black-and-white drawings from the Center for Research in Language & International Picture-Naming Project (see Szekely et al., 2004), including validated items from various sources with norms across a range of languages (see Bates et al., 2003; Székely et al., 2002), as well as from a subset of stimuli included in the standardized RAN/RAS battery (Form B; Wolf & Denckla, 2005).

Table 4.1

Sample Information for Each Grade and Language

	Grade	*N*	Age (*SD*)	Gender F:M
Greek				
	1	100	82.8 (3.4)	53:47
	3	103	107.1 (3.5)	53:50
	5	99	130.0 (3.4)	54:45
English				
	1*	101	81.6 (4.2)	50:51
	3	130	105.8 (3.9)	64:66
	5	122	129.7 (4.2)	70:52

Note: F = female; M = male; Mean age is reported in months. Information is reported for the final sample following the cleaning procedure. * The original sample size was 157 children (age = 81.4; *SD* = 4.2; F = 87).

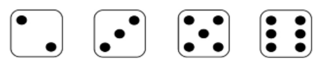
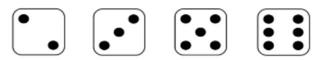
Materials	English	Greek
Digits	2 3 5 6	2 3 5 6
Objects		
Dice		
Number words	two three five six	δύο τρία πέντε έξι
Words	tea horse bike fox ...	νέο θεία ζούσε όλα ...

Figure 4.1. Material per task in each language.

Procedure and Apparatus

Each of the naming and reading tasks consisted of 36 items and was administered in two presentation formats: in a serial-trial and a discrete-trial format (see Figure 4.2). In the serial format, all stimuli were presented simultaneously on a computer screen, in a grid format of 4 rows × 9 items. Participants were asked to name (or read aloud), as fast and as accurately as possible, all presented stimuli starting from the first item on the top left corner and working row-by-row until the last item of the grid. The total naming time until the completion of the entire task was recorded. In the discrete format, stimuli were presented one-by-one, in the middle of the screen. Participants were asked to name (or read aloud), as fast and as accurately as possible, each stimulus—as soon as the item appeared on the screen. The total response time for each item was recorded, including onset latency and articulation, in order to match the serial naming data. The appearance of the next stimulus was controlled by the experimenter via pressing a key, following a complete response of the stimulus. Prior to testing, familiarity with the specific items and the discrete vs. serial trial procedure was ensured. During testing, four practice items preceded each trial (for both formats) to ensure compliance with the demands of the task and familiarity with the intended names of the stimuli. The order of the trials was pseudorandomly determined, the same for all participants, with the restriction that the same item could not appear in consecutive trials (in the discrete format) or adjacent positions (in the serial format). All ten tasks were administered to all participants in individually randomized order.

Participants were seated in front of a 15.4 inches computer laptop screen. The experimental software DMDX (Forster & Forster, 2003) was used for stimulus presentation and response recording. Vocal responses were recorded via a headset microphone (Logitech USB H340 or Sennheiser PC131). Each participant was tested individually in a private and quiet room provided by the school, during school hours, either by the first or the third author, or by trained assistants. Individual testing took approximately 30 to 50 minutes depending on the participant's grade level. Data collection took place during the last trimester of the academic year (April to June). A consistent protocol was followed across sites.

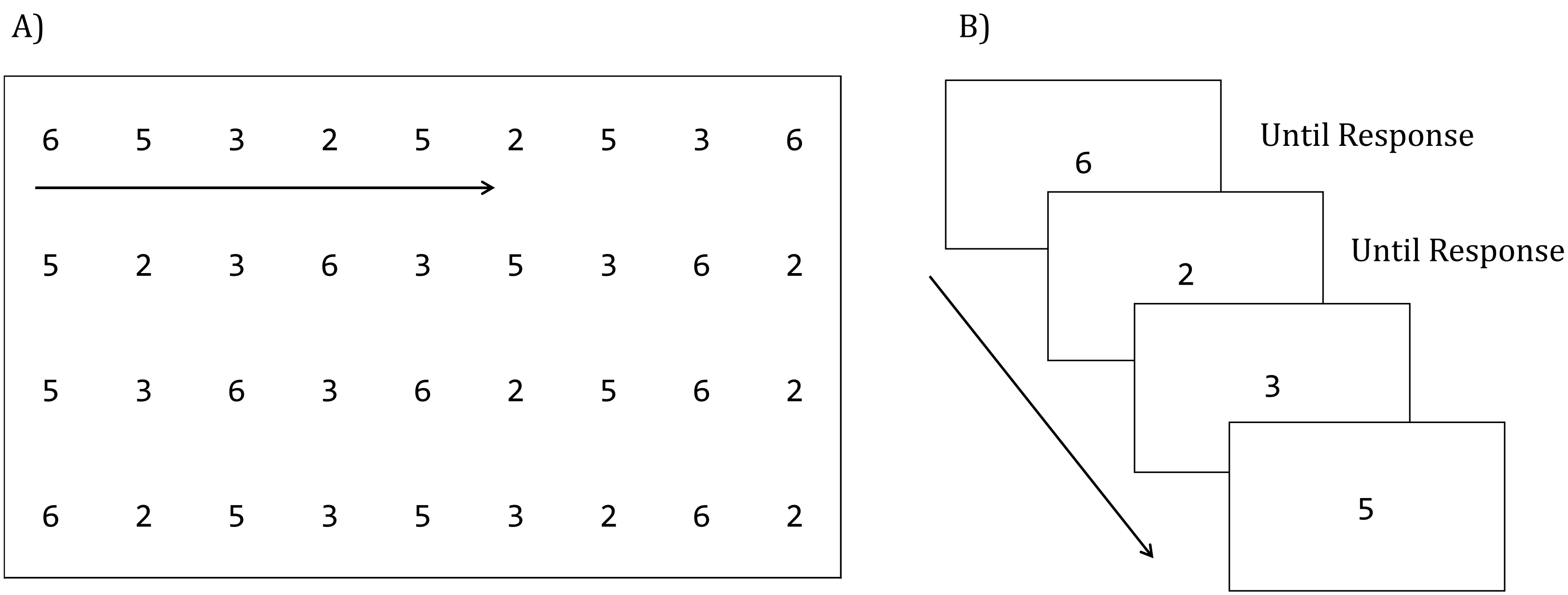


Figure 4.2. Example of (A) serial-trial and (B) discrete-trial format in digit naming.

Results

Data Extraction and Preparation

Response times (RTs) and accuracy were determined off-line using Check Vocal (Protopapas, 2007). For serial tasks, response time consisted of the completion time of the entire task, including articulation duration and any intermediate pauses. Both correct and incorrect responses were included. For discrete tasks, response time consisted of both onset latency and articulation duration. Thus, both serial and discrete trials included the time required for response preparation and response execution. Finally, RTs were transformed into a scale of "item per second" by inversion. Specifically, for discrete tasks, we averaged naming rate over the correctly named items to compute a mean response for each person and task; while, for serial tasks, we divided the serial rate by 36 (the number of items presented in each of the serial trials) to acquire comparable scales across serial and discrete trials. Hence, all of the following results refer to *rate* (i.e., number of stimuli named or read per second).

All statistical analyses were performed using R version 3.4.1 (R Development Core Team, 2017). First, we inspected the proportion of errors in discrete tasks to examine the level of accuracy in naming each type of stimuli (see Figures S4.1-S4.2 in Supplementary Material). Participants with error rate higher than 30% in two or more naming tasks (English: 56 children in Grade 1; [8] Greek: 3 children in Grade 1, 5 children in Grade 3, and

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[8] A minimum level of 70% score in word reading/word naming accuracy has been previously reported as a reliable threshold before speed variability can emerge (see Juul et al., 2014; Altani et al., submitted). To retain a consistent sample across conditions, all data from first graders in English with an error rate higher than 30% in word naming were removed from subsequent analyses.

2 children in Grade 5) were excluded from subsequent analyses. Additionally, a small number of individual data points were removed, associated with outliers based on the examination of quantile-quantile (Q-Q) plots per task and grade, or with low accuracy on individual tasks (English: 1 data point in Grade 1, and 5 in Grade 3; Greek: 4 data points in Grade 1, and 4 in Grade 5). Descriptive statistics for the final dataset are reported in Table 4.2. Examination of Q-Q plots (Figures S4.3-S4.4) and Anderson-Darling (Table S4.1) tests indicated good approximation to the normal distribution, with at most minor deviations.

Serial Advantage for Each Task

Serial advantage refers to the rate difference between the two different formats, that is, the serial naming rate minus the discrete naming rate for each content type. Serial naming rate is the performance, expressed as number of items named per second, when items are presented simultaneously, in a grid format; discrete naming rate is the mean performance, expressed as number of items named per second, when items are presented individually, in isolation. This difference describes the gain in serial compared to the discrete-trial format per task content. (Descriptive statistics for this new set of variables are available in the Supplementary Material, Table S4.2.)

Table 4.2
Descriptive Statistics for Serial and Discrete Tasks for Each Grade and Language

	Grade 1					Grade 3					Grade 5				
English	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Serial Tasks															
Digit	101	1.23	0.30	0.14	−0.05	130	1.69	0.39	0.28	−0.18	122	1.92	0.38	0.29	−0.38
Object	101	0.82	0.18	0.12	−0.55	127	1.09	0.20	0.33	0.40	122	1.26	0.20	0.31	−0.24
Dice	101	0.92	0.26	0.35	0.02	130	1.29	0.32	0.17	−0.55	122	1.53	0.31	0.32	1.07
Number word	101	1.31	0.30	−0.12	−0.54	130	1.77	0.32	−0.10	−0.39	122	1.95	0.35	0.07	−0.72
Word	99	0.93	0.38	0.02	−0.98	130	1.56	0.39	−0.25	−0.34	122	1.8	0.37	0.11	−0.40
Discrete Tasks															
Digit	101	0.84	0.14	0.25	−0.58	130	1.04	0.14	0.06	−0.19	122	1.17	0.13	0.01	0.38
Object	101	0.71	0.10	0.09	0.47	130	0.85	0.10	−0.15	0.30	122	0.95	0.10	−0.05	0.09
Dice	101	0.70	0.14	−0.07	−0.47	129	0.86	0.13	0.16	−0.38	122	1.01	0.13	0.11	−0.02
Number word	101	0.89	0.15	0.28	−0.62	130	1.06	0.15	0.16	0.44	122	1.19	0.14	0.02	−0.14
Word	101	0.72	0.16	0.02	−0.04	129	0.98	0.13	0.09	0.66	122	1.09	0.12	−0.30	−0.03
Greek	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Serial Tasks															
Digit	100	1.38	0.27	0.04	−0.43	103	1.91	0.34	−0.17	−0.47	99	2.13	0.38	−0.59	0.47
Object	100	0.74	0.16	0.34	−0.64	103	1.05	0.20	0.33	−0.35	99	1.20	0.23	0.19	0.77
Dice	100	1.12	0.27	0.00	−0.17	103	1.55	0.30	0.01	−0.35	98	1.72	0.34	0.26	0.27
Number word	100	1.24	0.31	−0.02	0.27	103	1.92	0.33	−0.33	−0.08	99	2.16	0.38	−0.33	0.06
Word	98	0.67	0.26	0.52	−0.36	103	1.40	0.40	−0.01	0.02	98	1.67	0.35	−0.14	−0.49
Discrete Tasks															
Digit	100	0.90	0.15	0.29	0.18	103	1.13	0.16	0.39	0.95	99	1.21	0.17	0.23	−0.10
Object	100	0.69	0.10	0.53	0.43	103	0.89	0.13	0.28	0.45	99	0.94	0.13	0.21	−0.10
Dice	100	0.80	0.15	−0.03	−0.02	103	1.00	0.16	0.33	0.10	98	1.06	0.15	0.40	0.07
Number word	100	0.86	0.15	0.08	−0.23	103	1.14	0.17	0.31	0.78	99	1.20	0.18	0.15	−0.44
Word	98	0.60	0.15	0.01	−0.57	103	0.96	0.17	−0.04	0.16	99	1.06	0.16	0.01	−0.50

Note. Skew = skewness; Kurt = kurtosis.

