From Individual Word Recognition to Word List and Text Reading Fluency

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Abstract

This study aimed to examine (a) the developing interrelations between the efficiency of reading individually presented words (i.e., isolated word recognition speed) and the efficiency of reading multiword sequences (i.e., word list and text reading fluency), (b) whether serial digit naming, indexing the ability to process multi-item sequences, accounts for variance in word list and text reading fluency beyond isolated word recognition speed, and (c) if these patterns of relations/effects differ between two alphabetic languages varying in orthographic consistency (English and Greek). In total, 710 Greek- and English-speaking children from Grades 1, 3, and 5 completed a serial digit naming task and a set of reading tasks, including unconnected words presented individually, unconnected words presented in lists, and sentences forming a meaningful passage. Our results showed that the relation between isolated word recognition speed and both word list and text reading fluency gradually decreased across grades, irrespective of contextual processing requirements. Moreover, serial digit naming uniquely predicted both word-list and text reading fluency in Grades 3 and 5, beyond isolated word recognition speed. The same pattern of results was observed across languages. These findings challenge the notion that individual word recognition and reading fluency differ only in text-level processing requirements. Instead, 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 words one at a time to efficient processing of word sequences.

Keywords: reading fluency, word recognition, serial naming, RAN, cross-linguistic.

From Individual Word Recognition to Word List and Text Reading Fluency

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[1] (Jenkins, Fuchs, van den Broek, Espin, & Deno, 2003; Kim, 2015; Rasinski, Reutzel, Chard, & Linan-Thompson, 2012; Stafura & Perfetti, 2017). However,

[1] 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'.

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; 2018; Zoccolotti et al., 2014, 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,[2] 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 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

[2] 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.

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 attending Grades 1, 3, and 5. Information about the sample size, gender, and mean age of participants for each grade and language are available in Table 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, or had exclusively attended an English-Canadian or a Greek elementary school until data collection, ensuring fluent oral skills in the respective language. Children with severe learning disabilities were excluded, 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 (or a subsample) of children has been used in previous studies (Altani, Georgiou, et al., 2017; Altani et al., 2018; Protopapas et al., 2018). However, both the questions asked, and the analyses performed in previous studies differ from the ones in the current study.

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[3] 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).

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

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 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. [4]

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

[4] 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).

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 2 presents the mean accuracy (proportion correct) and rate (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 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 1 and 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 S1 in the Supplementary Material. Based on the distributions of scores in speed and accuracy (Figures 1 and 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 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.

Finally, a threshold of 70% correct was applied, based on Juul et al. (2014) and visually confirmed by the distributions in Figures 1 and 2.[5] Examining the proportion of children who 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 S6.

Following this extensive screening procedure, Table 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,

[5] 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 S2–S5). Therefore, children who scored at least 70% correct were included in our main analyses, following the accuracy level proposed by Juul et al. (2014).

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 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).

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 5 shows the regression model coefficients with both measures entered simultaneously in the regression equation. Table 6 shows the unique and total contribution of each predictor to serial word reading and text reading in each grade and language.

In Grade 1, discrete word reading predicted larger unique and total amounts of variance in serial word reading compared to that predicted by serial digit naming (Table 6). A reversed pattern was observed among Grade 5 children, as serial naming became a significant predictor of serial word reading, accounting for larger unique and total amounts of variance compared to the corresponding variance predicted by discrete word reading.

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 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 5).

Comparing Results Across Languages

With respect to our third goal, we found very similar patterns of interrelations across languages (see Table 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 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 5). Interaction plots between language and the other two predictors are presented in Figure 3 (with serial word reading as outcome variable) and Figure 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.

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 S6). 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 1 and 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, 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; 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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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

	Number words				Word list 1				Word list 2				Text			
Measure	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
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
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
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
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
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
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
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
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
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

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).

Table 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.

Table 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.

Table 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.

