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# The anatomy of the RAN-reading relationship

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**Abstract** The purpose of this study was to contrast three models of the RAN-reading relationship derived from the most prominent theoretical accounts of how RAN is related to reading: the phonological processing, the orthographic processing and the speed of processing accounts. Grade 4 Greek-speaking children ($n = 208$; 114 girls, 94 boys; mean age = 117.29 months) were administered measures of general cognitive ability, RAN, phonological processing, orthographic processing, speed of processing, and reading fluency. Phonological processing and orthographic processing were assessed with both accuracy and speeded measures. Structural equation modeling showed that the most parsimonious model was one in which RAN predicted reading fluency directly and through orthographic processing. Phonological processing did not predict reading fluency and speed of processing was more important for the RAN-orthographic/phonological processing relationships than for the RAN-reading relationship. Taken together, these findings suggest that what is unique to RAN is more important for the prediction of reading fluency than what it shares with either speed of processing, phonological processing, or orthographic processing.

**Keywords** Rapid automatized naming · Reading fluency · Orthographic processing · Phonological processing · Speed of processing · Greek

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## Introduction

RAN, the ability to name as fast as possible highly familiar stimuli such as digits, letters, colors and objects, is a strong predictor of reading in different languages (e.g., Chinese: Pan et al., 2011; Dutch: de Jong, 2011; Greek: Protopapas, Altani, & Georgiou, 2013; German: Landerl & Wimmer, 2008; English: Compton, 2003; Norwegian: Lervåg & Hulme, 2009; Sinhala: Wijayathilake & Parrila, 2014), in different age groups (e.g., Georgiou, Papadopoulos, & Kaizer, 2014; van den Bos, Zijlstra, & Spelberg, 2002), and in different reading-ability levels (e.g., poor readers: McBride-Chang & Manis, 1996; normal readers: Parrila, Kirby, & McQuarrie, 2004). However, the mechanisms underlying the RAN-reading relationship remain unclear (Kirby, Georgiou, Martinussen, & Parrila, 2010). Thus, the purpose of our study was to examine how RAN is related to reading by contrasting the three most prominent theoretical accounts of the RAN-reading relationship: the phonological processing, the orthographic processing, and the speed of processing accounts. The goal of this line of research is not only to solve a mystery that remains unresolved since the introduction of RAN to reading research (Denckla & Rudel, 1974), but also to help us build better models of reading development that incorporate all possible paths (direct and indirect) between the key predictors and reading outcomes.

Evidence from two recent meta-analyses suggests that RAN exerts a stronger effect on reading fluency than on reading accuracy (Araújo, Reis, Petersson, & Faísca, 2015; Song, Georgiou, Su, & Shu, 2016). Researchers have argued that examining the relationship between RAN and reading fluency can help us better understand the underlying reading processes (e.g., de Jong, 2011; Protopapas et al., 2013; van den Boer & de Jong, 2015; van den Boer, Georgiou, & de Jong, 2016). For example, if single words are read by sight, or processed in parallel, a high correlation should be found with discrete RAN. If, however, single words are read through serial decoding, a stronger correlation would be expected with serial RAN. In line with these assumptions, de Jong (2011) found that for beginning readers in Grade 1, discrete reading of monosyllabic words was more strongly related to serial RAN, whereas in more advanced readers in Grades 2 and 4, discrete reading was more strongly related to discrete RAN. Protopapas et al. (2013) reported very similar patterns in Greek.

Another way of looking at the shift between serial and holistic processing of words would be to examine the role of phonological and orthographic processing in the RAN-reading fluency relationship. Phonological and orthographic processing have been linked to the most prominent RAN-reading theoretical accounts (Georgiou & Parrila, 2013). Initially, Torgesen, Wagner, and colleagues viewed RAN as part of phonological processing and hypothesized that it relates to reading because it requires quick access to and retrieval of phonological representations from long-term memory (e.g., Torgesen, Wagner, & Rashotte, 1994; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Wagner & Torgesen, 1987). In support of this hypothesis, Torgesen et al. (1994) found that the effects of RAN on reading overlapped with those of phonological awareness. However, several studies have shown that RAN accounts for variance in reading beyond the effects of other measures of phonological processing, such as phonological awareness (e.g., de Jong & van der Leij, 1999; Parrila et al., 2004) and phonological short-term memory (e.g., Bowers, Steffy, & Tate, 1988; Parrila et al., 2004). In addition, children with both phonological awareness and RAN deficits have been found to experience more severe reading difficulties than children with deficits in either RAN or phonological awareness (e.g., Kirby, Parrila, & Pfeiffer, 2003; Papadopoulos, Georgiou, & Kendeou, 2009; Steacy, Kirby, Parrila, & Compton, 2014; Torppa, Georgiou, Salmi, Eklund, & Lyytinen, 2012).

In contrast, Bowers and colleagues (e.g., Bowers & Wolf, 1993; Bowers, Sunseth, & Golden, 1999; Sunseth & Bowers, 2002) proposed that RAN is related to reading because it contributes to the development of orthographic processing. Orthographic processing has been defined as “the ability to form, store, and access orthographic representations” (Stanovich & West, 1989, p. 404). According to Bowers and Wolf (1993), if letter identification proceeds too slowly, as indexed by slow naming speed performance, letter representations in words will not be activated in close enough temporal proximity to induce sensitivity to commonly occurring orthographic patterns. In support of this hypothesis, researchers have shown that RAN is a unique predictor of orthographic processing (e.g., Compton, DeFries, & Olson, 2001; Lervåg, Bråten, & Hulme, 2009; Manis, Doi, & Bhadha, 2000). However, others have shown that RAN is not strongly related to measures of orthographic processing (e.g., Conrad & Levy, 2007; Georgiou, Parrila, & Kirby, 2009; Rothe, Schulte-Körne, & Ise, 2014) and that it accounts for unique variance in reading even after controlling for the effects of orthographic processing (e.g., Georgiou, Parrila, & Papadopoulos, 2008; Li, Shu, McBride-Chang, Liu, & Peng, 2012).

Alternatively, some researchers have argued that the RAN-reading relationship may be due to the role of some domain-general factors such as speed of processing. For example, Kail and colleagues (e.g., Kail & Hall, 1994; Kail, Hall, & Caskey, 1999) suggested that RAN and reading are related because both rely on the efficient execution of their underlying cognitive processes (indexed by processing speed). Wolf and Bowers (1999) also argued that speed of processing plays an important role in naming speed because information must be timely integrated within and between multiple sub-processes. However, similar to the phonological and orthographic processing accounts, there is evidence that RAN is not strongly related to measures of speed of processing (e.g., Bowey, McGuigan, & Ruschena, 2005; McBride-Chang et al., 2003; Poulsen, Juul, & Elbro, 2015) and that RAN accounts for variance in reading over and above speed of processing (e.g., Bowey et al., 2005; Georgiou et al., 2009).

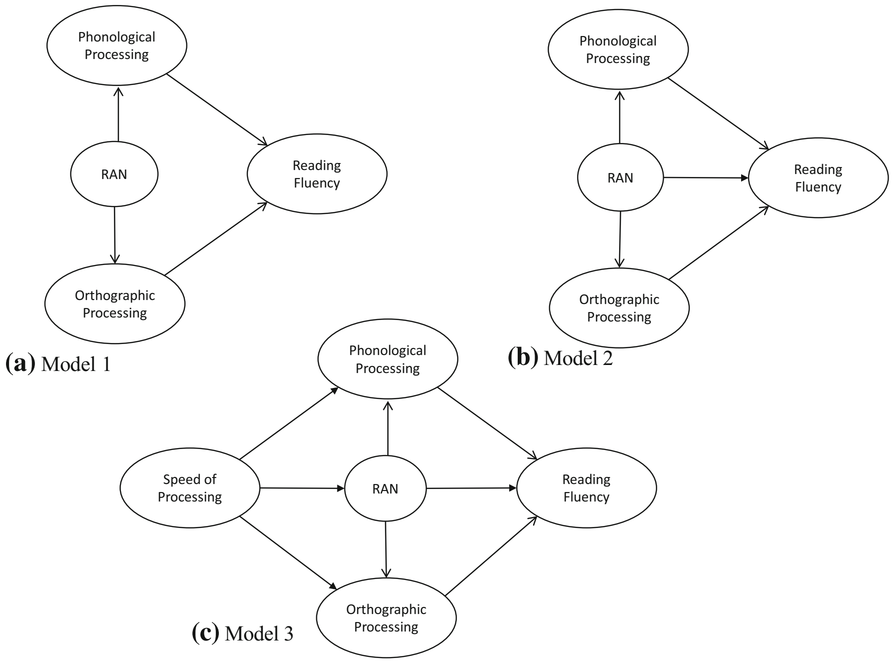
The inability of the existing theoretical accounts to explain the RAN-reading relationship can be attributed to two factors: First, most previous studies sought to provide evidence in favor or against a specific theoretical account and did not examine multiple pathways between RAN and reading (e.g., Moll, Fussenegger, Willburger, & Landerl, 2009; Pan et al., 2011; Powell, Stainthorp, Stuart, Garwood, & Quinlan, 2007; Savage, Pillay, & Melidona, 2007). Nevertheless, even the few studies that considered multiple pathways between RAN and reading have produced mixed findings (e.g., Cutting & Denckla, 2001; Holland, McIntosh, & Huffman, 2004; Poulsen et al., 2015). Cutting and Denckla (2001), for example, found that RAN, phonological awareness, and orthographic processing all directly affected reading accuracy and that RAN had no direct effects on either phonological awareness or orthographic processing (particularly after controlling for speed of processing). In contrast, Holland et al. (2004) found that the best fitting model in their study was one in which RAN predicted reading accuracy indirectly through the effects of phonological awareness and orthographic processing. Speed of processing was not assessed in this study. Finally, Poulsen et al. (2015) showed that RAN's effects on reading accuracy and fluency were partly mediated by phonological awareness and letter knowledge. Because speed of processing was not correlated with reading, it was left out of the model.