Group Differences in Serial Advantage

Mean serial advantage per task content and grade is displayed in Figure 4.3, for both languages. We first performed targeted linear contrasts to examine (a) whether there are significant differences in the serial advantage between successive grades for each type of content, and (b) whether this difference in the serial advantage between grades is further influenced by the task content.

Overall, serial advantage appears to gradually increase across grades in both English and Greek. To further examine whether the serial advantage differs significantly between successive grade levels per task content, we performed a set of multiple linear contrasts, using function glht of package multcomp v. 1.4-8 (Hothorn, Bretz, & Westfall, 2008). The results (Table 4.3) showed that serial advantage differed significantly between Grades 1 and 3 for all types of content in both languages. That is, there was a significantly larger gain in children's naming rate in the serial format compared to the corresponding discrete format–irrespective of task content. Serial advantage was also significantly greater in Grade 5 compared to Grade 3, except for object naming in both languages, and for number words and dice in English.

Table 4.3

Linear Contrasts Testing Differences in Serial Advantage Between Successive Grades per Task Content

		English			Greek		
Grades	Task Content	Est.	*z*	*p*	Est.	*z*	*p*
G1 vs. G3	Digits	0.272	7.338	<0.001	0.311	8.509	<0.001
G1 vs. G3	Objects	0.126	3.382	0.006	0.121	3.309	0.009
G1 vs. G3	Dice	0.202	5.448	<0.001	0.231	6.332	<0.001
G1 vs. G3	Number words	0.281	7.580	<0.001	0.411	11.271	<0.001
G1 vs. G3	Words	0.377	10.117	<0.001	0.377	10.276	<0.001
G3 vs. G5	Digits	0.098	2.782	0.045	0.130	3.556	0.004
G3 vs. G5	Objects	0.074	2.084	0.250	0.096	2.625	0.070
G3 vs. G5	Dice	0.955	2.703	0.057	0.104	2.828	0.040
G3 vs. G5	Number words	0.049	1.380	0.732	0.173	4.725	<0.001
G3 vs. G5	Words	0.125	3.525	0.004	0.161	4.406	<0.001

Note. Est. = contrast estimate; *p* values are adjusted for multiple comparisons using the "single-step" method; G = grade; Serial advantage = difference between serial and discrete naming rate of the same task content (i.e., Serial naming rate – Discrete naming rate)

However, the pattern seen in Figure 4.3 suggests that serial advantage follows different trajectories in different types of content, concerning both their starting point (in Grade 1) and the magnitude of the increase (in successive grades). For example, a substantial serial advantage in digit naming is already evident in Grade 1 in both languages. In contrast, serial advantage in words and objects seems to start off much lower in Grade 1 compared to the other tasks. Yet, this initial smaller serial advantage in words is followed by a steep increase in the following two grades, greatly exceeding the corresponding serial advantage in objects and gradually approaching serial advantage of digit and number word naming in English, or dice naming in Greek. In comparison, serial advantage in object naming continues to lag behind, across grades, compared to the rest of the tasks.

To further examine how the serial advantage develops for different types of material, a second set of contrasts tested the interaction between grades and task content, using function contrast of package lsmeans v. 2.27-62 (Lenth, 2016). Specifically, we examined whether differences in serial advantage between successive grades were different based on task content. Serial advantage differences between Grades 1 and 3 were found to be significantly greater for words than for objects (English: $t = -6.582$, $p = <.0001$; Greek: $t = -6.273$, $p = <.0001$) or dice (English: $t = -0.176$, $p = <.001$; Greek: $t = -0.179$, $p = <.001$). The increase for number words was also greater compared to objects ($t = -6.861$, $p = <.0001$) and dice ($t = 4.829$, $p = <.0001$) between Grades 1 and 3 in Greek. In contrast, the different content of the naming tasks did not cause differential development of serial advantage between Grades 3 and 5. All comparisons (task content pairs fully crossed with successive grade pairs) are listed in Supplementary Material (Table S4.3).

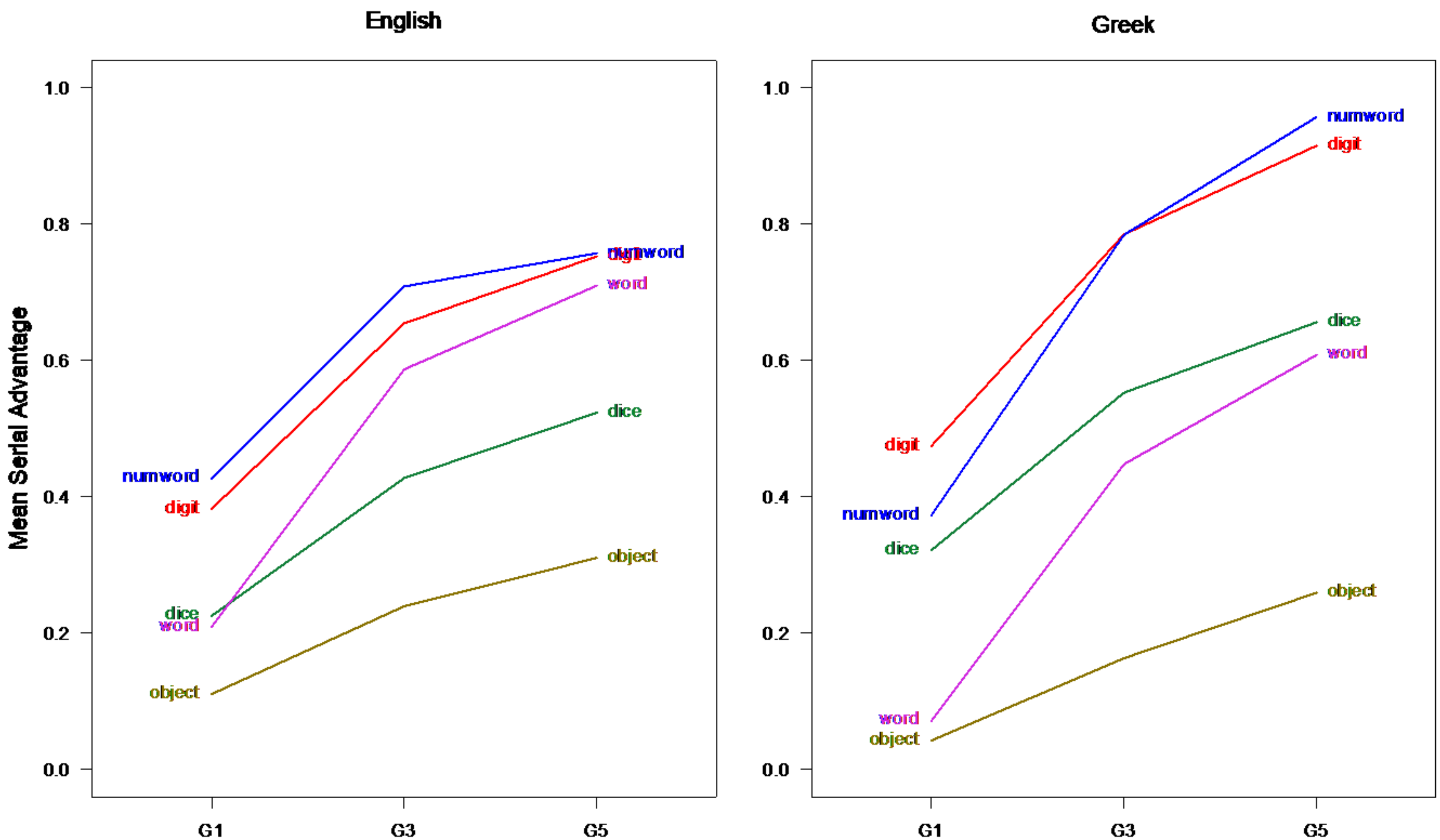

Figure 4.3. Mean serial advantage per task content and grade in each language.

In sum, serial advantage was found to grow significantly in higher grades, with a few important exceptions (such as object naming in both languages) of no significant change between Grades 3 and 5. Task content affected the magnitude of the increase in serial advantage between Grades 1 and 3. Specifically, tasks with orthographic stimuli (words, number words) yielded greater difference in serial advantage between first and third graders compared to the corresponding change in serial advantage for the nonalphanumeric naming tasks (objects and dice) between the same grades.

Furthermore, we sought to examine whether the serial advantage depends on the increasing rate in discrete naming. If the serial advantage is an expression of more efficient individual stimulus processing, then one might expect its growth to track discrete naming rate. Indeed, when plotted against the mean discrete rate (Figure 4.4), the group mean serial advantage appeared to increase across grades as a function of mean discrete naming rate. In other words, as children's average rate of naming individually presented stimuli improved, their average serial advantage also increased. However, this group analysis does not imply that the two variables are directly related at the individual participant level. Both averages could simply exhibit a generic maturational effect. In general, group differences do not necessarily reflect similar trends in individual differences (Berry & Willoughby, 2017; Fisher, Medaglia, & Jeronimus, 2018). Therefore, to find out whether the development of serial advantage depends on the efficiency of discrete or serial naming (or something else), we must turn to analyses of individual differences.

