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"Zooming in" on orthographic knowledge to clarify the relationship between rapid automatised naming (RAN) and word reading

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ABSTRACT

Studies of relationships between orthographic knowledge (OK), rapid automatised naming (RAN) and reading have yielded mixed results due to inconsistency in measures used, the definition of OK and group characteristics. We comprehensively examined OK (MGR; mental graphemic representations and GOK; generic orthographic knowledge, accuracy/efficiency); alpha/non-alphanumeric RAN (ANRAN/NANRAN) and word reading (accuracy/efficiency) with control for nonverbal reasoning and phonological awareness. In 169 Grade 6 children, ANRAN uniquely influenced MGR (accuracy/efficiency), with NANRAN influencing only GOK efficiency. ANRAN/NANRAN influenced word reading efficiency directly/indirectly through MGR efficiency. We observed similar direct/indirect effects on word reading accuracy from ANRAN and MGR accuracy but only indirect influence from NANRAN through MGR accuracy. Further analyses indicated that RAN and OK relate reciprocally when influencing word reading. Our inference that both RAN and OK types, especially ANRAN and MGR, influence word reading by interactively and differentially accessing the same neural substrata as reading, should inform future research and intervention.

1. Introduction

Rapid automatised naming (RAN) is a well-known task that measures serial naming speed for highly familiar visually presented stimuli (Denckla & Rudel, 1976), and is commonly subdivided into alphanumeric RAN (ANRAN: naming digits or letters) and non-alphanumeric RAN (NANRAN: naming colours or objects). Slower RAN is related to poorer reading fluency and efficiency (fast and accurate word reading; e.g., Denckla & Rudel, 1976; Norton & Wolf, 2012; Wolf & Bowers, 1999). This is true even when controlling for phonological awareness (Gillon, 2004), morphological awareness (e.g., Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009), IQ (e.g., Lervåg, Bråten, & Hulme, 2009), speed of processing (e.g., Cutting & Denckla, 2001), letter knowledge (e.g., Kirby, Parrila, & Pfeiffer, 2003), short-term memory (e.g., Parrila, Kirby, & McQuarrie, 2004), and orthographic knowledge (OK). According to Apel (2011), OK refers to information held in memory that guides how we represent spoken language in written form. This includes information that is both lexical (i.e., word-specific representations) and sublexical (i.e., orthographic information applied within and across words).

However, despite decades of research there is still little clarity about the precise nature of the RAN-reading relationship. As will be highlighted below, we suggest that this likely stems from methodological issues including high levels of sample heterogeneity (age, language, diagnostic status of participants), inconsistent operational definitions, and uncertain task validity. We then go on to address these concerns, while focusing on two key empirical issues: 1) the role of the two different types of OK in the RAN-word reading relationship, and 2) the unique contribution of each RAN type to word reading.

1.1. The role of orthographic knowledge in the RAN-reading relationship

Over the last three decades, the development and use of OK have emerged as central issues in literacy acquisition (e.g., Araújo, Faísca, Bramão, Petersson, & Reis, 2014; Bowers & Wolf, 1993; Georgiou, Aro, Liao, & Parrila, 2016; Georgiou, Parrila, Kirby, & Stephenson, 2008; Georgiou, Parrila, & Papadopoulos, 2016; Hagiliassis, Pratt, & Johnston, 2006; Roman et al., 2009). Early work by Bowers and colleagues suggested that RAN relates to word reading because it reflects the efficiency of access to, and the quality of orthographic representations (Bowers, Sunseth, & Golden, 1999; Bowers & Wolf, 1993; Sunseth & Bowers, 2002). They reasoned that if children's speed of visual letter identification (as indexed by naming speed) is too slow to permit contemporaneous activation and representation of letter sequences

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while reading, this could blunt sensitivity to orthographic patterns and thereby undermine the development of OK. Along similar lines, but in more general terms, Manis, Seidenberg, and Doi (1999) proposed that RAN might reflect the capacity to learn the arbitrary sound-symbol pairings that underpin OK. More recently, Norton and Wolf (2012), within their conceptualisation of RAN as "a microcosm of the processes involved in reading" (p. 427), have suggested that RAN is indexing the automaticity of these auditory-visual associations at the neuronal level.

Despite this robust theoretical foundation, however, empirical work on conceptualizing and effectively measuring OK and quantifying and describing its relationship to RAN and reading appears to have made relatively slow progress. Results have been decidedly mixed with numerous significant correlations between OK and RAN (Compton, Defries, & Olson, 2001; Georgiou, Parrila, & Kirby, 2009; Hagiliassis et al., 2006; Loveall, Channell, Phillips, & Conners, 2013; Powell, Stainthorp, & Stuart, 2014) offset by instances of failure to obtain such a relationship (Bowey & Miller, 2007; Moll, Fussenegger, Willburger, & Landerl, 2009; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997).

An examination of this existing literature suggests a number of possible issues that could be contributing to the heterogeneous outcomes of existing studies. One issue seems to be an evolving view of the nature of OK. As noted by Apel (2011), some researchers have narrowly defined OK as the stored mental representations of written words saved in long-term memory (e.g., Bowers & Wolf, 1993; Ehri, 1980; Ehri & Wilce, 1982; Masterson, Apel, & Wasowicz, 2006; Moll & Landerl, 2009; Stanovich & West, 1989; Wolter & Apel, 2010). By comparison, an emerging consensus suggests that OK consists not only of this word-specific knowledge (variously referred to as lexical OK or mental graphemic representations [MGR]; Deacon, Benere, & Castles, 2012; Apel, 2011), but also "generic OK" (GOK) consisting of sublexical knowledge about graphemic patterns. This knowledge is not word-specific but generalised across words (e.g., which letters are allowed to follow other letters, legal letter combinations, and the frequency of letter positions [Conrad, Harris, & Williams, 2013; Vellutino, Scanlon, & Tanzman, 1994]). As a result, Apel (2011) argues, some studies have ended up examining only a portion of OK (i.e., MGR), while leaving the contribution of GOK untested.

A second issue concerns the age-appropriateness and validity of tasks used to assess GOK and MGR. Some of the most common tasks used to assess GOK are the *wordlikeness*, *orthographic awareness* and *letter string tasks* (e.g., Conrad et al., 2013; Siegel, Geva, & Share, 1992), which require participants to choose which nonword or letter string from a pair looks more like a real word. However, Powell et al. (2014) reported that most of their Grade 5 and 6 participants were performing at ceiling levels on a *wordlikeness* task (adapted from Cassar & Treiman, 1997) and similar issues would almost certainly arise with other variants using homophones (Conrad et al., 2013) or strings containing digits (Levy, Gong, Hessels, Evans, & Jared, 2006; Ouellette & Sénéchal, 2008). An additional concern is that current GOK tasks seem to be confounded with phonological skill (Conrad et al., 2013; Hagiliassis et al., 2006).

Close examination of common MGR tasks suggests that they may also have significant confounds. For example, Roman et al. (2009; also Loveall et al., 2013, Powell et al., 2014) used an *orthographic choice* measure (Olson, Forsberg, Wise, & Rack, 1994), in which participants viewed a real word and its pseudohomophone, and made a speeded decision about which looked more like a real word. Our examination of the word pairs used in this task shows that GOK could also influence performance (see also Castles & Nation, 2006). For example, in the pair "take-taik" the spelling in the correct word 'take' has a much higher probability of representing long /a/ + /k/ in the final position of a single syllable word in English (i.e., "ake") than the spelling in the foil (i.e., "aik"). Other MGR tasks may be similarly confounded by semantic knowledge (homonym task; Hagiliassis et al., 2006), phonological knowledge (irregular word reading task; Castles & Coltheart, 1993) or visual search strategy (word chain task; Georgiou et al., 2009).

A final issue is that existing studies have looked primarily at relationships with OK performance accuracy, while typically ignoring efficiency (defined here as accuracy over latency). This is potentially important because recent evidence suggests a stronger link between RAN and OK efficiency than with OK accuracy (e.g., O'Brien, Wolf, Miller, Lovett, & Morris, 2011), especially in older children, who are expected to have advanced literacy skills. These studies suggest that there is substantial value in assessing the accuracy and efficiency of both types of OK in order to better understand their relationships with RAN and word reading.

One further issue may contribute to the current confusion around the nature of the relationships between RAN, OK and reading: It is not yet clear whether ANRAN and NANRAN relate differently to MGR and/or GOK. Most of the current literature has used ANRAN which has been suggested "to better capture underlying processing abilities that are important for reading and therefore should be preferred over non-alphanumeric ones whenever a prediction of the reading ability is of interest" (Araújo, Reis, Petersson, & Faísca, 2015; p. 879). However, recent research strongly suggests that NANRAN may require additional processes compared to ANRAN (Donker, Kroesbergen, Slot, Van Viersen, & De Bree, 2016).