A second factor may relate to the nature of the tasks used to operationalize the possible mediators of the RAN-reading relationship. RAN and reading fluency are operationalized with speeded measures. In contrast, phonological processing and orthographic processing are traditionally operationalized with accuracy measures. Georgiou et al. (2009) showed that when orthographic processing was operationalized with accuracy measures, it did not mediate the RAN-reading relationship. However, when operationalized with speeded measures, it explained part of RAN's predictive value in reading fluency. This finding needs to be replicated with speeded measures of both phonological processing and orthographic processing.

## The present study

In the current study, we examined how RAN is related to reading fluency by contrasting three prominent RAN-reading theoretical accounts (the phonological processing, the orthographic processing, and the speed of processing accounts) in a large sample of Greek-speaking children in Grade 4. The theoretical accounts discussed earlier were used to develop three alternative models (see Fig. 1) that were tested using both accuracy and speeded measures of phonological processing and orthographic processing.

The present study makes four important contributions to the literature: First, to our knowledge, this is only the second study (Cutting & Denckla, 2001, being the first) to simultaneously contrast the most prominent theoretical accounts of the RAN-reading relationship. This allows us to obtain a more comprehensive picture of the processing skills that underlie the RAN-reading fluency relationship. Importantly, Cutting and Denckla's (2001) sample of Grade 1–3 children was small ($n = 79$) and they assessed both phonological processing and orthographic processing with single accuracy measures. Second, we employed both accuracy and speeded measures to operationalize phonological processing and orthographic processing. This allows us to examine if RAN is uniquely related to reading fluency only when the rest of the processing skills are assessed with accuracy measures. Third, following Kail and Hall (1994), we treated speed of processing as a "common cause" variable (speed of processing predicting both RAN and reading) rather than as an intervening variable (see Cutting & Denckla, 2001, for a similar model). We



**(a)** Model 1

**(b)** Model 2

**(c)** Model 3

**Fig. 1** The three alternative models linking RAN to reading fluency

expected that the effects of speed of processing on reading fluency would be fully mediated by RAN and orthographic processing. Finally, we conducted our study in a relatively consistent orthography (Greek). This is important for two reasons: First, some studies have shown that similar to other consistent orthographies (i.e., Finnish, German), the effects of phonological awareness (a component of phonological processing) on reading fluency in Greek are time limited and become non-significant by Grade 2 (Georgiou et al., 2008; Papadopoulos et al., 2009). If this is true, then RAN's effects on reading fluency cannot be mediated by the effects of phonological processing. Second, all previous studies that contrasted rival hypotheses of the RAN-reading relationship (e.g., Cutting & Denckla, 2001; Georgiou et al., 2009; Holland et al., 2004; Poulsen et al., 2015) have been conducted in opaque orthographies (English and Danish). Therefore, a study in a relatively consistent orthography like Greek is much needed.

## Methods

### Participants

Participants were 208 Grade 4 Greek-speaking children (114 girls and 94 boys; mean age = 117.29 months, SD = 3.96 months) recruited on a voluntary basis from seven public schools (five urban and two rural; 12 classes) in Cyprus. Cyprus has a centralized educational system and children follow the same curriculum and use the same books across the country. Children start school at the age of six and graduate from elementary school at the age of 12. All children in our study were Caucasian (immigrant children were excluded from the study) and came from middle-to-upper-middle socioeconomic backgrounds (based on parents' education and occupation). General cognitive ability, measured with Block Design and Vocabulary (WISC III; Wechsler, 1992; Greek adaptation; Georgas, Paraskevopoulos, Bezevegis, & Giannitsas, 1997) was within average range (Mean standard score for Block Design = 10.44, *SD* = 2.42 and Mean standard score for Expressive Vocabulary = 8.89, SD = 2.77). School and parental consent was obtained prior to testing.

## Measures

### *General cognitive ability*

Block Design and Vocabulary from WISC-III (Wechsler, 1992) were used to assess general cognitive ability. In Block Design, children were asked to reproduce a series of two-color (red and white) designs within specified time limits. The task included 12 items and the maximum possible score was 69. In Vocabulary, children were asked to provide a definition for a given word. The task consisted of 30 items. For every given response, the experimenter assigned a 0 (incorrect response), 1 (partly correct), or 2 (complete definition). The maximum score was 60. Georgas et al. (1997) reported internal consistency coefficient to be .85 and .84 for Block Design and Vocabulary, respectively.

### *Phonological processing*

Phonological processing was assessed with three tasks: Phoneme Elision, Spoonerisms, and Phoneme Matching. We adapted Phoneme Elision from the Comprehensive Test of Phonological Processing battery (Wagner, Torgesen, & Rashotte, 1999) by adding six more items, to make a total of 29 items: five items required children to say a word without saying one of the syllables and 24 items required children to say a word without saying a designated sound in the word. The position of the phoneme to be deleted varied across those 24 items: eight items involved the initial phoneme (e.g., πόλη /'poli/ "town" without the /p/ is όλη /'oli/ "all"), eight items the final phoneme (e.g., ζώα /'zoa/ "animals" without the/a/is ζω /'zo/ "I live"), and eight items the medial phoneme (e.g., δίνω /'ðino/ "give" without the /n/ is δύο /'ðio/ "two"). Both accuracy and response times were registered using Direct RT software and were used as the participant's score. Testing was discontinued after three consecutive errors. Cronbach's alpha reliability coefficient for accuracy was .90. Test–retest reliability coefficient for response time using a subsample of our participants ($n = 23$) was .89.

Spoonerisms was adapted in Greek from Frederickson, Frith, and Reason (1997). In this task the children heard pairs of words with the instruction to repeat back the two words after having swapped the initial sound around (e.g., μήλο /milo/ - πάνω /pano/ should be repeated as πήλο /pilo/ - μάνω /mano/). The resulting pair always consisted of nonwords. The first six pairs of words consisted of two-syllable, highly-familiar words and the last six pairs consisted of three-syllable, highly-familiar words. All 24 words used in the task were selected to have clear syllable divisions and no consonant clusters in their onsets. The task was discontinued after four consecutive errors. The children were given one point for each correctly reversed pair of words. Cronbach's alpha reliability coefficient in our sample was .90.

Finally, Phoneme Matching was adapted in Greek from the work of McQuarrie and Parrila (2009) to assess phonological processing response time. A picture of an object (embedded in a red frame) was presented on the top half of a laptop screen along with three pictures of different objects (embedded in yellow frames) on the bottom half of the laptop screen. The children were asked to say as fast and as accurately as possible which one of the three pictures in yellow frames shared the same initial or final sound as the picture in the red frame. At the onset of the child's response the experimenter pressed keypad numbers 1, 2, or 3 that corresponded to the pictures in yellow frames. Prior to testing, all the pictures included in the task (targets and choices) were shown to the children who named them in order to ensure that they were all familiar with the names of the pictures. The first eight items required participants to match the initial sound and the last eight items required participants to match the final sound. Each session was preceded by three practice trials. Both the accuracy and the response time were recorded. Cronbach's alpha reliability coefficient for accuracy in our sample was .56 (likely due to low variability in the task). Test–retest reliability for response time using a subsample of our participants ($n = 23$) was .84.