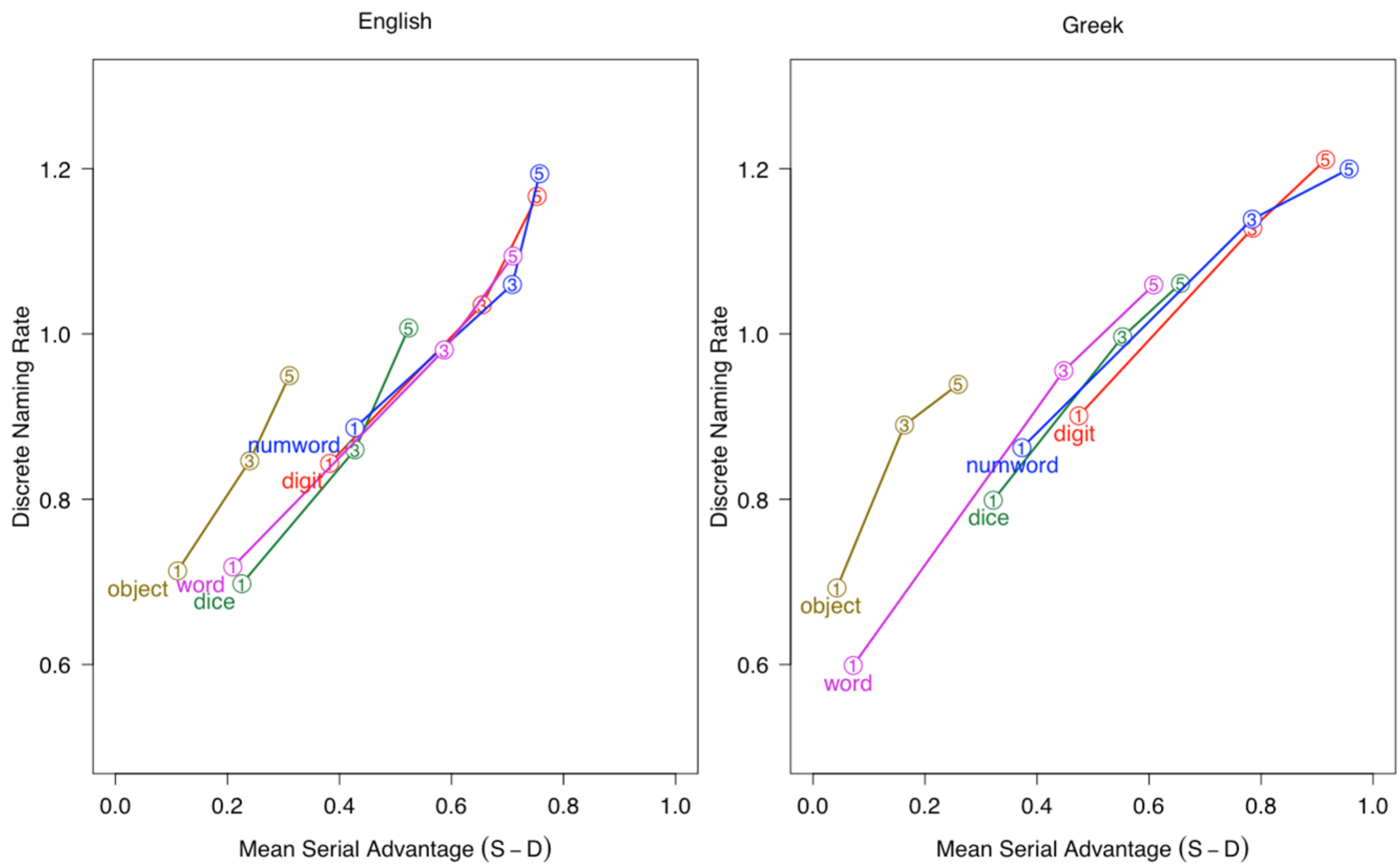

Figure 4.4. Average performance in discrete naming rate (y-axis) as a function of mean serial advantage (x-axis) per task content and grade in each language.

Individual Differences in Serial Advantage

Our second objective was to examine (a) whether differences in the serial advantage depend on differences in the discrete or the serial dimension of each naming task of the same content, and (b) how the serial-discrete correlation per task content is associated with their corresponding serial advantage.

We were particularly interested in examining whether group findings also apply for individuals. Thus, we investigated the association of within-grade individual differences in serial advantage with those in discrete and serial tasks. Table 4.4 shows the correlations between serial advantage and the corresponding serial- and discrete-trial format per task content. Results showed that performance in the serial-trial format of each type of content was strongly associated with serial advantage. In contrast, the correlation between serial advantage and the corresponding discrete-trial format of each naming task was weak, irrespective of the task content. The only exception concerns word naming in Grade 1, in which discrete-trial format and serial advantage were moderately to strongly associated; followed by a relatively weak correlation in Grades 3 and 5. This pattern of results was consistent across languages and task content. Thus, even though the serial advantage in naming rate is defined as the simple difference between serial and discrete naming rates of the same content, thus potentially affected by both formats, individual differences in the serial advantage are in fact dominated by variance in serial naming rate. In other words, the serial advantage in naming rate is primarily a reflection of serial naming rate.

Table 4.4

Correlations Between Serial Advantage and Each Pair of Discrete-Serial Task

English	Grade 1		Grade 3		Grade 5	
Serial Advantage	Serial Task	Discrete Task	Serial Task	Discrete Task	Serial Task	Discrete Task
Digits	0.87	0.13	0.92	0.02	0.94	0.07
Objects	0.84	−0.08	0.86	−0.15	0.86	−0.03
Dice	0.82	0.20	0.92	0.25	0.91	0.12
Number words	0.86	0.09	0.89	−0.14	0.92	0.01
Words	0.93	0.57	0.96	0.22	0.94	0.17

Greek	Grade 1		Grade 3		Grade 5	
Serial Advantage	Serial Task	Discrete Task	Serial Task	Discrete Task	Serial Task	Discrete Task
Digits	0.86	−0.11	0.88	0.01	0.86	−0.11
Objects	0.79	−0.30	0.78	−0.17	0.83	0.15
Dice	0.89	0.23	0.83	0.03	0.89	0.06
Number words	0.86	0.09	0.81	−0.04	0.89	0.04
Words	0.85	0.52	0.91	0.30	0.90	0.15

Note. Serial advantage = difference between serial and discrete naming rate of the same task content (i.e., Serial naming rate – Discrete naming rate)

If the serial advantage is indeed an index of serial naming efficiency beyond discrete naming, reflecting a separable dimension of individual differences concerning serial processing rather than a simple difference between serial and discrete naming that is constant across participants (e.g., reflecting a simple difficulty difference), then average serial advantage should be inversely related to the correlation between serial and discrete naming. That is, serial advantage should reflect the extent to which individual serial naming performance is not predictable by discrete naming performance. To visually illustrate this implication, mean serial advantage was plotted against the corresponding correlation coefficients for the pair of serial-discrete tasks with the same content (Figure 4.5). A negative relationship is evident, indicating that as mean serial advantage increased across grade levels, the correlation between the serial and corresponding discrete task (of the same content) either decreased or remained stable between successive grades. The only exception was with object naming in Greek, in which both serial advantage and serial-discrete correlation increased across grades, further confirming the qualitative difference in processing objects comparing to the other types of content.

Intercorrelations among all serial and discrete tasks for each grade and language are available in Supplementary Material (Table S4.4). Also, Supplementary Table S4.5 provides a summary of the correlations between serial and corresponding discrete naming tasks for each type of content.

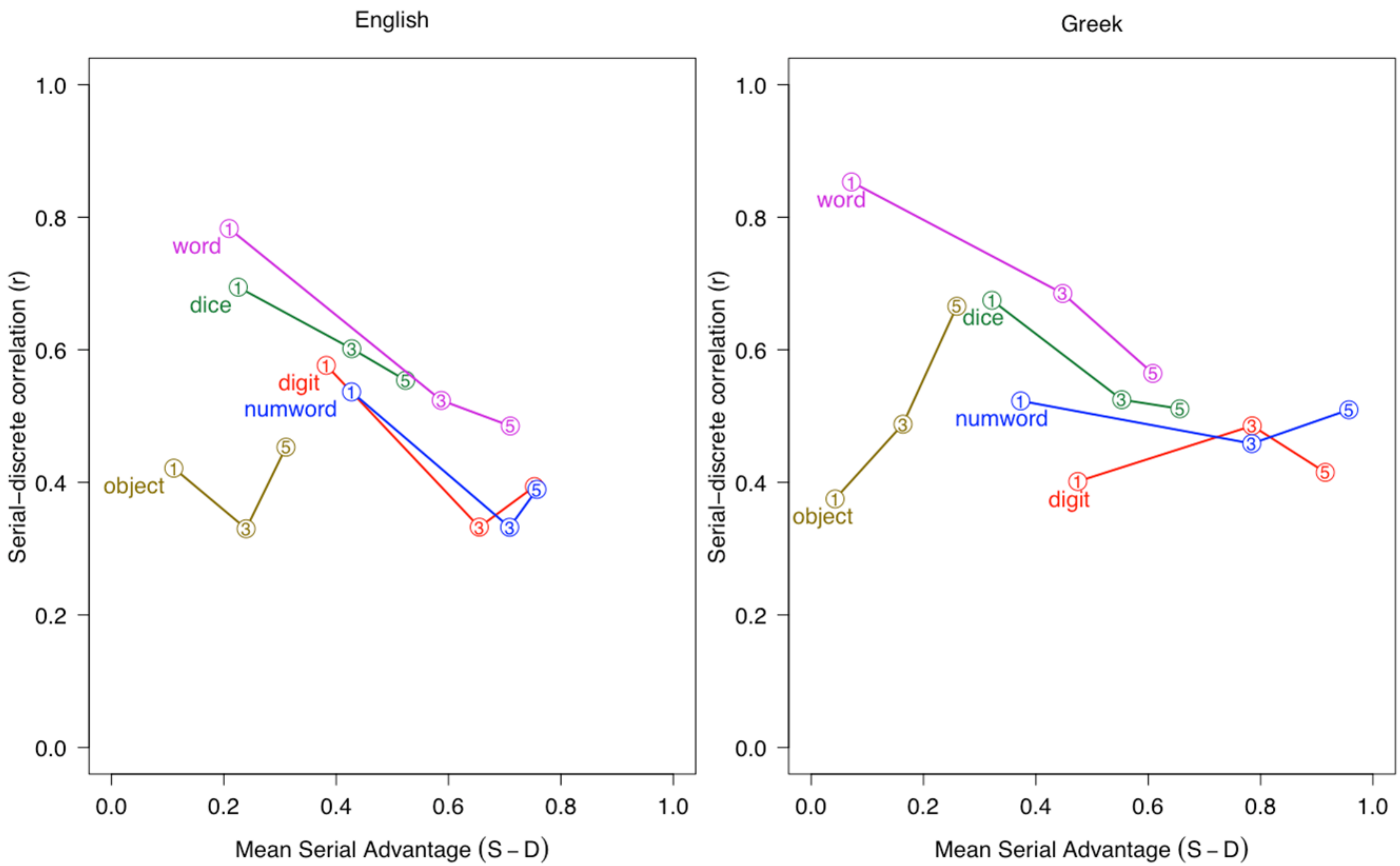

Figure 4.5. Serial advantage (y-axis) as a function of serial-discrete correlation (Pearson's *r* coefficient; x-axis) per task content and grade in each language.

Discussion

We examined the development of serial advantage across grade levels and naming tasks of different types of content, in two languages (English and Greek). Serial advantage was defined as the gain in naming rate of multiple over isolated stimulus displays—expressed as the numerical difference between serial and discrete naming rate of the same task content. We used a set of naming tasks, including stimuli corresponding to identical or well-matched words, but differing in the way the words were depicted. In line with our expectation, we found an increase in serial advantage at higher grades for all naming tasks, but at different growth rates for different types of content. The serial advantage for words, in particular, increased at a higher rate than for other kinds of material. The increase in mean serial advantage for all types of content appeared to track the corresponding increase in discrete stimulus naming rate, when examined at the group level, but turned out to be related to the serial naming rate when examined at the individual differences level. As an expression of the development of efficient sequence processing, increased serial advantage was associated with a decreased correlation between serial and discrete naming tasks of the same content. This is the first study to directly link the serial advantage during naming with the previously reported format-specific correlations between naming/reading tasks (i.e., tasks of different format are correlated to a lesser degree than tasks of the same format). Importantly, this pattern of findings held across two languages with very different degrees of orthographic consistency, thus demonstrating that the development of serial advantage does not depend on the consistency of orthographic representations (see also Wimmer & Goswami, 1994, reporting a similar level of performance in serial naming of number words and digits among children aged 8 and 9 who learned to read English and German).

Development of Serial Advantage

Our results showed that there is a significant difference in serial advantage between grade levels, further supporting the idea that multiple stimulus displays facilitates performance in naming tasks among older typically-developing children (Protopapas et al., 2013; Protopapas et al., 2018; Zoccolotti et al., 2013; Zoccolotti et al., 2015) and adults (Jones et al., 2009). This increase between grade levels was significant across types of naming materials, suggesting that children benefited from multiple stimulus displays in naming tasks regardless of the task content. However, we found content-specific effects in the magnitude of the serial advantage and in the increase in serial advantage between grades, especially between Grades 1 and 3.