Indeed, the only study we are aware of that examined both types of RAN and OK together found ANRAN was related more strongly to MGR while NANRAN was more strongly related to GOK in Grade 2–3 children (Loveall et al., 2013). Although intriguing, this study still leaves questions unanswered, because the authors did not measure efficiency in either OK task and they used only younger readers. Research suggesting that older children progress from a greater reliance on phonological skills to a greater reliance on orthographic skills (Ehri, 2005; Martin, Pratt, & Fraser, 2000; Share, 2008) might predict that relationships between the two OK and RAN types and the role of efficiency would change as children's literacy develops.

1.2. The present study

Taken together, the findings reviewed above suggest that differentiating between MGR-GOK, ANRAN-NANRAN and word reading accuracy/efficiency may clarify our understanding of the relationships between RAN, OK and word reading. Although individual studies have examined various elements of these relationships multiple times in the past, to our knowledge, no one study has assessed both types of RAN, both types of OK (accuracy and efficiency), and word reading accuracy and efficiency in a single sample using measures of each construct that were not potentially flawed by confounds or ceiling effects. Thus, the principal aim of this study is to explore the relative amounts of variance that the two RAN types contribute to the accuracy and efficiency of each type of OK.

An additional aim of the present study is to clarify how RAN is related to word reading. The extant research largely appears to conceptualize this relationship as being indirect, with effects being mediated through OK. The present work takes the same general approach and theorises that at least part of RAN's influence on reading is related to OK. However, influential workers in this area (e.g., Georgiou & Parrila, 2013; Norton & Wolf, 2012) concur that in addition to its indirect influence on reading, RAN also likely taps into some of the underlying processing factors that impact directly on reading. As it is now well accepted that the human brain is not biologically predisposed to reading (e.g., Wolf, 2007), there is a strong inference that this underlying processing must involve pre-existing neural faculties recruited for literacy development (e.g., circuits involved in object identification and naming co-opted for visual word recognition in reading; Lervåg & Hulme, 2009). With this in mind, Norton and Wolf (2012) have proposed that RAN is broadly capturing the automaticity of functioning in the neurological circuitry that underpins reading in literate individuals. Although work on the precise brain areas and functions involved is still very much in progress, this suggests that RAN might be expected to

Table 1
Intercorrelations of variables and descriptive statistics.

Measure	Age	WID	SWE	ANRAN	NANRAN	PA	NVR	MGRa	MGRl	MGRef	GOKa	GOKl	GOKef
Age	1												
WID	0.00	1											
SWE	0.05	0.56‡	1										
ANRAN	−0.01	0.33‡	0.66‡	1									
NANRAN	0.01	0.19†	0.52‡	0.61‡	1								
PA	0.03	0.56‡	0.34‡	0.09	0.10	1							
NVR	−0.08	0.33‡	0.20‡	0.04	0.14	0.34‡	1						
MGRa	0.08	0.65‡	0.47‡	0.29‡	0.22‡	0.36‡	0.30‡	1					
MGRl	0.04	−0.27‡	−0.38‡	−0.26‡	−0.26‡	−0.14	−0.08	−0.27‡	1				
MGRef	0.02	0.49‡	0.52‡	0.35‡	0.30‡	0.23‡	0.18†	0.60‡	−0.89‡	1			
GOKa	0.02	0.28‡	0.19†	0.08	0.08	0.29‡	0.28‡	0.39‡	0.08	0.07	1		
GOKl	−0.01	0.04	−0.14	−0.08	−0.16†	0.07	0.16†	0.07	0.52‡	−0.37‡	0.16†	1	
GOKef	0.01	0.09	0.23‡	0.12	0.21‡	0.05	−0.08	0.08	−0.50‡	0.43‡	0.18†	−0.88‡	1
MEAN	11.65	104.59	106.98	96.95	92.40	102.93	11.10	0.90	1.18	0.80	0.83	1.42	0.63
SD	0.36	10.39	11.55	13.93	13.60	22.96	2.33	0.08	0.26	0.20	0.09	0.43	0.17

Note: Age in years; WID: word identification (word reading accuracy); SWE: sight word efficiency (word reading efficiency); ANRAN: alphanumeric RAN; NANRAN: nonalphanumeric RAN; PA: phonological awareness; NVR: nonverbal reasoning; GOKa, GOKl, GOKef: GOK accuracy, GOK latency, GOK efficiency; MGRa, MGRl, MGRef: MGR accuracy, MGR latency, MGR efficiency; Accuracy: proportion correct; Latency: median correct latency; Efficiency: accuracy/latency; WID, SWE, ANRAN, NANRAN, PA: standard scores, mean = 100, SD = 15; NVR: standard test, mean = 10; SD = 3.

‡ $p < .01$.

† $p < .05$.

make a direct contribution – especially perhaps to reading fluency and/or efficiency – in addition to effects mediated by OK. This prediction is consistent with several studies showing that RAN continues to predict reading over and above the effect of OK (e.g., Cutting & Denckla, 2001; Georgiou et al., 2009; Georgiou, Aro, et al., 2016).

Participants in our study were Grade 6 students (aged 11 to 12 years) on the cusp of High School entry, who would be expected to have fluent literacy so that the factors involved in word reading efficiency should be maximally observable. In response to the issues raised above, we added nonword homophones to our GOK measure to minimise the risk of it being confounded by phonological processing and to reliably tap into more advanced knowledge of orthographic patterns (see Method section), thereby avoiding ceiling effects. To ensure our MGR task could not be completed on the basis of GOK, we used *only* irregular words as our target stimuli, which forced children to use their mental dictionary (see Method section). We also ensured that the item pairs were age-appropriate to avoid the ceiling effects that have been problematic in earlier studies (e.g., Georgiou et al., 2009). Finally, we concurrently examined the relationships between both types of RAN, both types of OK (in terms of accuracy, latency and efficiency), and word reading accuracy and efficiency, while controlling for phonological awareness and IQ (i.e., nonverbal reasoning).

Given the lack of consistency in relevant, past studies, it was difficult to generate firm predictions about the relationships we might find here. However, several strands in the wider literature mentioned above were helpful in this regard: Share (2008) and Ehri (2005) among others have pointed to a much greater reliance by skilled readers on word-specific or 'sight word' skills (i.e., MGRs), while GOK is invoked as necessary to more effortfully decode unfamiliar words. Further, ANRAN has been established as a stronger concurrent predictor of reading in older children than NANRAN, especially of reading fluency and efficiency (Norton & Wolf, 2012). Finally, as mentioned above, there appears to be general agreement that RAN is tapping into the same underlying processing factors that also underpin reading (e.g., Georgiou & Parrila, 2013; Norton & Wolf, 2012).

Hence, although previous under-exploration of NANRAN precluded precise predictions in that direction, we reasoned as follows:

(1) If RAN does in fact influence efficiency of access to or actual quality of MGRs – either of which could underpin increased reading efficiency, then ANRAN should contribute significantly more variance to MGR than to GOK and these effects should be particularly pronounced in our sample of older children.
(2) The effect of RAN on word reading should transact at least partly through MGR efficiency, and this effect should be most strongly observed in the ANRAN – word reading efficiency relationship.
(3) Consistent with previous observations of variance accounted for by RAN measures over and above the contribution of OK, there might well be an additional direct effect of ANRAN on word reading (especially word reading efficiency) over and above its indirect effect through OK.

2. Method

2.1. Participants

English speaking participants were recruited from two non-government and seven government Primary Schools in metropolitan Perth, Western Australia. The University of Western Australia Human Ethics Research Committee (RA/4/1/5246) approved this project. Initial contact was made with school principals inviting their school to participate. Written consent was obtained at each level with the parents/guardians of participating children also providing written consent for the participation of their child. Participants (principals, parents/guardians and children) were free to withdraw at any time from the project without prejudice or the need to justify their decision. Convenience sampling was carried out. One hundred and seventy-eight Grade 6 students were initially tested. Nine students were excluded from the study because teachers reported that English was their second language but there were no other selection criteria. The final sample consisted of 169 students (77 females, 92 males) aged 10.75–12.42 years (M = 11.65 years; SD = 0.36 years). Participants were given an inexpensive reward for their participation (e.g., pencil sharpener). Further information about the final sample may be found in Table 1.

2.2. Measures

2.2.1. General procedure

Data reported here were collected as part of a larger battery administered to each participant in one session lasting approximately 75 min with appropriate breaks. The tasks were administered in the same order to all participants (word reading accuracy, word reading efficiency, RAN, phonological awareness, MGR, GOK, nonverbal reasoning) interspersed among other tasks in the larger battery. All tasks were administered individually by the first author in a quiet room at the children's school. Age-based norms were used for standardised tests. For these tests scoring was completed by the first author according to the instructions in the test manuals. The OK tasks were conducted on *MatLab*. These experimental tasks had high split half reliability. Reliability checking was also conducted by one other author. All students completed all tasks.