### *Rapid automatized naming*

Two RAN tasks were administered: Digits and Objects. Children were asked to name as fast as possible five recurring digits (2, 4, 5, 7, 9; pronounced /ðio/, /tɛsɛra/, /pɛdɛ/, /ɛfta/, /ɛɲa/) or objects (ball, cat, chicken, boat, tree, apple; pronounced /bala/, /γata/, /kota/, /plio/, /ðedro/, /milo/) that were arranged semi-randomly in five rows of ten. Prior to testing, each participant was asked to name the digits or objects in a practice trial to ensure familiarity. The participant's score was the time to name all the stimuli in each task. Because only a few naming errors occurred (mean number of errors was $<1$), they were not considered further. Test–retest reliability for RAN Digits and Objects using a subsample of children in our study ($n = 23$) was .92 and .89, respectively.

### *Orthographic processing*

Three measures of orthographic processing were administered: Orthographic Choice, Spelling to Dictation, and Quick Spelling Test. Orthographic Choice was adapted from the work of Olson and colleagues (e.g., Olson, Forsberg, Wise, & Rack, 1994; Olson, Wise, Conners, Rack, & Fulker, 1989). Children viewed pairs of letter strings that sounded alike (e.g., σχολείο–σχολίο) and were asked to choose the one that spelled a word correctly by pressing the left or the right Ctrl button on a laptop computer. Thirty pairs of phonologically-similar letter strings were presented in random order. In half of the items the correct spelling was in the right and in the other half in the left. The score was the number of correctly chosen real words and the response time to select the correct response was noted. Cronbach's alpha reliability coefficient for accuracy in our sample was .75. Test–retest reliability for response time using a subsample of our participants ($n = 23$) was .81.

The Spelling to Dictation task was adopted from Nunes, Aidinis, and Bryant (2006) and required children to write on a form with numbered spaces a word that was dictated to them. The examiner first read the word aloud, then read a sentence in which the target word was embedded, and then repeated the target word. The task contained 64 Greek words that were derived from the children's Grade 1–6 language textbooks. The words were ordered in terms of difficulty (depending on the number of vowel irregularities in a word and the grade from which the word was taken) and the task was discontinued after 10 consecutive errors. A participant's score was the number of correctly spelled words. Cronbach's alpha reliability coefficient in our sample was .93.

Finally, Quick Spelling Test was adapted in Greek from Rueffer (2000) and required children to write on a piece of paper four-letter words (e.g., *πίσω*), pseudowords (e.g., *σώδε*), or nonwords with high (e.g., *ντμπ*) or low frequency bigram combinations (e.g., *φθργ*) that were presented in random order on a computer screen for 250 ms. The pseudowords were formed by either substituting one of the letters in a real word (e.g., κότα → λότα) or by switching two of the letters in a real word (e.g., δώσε → σώδε). The nonwords were formed by combining bigrams (e.g., ντ + μπ → ντμπ). In the high frequency nonword condition, the bigrams were selected from the Institute for Language and Speech Processing (ILSP) Psycholinguistic Resource (http://speech.ilsp.gr/iplr; see Protopapas, Tzakosta, Chalamandaris, & Tsiakoulis, 2012) to have at least 1000 occurrences in a body of approximately two million bigram combinations (mean frequency = 5116.70, *SD* = 6124.69). In the low frequency nonword condition, the bigrams were selected to have <500 occurrences (mean frequency = 303.70, SD = 133.84). There were 10 letter strings in each condition and the number of strings correctly written was scored (max = 40). The time limit to generate a response was 30 s per item. The children were also given three practice trials at the beginning of the test to make sure they understood the demands of the task. Cronbach's alpha reliability coefficient in our sample was .92.

### *Speed of processing*

Visual Matching and Symbol Search, adopted from Woodcock–Johnson Tests of Cognitive Ability (Woodcock & Johnson, 1989) and Wechsler Intelligence Scale for Children (WISC IV; Wechsler, 2003), respectively, were used to measure speed of processing. In Visual Matching, individuals were asked to circle identical numbers dispersed in 60 rows. Each one of the 60 rows in the task included six digits, two of which were identical (e.g., 8 9 5 2 9 7) and the children were asked to circle the identical digits in each row. The children completed four practice items prior to timed testing. The performance measure was the number of rows completed correctly within a 3-min time limit. Test–retest reliability coefficient using a subsample of our participants (*n* = 23) was .89. In Symbol Search, children were asked to scan a search group and indicate by circling Yes or No whether the target symbols that appeared to the left of the search group matched any of the symbols in the search group. The test consisted of 60 items and was discontinued after 2 min. Test–retest reliability coefficient using a subsample of our participants (*n* = 23) was .80.

### *Reading fluency*

Reading fluency was assessed with three measures: word reading efficiency, phonemic decoding efficiency, and text reading fluency. The word reading efficiency and the phonemic decoding efficiency tasks were adapted in Greek from the Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 1999). High frequency words were initially selected on the basis of frequency of occurrence within a corpus of approximately 36 million lexical units compiled from a wide selection of texts (mainly popular Greek books published after 1990 and daily newspapers). This corpus is available through the Institute for Language & Speech Processing (http://hnc.ilsp.gr/; Hatzigeorgiu et al., 2000). All 104 tokens in the word list were among the one thousand most frequent words in the corpus. In turn, pseudowords were developed by altering one or two letters in 63 words matched on mean frequency of occurrence with those included in the real word list, maintaining though some of the phonological and/or morphological characteristics of the original word (e.g., εδώ → εμώ).

In the word reading efficiency task, children were asked to read as fast as possible the list of 104 words, divided into four columns of 26 words each. In the phonemic decoding efficiency task, the children were asked to read as fast as possible a list of 63 nonwords divided into three columns of 21 words each. A short, 8-word/nonword practice list was presented before each subtest. In each task, children's score was the number of correct words/nonwords read within a 45-second time limit. Test–retest reliability for word reading efficiency and phonemic decoding efficiency with a subsample of children in our study (n = 23) was .92 and .94, respectively.

Finally, in text reading fluency, children were asked to read as fast and as accurately as possible a short passage (30 words). The passage was selected following the recommendation of a group of teachers from the participating schools so that it is within the reading ability of almost all Grade 4 children. The participant's score was the time to read the passage. Because only a few reading errors occurred (mean number of errors was $<1$), they were not considered further. Test–retest reliability using a subsample of our participants (*n* = 23) was .88.

## **Procedure**

Participants were assessed individually by the first author and two graduate students between April and May of the school year (8/9 months after the beginning of the school year). Testing was conducted in a quiet room at school during school hours and was divided into two sessions lasting roughly 40 min each. Session A consisted of Block Design, Vocabulary, reading fluency, spelling to dictation, and speed of processing measures. Session B was administered by the same tester on a laptop computer and consisted of RAN, phonological awareness, and orthographic processing measures. Half of the participants received first Session A, whereas the other half received first Session B. The order of the tasks within each session was fixed across participants.

## Response time data

Response time data were collected from three tasks, Phoneme Elision, Phoneme Matching, and Orthographic Choice. Direct RT (the experiment generation software used for the development and the administration of the computerized tasks) registered response times from target onset to response onset. In the case of the Phoneme Matching task, the experimenter pressed a button on a keypad at the onset of a child's response. The calculation of the mean response time in each task was completed in four steps. First, in order to reduce the possibility of confounding accuracy with response time (e.g., better performers having slower response times because of trying harder items), we selected items in each task in which at least 80 % of our sample answered correctly. In Phoneme Matching, this was not an issue as accuracy rates were high across all items. In Phoneme Elision and Orthographic Choice, we selected 17 and 13 items, respectively. Second, the response time data across the selected items were cleaned from the responses that were incorrect. Third, any responses below 200 ms or above 20,000 ms were removed. Fourth, responses that were 2SD below or above the individual's mean (after steps 2 and 3 were completed) were removed. As a result, 85 % of the scores in Phoneme Elision and 83 % of the scores in Orthographic Choice were used for the calculation of the mean response times in these tasks.