More specifically, there was a stable ranking of task content (material types) with respect to serial advantage, across grades. In particular, objects—and, to a lesser degree, dice—lagged behind in the development of serial advantage compared to alphanumeric stimuli (digits) and orthographic stimuli (number words). This finding is consistent with the idea that object naming and generally image naming requires semantic mediation to retrieve the name, in contrast to alphanumeric (e.g., digits) or orthographic stimuli (e.g., words), which permit direct access from visual to phonological forms (Liu & Georgiou, 2017; Pan, Yan, Laubrock, Shu, & Kliegl, 2013; Poulsen & Elbro, 2013; Roelofs, 2006). In our data, serial advantage in dice naming was intermediate between serial digit and object naming. This can be attributed to the specific dice images being not only fixed, but also familiar, presumably better-practiced than objects, and thus permitting partial access to unmediated naming due to repeated prior exposure (cf. Roelofs, 2003, 2006).

At the other end, digits and number words (especially after Grade 1) ranked highest in serial advantage across grades and languages, consistent with the idea of fast, direct mappings between visual and phonological forms for stimuli that are highly familiar and largely predictable due to their status as members of small sets. In particular, past the beginner reader stage, number words exhibited as large a serial advantage as digits because they were 25% predictable in the context of the naming task, since there were only four of them in the task. In contrast, word lists exhibited significantly less serial advantage, even though the words were chosen to be comparably familiar, and equally short and pronounceable as the number words, because each word in the list had to be recognized from among an unlimited potential set.

The stable ranking of task content with respect to serial advantage across grades and languages is consistent with the idea that there are important differences in how different types of stimuli are processed, when it comes to serial naming, in the sense that some kinds of processes lend themselves to efficient serial processing whereas other kinds do not. This is not a function of individual stimulus processing rate, because the differences between material types in serial advantage are much greater than the corresponding differences in discrete naming (compare the ranges of values in Table 4.2). It remains to be elucidated exactly what kinds of mechanisms are involved in the processing of each type of material that facilitate or impede their accessibility to efficient serial processing in multiple stimulus displays (however, see Alario et al., 2004; Levelt, Roelofs, & Meyer, 1999; Roelofs, 2003, for models of isolated object and/or word naming).

At the same time, between-grade differences in serial advantage were greatest for word naming, especially when compared to objects. Both objects and words can be considered less practiced items, derived from large open sets, compared to the small closed set of numbers from which digits, number words, and dice were sampled. Yet the development of serial advantage between grades differed greatly between words and objects, even though they started off at similar levels in Grade 1. In particular, serial advantage in word naming took off by Grade 3 and gradually approached serial advantage of number words and digits, or dice, by Grade 5. Instead, serial advantage for object naming lagged far behind.

Taken together with the otherwise stable ordering of task content, the steep increase in word serial advantage suggests that the processing of words undergoes a qualitative change in cognitive processing mechanisms, starting off in some way similar to object naming in Grade 1 but ending up similar to digit or dice naming by Grade 5. This processing change may be related to intra-word processing, that is, processing of the words as complex objects composed of parts (letters, graphemes, or syllables) that must be dealt with individually. This is expected to be the case in Grade 1. In contrast, more advanced readers are expected to read words "by sight" (Ehri, 2005), that is, with their internal constituents processed in parallel (de Jong, 2011; van den Boer, Georgiou, & de Jong, 2016; van den Boer & de Jong, 2015). The serial advantage growth curve corroborates this qualitative leap in word processing, which likely underlies efficient serial word naming, that is, word list reading fluency.

This could also account for the apparently smaller serial advantage for Greek words—in comparison to the other materials. Greek words were bisyllabic, hence composed of more internal elements/constituents, or of a more complex internal structure than the monosyllabic English words. If the steep slope (in English) reflects a complete qualitative shift from intra- to inter-word processing, and words in Greek have more complex internal structure, and therefore more involved intra-word processing, then serial advantage in word naming should be expected to be smaller in Greek than in English relative to digits/dice.

Group Trends versus Individual Differences

Analyses of group average performance appeared to confirm the hypothesis that serial advantage increases as a function of the increase in discrete naming rate. In other words, group differences suggested that performance in discrete naming rate largely determined the corresponding increase in serial advantage between grades. Indeed, the graphs in Figure 4.4 show an almost perfectly linear relationship across grades between discrete naming rate and serial advantage. The same linear relationship (same slope) seems to hold even for objects, despite their overall lower serial advantage relative to the observed discrete naming rate. However, this image is misleading, because it simply reflects the almost-inevitable outcome that skills increase with age. Thus, anything that exhibits developmental growth can appear to be strongly associated in such a group-level analysis. The important question here is not whether differences in mean serial advantage across grades track corresponding mean differences in discrete (or serial) naming rate but, rather, whether individual differences in serial advantage are consistently associated with individual differences in discrete (or serial) naming rate within age (or grade-level) groups.

As it turns out, individual differences tell a very different story. In particular, we found that serial advantage in naming rate is largely independent from discrete naming rate. In other words, the efficiency with which children within a grade group retrieve and produce the names of individually presented items seems to have limited influence on their serial advantage for these items. In contrast, differences in the serial naming tasks were strongly associated with differences in serial advantage. In other words, the serial advantage seems to be primarily a reflection of serial naming rate, even though by the nature of its calculation one might expect it to depend equally on both serial and discrete naming rate.

Moreover, we found that increase in serial advantage is associated with decrease in the correlation between serial and discrete naming rate. That is, as serial naming rate dissociates from discrete naming rate, the corresponding serial advantage increases. This pattern was evident in both languages, across naming tasks of different content (with the exception of object naming, for which the relationship between serial and discrete naming was unstable or increasing).

The relevance of the serial-discrete correlation can be seen with respect to the processing mechanisms that are responsible for serial naming. In particular, a high correlation between discrete and serial naming indicates that there is not much difference in processing individually presented stimuli and stimuli presented within a matrix of other stimuli. This can be interpreted as processing of the stimuli in the serial task one by one, that is, the serial naming task is effectively a succession of discrete naming trials. In contrast, a low correlation between discrete and serial naming indicates that what determines single-item processing efficiency is different from what determines multi-item display processing efficiency. This can be interpreted as involvement of different—or additional—mechanisms in serial naming tasks (as has been suggested by Altani, Protopapas, et al., 2017; Protopapas et al., 2013; Protopapas et al., 2018).

How can we understand then the relationship between serial advantage and serial and discrete naming rates in this context? Let us consider some hypothetical limiting cases to help elucidate these relationships. First, assume that there is a constant serial advantage for some reason, that is, serial naming rate is higher than discrete naming rate, but the difference is the same for everyone. This amounts to a constant difference in processing difficulty but no qualitative difference in processing mechanisms between serial and discrete naming. In this case, there is equal variance in discrete and serial naming rate, and a perfect (r = 1.00) correlation between them, but there is zero variance in serial advantage and, therefore, no correlation between serial advantage and either serial or discrete naming. In a second case, assume that there is a constant discrete naming rate, that is, everyone names isolated stimulus displays equally fast, but there are individual differences in serial naming rate. Therefore, there will be individual differences in their difference, that is, in serial advantage, which will be perfectly correlated with serial naming rate. The lack of variance in discrete naming rate implies a zero correlation with both serial naming rate and serial advantage. Finally, if we assume the converse, that is, individual differences in discrete naming rate but no differences in serial naming rate, in other words, everyone names multiple-stimulus displays equally fast despite differences in isolated stimulus naming. In this case, there will be zero correlation of serial naming rate with both discrete naming rate and serial advantage, and a perfect correlation between discrete naming rate and serial advantage.

Our findings are mostly in line with the second of these hypothetical scenarios. Discrete naming rate is not constant, of course. It is less variable than serial naming rate (about a quarter to one tenth of the variance, if we square the standard deviations in Table

4.2), but this difference seems insufficient to account for the huge differences in correlations with serial advantage (Table 4.4), which exceed 0.80 for serial naming rate in most cases, often approaching 1.00, and hover near zero for discrete naming rate, with some exceptions (such as words). The differences in shared variance implied by these correlations is very much greater than the observed difference in available variance in the two naming rates. Thus, despite the moderate correlations between serial and discrete naming rate, differences in serial advantage arise mostly or entirely from differences in serial naming rate, as if differences in discrete naming rate did not exist.

Overall, these findings are in line with previous evidence suggesting that with increasing proficiency and among well-practiced items, individual differences in serial naming are gradually determined to a lesser degree from differences in the discrete version of the naming tasks (Altani et al., 2018; de Jong, 2011; Protopapas et al., 2018). This has been attributed to the gradual dominance of a "serial" processing skill, which concerns inter-item processing of multiple stimuli in a cascaded manner. That is, a stimulus is processed while the previous one is uttered, and the next one is viewed (and possibly the one further down previewed) at the same time. This overlap of processing among consecutive stimuli must be the origin of the serial advantage, saving time over the serial task because successive stimuli can be processed simultaneously through the different stages in a "cascaded processing" pipeline. In this context, one way to interpret the differential correlation of serial advantage with serial and discrete naming rate is the following: As serial naming becomes increasingly efficient, it matters less how long each stimulus takes to name; what matters most is how soon one can begin to process the next stimulus in the sequence (while processing of the current stimulus is still in progress). A tightly packed pipeline of cascaded processing amounts to a greater serial advantage, regardless of how long it takes for each stimulus to finish. Thus, the cascaded processing hypothesis seems to be consistent with the differential correlation pattern observed for the serial advantage.

Some limitations of the present study are worth mentioning. First, our study was cross-sectional. Although serial advantage was estimated as the absolute difference between serial and discrete naming rate concurrently (within grade level), an examination of how serial advantage develops across time (between grade levels) would ideally involve a longitudinal design. Second, our study included only alphabetic languages. A future study should replicate these findings in non-alphabetic languages (e.g., Chinese). Finally, our study design does not elucidate the cognitive mechanisms involved in the serial processing of naming tasks of different content, and the cascaded (temporally overlapped) processing hypothesis as a candidate mechanism underlying serial advantage in RAN-type tasks remains speculative. Future studies should investigate this hypothesis using more fine-grained measures, decomposing the rather complex serial naming/reading tasks.

Conclusions

Our results confirm that multiple stimulus displays facilitate naming rates across stimulus types and languages. However, content-specific characteristics influence the trajectory of serial advantage between grades. We have suggested that practice and familiarity with the task content may influence the development of serial advantage, irrespective of initial difficulty. Notably, we observed a steep increase for serial advantage in words (from being similar to objects in Grade 1 to being more similar to digits by Grade 5), suggesting that words undergo a qualitative shift in how they are processed and named.

In addition, growth in serial advantage was found to be associated with growth in discrete naming rate only in group (grade level) analysis. For individuals, greater serial advantage was associated with greater serial naming rate and with a decrease in the correlation between discrete and serial naming rate (with the exception of objects). This has important implications, as findings derived from group differences might not generalize to individuals (see Fisher et al., 2018, for a similar argument). Our findings suggest that individual differences in serial advantage rely on fluency-specific skills of serial naming rather than on differences in the rate of naming individual items. Thus, training naming of individual items is not expected to result in transfer of gains to serial naming rates for the same material. Future studies should investigate the nature of the cognitive mechanisms involved in naming processes, focusing on the difference between discrete and serial naming and on the prerequisites of efficient serial naming.