2.2.2. Nonverbal reasoning

Nonverbal reasoning (or intelligence) is the ability to think and reason without using too many words (Reber, Allen, & Reber, 2009). The Matrix Reasoning Subtest from the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) measures nonverbal reasoning ability using pattern completion, classification, analogy and serial reasoning with 32 items. For each item, participants were required to examine a matrix with a section missing and asked to complete the matrix by choosing one of five response options. Reliability coefficients for children aged 6 to 16 years range from 0.86 to 0.96 with a mean of 0.92 (Wechsler, 1999).

2.2.3. Phonological awareness

This was assessed using the Segmenting Nonwords and Phoneme Reversal Subtests from the Comprehensive Test of Phonological Processing (CTOPP; Wagner, Torgesen, & Rashotte, 1999). The Segmenting Nonwords Subtest required participants to divide 20 nonwords into their constituent phonemes. The Phoneme Reversal Subtest required students to reverse the order of the phonemes in 18 nonsense words to derive real words. As these measures both require the use of meta-analytic phonological awareness (Gillon, 2004), and also involve nonsense words, we believed that they would be more discriminating among older children than the real word deletion and blending activities in the CTOPP core phonological awareness composite. An alternative composite phonological awareness score was created from these subtests. The split-half reliability for both Phoneme Reversal and Segmenting Nonwords in the age range of 8 to 17 is 0.79 (Wagner et al., 1999).

2.2.4. RAN

ANRAN was measured with the CTOPP Digits and Letters Subtests. NANRAN was assessed with the CTOPP Objects and Colours Subtests (Wagner et al., 1999). For each subtest, participants are asked to name as quickly as possible 36 items in a 4×9 array based on a set of six stimuli repeated six times at random (e.g., the digits 234578). The split-half reliability for the age range of 8 to 17 is 0.89 for RAN Colours, 0.93 for RAN Objects, 0.80 for RAN Digits and 0.72 for RAN Letters (Wagner et al., 1999). Raw naming times were converted to standard scores for each subtest, and then used to create ANRAN and NANRAN composite scores. The correlation between composite scores was $r = 0.61$ ($p < .01$).

2.2.5. Word reading accuracy

Word recognition was assessed by the Word Identification (WID) Subtest of the Woodcock Word reading Mastery Tests–Revised/Normative Update (Woodcock, 1998). Participants read aloud from a graded list of 106 words until they reached their ceiling level. Testing was discontinued if six consecutive items were missed. This subtest has reliability > 0.94 (Woodcock, 1998).

2.2.6. Word reading efficiency

Speed and accuracy of word recognition was measured by the Sight Word Efficiency (SWE) Subtest of the Test of Word reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999). Participants read aloud as many real words as they could from a graded list of 104 words in 45 s. The split-half reliability for the age range of 10 to 18 is 0.84 (Torgesen et al., 1999).

2.2.7. MGR task

To resolve the problems described above with the Olson et al. (1994) *orthographic choice* task and similar other MGR tasks, stimuli that could potentially be solved using GOK were replaced with items where this would be impossible (i.e., where the real words were irregular). Stimuli were deemed "irregular" if the word contained: a) at least one instance where the orthography failed to represent the spoken sounds of the word as per accepted English orthographic patterns (e.g., "answer" and "salmon"); b) an orthographic pattern which has a particularly low probability of occurring in English (e.g., "hearth" and "gauge"); or c) multiple irregularities (e.g., "meringue" and "choir"). Using these criteria, twelve of the Olson word pairs were retained and 29 new pairs of words added from different sources (Castles & Coltheart, 1993; Clutterbuck, 2000; Hope, 2001; Westwood, 1999; Woodcock, 1998). Consistent with the seminal Olson task, we generated our word-pseudohomophone pairs according to the Olson methodology (i.e., that both the real word and its pair "would be pronounced the same in English"; Olson, Wise, Conners, Rack, & Fulker, 1989, p. 339). Split-half reliabilities were 0.81 for accuracy, 0.91 for latency and 0.93 for efficiency scores (percent correct/latency). Mean response times were calculated using reaction times that were associated with a correct response (MGR task stimuli are presented in Appendix A).

2.2.8. GOK task

The task consisted of 39 pairs of nonwords similar to those of Loveall et al. (2013) and Powell et al. (2014). In each pair, one of the nonsense words contained a plausible English orthographic pattern (e.g., "phim") and a pseudohomophone foil that included an improbable English spelling (e.g., an orthographic pattern that violated positional constraints such as "ffim"). We also included nonwords that would be expected to tap into more complex OK (e.g., morphemic information such as "impliction" paired with the foil "implikshen"). Split-half reliabilities were 0.69 for accuracy, 0.91 for latency and 0.86 for efficiency scores (defined as accuracy/latency). Once again, mean response times were calculated using reaction times that were associated with a correct response (see Appendix A for GOK task stimuli).

2.2.9. Procedure for MGR and GOK tasks

Both tasks were delivered in a standardised format: Participants were presented with a randomly chosen (without replacement) pair of black-coloured stimuli (Arial, 22 pt font), with one item on either side of a central fixation. Items were presented against a white background. In both tasks, participants were asked to indicate the side of the display that contained the item that "looked more like a real word" as quickly and accurately as possible by pressing a button on a response box. No feedback was given and there was no time limit to complete the tasks. A laptop computer running custom-programmed software in *MatLab* presented stimuli and recorded response accuracy and latency. Participants completed practice trials prior to beginning the main tasks.

3. Results

3.1. Sample description and correlations

Means, standard deviations and intercorrelations for each measure are shown in Table 1. Since GOK latency did not correlate with word reading and the variables of main interest were the efficiency variables we excluded both GOK latency and MGR latency from further analyses. Instead, we used GOK efficiency alongside MGR efficiency as speeded measures of OK. Neither type of RAN was significantly correlated with phonological awareness which could be attributed to the use of meta-analytic measures of phonological awareness (i.e., phonological awareness measures that are more discriminating among older children).

3.2. Hierarchical multiple regression analyses

Before interpreting the results of the regressions, a number of assumptions were tested, and checks performed. Our sample size produces a reasonable ratio of cases to predictors (Tabachnick & Fidell, 2013). We detected eight univariate outliers across our variables which were > 3.29 standard deviations from the mean. These outliers were winsorised by substituting them with the next highest score which was not an outlier (Field, 2013). As expected, MGR accuracy and GOK accuracy were slightly negatively skewed but the standardised residuals had a mean of 0 and a standard deviation of 1. In addition, inspection of the histograms suggested there was a reasonable range of scores in MGR accuracy (0.320) and less skew but a broader range of scores in GOK accuracy (0.436). Overall, inspection of the normal probability plot and scatterplot of standardised residuals against standardised predicted values indicated that the assumptions of normality, linearity and homoscedasticity were met. No multivariate outliers were found. Relatively high tolerances for all the predictors in the final regression models indicated that multicollinearity did not interfere with our data interpretation. In all analyses we controlled for nonverbal reasoning and phonological awareness, by entering these variables into the model first. Finally, we adjusted for age on our four variables that were not age normed (i.e., MGR accuracy, MGR efficiency, GOK accuracy, GOK efficiency) by running regression analyses with Age as the DV and the raw score variable as the IV. We then ran more regression analyses with the residuals as the IV. The overall models were not significant; hence, we were able to use the raw scores for further analyses. We also applied a Holm-Bonferroni adjustment for multiple regressions in order to deal with familywise error rates (FWER) for multiple hypothesis tests (Holm, 1979; see Appendix C).

Our preliminary analyses included hierarchical multiple regressions exploring the relative variance in word reading accuracy and efficiency accounted for by both types of RAN and OK. As these analyses were broadly consistent with what has been reported in previous studies, details are not reported here. However, for the interested reader, they are included in Appendix B.

3.2.1. Predicting MGR and GOK from RAN (see Table 2)

Our first prediction was that RAN should contribute more variance to MGR than GOK in an older group of children and that these effects would be more pronounced for MGR efficiency. Indeed, ANRAN contributed significantly to MGR accuracy (4% - 7%; $p < .01$; whether it was entered before or after NANRAN) and efficiency (4% - 11%; $p < .01$; whether it was entered before or after NANRAN). But NANRAN contributed significantly to MGR accuracy and MGR efficiency only if it was entered into the model before ANRAN (3% and 7% respectively). Furthermore, only NANRAN contributed significantly to GOK efficiency (3% - 5%; $p < .01$; whether it was entered before or after ANRAN). However, neither type of RAN accounted for significant variance in GOK accuracy.

