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How does rapid automatized naming influence orthographic knowledge?

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ABSTRACT

Rapid automatized naming (RAN) is a strong predictor of reading fluency across languages, and some researchers have attributed this to the contribution of RAN to the development of orthographic knowledge, which is predictive of reading fluency. However, to date, it remains unclear whether RAN (alphanumeric and nonalphanumeric) predicts orthographic knowledge (OK) and what skills may mediate their relation. To examine the RAN–OK relations, we assessed 114 Grade 3 Spanish-speaking Mexican children (58 girls; M_{age} = 7.9 years, *SD* = 0.3) on RAN (objects and digits), orthographic knowledge (lexical and sublexical; accuracy and response time), speed of processing, multi-element processing, phonemic awareness, and reading fluency. Path analyses showed first that, OK (both lexical and sublexical) partly mediated the effects of RAN on reading fluency. Second, multiple mediation analyses showed an indirect effect of both RAN tasks on lexical and sublexical OK through phonological awareness. In view of Ehri's amalgamation hypothesis and Share's self-teaching hypothesis, our findings suggest that RAN may reflect, in part, the speed with which the phonological representations of letters are accessed and retrieved, which subsequently influences how quickly orthographic representations can be formed and accessed.

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Introduction

Rapid automatized naming (RAN), defined as the ability to name as fast as possible highly familiar visual stimuli such as letters, digits, colors, and objects, is a strong predictor of reading (see Araújo, Reis, Petersson, & Faísca, 2015, for a meta-analysis). Bowers and Wolf (1993) proposed that RAN is related to word reading because of its contribution to the development of orthographic knowledge (OK).[1] More specifically, they argued that if readers are slow (indexed by their performance in RAN letters) when identifying the letters in words, then these letters will not be activated quickly enough to allow their unitization (i.e., encoded as single units). As a result, readers will not be sensitive to frequently occurring letter patterns they see in print, the quality of their orthographic representations will be poor, and their reading ability (particularly reading fluency) will be compromised.

Although this theoretical account is considered prominent in the RAN–reading literature (see Georgiou & Parrila, 2013, for a review), three issues remain unclear. First, we do not know whether both types of RAN tasks (alphanumeric and nonalphanumeric) predict OK equally well or whether OK is more strongly influenced by alphanumeric RAN (as would be implied by Bowers & Wolf, 1993). Second, we do not know whether RAN influences both types of OK (lexical and sublexical) and both ways in which OK tasks have been scored in the literature (accuracy and response time [RT]). Finally, although Bowers and Wolf's (1993) hypothesis implies a unitization mechanism that allows the formation of orthographic representations, we do not know what processing skills underlie the RAN–OK relation. Thus, the purpose of this study was to explore the relation between RAN (alphanumeric and nonalphanumeric) and OK (lexical and sublexical; accuracy and RT) in a sample of Spanish-speaking Grade 3 children.

The relation of RAN with OK

The assumption that RAN influences word reading through the effects of OK rests first on the assumption that RAN and OK are related. Indeed, in their meta-analysis, Swanson, Trainin, Necoechea, and Hammill (2003) reported a significant correlation between RAN and OK (r = .41), which was as high as the average weighted correlation between RAN and word reading (r = .42) and higher than the average correlation between RAN and phonological awareness (r = .36). Swanson et al. also found significant heterogeneity in the correlations between RAN and OK, but they did not explore further whether the type of RAN or OK tasks accounted for this heterogeneity.

The studies that have examined whether RAN influences OK can be grouped into three broad categories. First, some researchers hypothesized that if RAN contributes to the development of OK, then it should not predict word reading after controlling for the effects of spelling (which presumably relies on OK). In addition, RAN should continue to predict reading real words even after controlling for nonword reading (which presumably requires minimal OK). Previous studies (Moll, Fussenegger, Willburger, & Landerl, 2009; Rakhlin, Cardoso-Martins, & Grigorenko, 2014) have failed to support either hypothesis, and Moll et al. (2009) concluded that RAN (operationalized in their study with digit naming) is not a measure of orthographic processing—a conclusion that obviously challenges Bowers and Wolf's (1993) theoretical account.

Second, some studies have examined the direct contribution of RAN to OK and produced mixed findings (e.g., Lervåg, Bråten, & Hulme, 2009; Loveall, Channell, Phillips, & Conners, 2013; Manis, Doi, & Bhadha, 2000; Mesman & Kibby, 2011; Pae, Sevcik, & Morris, 2010). For example, in a study with Grade 2 English-speaking children, Manis et al. (2000) found that RAN letters accounted for 11% to 17% and RAN digits accounted for 6% to 11% of unique variance in OK accuracy after controlling for phonological awareness. In contrast, working with a sample of kindergarten to Grade 2 English-speaking children,

[1] Orthographic knowledge refers to the information that is stored in memory that tells us how to represent spoken language in written form (Apel, 2011). Different terms have been used to represent the components of OK in the literature. Some researchers refer to them as "general" and "word specific" (see Conrad, Harris, & Williams, 2013) or as "lexical" and "sublexical" (see Commissaire & Besse, 2019). Irrespective of terminology, the same tasks are used to represent each component. For the purpose of this study, we use the terms lexical OK and sublexical OK. Lexical OK refers to the stored mental representation of known words. In turn, sublexical OK refers to knowledge of permissible language-specific orthographic patterns.