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Supplementary Material

Table S4.1

Anderson−Darling tests of normality for the data per task format and grade

		Digits		Objects		Dice		Number words		Words	
English	Grade	*A*	*p*	*A*	*p*	*A*	*p*	*A*	*p*	*A*	*p*
Serial	1	0.41	0.34	0.19	0.90	0.22	0.82	0.39	0.38	0.73	0.05
	3	0.29	0.62	0.20	0.88	0.46	0.26	0.27	0.67	0.32	0.54
	5	0.53	0.18	0.46	0.26	0.33	0.51	0.53	0.17	0.44	0.29
Discrete	1	0.71	0.06	0.54	0.17	0.29	0.62	0.77	0.05	0.30	0.57
	3	0.29	0.61	0.27	0.68	0.23	0.79	0.32	0.52	0.49	0.22
	5	0.86	0.03	0.21	0.85	0.24	0.78	0.26	0.71	0.41	0.34
		Digits		Objects		Dice		Number words		Words	
Greek	Grade	*A*	*p*	*A*	*p*	*A*	*p*	*A*	*p*	*A*	*p*
Serial	1	0.30	0.59	0.85	0.03	0.16	0.95	0.74	0.05	0.83	0.03
	3	0.45	0.27	0.42	0.33	0.26	0.70	0.33	0.51	0.40	0.36
	5	0.88	0.02	0.47	0.24	0.46	0.26	0.25	0.74	0.30	0.57
Discrete	1	0.38	0.39	0.48	0.23	0.27	0.68	0.36	0.44	0.23	0.79
	3	1.01	0.01	0.44	0.28	0.33	0.51	0.47	0.25	0.24	0.76
	5	0.41	0.34	0.42	0.32	0.85	0.03	0.60	0.12	0.37	0.42

Table S4.2

Descriptive statistics for serial advantage in each grade and language

	Grade 1					Grade 3					Grade 5				
English	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Serial Advantage															
Digits	101	0.38	0.25	0.07	−0.36	130	0.65	0.36	0.37	0.54	122	0.75	0.35	0.11	−0.64
Objects	101	0.11	0.17	0.46	0.29	127	0.24	0.19	0.36	0.52	122	0.31	0.18	0.43	0.21
Dice	101	0.23	0.19	0.34	0.55	129	0.43	0.26	0.30	−0.20	122	0.52	0.27	0.22	0.04
Number words	101	0.43	0.26	0.17	−0.30	130	0.71	0.31	0.00	−0.48	122	0.76	0.33	−0.04	−0.64
Words	99	0.21	0.27	0.42	−0.39	129	0.59	0.33	−0.04	−0.53	122	0.71	0.33	0.18	−0.23
Greek	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt	*N*	*M*	*SD*	Skew	Kurt
Serial Advantage															
Digits	100	0.47	0.25	−0.15	−0.72	103	0.79	0.29	−0.11	−0.01	99	0.92	0.34	−0.74	0.50
Object	100	0.04	0.15	0.38	−0.29	103	0.16	0.18	0.10	−0.56	99	0.26	0.17	0.19	−0.30
Dice	100	0.32	0.20	0.31	0.14	103	0.55	0.26	0.04	−0.28	98	0.66	0.29	0.23	0.03
Number words	100	0.37	0.27	0.14	0.21	103	0.78	0.30	−0.46	0.52	99	0.96	0.33	−0.20	−0.17
Words	97	0.07	0.16	0.84	0.04	103	0.45	0.30	0.24	0.01	98	0.61	0.29	0.01	−0.20

Note. Skew = skewness; Kurt = kurtosis.

Table S4.3

Linear contrasts testing differences in serial advantage between pairs of task content and successive grades

Grades	Task content	English			Greek		
		Est.	*t*	*p*	Est.	*t*	*p*
G1 vs. G3	word vs. dice	–0.176	–4.638	0.000	–0.179	–4.241	0.001
G1 vs. G3	word vs. digit	–0.103	–2.719	0.096	–0.107	–2.529	0.153
G1 vs. G3	word vs. number word	–0.095	–2.492	0.168	0.025	0.589	0.999
G1 vs. G3	word vs. object	–0.250	–6.582	<.0001	–0.265	–6.273	<.0001
G1 vs. G3	dice vs. digit	0.073	1.928	0.485	0.072	1.712	0.634
G1 vs. G3	dice vs. number word	0.082	2.156	0.335	0.204	4.829	<.0001
G1 vs. G3	dice vs. object	–0.074	–1.958	0.465	–0.086	–2.032	0.410
G1 vs. G3	digit vs. numword	0.009	0.228	1.000	0.132	3.117	0.031
G1 vs. G3	digit vs. object	–0.147	–3.884	0.002	–0.158	–3.744	0.003
G1 vs. G3	number word vs. object	–0.156	–4.111	0.001	–0.290	–6.861	<.0001
G3 vs. G5	word vs. dice	0.028	0.769	0.995	0.033	0.803	0.993
G3 vs. G5	word vs. digit	0.028	0.780	0.994	0.003	0.063	1.000
G3 vs. G5	word vs. number word	0.077	2.147	0.341	–0.024	–0.575	0.999
G3 vs. G5	word vs. object	0.052	1.429	0.821	0.056	1.367	0.848
G3 vs. G5	dice vs. digit	0.000	0.010	1.000	–0.030	–0.741	0.996
G3 vs. G5	dice vs. number word	0.049	1.375	0.849	–0.057	–1.379	0.842
G3 vs. G5	dice vs. object	0.024	0.661	0.998	0.023	0.563	0.999
G3 vs. G5	digit vs. numword	0.049	1.367	0.853	–0.026	–0.639	0.998
G3 vs. G5	digit vs. object	0.023	0.651	0.998	0.053	1.306	0.878
G3 vs. G5	number word vs. object	–0.026	–0.711	0.997	0.080	1.945	0.469

Note. Est. = contrast estimate; G = grade.

Table S4.4

Correlation coefficients (Pearson's r) among all tasks for each grade and language

G1			1.sDig	2.sObj	3.sDic	4.sNwrd	5.sWrd	6.dDig	7.dObj	8.dDic	9.dNwrd	10.dWrd
1	serial	Digit		0.27	0.60	0.54	0.53	0.40	0.38	0.47	0.44	0.49
2	serial	Object	0.42		0.36	0.34	0.40	0.20	0.38	0.24	0.25	0.23
3	serial	Dice	0.67	0.51		0.45	0.41	0.54	0.55	0.67	0.48	0.47
4	serial	Number word	0.60	0.50	0.50		0.77	0.33	0.32	0.35	0.52	0.71
5	serial	Word	0.29	0.34	0.18	0.59		0.32	0.32	0.38	0.51	0.85
6	discrete	Digit	0.58	0.24	0.45	0.48	0.25		0.65	0.77	0.74	0.53
7	discrete	Object	0.48	0.42	0.50	0.39	0.10	0.66		0.73	0.65	0.49
8	discrete	Dice	0.62	0.38	0.69	0.45	0.19	0.67	0.67		0.77	0.59
9	discrete	Number word	0.46	0.35	0.46	0.54	0.37	0.73	0.62	0.71		0.73
10	discrete	Word	0.37	0.24	0.20	0.64	0.78	0.51	0.34	0.37	0.63	

G3			1.sDig	2.sObj	3.sDic	4.sNwrd	5.sWrd	6.dDig	7.dObj	8.dDic	9.dNwrd	10.dWrd
1	serial	Digit		0.61	0.68	0.81	0.62	0.49	0.47	0.50	0.41	0.60
2	serial	Object	0.64		0.56	0.58	0.49	0.38	0.49	0.38	0.40	0.50
3	serial	Dice	0.71	0.70		0.59	0.57	0.44	0.44	0.52	0.41	0.56
4	serial	Number word	0.67	0.50	0.52		0.75	0.52	0.48	0.45	0.46	0.65
5	serial	Word	0.56	0.42	0.36	0.67		0.48	0.41	0.38	0.42	0.69
6	discrete	Digit	0.33	0.16	0.26	0.40	0.26		0.80	0.83	0.85	0.82
7	discrete	Object	0.23	0.33	0.27	0.30	0.14	0.62		0.80	0.82	0.77
8	discrete	Dice	0.41	0.49	0.60	0.30	0.20	0.59	0.61		0.85	0.78
9	discrete	Number word	0.25	0.16	0.13	0.33	0.31	0.76	0.64	0.54		0.84
10	discrete	Word	0.18	0.11	0.11	0.45	0.52	0.65	0.42	0.40	0.69	

G5			1.sDig	2.sObj	3.sDic	4.sNwrd	5.sWrd	6.dDig	7.dObj	8.dDic	9.dNmwrd	10.dWrd
1	serial	Digit		0.54	0.68	0.82	0.65	0.42	0.57	0.54	0.49	0.45
2	serial	Object	0.53		0.67	0.47	0.48	0.35	0.67	0.51	0.41	0.31
3	serial	Dice	0.70	0.60		0.60	0.52	0.25	0.50	0.51	0.35	0.20
4	serial	Number word	0.74	0.54	0.59		0.77	0.42	0.52	0.48	0.51	0.51

5	serial	Word	0.61	0.39	0.44	0.68		0.42	0.50	0.41	0.54	0.56
6	discrete	Digit	0.39	0.11	0.31	0.44	0.34		0.70	0.77	0.86	0.78
7	discrete	Object	0.45	0.45	0.46	0.46	0.27	0.65		0.76	0.74	0.68
8	discrete	Dice	0.51	0.31	0.55	0.51	0.40	0.79	0.78		0.77	0.68
9	discrete	Number word	0.28	0.09	0.28	0.39	0.37	0.85	0.59	0.73		0.83
10	discrete	Word	0.42	0.25	0.38	0.49	0.49	0.78	0.64	0.75	0.85	

Note. Correlation coefficients among all tasks in English are presented below the diagonal; correlation coefficients among all tasks in Greek are presented above the diagonal; s = serial; d = discrete. Correlations in Greek have been previously reported in (Protopapas et al., 2018).

Table S4.5

Correlation coefficients (Pearson's r) between serial and discrete version of each task across grades and languages

		s-d correlations				
		Digits	Objects	Dice	Number words	Words
English						
	G1	.58	.42	.69	.54	.78
	G3	.33	.33	.60	.33	.52
	G5	.39	.45	.55	.39	.49
Greek						
	G1	.40	.38	.67	.52	.85
	G3	.49	.49	.52	.46	.69
	G5	.42	.67	.51	.51	.56

Note. s = serial; d = discrete; G = grade.