## Statistical analysis

To examine the pathways from RAN to reading fluency, we used structural equation modeling (SEM). Maximum likelihood estimation procedures were used to analyze the variance/covariance matrix of the latent factors using AMOS 21. The analysis was performed in three steps. First, we examined the fit of a model in which the effects of RAN were mediated by phonological processing and orthographic processing (see Model 1 of Fig. 1). This is similar to the best fitting model in Holland et al.'s (2004) study. Second, we tested the fit of a model in which we added a direct path from RAN to reading (see Model 2 of Fig. 1). The assumption was that if RAN's effects are mediated by phonological processing and/or orthographic processing, then adding a direct path from RAN to reading fluency will not change the $\chi^2$ value significantly. Finally, we tested the fit of a model in which we added paths from speed of processing to phonological processing, orthographic processing, and RAN (see Model 3 of Fig. 1). This is similar to the model tested in Cutting and Denckla's (2001) study. We hypothesized that by adding these new paths, the indirect effects of RAN on reading fluency would decrease because RAN will no longer be a significant predictor of phonological processing and orthographic processing.

We used a set of fit indexes to evaluate the fit of each model: $\chi^2$ value, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), and Root Mean Square of Approximation (RMSEA). Non-significant Chi square values and CFI/TLI values above .95 suggest model acceptance (Hu & Bentler, 1999). RMSEA values below or at .05 indicate a close fit (Browne & Cudeck, 1993). In addition, to examine if the change from one model to the next was significant, we compared the $\chi^2$ value of the previous model to the $\chi^2$ value of the new model. If the difference in $\chi^2$ values, given the difference in the degrees of freedom between the two models (*df* new model–*df* old model), was significant, then this would indicate that the addition of the new path(s) has improved the model.

Finally, to examine if the effects of RAN on reading were mediated by phonological processing and/or orthographic processing, we performed a multiple mediation analysis on Model 3. The idea behind this analysis is that the total effects of RAN on the outcome measure can be broken down into direct and indirect effects. The direct effect of RAN is its effect on reading fluency when the effects of the mediators have been controlled for. The indirect effect through a mediator is the product of (a) the effect of RAN on the mediator and (b) the direct effect of the mediator on the outcome measure. To examine if the indirect effects of RAN on reading through phonological processing and/or orthographic processing were significant, we used Preacher and Hayes' (2008) bootstrapping technique (with 5000 resamples) that allowed us to establish confidence intervals (CIs) for multiple indirect effects. The CI can be used as a test of whether an indirect effect differs from zero, that is, whether inclusion of the specific mediator significantly reduces the effect of RAN on reading fluency.

## Model specifications

In the model with the accuracy measures, we used Phoneme Elision accuracy and Spoonerisms to operationalize phonological processing, and Orthographic Choice accuracy and Spelling to Dictation to operationalize orthographic processing. In turn, in the model with speeded measures, we used Phoneme Elision response time and Phoneme Matching response time to operationalize phonological processing, and Orthographic Choice response time and Quick Spelling Test to operationalize orthographic processing. Reading fluency (Word Reading Efficiency, Phonemic Decoding Efficiency, and Text Reading Fluency), RAN (Digits and Objects), and speed of processing (Visual Matching and Symbol Search) were operationalized with the same measures in both models.

## Multivariate outliers

Before running any analyses we examined if our sample contained any multivariate outliers. The analysis was performed with AMOS 21. The result showed that the scores of 10 children were farthest from the centroid (Mahalanobis $d^2 > 20.520$,

$p_1$ value $<.05$). Subsequently, we deleted these cases and our final sample consisted of 198 children.

## Results

### Preliminary data analysis

Table 1 presents the descriptive statistics for the measures used in the study. There were no missing data and all the subsequent analyses were performed with a complete dataset. In addition, the distribution of the variables was within acceptable levels of normality (Tabachnick & Fidell, 2007). Table 2 presents the correlations between the measures. As expected based on previous studies in Greek (e.g., Georgiou et al., 2014; Papadopoulos et al., 2009; Protopapas et al., 2013), RAN correlated strongly with all reading fluency outcomes (*r*s ranged from −.49 to −.59). In addition, both RAN tasks correlated significantly with the rest of the processing skills (with the exception of Phoneme Elision response time).

**Table 1** Descriptive statistics of the measures used in our study

| | *M* | *SD* | Min | Max | Skewness | Kurtosis |
|---|---|---|---|---|---|---|
| Block Design | 10.34 | 2.58 | 4 | 17 | −.406 | .005 |
| Vocabulary | 8.89 | 2.77 | 2 | 16 | .360 | .200 |
| RAN-Digits[a] | 25.73 | 6.32 | 16.91 | 47.61 | 1.004 | .958 |
| RAN-Objects[a] | 40.81 | 11.45 | 25.29 | 78.60 | .681 | .668 |
| Phoneme Elision AC | 24.96 | 3.83 | 12 | 29 | −.800 | .686 |
| Phoneme Elision RT[b] | 249.50 | 68.45 | 200.13 | 656.00 | .965 | 1.435 |
| Spoonerisms | 5.22 | 3.93 | 0 | 12 | .228 | −.909 |
| Phoneme Matching AC | 15.16 | 1.00 | 11 | 16 | −1.162 | 1.196 |
| Phoneme Matching RT[b] | 5549.11 | 1455.85 | 3094.14 | 11001.57 | .767 | 1.060 |
| Orthographic Choice AC | 20.13 | 4.86 | 8 | 30 | −.061 | −.636 |
| Orthographic Choice RT[b] | 2973.84 | 1371.62 | 1281.14 | 11842.00 | .938 | 1.172 |
| Spelling to Dictation | 39.27 | 10.70 | 8 | 63 | −.440 | .191 |
| Quick Spelling Test | 25.43 | 5.67 | 10 | 39 | −.109 | −.033 |
| Visual Matching | 35.03 | 5.51 | 22 | 47 | −.250 | −.335 |
| Symbol Search | 19.95 | 4.31 | 10 | 30 | −.033 | −.118 |
| WRE | 58.24 | 11.83 | 28 | 93 | .068 | .387 |
| PDE | 35.64 | 7.62 | 19 | 59 | .366 | −.136 |
| Text Reading Speed[a] | 21.35 | 5.04 | 6.10 | 33.65 | −.430 | .742 |

*RAN* rapid automatized naming, *WRE* word reading efficiency, *PDE* phonemic decoding efficiency, *AC* accuracy, *RT* response time

[a] Measured in seconds

[b] Measured in milliseconds

**Table 2** Correlations between all the measures in the study

| | | 2. | 3. | 4. | 5. | 6. | 7. | 8. | 9. | 10. | 11. | 12. | 13. | 14. | 15. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | RAN-Digits | .61 | −.30 | −.23 | −.24 | .05 | −.07 | .26 | −.22 | .33 | −.26 | −.34 | −.57 | −.59 | −.57 |
| 2. | RAN-Objects | | −.38 | −.25 | −.20 | .01 | −.16 | .35 | −.27 | .30 | −.31 | −.29 | −.53 | −.49 | −.50 |
| 3. | VM | | | .46 | .34 | .00 | .25 | −.36 | .29 | −.29 | .35 | .46 | .48 | .45 | .44 |
| 4. | SS | | | | .14 | −.18 | .09 | −.30 | .23 | −.17 | .25 | .24 | .28 | .21 | .22 |
| 5. | Elision AC | | | | | −.33 | .48 | −.29 | .38 | −.20 | .51 | .38 | .40 | .40 | .40 |
| 6. | Elision RT | | | | | | −.17 | .30 | −.11 | −.07 | −.19 | −.15 | −.08 | −.03 | −.11 |
| 7. | Spoonerisms | | | | | | | −.29 | .34 | −.06 | .39 | .36 | .28 | .28 | .30 |
| 8. | PM_RT | | | | | | | | −.32 | .17 | −.38 | −.26 | −.34 | −.28 | −.27 |
| 9. | OC_AC | | | | | | | | | −.32 | .62 | .34 | .51 | .44 | .40 |
| 10. | OC_RT | | | | | | | | | | −.39 | −.41 | −.43 | −.35 | −.38 |
| 11. | Spelling | | | | | | | | | | | .45 | .58 | .55 | .54 |
| 12. | QST | | | | | | | | | | | | .51 | .50 | .51 |
| 13. | WRE | | | | | | | | | | | | | .79 | .78 |
| 14. | PDE | | | | | | | | | | | | | | .67 |
| 15. | TRF | | | | | | | | | | | | | | |

Correlations below .14 are non-significant, correlations between .14 and .18 are significant at the .05 level, and correlations higher than .18 are significant at the .01 level