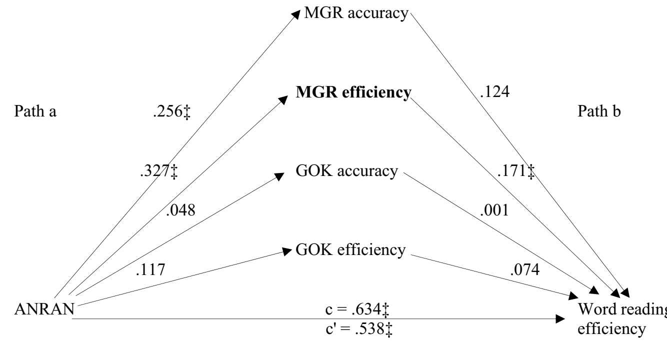

Fig. 1. Model A: Parallel multiple mediation analysis exploring the role of OK types in the ANRAN-word reading efficiency relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.

Effect sizes for our four multiple regression analyses (Cohen, 1988), regardless of order of entry for ANRAN or NANRAN, were as follows: Predicting MGR accuracy: Cohen's $f^2 = 0.297$; MGR efficiency: $f^2 = 0.216$; GOK accuracy: $f^2 = 0.139$; GOK efficiency: $f^2 = 0.006$. Post hoc power analyses using the software package G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) with $\alpha = 0.05$, the above f^2 values, our four predictors, and $N = 169$, the power for three of the four analyses was thoroughly acceptable (i.e., predicting MGR accuracy: 1.00; MGR efficiency: 0.9999; GOK accuracy: 0.9999). Even our fourth analysis (predicting GOK efficiency) with a low power of only 0.260, still allowed us to find a significant effect of NANRAN on GOK efficiency.

3.3. Parallel multiple mediation analyses (see Figs. 1–4 and Table 3)

In order to explore our second prediction regarding the contribution of OK to the RAN-word reading relationship and our third prediction of a possible direct contribution from RAN to word reading, four parallel, multiple mediation analyses were conducted according to the specifications set out by Hayes' (2013) PROCESS approach. This same method was employed by Poulsen, Juul, and Elbro (2015) to compare a different set of indirect effects against the background of RAN's direct contribution to reading. We also believed this to be the most parsimonious method of contemporaneously examining the potential indirect contributions of all our candidate 'mediator' variables at the same time as and in the context of the possible direct influence of each RAN type. Prior to conducting the parallel multiple mediations, we transformed the variables to z-scores to facilitate comparisons of the contribution of the independent variables to word reading. For each model we included nonverbal reasoning and phonological awareness as covariates (see Table 4 for covariate coefficients for all models).

Table 2
Predicting MGR and GOK from ANRAN and NANRAN.

Predicting MGR	Accuracy		Efficiency		Predicting GOK	Accuracy		Efficiency	
	ΔR^2	β	ΔR^2	β		ΔR^2	β	ΔR^2	β
Model A					Model A				
Step 1: NVR	0.09‡	0.20	0.03†	0.09	Step 1: NVR	0.08‡	0.21	0.01	−0.13
Step 2: PA	0.07‡	0.26	0.03†	0.16	Step 2: PA	0.04‡	0.21	0.01	0.08
Step 3: ANRAN	0.07‡	0.24	0.11‡	0.26	Step 3: ANRAN	0.00	0.05	0.01	−0.03
Step 4: NANRAN	0.00	0.02	0.01	0.11	Step 4: NANRAN	0.00	0.00	0.03†	0.24
Model B					Model B				
Step 3: NANRAN	0.03†	0.02	0.07‡	0.11	Step 3: NANRAN	0.00	0.00	0.05‡	0.24
Step 4: ANRAN	0.04‡	0.24	0.04‡	0.26	Step 4: ANRAN	0.00	0.05	0.00	−0.03

Note: β, full model betas; NVR: nonverbal reasoning; PA: phonological awareness.
‡ $p < .01$.
† $p < .05$.

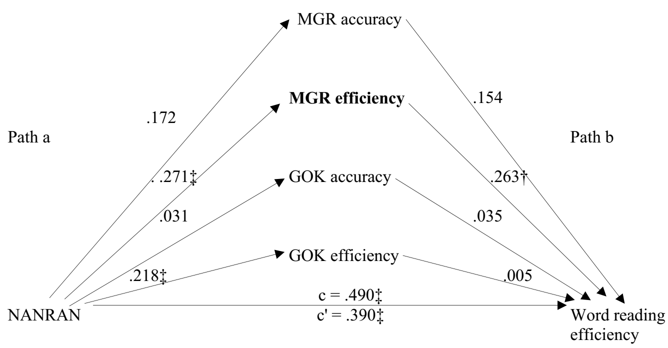

Fig. 2. Model B: Parallel multiple mediation analysis exploring the role of OK types in the NANRAN-word reading efficiency relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.

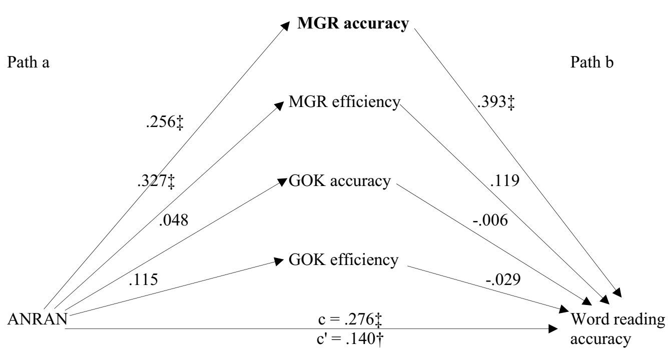

Fig. 3. Model C: Parallel multiple mediation analysis exploring the role of OK types in the ANRAN-word reading accuracy relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.

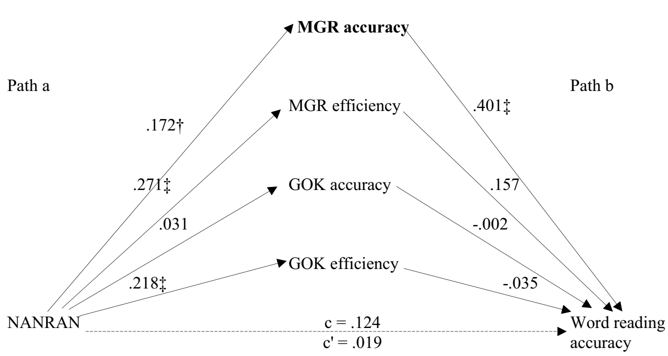

Fig. 4. Model D: Parallel multiple mediation analysis exploring the role of OK types in the NANRAN-word reading accuracy relationship; ‡$p < .01$, †$p < .05$; no mediation, only indirect effect of MGR accuracy (see bold).

Figs. 1 to 4 present the coefficients for paths a and b for each potential mediator as well as paths c and c′ (significant pathways are bolded). Table 3 presents the total and direct effects of RAN on word reading as well as the total indirect effect and individual indirect effects of the mediators. The 95% bias corrected and accelerated confidence intervals (CIs) were computed with a bootstrapping technique with 5000 resamples using Preacher and Hayes' (2008) SPSS macro. These researchers have adopted this bootstrapping method because they contend it is very powerful, effective and unlikely to lead to Type I errors in smaller samples. The CIs are used as a test of whether an indirect effect differs from zero (i.e., whether inclusion of a proposed mediator significantly reduces the effect of RAN on word reading).

3.3.1. Model A: ANRAN-OK-Word reading efficiency

After controlling for nonverbal reasoning and phonological awareness, the total effect of ANRAN on word reading efficiency (i.e., without taking into account the mediators) was significant (path c = 0.634, $p = .000$; $F(3, 165) = 59.89$, $p < .01$; $R^2 = 0.52$). After adjusting for the indirect effects of the mediators, the direct effect of ANRAN on word reading efficiency (i.e., when taking into account the mediators) decreased but was still significant implying a partial mediation (path c′ = 0.538, $p = .000$; $F(7, 161) = 33.43$, $p < .01$; $R^2 = 0.59$). MGR efficiency was the only significant mediator of the effect of ANRAN on word reading efficiency.

3.3.2. Model B: NANRAN-OK-Word reading efficiency

After controlling for nonverbal reasoning and phonological awareness, the total effect of NANRAN on word reading efficiency was significant (path c = 0.490, $p = .000$; $F(3, 165) = 30.53$, $p < .01$; $R^2 = 0.36$). After adjusting for the indirect effects of the mediators, the direct effect of NANRAN on word reading efficiency decreased but was still significant implying a partial mediation (path c′ = 0.390, $p = .000$; $F(7, 161) = 20.96$, $p < .01$; $R^2 = 0.48$). MGR efficiency was the only significant mediator of the effect of NANRAN on word reading efficiency.