Table 4

Interrelations Among Tasks in Each Grade and Language

	Grade 1				Grade 3				Grade 5			
Task	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 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. $^{*}p < .05$; $^{**}p < .005$; $^{***}p < .0005$

Table 6

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	.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

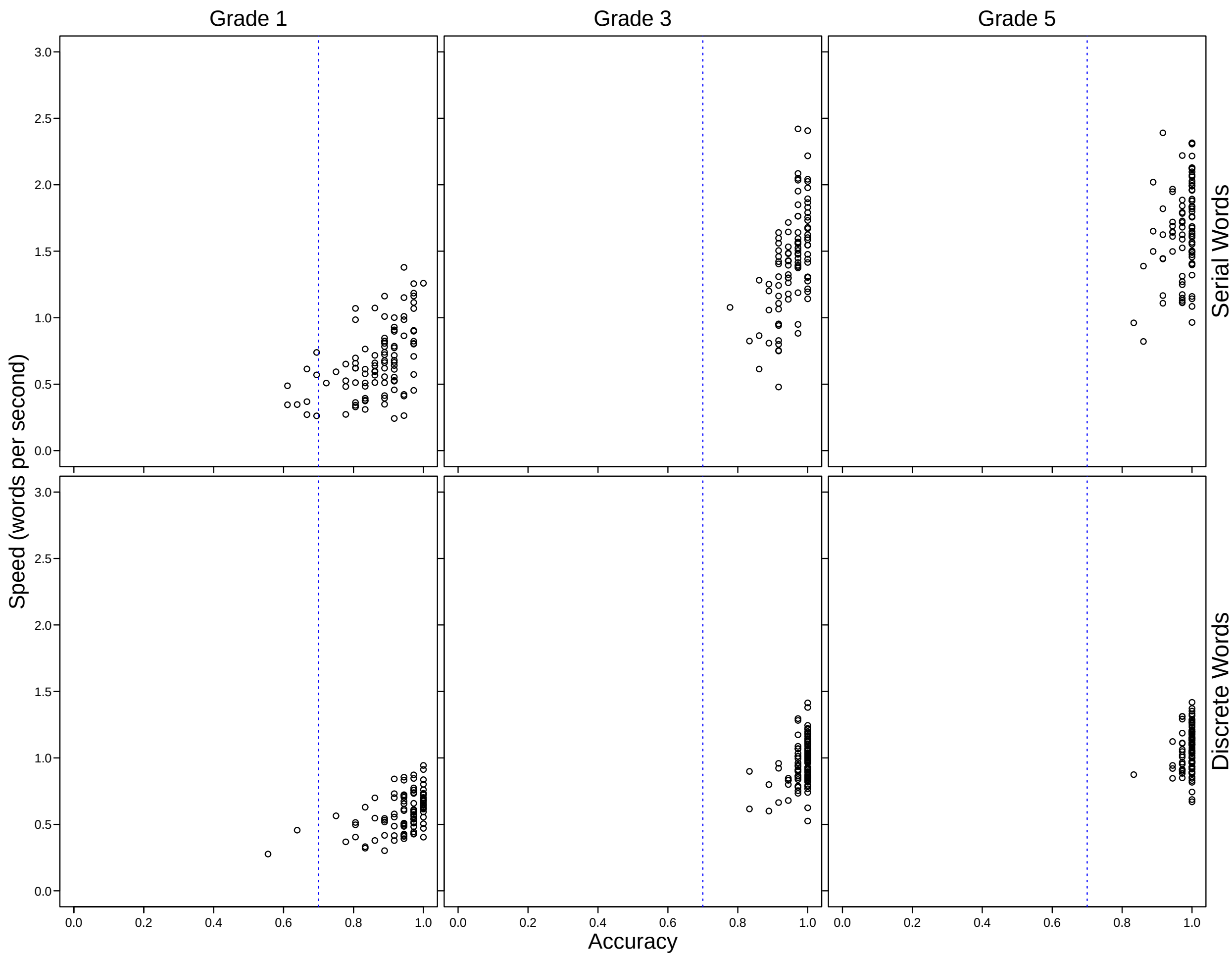

Figure 1. Scatterplots of accuracy (x-axis) and speed (y-axis) from the tests of serial and discrete word reading in each Grade in Greek. The blue dotted line indicates the threshold of 70% correct.