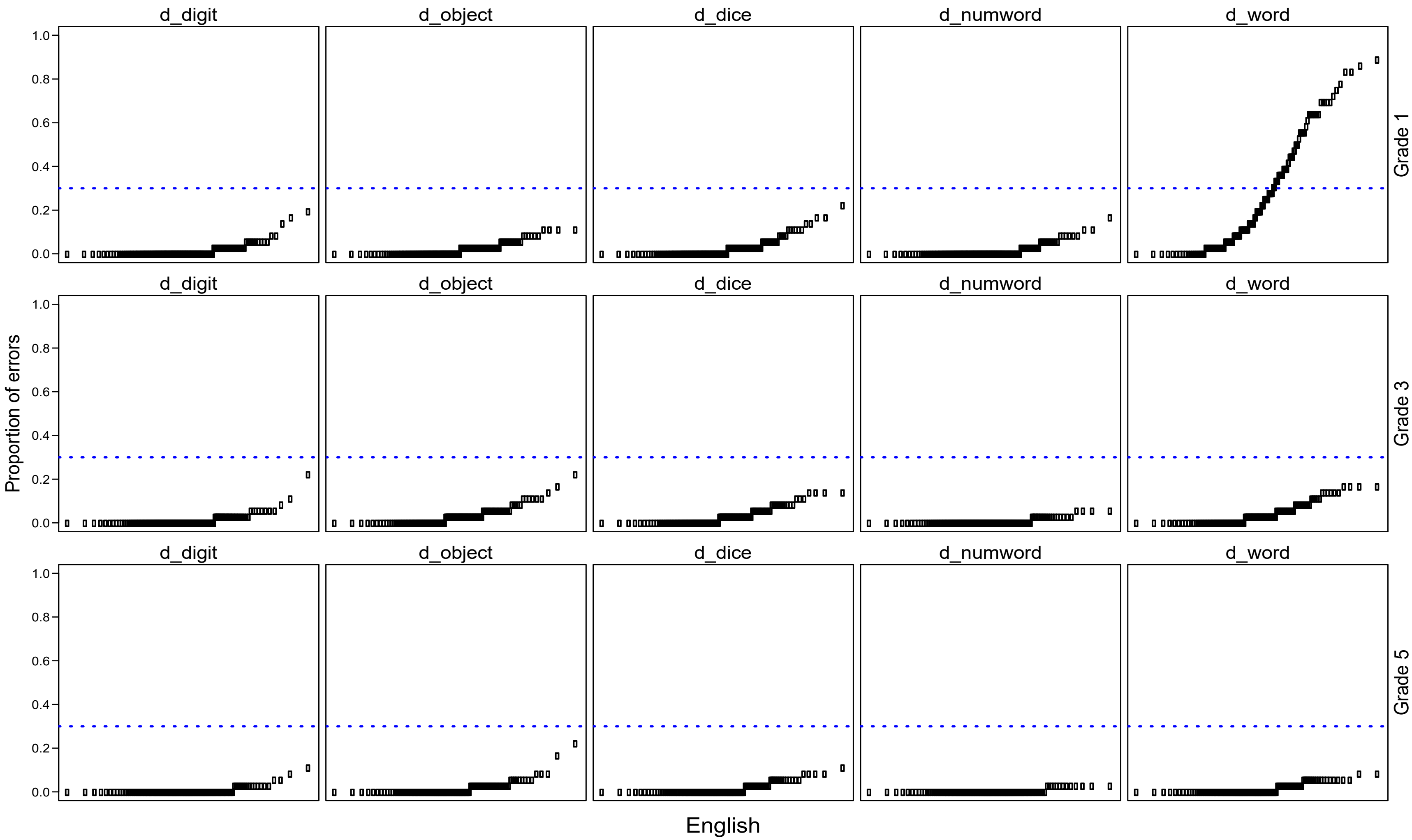

Figure S4.1. Proportion of errors per task content (discrete format) in each grade in English. The horizontal dashed line shows the outlier cutoff.

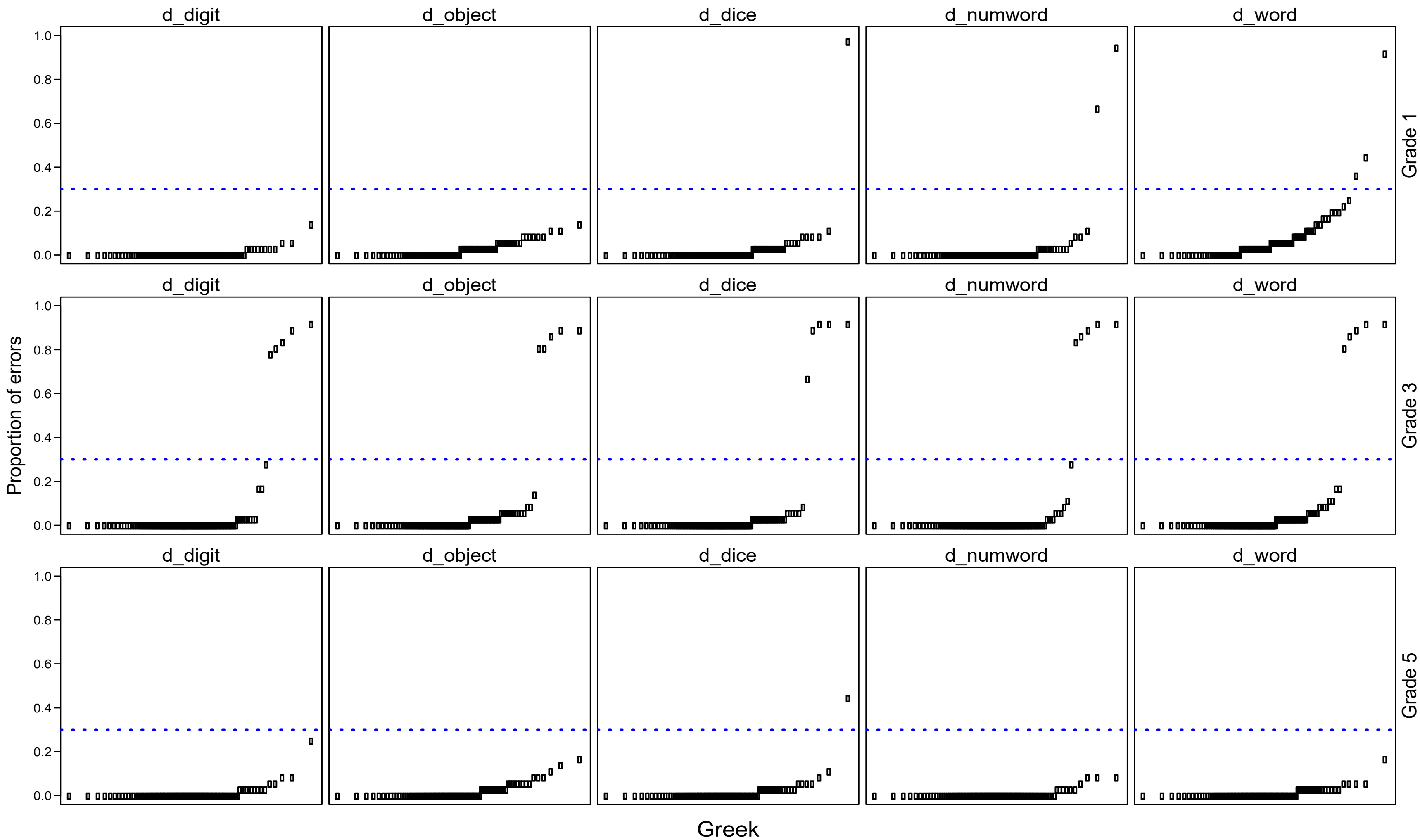

Figure S4.2. Proportion of errors per task content (discrete format) in each grade in Greek. The horizontal dashed line shows the outlier cutoff.

Chapter 5: General Discussion

The present dissertation focused on the distinction between serial and discrete processing in word reading and rapid naming tasks, and how understanding this distinction can provide insights into reading fluency development. First, the findings of the three studies of this dissertation are summarized and reviewed with respect to their contribution to previous empirical evidence. Then, the main results are discussed with respect to research and educational implications.

Summary and Review

Based on previous evidence showing that performance on naming and reading tasks may differ depending on their presentation format (serial vs. discrete), three studies were developed that examined serial- and discrete-trial naming and reading tasks across grades and orthographies, aiming to provide information about the multi-element and single-element processes involved in reading fluency development. The studies included children from three elementary grades, who learned to read in English or Greek and were at different phases of their reading development: beginning readers from Grade 1, intermediate readers from Grade 3, and more advanced readers from Grade 5.

The key element binding all three studies was the assumption that serial and discrete versions of reading and rapid naming tasks reflect both shared and distinct processes: Discrete naming or word reading reflect single-item processing, including processes such as identification of the item, lexical retrieval time, and word production. Serial naming or reading tasks reflect (beyond their shared components with discrete naming/reading) the ability to deal with multiple items at the same time and process them in a sequential manner.

The first study (Chapter 2) focused on the micro-level of individual word reading and examined how changes in the magnitude of the association between serial and discrete digit naming and word reading across grades can provide information about the development of intraword and interword processing. The study provided evidence of the intraword processing hypothesis in English and replicated previous findings in Dutch (e.g., van den Boer & de Jong, 2015) showing that among more advanced readers, the speed of reading single familiar words approximates the speed of naming single digits. This suggests that discrete words that are short and familiar are processed like unitized symbols (i.e., parallel intraword processing). The study also advanced the idea that serial digit naming (and its association with reading) can be used as an index of sequential multi-element processing both at the intraword level (processing multiple elements within the word) and at the interword level (processing multiple elements across word sequences). Findings along with a closer examination of previous studies further suggested that sequential processing occurs within a continuum (rather than a binary distinction between serial/sublexical and parallel/lexical processing) and may be flexibly adjusted depending on the context (i.e., word-specific and orthographic characteristics) and the level of reading proficiency. At the same time, this study extended in English the findings of previous studies in other alphabetic orthographies (de Jong, 2011; Protopapas, Altani, & Georgiou, 2013a) showing that discrete word reading and serial word reading are strongly associated in early development. Yet, the serial and discrete formats of reading tasks grow further apart among more advanced readers, once intraword processing becomes more efficient and words are processed in parallel, as unitized symbols. This finding advanced the idea that performance in word reading fluency (word list reading) is not exhausted by the efficiency of individual word recognition (i.e., efficient intraword processing), an aspect that was further examined in Chapter 3.

In the second study (Chapter 3), the focus shifted from intraword to interword processing, aiming to understand (a) the interrelations among single word recognition, word list reading, and text reading across grades, and (b) the role of sequential multi-item processing (indexed by serial digit naming) in word list and text reading (interword processing), beyond the efficiency of single word recognition (intraword processing). The study added to previous literature (Protopapas et al., 2013a; Protopapas, Katopodi, Altani, & Georgiou, 2018; Zoccolotti, De Luca, Marinelli, & Spinelli, 2014) by utilizing two tasks to probe multiword sequencing, including unrelated lists of words and related sentences forming a passage. It also aimed to examine the role of speed in word reading after taking into account accuracy (Juul, Poulsen, & Elbro, 2014), thus attempting to disentangle the two components to the extent possible. Our findings further advanced the idea that the emergence of a distinct skill of sequential multi-item processing (cascading) may be important for the development (and understanding) of reading fluency.

The third study (Chapter 4) focused on the serial advantage (the gain in naming rate of the serial versus the discrete task format of same content), aiming to understand how serial advantage may be influenced by different types of content, as well as how it relates to the efficiency of multi-item and single-item processing for each type of content. The study used various materials, including alphanumeric stimuli (digits), non-alphanumeric stimuli (dice and objects), and orthographic stimuli (number words and words), with all items across conditions corresponding to well-matched words in order to be comparably familiar, and equally short and pronounceable. Evidence of serial advantage was provided across grades and types of content from both English and Greek data, expanding on previous evidence from Greek and Italian (Protopapas et al., 2013a; Protopapas et al., 2018; Zoccolotti et al., 2013; Zoccolotti, De Luca, & Spinelli, 2015). This finding advanced the idea that the serial task format entails some type of temporal overlap across processing stages of successive items in order to yield faster naming rates over the discrete version of the task of the same content. Evidence of a strong association between the serial advantage and the serial format of the task (but not with the discrete format) was provided. This finding implied that the ability to deal with multiple items via overlapping processing stages (cascading) —and not so much the efficiency of naming or reading each item in the sequence— is a key element of fluent performance in serial naming and reading tasks. Evidence of content-specific variations in the development of the serial advantage further indicated that different properties of the stimuli might facilitate or hinder the emergence of efficient "cascading."

From Intraword to Interword Processing

One of the main findings in Chapters 2 and 3 that requires further discussion concerns the evidence of a gradual dissociation between intraword (i.e., within individual words) and interword (i.e., across multiple words) processing from Grade 1 to Grades 3 and 5. In particular, Chapter 2 replicated in English previous findings from Dutch and Greek (e.g., de Jong, 2011; Protopapas et al., 2013a; Protopapas et al., 2018), showing that discrete and serial word reading are strongly connected among beginning readers, but grow apart among more advanced readers. Moreover, Chapter 3 expanded on previous studies by providing a similar pattern of relations across orthographies, including isolated word reading as an index of intraword processing and both word list reading and text reading as reading fluency tasks that require interword processing.