3.3.3. Model C: ANRAN-OK-Word reading accuracy

After controlling for nonverbal reasoning and phonological awareness, the total effect of ANRAN on word reading accuracy was significant (path c = 0.276, $p = .000$; $F(3, 165) = 38.43$, $p < .01$; $R^2 = 0.41$). After adjusting for the indirect effects of the mediators, the direct effect of ANRAN on word reading accuracy decreased but was still significant implying a partial mediation (path c′ = 0.140, $p = .012$; $F(7, 161) = 33.43$, $p < .01$; $R^2 = 0.58$). MGR accuracy was the only significant mediator of the effect of ANRAN on word reading accuracy.

3.3.4. Model D: NANRAN-OK-Word reading accuracy

After controlling for nonverbal reasoning and phonological awareness, the total effect of NANRAN on word reading accuracy was nonsignificant (path c = 0.124, $p = .052$; $F(3, 165) = 29.73$, $p < .01$; $R^2 = 0.35$). After adjusting for the indirect effects of the mediators, the direct effect of NANRAN on word reading accuracy decreased and was also nonsignificant (path c′ = 0.019, $p = .734$; $F(7, 161) = 20.96$, $p < .01$; $R^2 = 0.56$). Although there was no mediation there was an indirect effect of MGR accuracy (indirect effect = 0.070, 95% CI: 0.065 to 0.151) and there was almost an indirect effect of MGR efficiency (i.e., indirect effect = 0.043, 95% CI: 0.001 to 0.111 but path $b_2 = 0.157$, $p = .053$, marginally significant).

In summary, with word reading efficiency as the outcome variable, only MGR efficiency was a significant partial mediator of the effect of both types of RAN on word reading efficiency. With word reading accuracy as the outcome variable, MGR accuracy was a partial mediator of the ANRAN–word reading accuracy relationship and had an indirect effect on the NANRAN–word reading accuracy relationship. That is, there were three partial mediations where the direct contributions of ANRAN and NANRAN remained significant after adjusting for the effects of MGR and GOK but no case of full mediation at all (i.e., where the direct contribution of ANRAN/NANRAN was significant before the effects of mediators were taken into account but did not remain so after this adjustment).

4. Discussion

This study, which was innovative in methodology and analytic approach, has permitted a comprehensive and controlled examination of key variables involved in the relationships between RAN, OK and word reading. As a result, we now have a more solid base than was previously available for grappling with key theoretical issues in this area. At the same time, we acknowledge that our results may have raised more questions than they have answered so there is patently still much work to be done. To this end, we discuss below clear inferences that emerge

Table 3
Total, direct, and indirect effects of RAN on word reading.

	Word reading efficiency		Word reading accuracy	
	Point estimate	95% BCa CI	Point estimate	95% BCa CI
Effects of ANRAN				
Total effect of ANRAN on word reading	0.634		0.276	
Direct effect of ANRAN on word reading	0.538		0.140	
Total indirect effect	0.097	0.050 to 0.163	0.136	0.069 to 0.210
Indirect effect of MGR accuracy	0.032	−0.001 to 0.086	0.101	**0.047 to 0.172**
Indirect effect of MGR efficiency	0.056	**0.006 to 0.129**	0.039	−0.016 to 0.099
Indirect effect of GOK accuracy	0.001	−0.008 to 0.015	−0.000	−0.016 to 0.008
Indirect effect of GOK efficiency	0.001	−0.004 to 0.041	−0.003	−0.033 to 0.010
Effects of NANRAN				
Total effect of NANRAN on word reading	0.490		0.124	
Direct effect of NANRAN on word reading	0.390		0.019	
Total indirect effect	0.100	0.044 to 0.183	0.105	0.027 to 0.200
Indirect effect of MGR accuracy	0.026	−0.000 to 0.081	0.070	**0.017 to 0.151**
Indirect effect of MGR efficiency	0.071	**0.022 to 0.159**	0.043	**0.001 to 0.111**
Indirect effect of GOK accuracy	0.001	−0.006 to 0.024	0.000	−0.013 to 0.012
Indirect effect of GOK efficiency	0.001	−0.033 to 0.034	−0.001	−0.047 to 0.019

Note: Indirect effects with confidence intervals that do not include zero are significant at the 0.05 level (see bold).

from these data, which we hope may inform future reading research and practice.

Our key findings were generally supportive of our hypotheses: Firstly, ANRAN contributed unique variance to both MGR accuracy and efficiency. However, this contribution was split between ANRAN and NANRAN when NANRAN was entered in the model before ANRAN. Additionally, NANRAN alone contributed unique variance to GOK efficiency and neither type of RAN contributed unique variance to GOK accuracy.

We also set out to establish which type(s) of OK may indirectly influence the relationship between RAN and word reading and whether RAN might make an additional direct contribution to word reading. ANRAN and NANRAN made both an indirect contribution to word reading efficiency, which was shared with MGR efficiency, and a direct contribution. Moreover, ANRAN also made a shared indirect contribution through MGR accuracy to word reading accuracy along with a direct contribution to word reading accuracy. In contrast, NANRAN did not make any direct contribution to word reading accuracy and although MGR accuracy made an indirect contribution to word reading accuracy this was not shared with NANRAN. Hence, there was also strong support for our second and third predictions.

Our finding that ANRAN was related to MGR accuracy and efficiency is in line with previous results (e.g., Bowers et al., 1999; Georgiou et al., 2009; Powell et al., 2014). However, our finding that ANRAN was unrelated to GOK (either accuracy or efficiency) is not. This discrepancy in our sample of older readers is consistent with the developmental perspectives of Ehri (2005) and Share (2008) which predict a shift away from reliance on GOK in older children. Even so, significant relationships reported by Georgiou et al., 2009 and Powell et al. (2014) between ANRAN and GOK in children close in age to those here suggest that this developmental argument cannot fully explain the present data. Further, given that this was a single group study with unique tasks, we are not in a position to make inferences about development. Nevertheless, it does seem particularly urgent to further explore these relationships in children at different developmental stages in future research.

Our parallel, multiple mediation approach clarified the separate and shared influences of our multiple variables on both types of word reading. The results of these analyses underline the primacy of ANRAN's influence on both word reading accuracy and efficiency in older children. Our prediction of a separate and direct contribution from ANRAN to word reading was also strongly supported. This was true not only in respect to efficiency, but also accuracy of word reading, though the effect was much stronger for efficiency. Our analyses also strengthen the inference from our regression data that the link between NANRAN and word reading may reflect not accuracy alone, but accuracy as a function of speed (i.e., efficiency).

Notwithstanding, we strongly advise caution in making directional or causal inferences from our cross-sectional and correlational data. Because OK skills are clearly directly related to reading and children have to learn OK over time, it could be assumed (as in much of the wider literature to date) that the direction of this indirect effect is from RAN through OK to reading. However, it could equally be argued that the development of OK, particularly OK efficiency, may influence RAN directly (e.g., Peterson et al.'s, 2018 report that children's prior literacy influenced RAN).

We explored this possibility post hoc by repeating relevant analyses with the two OK types as independent variables and both RAN types as dependent measures. As can be seen in Appendix D, these new regressions revealed similar patterns of relationship between the two types of

Table 4
Covariate coefficients for total and direct effect models.

Models	Model A	Model B	Model C	Model D
Total effect				
NVR	0.089 (p = .123)	0.038 (p = .568)	0.150[†] (p = .019)	0.138[†] (p = .041)
PA	0.250[‡] (p = .000)	0.276[‡] (p = .000)	0.485[‡] (p = .000)	0.502[‡] (p = .000)
Direct effect				
NVR	0.051 (p = .367)	−0.018 (p = .785)	0.056 (p = .335)	0.046 (p = .439)
PA	0.181[‡] (p = .002)	0.180[‡] (p = .006)	0.366[‡] (p = .000)	0.365[‡] (p = .000)

Note. NVR: nonverbal reasoning; PA: phonological awareness.

[‡] $p < .01$.

[†] $p < .05$.

RAN and OK to those observed in our primary analyses. We followed this up with reversed parallel multiple mediation analyses (Appendix D), which showed that both types of MGR made direct contributions to word reading accuracy and efficiency. MGR accuracy and efficiency also made indirect contributions shared with ANRAN to both word reading accuracy and efficiency and with NANRAN to word reading efficiency but not accuracy. There was a significant direct effect of GOK efficiency on word reading efficiency but not accuracy and neither GOK accuracy nor efficiency shared any significant contribution with either type of RAN to word reading accuracy or efficiency. In sum, these secondary analyses underlined the shared (and likely reciprocal) influences of RAN and OK on word reading.