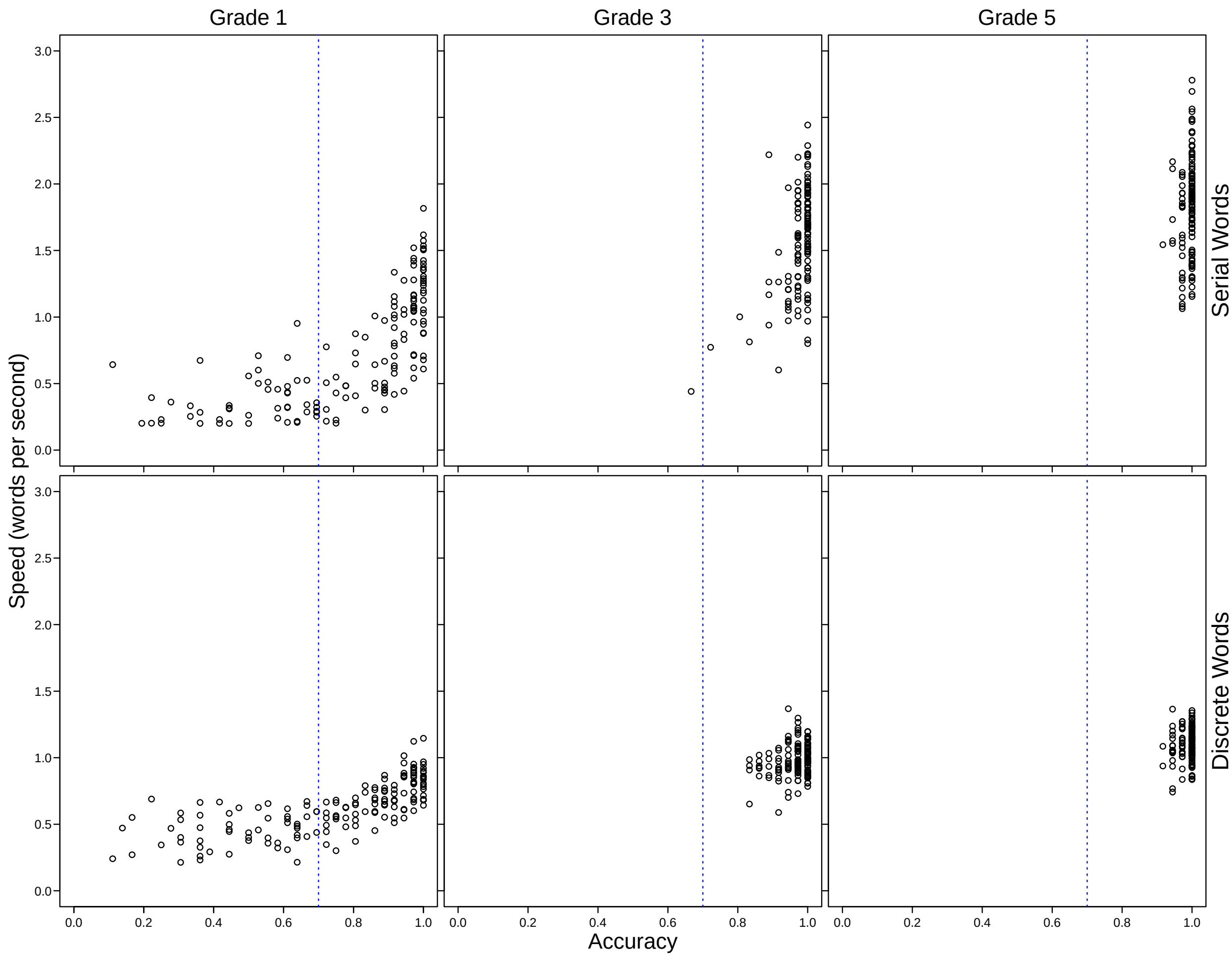

Figure 2. Scatterplots of accuracy (x-axis) and speed (y-axis) from the tests of serial and discrete word reading in each Grade in English. The blue dotted line indicates the threshold of 70% correct.