On the one hand, the finding that individual word recognition had a great impact on reading fluency in Grade 1 is not surprising. This finding fits well with previous evidence pointing towards a single reading skill in the early years of reading development (see Protopapas et al., 2018; Schwanenflugel et al., 2006), irrespective of how words are being presented (in isolation or in sequences) or whether they need to be processed among other surrounding words that are meaningfully related (i.e., text) or not (i.e., word lists). Hence, the expected strong association among all reading tasks (isolated word recognition, word list reading, and text reading) among children in Grade 1 further supported the idea that beginning readers deal with one word at a time, irrespective of context or presentation format. Results from Chapter 3 also showed that individual word reading speed was the main predictor of both text and word list reading fluency. This finding further suggested that intraword processes dominate performance in reading fluency during the early phases of reading development—irrespective of the consistency of the language.

On the other hand, the idea of a disconnection between single word recognition and word list or text reading fluency, as efficiency in single word recognition increases, may seem counterintuitive. Considering that text reading fluency requires high-speed word recognition that frees cognitive resources and allows attention to be allocated to the meaning of what is being read (National Reading Panel, 2000), one would expect that the association of efficient (accurate and speeded) word recognition with text reading fluency to remain strong and stable throughout development. At the same time, in the absence of any requirements for contextual processing and meaning construction, word (list) reading fluency would be expected to be determined by (and thus, strongly associated with and predicted by) single word recognition efficiency across grade levels. Thus, findings from Chapter 3 may seem contradictory to these ideas: Both tasks of reading fluency (word list and text) were found to be strongly related across grades, while they both gradually dissociated from isolated word recognition. To understand these seemingly puzzling findings, we need to consider that it is possible for two tasks that share several processes (like discrete word reading and serial word reading) to be only weakly (or moderately) correlated if performance on each of these tasks is dominated by distinct rather than shared processes. Findings in Chapter 3 instead suggested that for readers past the beginner stage, fluent reading of unrelated word lists shares more with reading meaningfully related sentences than with recognizing isolated words.

It is true that current conceptions of reading fluency advocate that although fluency depends on word recognition skills, it should not be viewed as the immediate outcome of word recognition proficiency (e.g., Fuchs, Fuchs, Hosp, & Jenkins, 2001; Hudson, Pullen, Lane, & Torgesen, 2009; Kuhn et al., 2010; Kuhn & Stahl, 2013; National Reading Panel, 2000; Wolf & Katzir-Cohen, 2001). Up to present, these additional skills of reading fluency, besides the fundamental word recognition efficiency, have been mainly ascribed to text-level supralexical processing skills, such as one's ability to group words into meaningful grammatical units in order to be able to interpret them or read them with expression (Kuhn et al., 2010; Rasinski, Reutzel, Chard, & Linan-Thompson, 2012; Schwanenflugel, Kuhn, Wisenbaker, & Stahl, 2004; Stafura & Perfetti, 2017). The findings from Chapter 3, however, highlighted that what is shared between word list and text reading fluency, beyond individual word recognition, cannot be solely attributed to supralexical processing involved in text reading (e.g., semantic integration or syntactic processing), but there should be other additional processes accounting for individual differences in multiword (interword) processing of both context-free word list and connected text.

The shared component between word list and text reading, beyond single word recognition, was hypothesized to lie in the ability to process efficiently sequences of multiple words presented at the same time (interword processing as opposed to intraword processing), indexed by a task of serial digit naming. Findings from Chapter 3 confirmed this hypothesis, showing that serial digit naming (indexing multi-item processing) accounted for unique variance in both word list and text reading fluency, beyond isolated word reading speed, across languages. Notably, the emergence of this additional component of sequential multi-item processing was observed by Grade 3 when the disconnection between intraword and interword processing was also detected, offering a potential mechanism underlying the developmental shift from dealing with one word at a time (intraword processing), to managing multiple words at the same time either in lists or in text (interword processing).

Most importantly, serial digit naming was shown to account for unique variance in both unrelated word lists and connected text. This finding suggests that this additional component skill of multi-item processing is important for multiword reading efficiency irrespective of contextual demands. This new evidence has further research and educational implications, indicating that individual differences in reading fluency of multiple words in lists and in text may be co-determined by a distinct skill of sequential multi-item processing – when individual word recognition has become efficient to allow uninterrupted processing of adjacent items. Therefore, it refers to word-level multi-element processing, an aspect that has been so far disregarded from theoretical accounts of reading fluency. Previous concepts concerning multi-element processing in reading fluency were limited to either intraword multi-letter processing that leads to single word recognition or processing of multiple words within connected text to form meaningful units of information that leads to comprehension.

Yet, this word-level multi-item processing skill may be relevant and even provide further insights into current concepts and empirical evidence in the field of reading fluency. Specifically, the distinct skill of sequential multi-item processing, indexed by serial digit naming, has been assumed to reflect the efficiency of managing sequences of successive items at different processing stages, termed cascading (Protopapas et al., 2013a; Protopapas et al., 2018). Therefore, in the context of serial naming and multiword reading, cascading skill refers to the ability to process one stimulus while articulating the previous one and concurrently viewing the next stimulus in line and previewing the one further down, effectively buffering information for previous stimuli that have been viewed but not yet pronounced (Protopapas et al., 2018). As such, efficient cascaded processing during text reading should allow readers to comprehend a sentence before pronouncing it, and thus may account for prosodic reading, which is considered a fundamental aspect of fluent (oral) reading (e.g., Kuhn et al., 2010; National Reading Panel, 2000; Schwanenflugel et al., 2004; Wolf & Katzir-Cohen, 2001). This speculative idea is in line with evidence from eye movement research, which has long revealed that there is a lag between the eyes and the voice during oral reading tasks (i.e., eye-voice span; Buswell, 1921), and most importantly, that keeping an optimal distance between the viewed and the spoken word by coordinating multi-item sequences is critical for efficient performance in both oral reading (e.g., De Luca, Pontillo, Primativo, Spinelli, & Zoccolotti, 2013; Laubrock & Kliegl, 2015) and rapid naming (e.g., Gordon & Hoedemaker, 2016). Evidence from the present research supports the speculative idea that the ability to coordinate multiple items through cascaded processing–also indirectly supported by eye movement evidence–may be a distinct component in reading fluency and can be indexed by serial naming tasks.

Reading Fluency: Theory vs. Practice

Reading fluency has been conceptualized differently over the past decades, including narrower or broader concepts, such as *speeded decoding* (Breznitz, 2006), or *sight-word reading* (Ehri, 2005), *automatic word recognition that allows simultaneous comprehension* (LaBerge & Samuels, 1974), or *accuracy, automaticity and oral reading prosody that facilitate comprehension* (Kuhn et al., 2010; Schwanenflugel, et al., 2004; Schwanenflugel et al., 2006). In practice, reading fluency is more commonly assessed by measures of word reading efficiency, where unrelated words are presented in sequences (typically in columns), or measures of oral text reading fluency.

In the context of this dissertation, word list reading fluency (i.e., serial word reading) was used as a measure of efficiency in reading unrelated word sequences, while text reading fluency was used as a measure of efficiency in reading meaningfully related words in sentences forming a passage. Both were viewed as reading fluency measures sharing the requirement of reading multiword sequences (i.e., interword processing), and differing in contextual processing (comprehension) demands involved in connected text reading. An important aspect of the design of this project was that reading measures consisted of familiar (short and high frequency) words that were very closely matched in several psycholinguistic aspects. This design was used to avoid introducing confounding variables on the one hand and to control the aspects in which the tasks differed to the extent possible on the other hand. Hence, both reading fluency tasks were relatively simple in terms of their decoding demands or comprehension requirements, at least for the readers in the middle and upper grades. In contrast, typical measures of reading fluency include word lists with increasing difficulty or texts varying in complexity (usually age-appropriate text). Therefore, performance on typical reading fluency tasks (word list or text reading fluency) is expected to be co-determined by accuracy and speed (or contextual processing) due to their greater decoding or comprehension demands.

In line with this idea, findings in Chapter 3 suggested that speed can be examined relatively unaffected by accuracy in word list reading only if children have scored at least 70% correct in the same reading task. In other words, evidence suggested that unless children have reached this minimum level of accuracy in word reading (at least 70% correct), performance in word list reading is co-determined by accuracy and speed. This was evident for a proportion of younger readers learning to read in English who scored below this accuracy threshold, showing great variability in accuracy and indicating that the task of word reading posed higher decoding demands for this group of readers. This finding also suggested that children first aim for accuracy and then for speed, even for tasks of word list reading that do not require meaning construction across multiple words. Along the same idea, evidence from Chapter 2 suggested that the extent of sequential intraword processing requirements (whether words require some form of internal composition and assembly) is determined by word-specific characteristics along with the degree of orthographic consistency and the level of reading proficiency. This line of evidence has further research and practical implications, suggesting that it may be important to examine the component of accuracy before investigating the concurrent component of speed in a reading task, especially if testing younger children, clinical samples, or in orthographies or tasks that may be more prone to errors, if the goal is to understand specific components that influence or limit reading ability. On the other hand, it also suggests that the power of typical measures of word list reading tests (such as the Test of Word Reading Efficiency; Torgesen, Wagner, & Rashotte, 1999) or of text reading fluency tests (such as DIBELS; Good & Kaminski, 2002) in predicting overall reading ability or in identifying struggling readers presumably lies in their confounded nature, accounting for both accuracy and speed (or comprehension) variability and limitations.

Thus, different approaches and tasks might be necessary based on the research or educational purpose: If the objective is to disentangle component processes and understand their distinct contribution to reading fluency (or even comprehension), less complex tasks that isolate specific components might be more appropriate. For example, considering the level of accuracy first may allow subsequent investigation of the concurrent speed component of the same task relatively unaffected from accuracy limitations. Similarly, by using sequences of familiar words that are presented simultaneously may allow the investigation of interword processing skills, and thus, the efficiency of processing multiple words relatively free from accuracy or comprehension problems. These approaches can be viewed as alternative ways to examine components of reading fluency and their distinct contribution to its development, which perhaps can lead us closer to understanding reading fluency in its totality.

Serial Naming and Multiword Reading Efficiency

In Chapter 4, evidence of serial advantage across naming/reading tasks and grades in both English and Greek was provided. This finding confirmed the idea that efficiency in serial naming and serial word reading is characterized by some type of temporal overlap in the serial task in order to yield faster naming rates over the discrete version of the task of the same content (e.g., Jones, Branigan, & Kelly, 2009; Protopapas et al., 2013a; Protopapas et al., 2018; Zoccolotti et al., 2013; Zoccolotti et al., 2015). This idea is also pertinent to the cascaded processing hypothesis, according to which the ability to schedule the processing of multiple (adjacent) items *with great overlap* may be the critical aspect of efficient serial naming and multiword reading. This procedure of sequential multi-item processing in serial naming and reading, which results in a temporal overlap of different processing stages across successive items, has been characterized as being *endogenously* controlled (i.e., governed by the own reader's planning; Altani, Protopapas, et al., 2017). That is, multiple items that are simultaneously displayed in naming and reading tasks require sequential processing in a self-paced manner, and thus "a more *internally driven* visual scanning of the items" (Zoccolotti et al., 2015, p.11). However, it is worth noting herein that according to previous evidence, efficiency in sequential processing in RAN and reading does not appear to concern a fixed direction of visual scanning (Kuperman, van Dyke, & Henry, 2016; Protopapas et al., 2013b), and thus cannot be attributed to any asymmetry in the perceptual span (resulting from reading practice) or direction-specific visual scanning.