Finally, we considered other explanations for why we did not get more consistent relationships with our GOK measure. One possibility is that the measure lacked construct validity. However, this seems unlikely since our task was grounded in the style of GOK tasks used in the field for the past two decades and analogous to those used by Loveall et al. (2013) and Powell et al. (2014). Another possibility is that participants performed at ceiling on the GOK measure; however, this is also belied by our results (less skew and a broader range of scores in the GOK accuracy distribution than for MGR accuracy). One remaining possibility arises from the fact that our nonword pairs were not formally matched on syllabification and stress patterns. Future studies may wish to do so as an additional means of enhancing the internal consistency of the GOK task.

4.1. Theoretical and practical implications

The present findings are consistent with the view that RAN taps into the same underlying brain regions and neural processes as word reading. Additionally, the fact that there was no case of full mediation by any OK type suggests that RAN also shares its influence on word reading with other variables that are more closely involved in the reading process like MGR. We believe that this may be the first time that RAN's dual influence has been highlighted in this way and that the present results offer a more nuanced understanding of RAN's contribution to word reading.

For one, if we accept that RAN performance reflects the recruitment of underlying processes as suggested by Norton and Wolf (2012) then our results imply that the processes driving the two RAN types may be different. In fact, we speculate that ANRAN may reflect increasing automatization of MGR access, at least in older children. In contrast, NANRAN may reflect activity in the complex language processing areas required for the more effortful use of GOK. This viewpoint is consistent with Loveall et al. (2013), who suggested that NANRAN and GOK are related because they are both less automatised than ANRAN and MGR; and also with Donker et al. (2016) who proposed that NANRAN has higher processing demands than ANRAN, which requires processing of stimuli that are overlearned or learned by rote. That said, the link between NANRAN and GOK efficiency (but not GOK accuracy) does seem to point to efficiency of processing rather than additional processing per se.

The results of our principal and post hoc regression and parallel multiple mediation analyses suggest that while both types of RAN may be tapping into different neural processes for their indirect influence on OK, both also draw at least partly on the same processes in their direct contribution to word reading. In addition, this shared variance appears to be found in relation to word reading efficiency, but not accuracy. This, combined with the fact that NANRAN appears to relate only to measures of efficiency, suggests that the shared direct effects of the two RAN types reflect some basic capacity to develop efficient neural functioning in the different areas they are tapping into. The outcome of our reverse analyses also suggests reciprocal influences from both ANRAN and NANRAN on MGR, and that both ANRAN and NANRAN are tapping into the same neurological substrata as word reading. Moreover, it seems to us highly unlikely that those shared substrata are inherently related to OK because word knowledge, by definition, involves learned rather than biologically pre-wired functioning which has been co-opted for literacy.

Our results point very strongly to the influence of both RAN types on word reading being related in some way to the timing of processing (i.e., accuracy at a reasonable rate), rather than to the processes themselves. This is consistent with the position that Wolf and colleagues have argued for some time (e.g., Norton & Wolf, 2012; Wolf & Bowers, 1999). Our findings also support their contention that RAN should no longer be viewed under the phonological processing umbrella. First, the relationship between RAN and word reading efficiency was significantly stronger than the relationship between phonological awareness and word reading efficiency. Second, neither ANRAN nor NANRAN was significantly related to phonological awareness. Although this latter relationship has been shown in other studies (e.g., Georgiou, Aro, et al., 2016; Snowling & Hulme, 1994; Torgesen et al., 1997), we think the critical difference is our use of a more sensitive meta-analytic phonological awareness measure that was more discriminating among older children.

Lastly, our data point emphatically to the involvement of both types of RAN in word reading, especially word reading efficiency, through MGR rather than GOK. Our results also underline the role of efficiency in relation to this information and imply that even when children with poor ANRAN learn phonics, they may still struggle with MGR efficiency. Put differently, these students are unlikely to develop well automatised ‘sight word’ knowledge. According to Norton and Wolf (2012), children with RAN deficits require intensive, multi-component intervention programs that address orthography, morphology, syntax and semantics as well as phonological decoding skills in order to learn to recognise words efficiently (i.e., accurately and at a reasonable rate). Our work suggests that the ANRAN task could be an efficient screening tool to identify poor readers in Upper Primary who need such specialist and targeted intervention.

4.2. Future directions

The present work directly suggests a number of important follow-up investigations: Although our improved measures of MGR and GOK appear to have been more discriminating than previous versions, further cross-linguistic studies are required to clarify the relationships of these dual aspects of OK with each RAN type and word reading accuracy and efficiency in languages differing in orthographic transparency.

Significant value could be gained from studies that combine comprehensive behavioural measures such as those employed here with neurophysiological measures to explore the timing, patterns of recruitment and brain areas that are involved with each type of RAN. If, as our data suggest, these neurophysiological measures varied with RAN type and reading outcome measure (accuracy or efficiency), this could clarify the brain areas and functions involved with each RAN type and what might be the sources of their shared and separate contributions to OK and word reading. Of course, it would also be very useful to compare these patterns at different developmental levels.

It is urgent to develop companion measures of MGR and GOK suited to younger children to permit further comprehensive exploration of these two OK types in earlier grades, together with longitudinal studies that can answer the developmental questions raised here. In particular, a cross-lagged design would permit exploration of how the variables of interest here may be altered by maturation and by exposure to literacy instruction and/or experience with written language. This would also facilitate the use of NANRAN as a screening tool in younger children to identify problems with MGR development and permit appropriate early intervention.

To date, relatively little attention appears to have been paid to spelling in the present context. However, given the recently emerging understanding that reading and spelling are reciprocal if not symbiotic processes (e.g., Coltheart & Prior, 2007; Jones & Rawson, 2016), we might expect to see similar relationship patterns between spelling and the variables of interest here to those we found with word reading. Indeed, Stainthorp, Powell, and Stuart (2013) have reported that ANRAN made a significant contribution to spelling in Grade 3 and 4 children, students with slow naming speed had poorer spelling overall and they showed particular difficulty on irregular words, though neither NANRAN nor OK was explored in that study. It would be of considerable further interest to examine the relationship patterns explored here in children with strong spelling but poor word reading skills, such as those identified by Lovett (1987) or Wimmer and Mayringer (2002).

Two areas of continuing relevance to the present questions are still in need of comprehensive investigation but were beyond the scope of our study. Firstly, we did not explore relationships between RAN types, OK types, and accuracy and efficiency of nonword reading. Neither did we examine the relationships of these variables to irregular and regular word reading. These comparisons could offer more powerful insights into the role of MGR and GOK efficiency both developmentally and in older children. It would also be of considerable importance to longitudinally investigate how the relationships between all these variables change with age. Additionally, previous studies have examined the influence of processing speed in the RAN-reading relationship and concluded that RAN continues to predict reading after controlling for speed of processing (Georgiou, Ghazyani, & Parrila, 2018). Given the strong suggestions here of timing-related factors, it would be of great interest to use the parallel multiple mediation approach to concurrently examine the contribution of typical processing speed measures to word reading accuracy and efficiency either directly or indirectly through both types of RAN and or OK.

4.3. Conclusions

This study was designed to establish a more substantial platform from which to move forward in research and practice and we would argue that it has done so. In summary, we contemporaneously examined relationships between both types of RAN and OK and word reading while controlling for PA and nonverbal intelligence within students expected to be fluent readers and in whom therefore, we expected these influences to be maximally observable. We developed MGR and GOK tasks designed to minimise possible confounds with each other and measured both accuracy and efficiency of word reading and OK. Finally, we utilised a parallel, multiple mediation approach that allowed us to concurrently examine the direct and indirect relationships between all our variables of interest.

The resulting format appears to have thrown the relationships of interest here into ‘high relief’ and therefore, to permit the following inferences: (1) Since both RAN and OK appear to tap into the same underlying neural processing as word reading, OK should no longer be explored purely as a mediator variable; (2) The processes underpinning each RAN type appear to differ at least in part; (3) Both types of RAN are reciprocally involved with both OK types in their influence on word reading efficiency; (4) ANRAN predominates through its reciprocal involvement with word-specific rather than generic orthographic information; and (5) The role of efficiency appears paramount in relation to both types of orthographic information.

Urgent initiatives suggested by this study include mapping the precise brain areas and neural processing streams underpinning the differential relationships of ANRAN and NANRAN with MGR and GOK and with word reading. We do not yet know whether these neurological substrata also account for the shared variance both RAN types contribute to MGR and if so how; or in what ways RAN and OK also reciprocally draw on these common substrata along with word reading.

Finally, we also contend that the highly significant relationships that feature prominently in our data between ANRAN, the efficient use of word-specific OK (i.e., MGR) and word reading efficiency have implications for practice. We suggest that ANRAN might be used to prospectively and concurrently identify children who will most likely struggle to develop efficient reading so that these students can access timely and appropriate intervention.