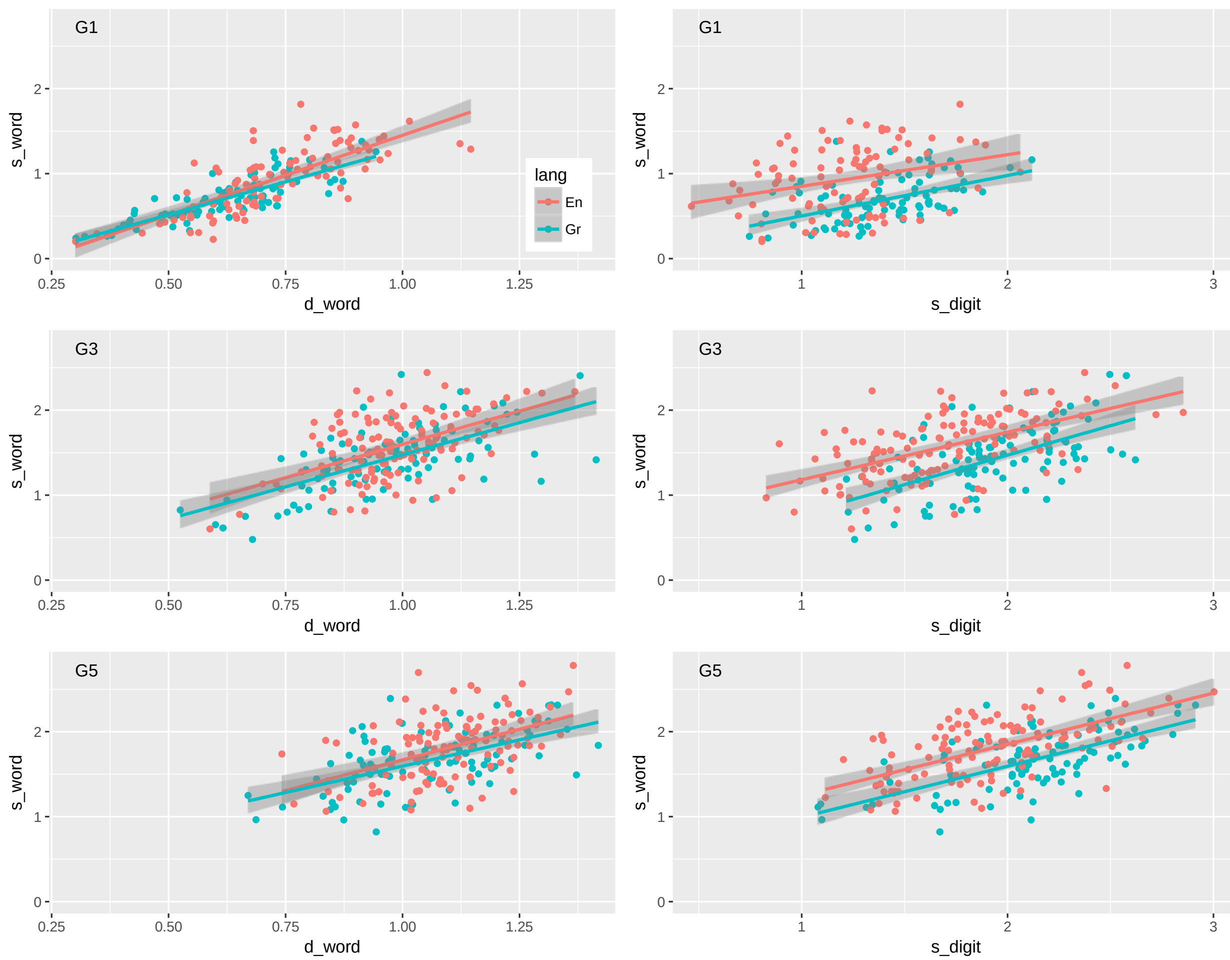

Figure 3. Interaction plots between language and discrete word reading (left) or language and serial digit naming (right) in the prediction of word list reading fluency. The regression lines represent the effects of the indicated predictor to serial words for each grade in Greek (Gr; blue) and English (En; red). Error bars show 95% confidence intervals. G = Grade; s = serial; d = discrete; lang = language.