*RAN* rapid automatized naming, *AC* accuracy, *RT* response time, *VM* visual matching, *SS* symbol search, *PM* phoneme matching, *OC* orthographic choice, *QST* Quick Spelling Test, *WRE* word reading efficiency, *PDE* phonemic decoding efficiency, *TRF* text reading fluency. N = 198

## Predicting reading fluency

Next, we compared the fit of three alternative models. First, we ran the analyses using the accuracy scores in phonological processing and orthographic processing. The results of this analysis are shown in the top panel of Table 3 and also in Fig. 2. Model 1, in which RAN predicted reading fluency through the effects of orthographic processing and phonological processing, fitted the data poorly. Adding a direct path from RAN to reading fluency (Model 2) improved the fit of the model significantly, $\Delta\chi^2(1) = 37.95$, $p < .001$, but the fit indexes continued to be below acceptable levels. Modification indices suggested that allowing the error variances in phonological processing and orthographic processing to covary would improve the model fit. After making this change, the model fitted the data very well, $\chi^2(21) = 27.22$, $p = .164$, TLI = .988, CFI = .993, RMSEA = .039, and accounted for 81.6 % of the variance in reading fluency. However, the addition of a direct path from RAN to reading fluency caused the effects of phonological processing to reading fluency to become non-significant. Finally, Model 3 that included the effects of speed of processing on RAN, phonological processing, and orthographic processing fitted the data very well, $\chi^2(35) = 44.37$, $p = .133$, TLI = .985, CFI = .991, RMSEA = .037, and accounted for 83.2 % of the variance in reading fluency. However, Model 3 was not significantly better than Model 2, $\Delta\chi^2(15) = 11.95$, ns. Adding paths from speed of processing to phonological processing and orthographic processing caused the effects of RAN on phonological processing and orthographic processing to become non-significant. In line with the results of the SEM analysis, mediation analysis showed that neither phonological processing nor orthographic processing mediated the effects of RAN on reading fluency (see Table 4).

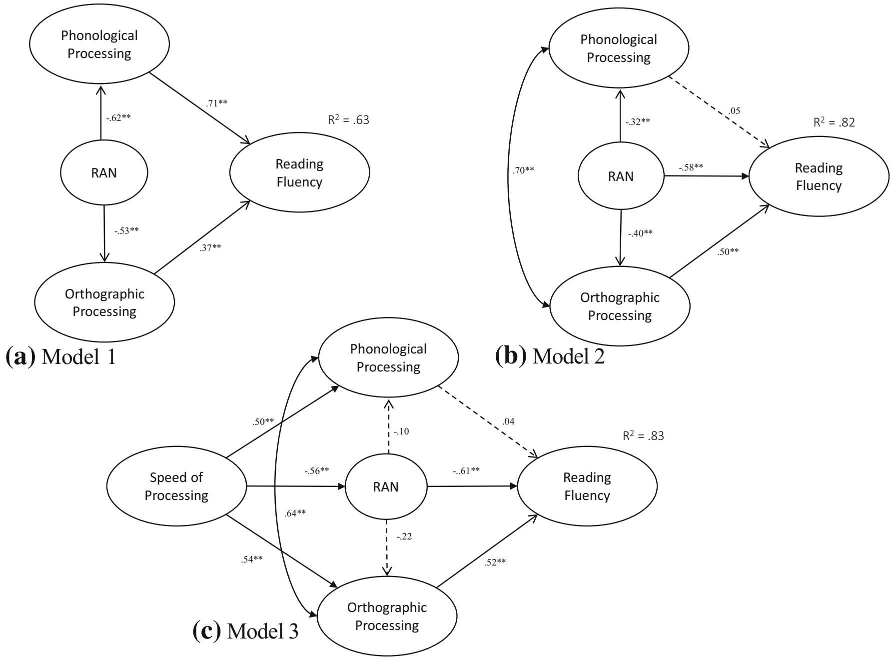
We then repeated the SEM analyses using speeded measures of phonological processing and orthographic processing. The results of this analysis are presented in the bottom panel of Table 3 and in Fig. 3. Similar to the results with accuracy measures, Model 1 did not fit the data well. In contrast, Model 2 fitted the data very well, $\chi^2(22) = 38.51$, $p = .017$, TLI = .955, CFI = .978, RMSEA = .062, and accounted for 78.1 % of the variance in reading fluency. Adding a direct path from RAN to reading fluency in Model 2 improved the model significantly compared to Model 1, $\Delta\chi^2(1) = 6.81$, $p < .01$. Finally, Model 3 fitted the data very well,

**Table 3** Fit indexes for each model and model comparisons

| | *df* | $\chi^2$ | TLI | CFI | RMSEA | $\Delta\chi^2$ |
|---|---|---|---|---|---|---|
| Model with accuracy measures of OP and PP | | | | | | |
| Model 1 | 23 | 117.64 | .836 | .895 | .145 | |
| Model 2 | 22 | 79.69 | .896 | .936 | .115 | 37.95*** |
| Model 3 | 36 | 67.74 | .952 | .969 | .067 | 11.95 |
| Model with speeded measures of OP and PP | | | | | | |
| Model 1 | 23 | 45.32 | .942 | .971 | .070 | |
| Model 2 | 22 | 38.51 | .955 | .978 | .062 | 6.81** |
| Model 3 | 36 | 49.22 | .972 | .985 | .043 | 10.71 |

*PP* phonological processing, *OP* orthographic processing

** $p < .01$; *** $p < .001$



**(a)** Model 1

**(b)** Model 2

**(c)** Model 3

**Fig. 2** The three alternative models of the relationship between RAN and reading fluency using accuracy measures to operationalize phonological processing and orthographic processing. $*p < .05$; $**p < .01$

**Table 4** Total, direct, and indirect effects of RAN on reading fluency

| Effects | With accuracy measures in OP and PP | | With speeded measures in OP and PP | |
|---|---|---|---|---|
| | Point estimate | 95 % CI | Point estimate | 95 % CI |
| Total effects of RAN | −.700 | | −.653 | |
| Direct effects of RAN | −.595 | | −.491 | |
| Total indirect effect | −.106 | | −.162 | |
| Indirect effect of PP | −.027 | −.044, .039 | −.028 | −.029, .064 |
| Indirect effect of OP | −.079 | −.185, .003 | −.135 | −.368, −.020 |

Indirect effects with confidence intervals that do not include zero are significant at the .05 level

*PP* phonological processing, *OP* orthographic processing, *CI* confidence interval

$\chi^2(36) = 49.22, p = .070$, TLI = .972, CFI = .985, RMSEA = .043, and accounted for 78.5 % of the variance in reading fluency. However, similar to the analyses with the accuracy scores, Model 3 was not significantly better than Model 2, $\Delta\chi^2(15) = 10.71$, ns. In this model, the addition of direct paths from speed of processing to orthographic processing and phonological processing did not eliminate RAN's effects on phonological processing and orthographic processing. Importantly, orthographic processing mediated 20.6 % (indirect effects of RAN

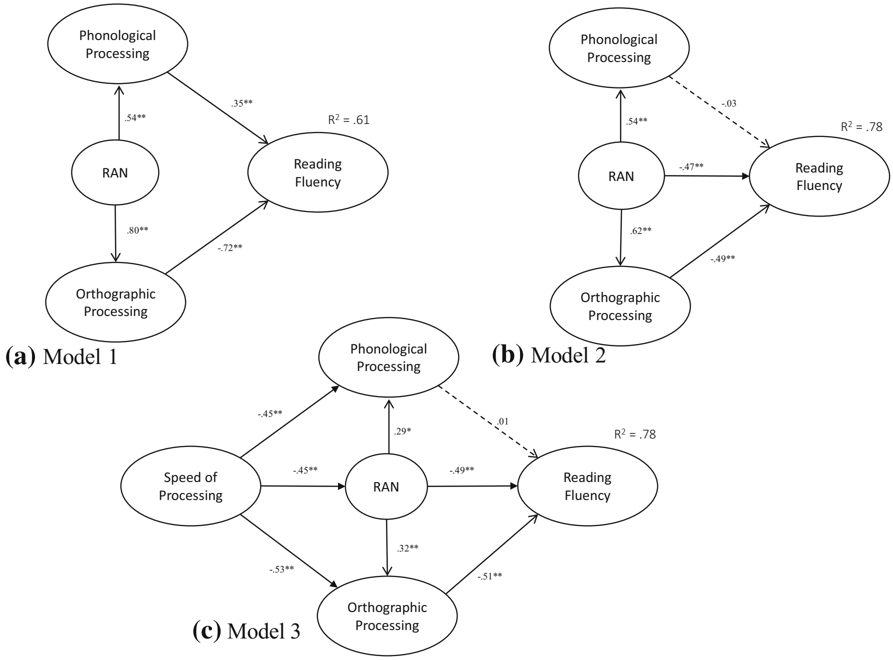


**Fig. 3** The three alternative models of the relationship between RAN and reading fluency using response time measures to operationalize phonological processing and orthographic processing. $^{*}p < .05$; $^{**}p < .01$

through orthographic processing divided by the total effects of RAN on reading fluency) of RAN's predictive variance in reading fluency (see Table 4).