Declaration of Competing Interest

None.

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Appendix A. Orthographic knowledge tasks

A.1. MGR task

Instructions: In this task two items at a time will appear on the screen. Both of these would sound like a real word, but only one is a real word. You will show me which item is a real word by pushing a button. Push the button that is on the same side as the real word. Try to answer as fast as you can without making mistakes.

Now we will do some words for practice. Which one is the real word? Yes, ___is a real word so you would push this button. (or: No, ____ is the real word so you would push this button). Do you have any questions?

1. MGR task	
Practice stimuli	
Real words	*Pseudohomophones*
room	rume
bowl	boal
young	yung
clown	cloun
turtle	tertle
circus	sircus
snow	snoe
wrote	wroat
Experimental trials	
Real words	*Pseudohomophones*

women	wimmen
kayak	kyak
word	wurd
answer	anser
forward	forwerd
salmon	sammon
muscle	mussle
nuisance	nusance
study	studdy
several	sevral
hearth	harth
salad	sallad
blood	blud
choir	cwire
friend	frend
island	iland
lose	luse
meringue	merang
surplus	sirplus
pretty	pritty
routine	rutine
sure	shor
tomb	toom
wolf	woolf
yacht	yaught
leisure	lesure
cemetery	semetery
sufficient	suffishent
permanent	permanant
cruel	crule
every	evry
heavy	hevvy
ghost	goast
cough	coff
gauge	gaige
orchestra	orchistra
equally	equaley
appreciate	appreshiate
familiar	familier
enthusiastic	enthuseastic
signature	signiture

A.2. GOK task

Instructions: In this task two items at a time will appear on the screen. Both of these are words that don't exist. You will show me which item looks more like a real word by pushing a button. Push the button that is on the same side as the nonword which looks more like a real word. Try to answer as fast as you can without making mistakes.

Now we will do some words for practice. Which one looks more like a real word? Yes, ___looks more like a real word so you would push this button. (or: No, ____ looks more like a real word so you would push this button). Do you have any questions?

2. GOK task	
Practice stimuli	
Target	Foil
daled	ddaled
yik	yikk
milg	meelg
gry	gri
chee	chii
Experimental trials	
Target	Foil
dake	daik
drick	drik
glank	glanck
mopple	moppul
mang	manng
damiff	ddamif
cretch	crech
brennet	brennut
swally	swolly
blimbask	blimbasc
prinkly	pringkly
rark	raak
drampelton	dramplton
queeble	kweeble
simp	symp

sedliest	sedlyest
clatally	clatalee
brocked	broct
ricious	rishus
vost	vosst
proceive	procieve
impliction	implikshen
marn	mahrn
thoal	thoel
phim	ffim
quoast	qoast
plass	plas
foll	ffol
skap	sckap
tiner	tighner
woor	wuur
bey	bei
yad	yadd
thail	thayl
mand	mande
slooth	sluthe
nake	naick
feak	fiek
tunos	ttunos

Appendix B. Contribution of RAN and OK to word reading accuracy and efficiency

Appendix B - Table 1
Predicting word reading efficiency from: ANRAN and NANRAN; MGR accuracy and GOK accuracy; MGR efficiency and GOK efficiency.

	ΔR^2	β		ΔR^2	β		ΔR^2	β		ΔR^2	β
Model A			Model A			Model A			Model A		
Step 1: NVR	0.04†	0.03	Step 1: NVR	0.04†	0.03	Step 1: NVR	0.04†	0.05	Step 1: NVR	0.04†	0.05
Step 2: PA	0.08‡	0.19	Step 2: PA	0.08‡	0.19	Step 2: PA	0.08‡	0.21	Step 2: PA	0.08‡	0.21
Step 3: ANRAN	0.40‡	0.48	Step 3: MGRa	0.13‡	0.22	Step 3: ANRAN	0.40‡	0.48	Step 3: MGRef	0.20‡	0.24
Step 4: NANRAN	0.02†	0.16	Step 4: GOKa	0.00	−0.01	Step 4: NANRAN	0.02†	0.13	Step 4: GOKef	0.00	0.04
Step 5: MGRa	0.04‡	0.22	Step 5: ANRAN	0.30‡	0.48	Step 5: MGRef	0.05‡	0.24	Step 5: ANRAN	0.27‡	0.48
Step 6: GOKa	0.00	−0.01	Step 6: NANRAN	0.02†	0.16	Step 6: GOKef	0.00	0.04	Step 6: NANRAN	0.01	0.13
Model B			Model B			Model B			Model B		
Step 3: NANRAN	0.24‡	0.16	Step 3: GOKa	0.01	−0.01	Step 3: NANRAN	0.25‡	0.13	Step 3: GOKef	0.05‡	0.04
Step 4: ANRAN	0.18‡	0.48	Step 4: MGRa	0.13‡	0.22	Step 4: ANRAN	0.18‡	0.48	Step 4: MGRef	0.15‡	0.24
Step 5: GOKa	0.00	−0.01	Step 5: NANRAN	0.18‡	0.16	Step 5: GOKef	0.02†	0.04	Step 5: NANRAN	0.14‡	0.13
Step 6: MGRa	0.04‡	0.22	Step 6: ANRAN	0.14‡	0.48	Step 6: MGRef	0.04‡	0.24	Step 6: ANRAN	0.13‡	0.48

Note. *β*, full model betas.
‡ $p < .01$.
† $p < .05$.

Appendix B - Table 2
Predicting word reading accuracy from: ANRAN and NANRAN; MGR accuracy and GOK accuracy; MGR efficiency and GOK efficiency.

	ΔR^2	β		ΔR^2	β		ΔR^2	β		ΔR^2	β
Model A			Model A			Model A			Model A		
Step 1: NVR	0.11‡	0.07†	Step 1: NVR	0.11‡	0.07	Step 1: NVR	0.11‡	0.11	Step 1: NVR	0.11‡	0.11
Step 2: PA	0.23‡	0.37	Step 2: PA	0.23‡	0.37	Step 2: PA	0.23‡	0.44	Step 2: PA	0.23‡	0.44
Step 3: ANRAN	0.08‡	0.21	Step 3: MGRa	0.21‡	0.47	Step 3: ANRAN	0.08‡	0.23	Step 3: MGRef	0.12‡	0.35
Step 4: NANRAN	0.00	−0.08	Step 4: GOKa	0.00	−0.04	Step 4: NANRAN	0.00	−0.09	Step 4: GOKef	0.01	−0.09
Step 5: MGRa	0.16‡	0.47	Step 5: ANRAN	0.02‡	0.21	Step 5: MGRef	0.08‡	0.35	Step 5: ANRAN	0.03‡	0.23
Step 6: GOKa	0.00	−0.04	Step 6: NANRAN	0.00	−0.08	Step 6: GOKef	0.01	−0.09	Step 6: NANRAN	0.01	−0.09
Model B			Model B			Model B			Model B		
Step 3: NANRAN	0.02	−0.08	Step 3: GOKa	0.01	−0.04	Step 3: NANRAN	0.02	−0.09	Step 3: GOKef	0.01	−0.09
Step 4: ANRAN	0.06‡	0.21	Step 4: MGRa	0.20‡	0.47	Step 4: ANRAN	0.06‡	0.23	Step 4: MGRef	0.13‡	0.35
Step 5: GOKa	0.01	−0.04	Step 5: NANRAN	0.00	−0.08	Step 5: GOKef	0.00	−0.09	Step 5: NANRAN	0.00	−0.09
Step 6: MGRa	0.15‡	0.47	Step 6: ANRAN	0.03‡	0.21	Step 6: MGRef	0.08‡	0.35	Step 6: ANRAN	0.03‡	0.23

Note. *β*, full model betas.
‡ $p < .01$.
† $p < .05$.