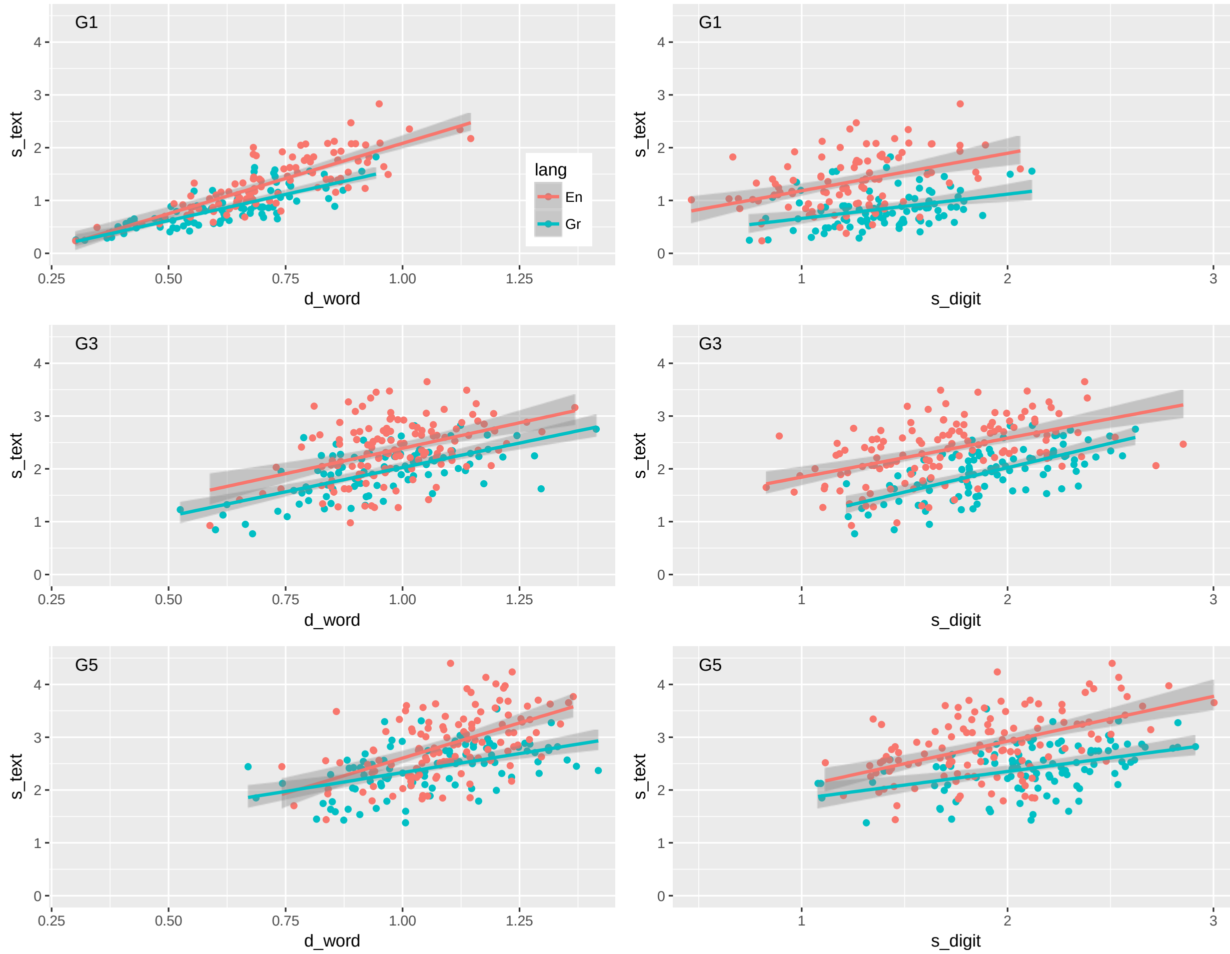

Figure 4. Interaction plots between language and discrete word reading (left) or language and serial digit naming (right) in the prediction of text reading fluency. The regression lines represent the effects of the indicated predictor to text for each grade in Greek (Gr; blue) and English (En; red). Error bars show 95% confidence intervals. G = Grade; s = serial; d = discrete; lang = language.

Supplementary Material

From Individual Word Recognition to Word List and Text Reading Fluency

Supplementary Tables S1 and S6 report complementary analyses to the results of the main text. Supplementary Tables S2–S5 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 S1

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 S2

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

Intrerrelations Among Tasks in Each Grade and Language

		Grade 1				Grade 3				Grade 5			
	Task	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 S4

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 S5

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 S6

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).