## Discussion

The purpose of this study was to contrast three prominent theoretical explanations of the RAN-reading relationship. In contrast to the majority of previous studies examining the RAN-reading relationship (e.g., Moll et al., 2009; Pan et al., 2011; Poulsen et al., 2015; Savage et al., 2007), we included accuracy and speeded measures of orthographic processing and phonological processing, and we modeled alternative ways in which RAN could relate to reading fluency. Our findings showed that RAN was a unique predictor of reading fluency and its effects were partly mediated by orthographic processing (when operationalized with speeded measures). Although RAN also predicted phonological processing, phonological processing did not predict reading fluency. This was expected on the basis of the findings of previous studies in consistent orthographies showing that the effects of phonological awareness on reading are time limited (e.g., Babayiğit & Stainthorp, 2010; de Jong & van der Leij, 1999; Di Filippo et al., 2005; Georgiou et al., 2008; Landerl & Wimmer, 2008; Papadopoulos et al., 2009). Notice that our measures of phonological awareness were sensitive enough (there were no signs of ceiling effects or restriction of range; Phoneme Matching was administered to assess response time and not accuracy) and therefore lack of sensitivity cannot explain the non-significant effects of phonological awareness on reading fluency (see Caravolas, Vólin, & Hulme, 2005; Ziegler et al., 2010, for this argument).

Our findings further showed that the relationship between RAN and phonological or orthographic processing depends on whether speed of processing is included in the analyses and on the measures that are used to operationalize phonological and orthographic processing. More specifically, in Model 2 with accuracy tasks, RAN's effects on reading fluency were partly mediated by the effects of orthographic processing. However, adding speed of processing in Model 3 turned the significant path from RAN to orthographic processing to non-significant. A similar finding has been reported by Cutting and Denckla (2001). The addition of direct paths from speed of processing to RAN, orthographic processing, and phonological processing did not add much explanatory power to the model (see Table 3). Model 2 (either with accuracy or speeded measures) fitted the data very well. Therefore, we conclude that speed of processing is more important for the RAN-phonological/orthographic processing relationships than for the RAN-reading relationship.

However, part of RAN's predictive variance in reading fluency was explained by orthographic processing (see Table 4) when orthographic processing was operationalized with speeded measures. This provides partial support to Bowers and Wolf's (1993) theoretical account according to which RAN contributes to the development of orthographic knowledge. Recently, Stainthorp, Powell, and Stuart (2013) have also shown that slow RAN led to poorer spelling particularly of irregular words. Thus, we now have some evidence to support the argument that RAN contributes to the building of high-quality orthographic representations that can then be used to read fluently.

The partial mediation of RAN's effects on reading fluency by orthographic processing combined with Poulsen et al.'s (2015) finding that phonological awareness and letter knowledge partly mediate RAN's effects on reading fluency in Grade 1, suggest that different cognitive processes may mediate the RAN-reading fluency relationship at different points of reading development. A developmental account has also been proposed by Bowey et al. (2005) who argued that at the beginning of reading development both over-learned letter knowledge and phonological processing ability mediate the relationship between RAN and reading while at later levels of reading development it is primarily phonological processing ability that mediates the relationship between RAN and reading. Notice though that Bowey et al. (2005) worked with English-speaking children and used reading accuracy measures as outcome variables. We argue here that when reading fluency is concerned, there might be a gradual shift in the mediators of the RAN-reading relationship from phonological processing (early grades) to orthographic processing (later grades). Beginning readers rely on phonological recoding to read words accurately and fluently and therefore some efficiency in retrieving the sounds from long-term memory is necessary. That explains why in Poulsen et al.'s (2015) study phonological awareness was a significant mediator of the RAN-reading fluency relationship. In contrast, advanced readers rely on whole word recognition to achieve reading fluency. That explains why in our study with Grade 4 readers orthographic processing mediated the RAN-reading fluency relationship. However, orthographic processing is not the only reason, or likely even the main reason, why RAN is related to reading fluency since a large proportion of RAN's predictive variance in reading fluency (100 − [(.135/.653) * 100] = 79.4 %) remained unaccounted for.

We speculate that this unexplained variance is related to two unique features of RAN that allow it to predict reading fluency even after controlling for speed of processing, phonological processing, and orthographic processing. First, because RAN tasks require children to name stimuli that are presented serially, children can preview, access the phonological representations, and prepare the articulation of subsequent stimuli while articulating the current stimulus. Recently, eye-movement studies have shown that, compared to normal readers, children and adults with dyslexia process RAN stimuli one at a time and do not take as much advantage of parafoveal processing as good readers (Pan, Yan, Laubrock, Shu, & Kliegl, 2013; Silva et al., 2015; Yan, Pan, Laubrock, Kliegl, & Shu, 2013). In addition, several studies have shown that serial RAN predicts reading significantly better than discrete RAN (e.g., Bowers & Swanson, 1991; Georgiou, Parrila, Cui, & Papadopoulos, 2013; Logan, Schatschneider, & Wagner, 2011). Obviously, if discrete RAN—a measure of speed of lexical access—requires as much access to phonological representations as serial RAN, then we must look beyond the phonological processing account for an explanation of the RAN-reading relationship. Kail et al. (1999) were not aversive to this idea either by indicating that their findings "might simply mean that rapid sequential processing is common to the processing speed and naming tasks and to reading" (p. 312). This may also explain why RAN has been found to predict more strongly reading fluency than reading accuracy. In reading accuracy tasks, words are presented either one at a time or in small groups. In reading fluency tasks, all words are typically printed on the same page. This allows children to preview and process subsequent items while articulating the current item.

Second, some studies have shown that RAN is a stronger predictor of oral reading fluency than silent reading fluency (e.g., Georgiou et al., 2013; Papadopoulos, Georgiou, & Spanoudis, 2015; Speece, Ritchey, Silverman, Schatschneider, Walker, & Andrusik, 2010; van den Boer, van Bergen, & de Jong, 2014) and that articulation time accounts for most of the variance in RAN total time and reading fluency particularly as children grow older (e.g., Georgiou et al., 2009, 2014). Taken together, these findings suggest that articulation is a crucial element of the RAN-reading relationship.

In this study, we used both accuracy and speeded measures to operationalize orthographic processing and phonological processing. This did not affect whether RAN predicts significantly reading fluency, but affected its connection with orthographic processing and phonological processing. Even after adding the paths from speed of processing to orthographic processing and phonological processing (see Model 3 in Fig. 3), RAN continued to predict phonological processing and orthographic processing. Therefore, operationalizing orthographic processing and phonological processing with speeded measures strengthens their relationship with

RAN, but does not reduce RAN's effects on reading fluency. This suggests that shared method variance is not the reason why RAN predicts reading fluency.

Some limitations of the present study are worth mentioning. First, our study was conducted with Grade 4 children. Our decision was based on the fact that RAN (at least digit naming) becomes automatic by that time (Cronin & Carver, 1998) and therefore its relationship with reading should be more stable. However, to the extent RAN's relationship with reading changes across time (e.g., van den Bos et al., 2002), by assessing these constructs in one grade we may have missed the opportunity to capture developmental changes in the RAN-reading relationship. The use of older children may also explain why phonological awareness was not a significant predictor of reading fluency. Some researchers have argued that the contribution of phonological awareness in orthographically consistent languages is time limited and fades away once children master decoding (e.g., Georgiou et al., 2008; Landerl & Wimmer, 2008). This may explain why in Ziegler et al.'s (2010) study with Grade 2 children phonological awareness was still a unique predictor of reading accuracy and speed in Finnish and Hungarian (both languages are orthographically consistent). Second, our study was conducted in a relatively consistent orthography (Greek). This may have reduced the effects of phonological awareness on reading fluency and, subsequently, the generalizability of our findings to opaque orthographies (i.e., English, French) in which phonological awareness has been found to predict reading fluency even in upper elementary grades (e.g., Kibby, Lee, Dyer, 2014; Torgesen et al., 1997). However, we have no reasons to believe that our selection of language had any impact on the strength of the RAN-reading fluency relationship. Recently, Georgiou, Aro, Liao, and Parrila (2015) have shown that the correlations between RAN and word reading fluency in Chinese, English, Greek, and Finnish were very similar (ranged from −.49 to −.54). Third, in Phoneme Matching the experimenter would press a button on a keypad to register the child's response. Although this may not be the optimal way to obtain response time data, when we tried alternative approaches as part of a pilot study (e.g., voice-onset key or children pressing a button on a keypad), the response times were erroneous (e.g., children were naming each picture before giving their answer, which was triggering the voice-onset key). To further examine if our results were impacted by Phoneme Matching being recorded by the tester, we reran the analyses excluding Phoneme Matching. The results remained the same and for this reason we decided to leave Phoneme Matching in the model. Finally, we only administered measures that tap lexical orthographic processing. Consequently, we do not know if similar results would be obtained with sub-lexical orthographic processing measures.