Appendix C. Holm-Bonferroni adjustment for multiple regressions

Variable	*p*-Value in ascending order	Holm-Bonferroni	New *p*-value
Predicting MGR accuracy			
Model A			
Nonverbal reasoning	0.000*	0.05/4	0.0125
Phonological awareness	0.000*	0.05/3	0.0166
ANRAN	0.000*	0.05/2	0.0250
NANRAN	0.783	0.05/1	0.0500
Model B			
Nonverbal reasoning	0.000*	0.05/4	0.0125
Phonological awareness	0.000*	0.05/3	0.0166
ANRAN	0.006*	0.05/2	0.0250
NANRAN	0.016*	0.05/1	0.0500
Predicting MGR efficiency			
Model A			
ANRAN	0.000*	0.05/4	0.0125
PA	0.016*	0.05/3	0.0166
Nonverbal reasoning	0.023*	0.05/2	0.0250
NANRAN	0.210	0.05/1	0.0500
Model B			
NANRAN	0.000*	0.05/4	0.0125
ANRAN	0.005*	0.05/3	0.0166
Phonological awareness	0.016*	0.05/2	0.0250
Nonverbal reasoning	0.023*	0.05/1	0.0500
Predicting GOK accuracy			
Model A			
Nonverbal reasoning	0.000*	0.05/4	0.0125
Phonological awareness	0.006*	0.05/3	0.0166
ANRAN	0.515	0.05/2	0.0250
NANRAN	0.981	0.05/1	0.0500
Model B			
Nonverbal reasoning	0.000*	0.05/4	0.0125
Phonological awareness	0.006*	0.05/3	0.0166
ANRAN	0.617	0.05/2	0.0250
NANRAN	0.678	0.05/1	0.0500
Predicting GOK efficiency			
Model A			
NANRAN	0.016*	0.05/4	0.0125
ANRAN	0.139	0.05/3	0.0166
Phonological awareness	0.276	0.05/2	0.0250
Nonverbal reasoning	0.318	0.05/1	0.0500
Model B			
NANRAN	0.005*	0.05/4	0.0125
Phonological awareness	0.276	0.05/3	0.0166
Nonverbal reasoning	0.318	0.05/2	0.0250
ANRAN	0.779	0.05/1	0.0500

Note.

* Significant *p* according to new *p*-value.

Appendix D. Multiple regression and parallel multiple mediation analyses with RAN (ANRAN and NANRAN) as dependent variables and OK (MGR accuracy/efficiency and GOK accuracy/efficiency) as independent variables

D.1. Multiple regressions

Appendix D - Table 1

Predicting RAN (ANRAN and NANRAN) from OK (MGR and GOK).

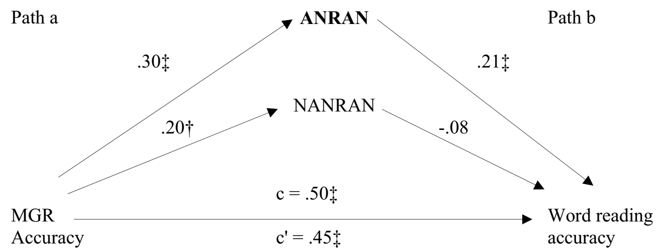
Predicting RAN	ANRAN		NANRAN			ANRAN		NANRAN	
	ΔR^2	β	ΔR^2	B		ΔR^2	β	ΔR^2	β
Model A					Model A				
Step 1: NVR	0.00	−0.05	0.02	0.08	Step 1: NVR	0.00	−0.04	0.02	0.10
Step 2: PA	0.01	0.01	0.00	0.01	Step 2: PA	0.01	0.02	0.00	0.01
Step 3: MGRa	0.08‡	0.31	0.03†	0.21	Step 3: MGRef	0.11‡	0.37	0.08‡	0.23
Step 4: GOKa	0.00	−0.03	0.00	−0.02	Step 4: GOKef	0.00	−0.05	0.01	0.12
Model B					Model B				
Step 3: GOKa	0.00	−0.03	0.00	−0.02	Step 3: GOKef	0.01	−0.05	0.05‡	0.12
Step 4: MGRa	0.08‡	0.31	0.03†	0.21	Step 4: MGRef	0.10‡	0.37	0.04‡	0.23

Note: β, full model betas.

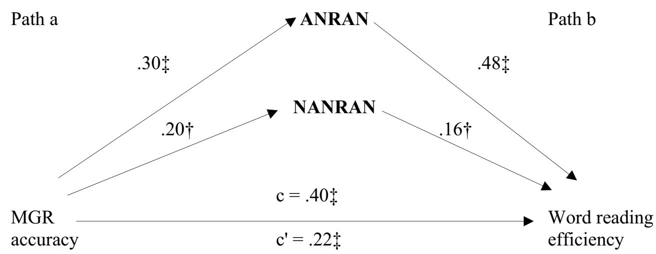
‡ $p < .01$.

† $p < .05$.

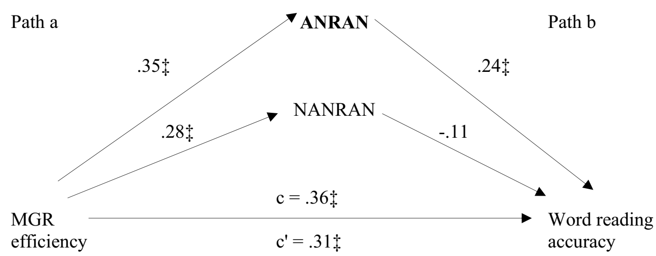
D.2. Parallel multiple mediations: exploring the role of RAN types in the OK-word reading relationship



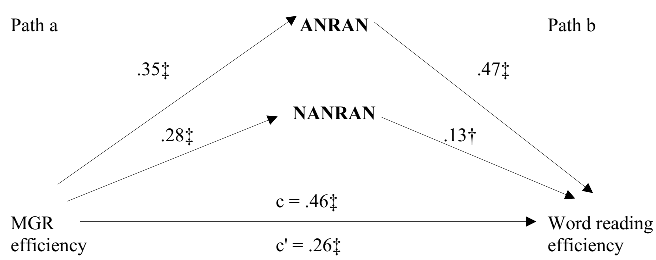
Appendix D - Fig. 1. Parallel multiple mediation analysis exploring the role of RAN types in the MGR accuracy – word reading accuracy relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.



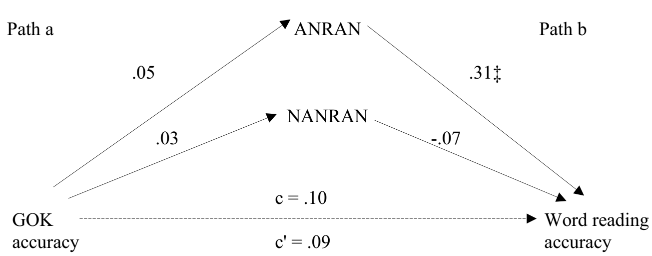
Appendix D - Fig. 2. Parallel multiple mediation analysis exploring the role of RAN types in the MGR accuracy – word reading efficiency relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.



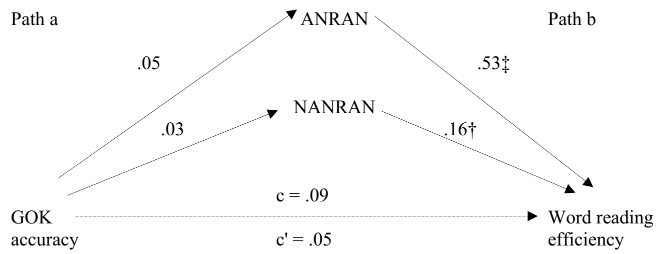
Appendix D - Fig. 3. Parallel multiple mediation analysis exploring the role of RAN types in the MGR efficiency – word reading accuracy relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.



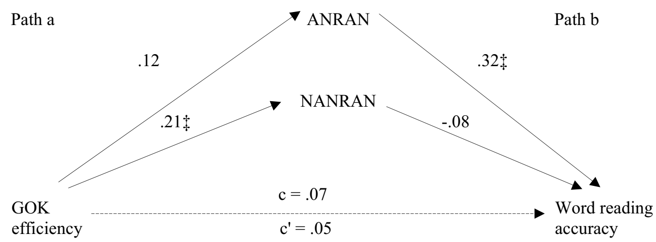
Appendix D - Fig. 4. Parallel multiple mediation analysis exploring the role of RAN types in the MGR efficiency–word reading efficiency relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.



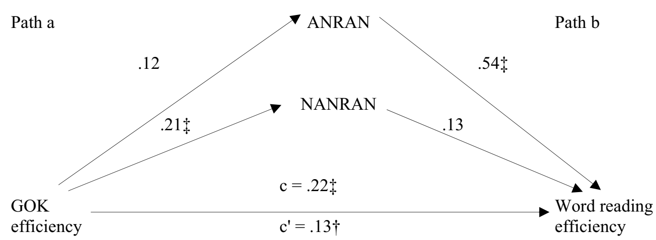
Appendix D - Fig. 5. Parallel multiple mediation analysis exploring the role of RAN types in the GOK accuracy – word reading accuracy relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.



Appendix D - Fig. 6. Parallel multiple mediation analysis exploring the role of RAN types in the GOK accuracy – word reading efficiency relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.



Appendix D - Fig. 7. Parallel multiple mediation analysis exploring the role of RAN types in the GOK efficiency – word reading accuracy relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.



Appendix D - Fig. 8. Parallel multiple mediation analysis exploring the role of RAN types in the GOK efficiency – word reading efficiency relationship; ‡$p < .01$, †$p < .05$; significant mediators in bold.

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