Turning to the present findings regarding serial advantage, evidence suggested that its development across grades (presumably reflecting improvement in cascading efficiency) was further influenced by content-specific factors. This is in line with the idea that different properties of material are more (or less) accessible to efficient multi-item (cascaded) processing. First, images of objects and dice lagged in the development of serial advantage compared to the alphanumeric (digits) and orthographic (number words and words) stimuli. This finding can be attributed to semantic mediation that is involved in naming objects and dice as images require first to be identified as concepts before their name can be accessed and retrieved, as opposed to digits or words whose phonological forms are directly derived from the visual input without the requirement of conceptual identification (e.g., Liu & Georgiou, 2017; Pan, Yan, Laubrock, Shu, & Kliegl, 2013; Poulsen & Elbro, 2013; Roelofs, 2003). Second, serial advantage in dice was found to be intermediate between digits and objects. This finding can be attributed to the images of dice that are fixed and more familiar, and perhaps better-practiced than objects, implying that practice and exposure with naming these items may allow for (at least partially) unmediated naming that can subsequently facilitate cascading.

Moreover, the finding that after Grade 1 number words (but not so much words) demonstrated as large a serial advantage as digits cannot be attributed to any word-specific features because all words were chosen to be comparably familiar and equally short and pronounceable. Instead, this finding suggests that the fact that number words were derived from a closed set of numbers and were more predictable (since there were only four of them in the task) likely rendered them more available for efficient sequential processing, compared to word lists that are derived from a large open set with unlimited available targets. This evidence also suggests that efficiency in the serial naming or serial reading tasks is not only determined by the individual items (in terms of stimulus-specific characteristics or familiarity), but it is further influenced by their context. For example, with a closed set of repeated well-practiced items, the phonological codes are more available as they have already been retrieved and presumably maintained active to be recalled again; presumably limiting the demands posed by single-item identification and retrieval and allowing for other factors like cascaded processing to emerge and perhaps dominate performance in the task.

In line with this idea, findings showed a gradual dissociation between the serial and discrete task (of each content) and a concurrent increase in the serial advantage. This evidence suggested that with increasing efficiency, individual differences in the serial naming efficiency were gradually determined to a lesser degree from differences in the discrete versions of the task. In other words, regardless of how long it takes to complete all processing stages of each stimulus—from initial stimulus identification all the way to its articulation—efficient multi-item processing amounts to greater serial advantage.

This line of evidence is also consistent with previous findings showing that differences between children with reading difficulties and typically developing readers (from samples of older readers) are not only greater in the serial format of naming/reading compared to the discrete format of the tasks, but they are also significantly amplified in the serial format of digits and words compared to that of objects or dice (Pan et al., 2013; Zoccolotti et al., 2013; Zoccolotti et al., 2015). If digits and words are more amenable to cascaded processing compared to objects or dice—due to stimulus-specific limitations—then performance in RAN digits and serial word reading should be dominated by efficiency in cascading among skilled readers. This also implies that the previously reported amplified difficulties in alphanumeric RAN and reading tasks among older children with dyslexia compared to their peers of typical development possibly express differences in cascaded processing efficiency, beyond any difficulties with individual item naming or single word decoding (see Zoccolotti et al., 2013; Zoccolotti et al., 2015, for a similar argument).

Conclusions and Future Directions

The findings of the three studies reported here provide evidence of a dissociation in the mechanisms involved in the serial and discrete versions of reading and naming tasks, highlighting that efficient multi-item processing may play a critical role for the development of reading fluency. This component of word-level multi-item processing has received little attention in previous research and has been largely overlooked in theories of reading fluency. This dissertation expands on previous work (Altani, Georgiou, et al., 2017; Altani, Protopapas, & Georgiou, 2017; de Jong, 2011; Protopapas et al., 2013a; Protopapas et al., 2018; Zoccolotti et al., 2014; Zoccolotti et al., 2015) by providing evidence of the role of efficient multi-item processing in reading multiword sequences both in context-free lists and in connected text reading across grade levels and languages varying in orthographic consistency.

Sequential multi-item processing was indexed by RAN tasks and was hypothesized to reflect a distinct skill domain that relates to the efficiency of scheduling multiple successive items through overlapping processing stages, termed cascading. This idea was supported by evidence of a serial advantage across naming and reading tasks, indicating that serial efficiency is associated with some type of temporal overlap that leads in faster naming rates in the serial over the discrete format of the naming and reading tasks. Therefore, within the present context, the idea of temporal overlap in cascading skill concerned processes involved in naming (single) words and symbols or images (e.g., visual identification, name retrieval, conceptual identification, articulation planning, and execution). That is, within the arrays of successive words, symbols, or images, readers process one item while articulating the previous one, and simultaneously viewing the next item in line and previewing the one further down, storing temporary information that has been already viewed but not yet pronounced. This idea seems to be in line with evidence from eye movement studies showing that there is a tight control between the eyes and the voice during naming and reading (i.e., eye-voice span; Gordon & Hoedemaker, 2016; Laubrock & Kliegle, 2015), and evidence showing that typical readers are affected more by removal of parafoveal information (Jones et al., 2009; Yan et al., 2013) or demonstrate larger visual attention span (Bosse, Tainturier, & Valdois, 2007). For example, if readers with broader visual attention span are able to perceive a larger number of multiple elements with a single glance, then they should also be able to chunk these multiple (orthographic) elements into unitized individual items (consistent with the idea of simultaneous intraword processing). This is also consistent with the idea that multiple adjacent items can be processed simultaneously through processing cascades, once individual items can be perceived with efficiency (as single units). Therefore, if longer words (forming a larger number of visual elements) can be perceived as single units at a glance, then multi-item processing (cascading) should emerge across words instead of within individual words.

However, this idea that cascaded processing—as a skill domain indexed by RAN—may be a crucial element in the development of reading fluency is still speculative, and follow-up work is needed to investigate whether it is on the right track. Eye movement studies with concurrent vocal responses might be a fruitful avenue for further research, as they may provide information about the onset and offset of specific elements and processing stages of the more complex serial naming and reading tasks. In addition, further investigation should aim to unravel the nature of the mechanisms involved in naming processes, accounting for the distinctive processing in the serial and discrete dimension, as well as specific properties or prerequisites of efficiency in serial naming.

RAN tasks may be used as indexes of multi-item (cascaded) processing, based on their well-documented association with reading fluency (Kirby, Georgiou, Martinussen, & Parrila, 2010), along with the fact that their stimuli consist of highly familiar items, permitting accurate visual identification and rapid name retrieval of each item. However, future research should investigate whether other tasks may capture rapid multi-item processing by shedding light upon domain-general and domain-specific aspects (e.g., visual or articulatory/motor processes). Future research should also investigate how practice and exposure on different types of material may enhance efficiency in multi-item processing and fluency tasks, and whether exposure on discrete versions may produce different outcomes compared to exposure on serial versions of tasks of the same content.

Overall, this dissertation points out an important gap in the current conceptualization of reading fluency and suggests that understanding reading fluency and its development will require an additional skill, which lies between single word recognition and supralexical processing skills. This skill was indexed by serial naming tasks and was assumed to constitute a distinct component in reading fluency that reflects the efficiency of scheduling the processing of multiple successive items with temporal overlap. Sequential multi-item processing efficiency was shown to emerge once individual items were recognized and retrieved with efficiency, as single units, through simultaneous and unmediated processing. Further research is required to investigate whether the hypothesis of cascading is on the right track and how this skill may be associated with reading fluency development, as well as reading difficulties.

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Appendix A

Materials	Greek	English
Digits	2, 3, 5, 6	2, 3, 5, 6
Number words	δύο, τρία, πέντε, έξι	two, three, five, six
Word list 1	αίμα, άλλος, βάση, γάτα, γέλιο, δάση, δίνω, δίκιο, είδα, ήταν, είπε, είχε, έργο, ζούσε, ζώο, ήμουν, θέλει, θέμα, ίδιο, κάνω, λύση, κύμα, λέω, μόνη, λόγια, μάχη, μέρα, νέο, όλη, πήρε, σώμα, φίλη, φύλλο, χάρη, χώρα, ώρες	air, boy, say, tea, know, ask, bag, bed, cat, cup, let, pot, run, sit, son, ball, been, boat, book, cake, deep, feel, food, girl, slow, tall, horse, light, noise, watch, fox, white, cold, hand, milk, glass
Word list 2	άκρη, άλλο, βάζω, βήμα, γάλα, γέλια, δέκα, δίνει, δώρο, είδος, είδε, είπα, ένας, έργα, έχω, ζώνη, ήρθε, θεία, θέση, ίδια, κάνει, κόμμα, μάτι, μέλη, μένω, νέα, όλα, πήγε, πάει, πόδι, πόλη, φίλοι, φύση, χέρι, χιόνι, χώμα	buy, eat, may, sea, show, car, hat, dog, end, fun, has, top, lot, set, sun, bike, bird, call, cook, coat, door, feet, keep, seen, snow, tell, catch, large, mouse, night, while, box, gold, land, salt, class
Text	Εμείς έχουμε μία αυλή με πολύ χώρο. Όσο κάνει κρύο μένω μέσα. Ενώ άμα έχει καλό καιρό είμαι πάντα έξω. Κάθε πρωί παίζω εκεί στον κήπο έως αργά. Τότε μόνο πάω πίσω επειδή θέλω λίγο ύπνο.	My cat likes to rest on the roof. She goes up the tall tree by the new house. She looks at black birds for hours. But she comes down fast when it is time to eat.

Appendix B

Measure	Number words				Word list 1				Word list 2				Text				Object words			
	M	SD	min	max	M	SD	min	max	M	SD	min	max	M	SD	min	max	M	SD	min	max
Greek																				
Number of letters	3.8	1.0	3	5	4.1	0.6	3	5	4.1	0.5	3	5	4.0	0.8	2	6	4.2	1.0	3	5
Number of phonemes	3.8	0.5	3	4	3.8	0.4	3	4	3.8	0.4	3	4	3.8	0.6	2	5	3.8	0.5	3	4
Number of syllables	2.0	0.0	2	2	2.0	0.0	2	2	2.0	0.0	2	2	2.0	0.3	1	3	2.0	0.0	2	2
Printed frequency (children)	5.5	0.4	5.1	6.0	5.2	0.5	4.6	6.5	5.3	0.4	4.4	6.1	5.6	0.5	4.8	7.1	5.5	0.4	5.1	6.0
Printed frequency (adult)	5.6	0.5	5.2	6.3	5.1	0.7	3.9	6.5	5.0	0.6	3.7	6.0	5.4	0.8	3.7	7.2	5.6	0.5	5.2	6.3
English																				
Number of letters	3.8	1.0	3	5	3.8	0.7	3	5	3.8	0.7	3	5	3.4	1.0	2	5	3.8	1.0	3	5
Number of phonemes	3.0	0.8	2	4	3.0	0.5	2	4	3.0	0.5	2	4	2.8	0.8	2	5	3.0	0.8	2	4
Number of syllables	1.0	0.0	1	1	1.0	0.0	1	1	1.0	0.0	1	1	1.0	0.0	1	1	1.0	0.0	1	1
Printed frequency (children)	5.6	0.4	5.2	6.0	5.6	0.3	5.2	6.1	5.6	0.3	5.3	6.1	6.3	0.8	4.4	7.8	5.7	0.4	5.2	6.0
Printed frequency (adult)	5.7	0.4	5.3	5.8	5.1	0.5	4.1	6.4	5.2	0.5	4.0	6.4	6.1	1.0	4.5	7.8	5.6	0.5	5.2	5.8

Note. Printed word frequencies are in the Zipf scale (Van Heuven et al., 2014). Greek: children's frequencies are based on the language arts textbooks for Grades 1–6; adult frequencies from the IPLR C corpus (Protopapas et al., 2012). English: children's frequencies are based on Children's Printed Word Database of words which appear in books for children in Grades 1–4 (Masterson, Stuart, Dixon, & Lovejoy, 2010); adult frequencies from the MRC psycholinguistic database (Coltheart, 1981).