To conclude, our findings add to those of previous studies examining the nature of the RAN-reading relationship by showing that only part of RAN's predictive variance in reading fluency is mediated by orthographic processing and that operationalizing phonological processing or orthographic processing with speeded measures impacts only their association with RAN, but not RAN's effect on reading fluency. Taken together, these findings suggest that what is unique to RAN is more important in terms of predicting reading fluency than what it shares with speed of processing, orthographic processing, and phonological processing.

## References

Araújo, S., Reis, A., Petersson, K. M., & Faísca, M. (2015). Rapid automatized naming and reading performance: A meta-analysis. *Journal of Educational Psychology, 107*, 868–883.

Babayiğit, S., & Stainthorp, R. (2010). Component processes of early reading, spelling, and narrative writing skills in Turkish. *Reading and Writing, 23*, 539–568.

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

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

Bowers, P. G., & Swanson, L. B. (1991). Naming speed deficits in reading disability. *Journal of Experimental Child Psychology, 51*, 195–219.

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

Bowey, J. A., McGuigan, M., & Ruschena, A. (2005). On the association between serial naming speed for letters and digits and word-reading skill: Towards a developmental account. *Journal of Research in Reading, 28*, 400–422.

Browne, M. W., & Cudeck, R. (1993). Alternative ways in assessing model fit. In K. Bollen & J. S. Long (Eds.), *Testing structural equation models* (pp. 136–162). Newbury Park, CA: Sage.

Caravolas, M., Vólin, J., & Hulme, C. (2005). Phoneme awareness is a key component of alphabetic literacy skills in consistent and inconsistent orthographies: Evidence from Czech and English children. *Journal of Experimental Child Psychology, 92*, 107–139.

Compton, D. L. (2003). Modeling the relationship between growth in rapid naming speed and growth in decoding skill in first-grade children. *Journal of Educational Psychology, 95*, 225–239.

Compton, D. L., DeFries, J. C., & Olson, R. K. (2001). Are RAN and phonological deficits additive in children with reading disabilities? *Dyslexia, 7*, 125–149.

Conrad, N. J., & Levy, B. A. (2007). Letter processing and the formation of memory representations in children with naming speed deficits. *Reading and Writing, 20*, 201–223.

Cronin, V., & Carver, P. (1998). Phonological sensitivity, rapid naming, and beginning reading. *Applied Psycholinguistics, 19*, 447–461.

Cutting, L. E., & Denckla, M. B. (2001). The relationship of rapid serial naming and word reading in normally developing readers: An exploratory model. *Reading and Writing, 14*, 673–705.

de Jong, P. F. (2011). What discrete and serial rapid automatized naming can reveal about reading. *Scientific Studies of Reading, 15*, 314–337.

de Jong, P. F., & van der Leij, A. (1999). Specific contributions of phonological abilities to early reading acquisition: Results from a Dutch latent variable longitudinal study. *Journal of Educational Psychology, 91*, 450–476.

Denckla, M. B., & Rudel, R. G. (1974). "Rapid automatized naming" of pictured objects, colors, letters, and numbers by normal children. *Cortex, 10*, 186–202.

Di Filippo, G., Brizzolara, D., Chilosi, A., De Luca, M., Judica, A., Pecini, C., et al. (2005). Rapid naming, not cancellation speed or articulation rate, predicts reading in an orthographically regular language (Italian). *Child Neuropsychology, 11*, 349–361.

Frederickson, N., Frith, U., & Reason, R. (1997). *Phonological Assessment Battery: Standardisation edition*. Windsor: NFER-Nelson.

Georgas, D. D., Paraskevopoulos, I. N., Bezevegis, I. G., & Giannitsas, N. D. (1997). *Ελληνικό WISC-III: Wechsler κλίμακες νοημοσύνης για παιδιά [Greek WISC-III: Wechsler intelligence scale for children]*. Athens: Ellinika Grammata.

Georgiou, G., Aro, M., Liao, C.-H., & Parrila, R. (2015). The contribution of RAN pause time and articulation time to reading across languages: Evidence from a more representative sample of children. *Scientific Studies of Reading, 19*, 135–144.

Georgiou, G., Papadopoulos, T. C., & Kaizer, E. L. (2014). Different RAN components predict reading at different points in time. *Reading and Writing, 27*, 1379–1394.

Georgiou, G., & Parrila, R. (2013). Rapid naming and reading: A review. In H. L. Swanson, K. Harris, & S. Graham (Eds.), *Handbook of learning disabilities* (pp. 169–185). New York: The Guilford Press.

Georgiou, G., Parrila, R., Cui, Y., & Papadopoulos, T. C. (2013). Why is rapid automatized naming related to reading? *Journal of Experimental Child Psychology, 115*, 218–225.

Georgiou, G., Parrila, R., & Kirby, J. (2009). RAN components and reading development from Grade 3 to Grade 5: What underlies their relationship? *Scientific Studies of Reading, 13*, 508–534.

Georgiou, G., Parrila, R., & Papadopoulos, T. C. (2008). Predictors of word decoding and reading fluency in English and Greek: A cross-linguistic comparison. *Journal of Educational Psychology, 100*, 566–580.

Hatzigeorgiu, N., Gavrilidou, M., Piperidis, S., Carayannis, G., Papakostopoulou, A., Spiliotopoulou, A., et al. (2000). Design and implementation of the online ILSP corpus. In *Proceedings of the 2nd international conference of language resources and evaluation (LREC)* (Vol. 3, pp. 1737–1740). Athens, Greece.

Holland, J., McIntosh, D., & Huffman, L. (2004). The role of phonological awareness, rapid automatized naming, and orthographic processing in word reading. *Journal of Psychoeducational Assessment, 22*, 233–260.

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indices in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling, 6*, 1–55.

Kail, R., & Hall, L. K. (1994). Speed of processing, naming speed, and reading. *Developmental Psychology, 30*, 949–954.

Kail, R., Hall, L. K., & Caskey, B. J. (1999). Processing speed, exposure to print, and naming speed. *Applied Psycholinguistics, 20*, 303–314.

Kibby, M. Y., Lee, S. E., & Dyer, S. M. (2014). Reading performance is predicted by more than phonological processing. *Frontiers in Psychology, 5*, 960. doi:10.3389/fpsyg.2014.00960.

Kirby, R., Georgiou, G., Martinussen, R., & Parrila, R. (2010). Naming speed and reading: A review of the empirical and theoretical literature. *Reading Research Quarterly, 45*, 341–362.

Kirby, J., Parrila, R., & Pfeiffer, S. (2003). Naming speed and phonological awareness as predictors of reading development. *Journal of Educational Psychology, 95*, 453–464.

Landerl, K., & Wimmer, H. (2008). Development of word reading fluency and spelling in a consistent orthography: An 8-year follow-up. *Journal of Educational Psychology, 100*, 150–161.

Lervåg, A., Bråten, I., & Hulme, C. (2009). The cognitive and linguistic foundations of early reading development: A Norwegian latent variable longitudinal study. *Developmental Psychology, 45*, 764–781.

Lervåg, A., & Hulme, C. (2009). Rapid automatized naming (RAN) taps a mechanism that places constraints on the development of early reading fluency. *Psychological Science, 20*, 1040–1048.

Li, H., Shu, H., McBride-Chang, C., Liu, H., & Peng, H. (2012). Chinese children's character recognition: Visuo-orthographic, phonological processing and morphological skills. *Journal of Research in Reading, 35*, 287–307.

Logan, J. A. R., Schatschneider, C., & Wagner, R. (2011). Rapid serial naming and reading ability: The role of lexical access. *Reading and Writing, 24*, 1–25.

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

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

McBride-Chang, C., Shu, H., Zhou, A., Wat, C. P., & Wagner, R. K. (2003). Morphological awareness uniquely predicts young children's Chinese character recognition. *Journal of Educational Psychology, 95*, 743–751.

McQuarrie, L., & Parrila, R. (2009). Phonological representations in deaf children: Rethinking the "functional equivalence" hypothesis. *Journal of Deaf Studies and Deaf Education, 14*, 137–154.

Moll, K., Fussenegger, B., Willburger, E., & Landerl, K. (2009). RAN is not a measure of orthographic processing: Evidence from the asymmetric German orthography. *Scientific Studies of Reading, 13*, 1–25.

Nunes, T., Aidinis, A., & Bryant, P. (2006). The acquisition of written morphology in Greek. In M. Joshi & P. G. Aaron (Eds.), *Handbook of orthography and literacy* (pp. 201–218). Mahwah, NJ: Erlbaum.

Olson, R. K., Forsberg, H., Wise, B., & Rack, J. (1994). Measurement of word recognition, orthographic, and phonological skills. In G. R. Lyon (Ed.), *Frames of reference for the assessment of learning disabilities* (pp. 243–277). Baltimore, MD: Brookes.

Olson, R. K., Wise, B., Conners, F., Rack, J., & Fulker, D. (1989). Specific deficits in component reading and language skills: Genetic and environmental influences. *Journal of Learning Disabilities, 22*, 339–348.

Pan, J., McBride-Chang, C., Shu, H., Liu, H., Zhang, Y., & Li, H. (2011). What is in the naming? A 5-year longitudinal study of early rapid naming and phonological sensitivity in relation to subsequent reading skills in both native Chinese and English as a second language. *Journal of Educational Psychology, 103*, 897–908.

Pan, J., Yan, M., Laubrock, J., Shu, H., & Kliegl, R. (2013). Eye–voice span during rapid automatized naming of digits and dice in Chinese normal and dyslexic children. *Developmental Science, 16*, 967–979.

Papadopoulos, T. C., Georgiou, G., & Kendeou, P. (2009). Investigating the double-deficit hypothesis in Greek: Findings from a longitudinal study. *Journal of Learning Disabilities, 42*, 528–547.

Papadopoulos, T. C., Georgiou, G., & Spanoudis, G. (2015, September). *Demystifying the RAN-reading relationship: Beyond unitary explanations*. Paper presented at the 17th European Conference on Developmental Psychology in Braga, Portugal.

Parrila, R., Kirby, J. R., & McQuarrie, L. (2004). Articulation rate, naming speed, verbal short-term memory, and phonological awareness: Longitudinal predictors of early reading development. *Scientific Studies of Reading, 8*, 3–26.

Poulsen, M., Juul, H., & Elbro, C. (2015). Multiple mediation analysis of the relationship between rapid naming and reading. *Journal of Research in Reading, 38*, 124–140.

Powell, D., Stainthorp, R., Stuart, M., Garwood, H., & Quinlan, P. (2007). An experimental comparison between rival theories of rapid automatized naming performance and its relationship to reading. *Journal of Experimental Child Psychology, 98*, 46–68.

Preacher, K. J., & Hayes, A. F. (2008). Contemporary approaches to assessing mediation in communication research. In A. F. Hayes, M. D. Slater, & L. B. Snyder (Eds.), *Advanced data analysis methods for communication research* (pp. 13–54). Los Angeles, CA: Sage.

Protopapas, A., Altani, A., & Georgiou, G. (2013). Development of serial processing in reading and rapid naming. *Journal of Experimental Child Psychology, 116*, 914–929.

Protopapas, A., Tzakosta, M., Chalamandaris, A., & Tsiakoulis, P. (2012). IPLR: An online resource for Greek word-level and sub-lexical information. *Language Resources and Evaluation, 46*, 449–459.

Rothe, S., Schulte-Körne, G., & Ise, E. (2014). Does sensitivity to orthographic regularities influence reading and spelling acquisition? A 1-year prospective study. *Reading and Writing, 27*, 1141–1161.

Rueffer, A. (2000). *An examination of the factors underlying the development of skilled reading.* Unpublished master's thesis, University of Waterloo, Waterloo, Ontario, Canada.

Savage, R., Pillay, V., & Melidona, S. (2007). Deconstructing rapid automatized naming: Component processes and the prediction of reading difficulties. *Learning and Individual Differences, 17*, 129–146.

Silva, S., Faísca, L., Araújo, S., Casaca, L., Carvalho, L., Petersson, K. M., et al. (2015). Too little or too much? Parafoveal preview benefits and parafoveal load costs in dyslexic adults. *Annals of Dyslexia,*. doi:10.1007/s11881-015-0113-z.

Song, S., Georgiou, G., Su, M.-M., & Shu, H. (2016). How well do phonological awareness and rapid automatized naming correlate with reading accuracy and fluency in Chinese? A meta-analysis. *Scientific Studies of Reading, 20*, 99–123.

Speece, D. L., Ritchey, K. D., Silverman, R., Schatschneider, C., Walker, C. Y., & Andrusik, K. N. (2010). Identifying children in middle childhood who are at risk for reading problems. *School Psychology Review, 39*, 258–276.

Stainthorp, R., Powell, D., & Stuart, M. (2013). The relationship between rapid naming and word spelling in English. *Journal of Research in Reading, 36*, 371–388.

Stanovich, K. E., & West, R. F. (1989). Exposure to print and orthographic processing. *Reading Research Quarterly, 24*, 402–433.

Steacy, L. M., Kirby, J. R., Parrila, R., & Compton, D. (2014). Classification of double deficit groups across time: An analysis of group stability from kindergarten to second grade. *Scientific Studies of Reading, 18*, 255–273.

Sunseth, K., & Bowers, P. G. (2002). Rapid naming and phonemic awareness: Contributions to reading, spelling, and orthographic knowledge. *Scientific Studies of Reading, 6*, 401–429.

Tabachnick, B. G., & Fidell, L. S. (2007). *Using multivariate statistics*. Boston: Allyn and Bacon.

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

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). *Test of word reading efficiency*. Austin, TX: PRO-ED.

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

Torppa, M., Georgiou, G., Salmi, P., Eklund, K., & Lyytinen, H. (2012). Examining the double-deficit hypothesis in an orthographically consistent language: The effect of familial risk for dyslexia. *Scientific Studies of Reading, 16*, 287–315.

van den Boer, M., & de Jong, P. F. (2015). Parallel and serial reading processes in children's word and nonword reading. *Journal of Educational Psychology, 107*, 141–151.

van den Boer, M., Georgiou, G., & de Jong, P. F. (2016). The naming of short words is (almost) the same as the naming of alphanumeric symbols. *Journal of Experimental Child Psychology, 144*, 152–165.

van den Boer, M., van Bergen, E., & de Jong, P. F. (2014). Underlying skills of oral and silent reading. *Journal of Experimental Child Psychology, 128*, 138–151.

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

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

Wagner, R., Torgesen, J., & Rashotte, C. A. (1999). *CTOPP: Comprehensive test of phonological processing*. Austin, TX: PRO-ED.

Wechsler, D. (1992). *Wechsler intelligence scale for children* (3rd ed.). San Antonio: Psychological Corporation.

Wechsler, D. (2003). *Wechsler intelligence scale for children* (4th ed.). San Antonio: The Psychological Corporation.

Wijayathilake, M. A. D. K., & Parrila, R. (2014). Predictors of word reading skills in good and struggling readers in Sinhala. *Writing Systems Research, 6*, 120–131.

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

Woodcock, R. W., & Johnson, M. B. (1989). *Woodcock–Johnson tests of cognitive ability—Revised*. Chicago: Riverside Publishing.

Yan, M., Pan, J., Laubrock, L., Kliegl, R., & Shu, H. (2013). Parafoveal processing efficiency in rapid automatized naming: A comparison between Chinese normal and dyslexic children. *Journal of Experimental Child Psychology, 115*, 579–589.

Ziegler, J. C., Bertrand, D., Tóth, D., Csépe, V., Reis, A., Faísca, L., & Blomert, L. (2010). Orthographic depth and its impact on universal predictors of reading: A cross-language investigation. *Psychological Science, 21*, 551–559.