Pae et al. (2010) found that RAN (a composite score from RAN letters and objects) accounted for a nonsignificant 1% of the variance in OK accuracy after controlling for phonological awareness. Unfortunately, none of these studies examined the role of alphanumeric and nonalphanumeric RAN in OK RTs.

Finally, some researchers have employed an experimental approach to examine the RAN–OK relation. This was done either by manipulating the orthographic information available in target stimuli to examine whether that affects the relations with RAN (e.g., Manis, Seidenberg, & Doi, 1999; Kruk, Mayer, & Funk, 2014; Onochie-Quintanilla, Defior, & Simpson, 2019) or by examining whether children with a RAN deficit perform poorer than controls in different OK measures (e.g., Bowers, Sunseth, & Golden, 1999; Conrad & Levy, 2007; Powell, Stainthorp, & Stuart, 2014). For example, in a study with Spanish-speaking children followed from kindergarten to Grade 5, Onochie-Quintanilla et al. (2019) examined whether RAN (operationalized with color and object naming) predicts equally well the reading of (a) highly unfamiliar items (nonwords composed of unfamiliar orthographic patterns), (b) semifamiliar items (nonwords composed of familiar orthographic patterns), and (c) highly familiar items (well-known real words). Their results showed no significant differences in the concurrent or longitudinal effects of RAN on the three types of words, which led them to conclude that "naming speed does not relate to orthographic processing of familiar spelling patterns any more than it does to simple decoding of unfamiliar spelling patterns" (p. 11). In contrast, working with a group of Grade 1 English-speaking children followed through Grade 2, Manis et al. (1999) found that RAN (digits and letters) was more strongly related to exception word reading than to nonword reading. On the basis of these findings, Manis et al. concluded that RAN is related to reading because it assesses the ability to form "arbitrary" connections between visual symbols and their names. For example, seeing the digit *4* does not equip the participant with the phonological information needed to say the word *four*. Likewise, producing the correct pronunciation for an exception word (e.g., *yacht*) requires the retrieval of partially arbitrary item-specific knowledge.

To summarize, previous studies have provided mixed findings regarding the RAN–OK relation irrespective of the research approach used. To our knowledge, no studies have examined whether RAN tasks predict OK RT measures, and no studies have examined what cognitive processes may mediate the RAN–OK relation.

The mediators of the RAN–OK relation

There are at least three candidate mechanisms that may uniquely or jointly underlie the RAN–OK relation. First, as suggested by Bowers and Wolf (1993), quick performance in RAN allows the unitization of successive letters, which then allows the formation of high-quality orthographic representations. Thus, a unitization mechanism may be partly responsible for the RAN–OK relation. Here, we assessed an individual's ability to unitize orthographic information with a multi-element processing (MEP) task (Onochie-Quintanilla, Defior, & Simpson, 2017). In MEP, individuals are presented with an array of elements (usually three to five symbols in each array) for a limited time and afterward is asked to select the correct string that they had seen before among two options. To succeed in this task, individuals need to encode elements in parallel instead of processing them individually because the targets are relatively long and are presented rapidly. Given that the stimuli used in our task were Russian letters that our participants did not know (the stimuli included letters of the Cyrillic alphabet that do not overlap with the Roman alphabet), we could test the hypothesis that efficient visual identification of letters allows unitization, which then contributes to the development of OK.

A second candidate mechanism might be phonemic awareness. According to the amalgamation hypothesis (Ehri, 1980), children first develop an awareness of the sounds of their written language (phonemic awareness) and knowledge of letter–sound correspondences. With the help of these skills, they begin to phonologically recode unknown words.[2] As they phonologically recode these words, the phonemes are bonded to the letters in the words; these letter–sound bonds help children to construct orthographic representations of words. Thus, the ability to construct initial orthographic representations of words relies on children's phonemic awareness. However, for amalgamation to take place, the sounds

[2] This is very similar to Share's (1995) self-teaching hypothesis, according to which orthographic representations of words are built through phonological recoding, which functions as a self-teaching mechanism.

should also be accessed and retrieved quickly from long-term memory. Given that RAN is frequently described as an indicator of the speed of access to phonological representations from long-term memory (e.g., Wagner & Torgesen, 1986; Ziegler et al., 2010), it is reasonable to expect that phonemic awareness may mediate RAN's effects on OK.

Finally, speed of processing may mediate the RAN–OK relation. Kail and colleagues (e.g., Kail & Hall, 1994; Kail, Hall, & Caskey, 1999) have argued that because RAN and reading involve several subprocesses (this may also apply to OK because it involves at least two subprocesses: visual identification of letters and activation of phonological codes), efficient performance in both requires integration and coordination of the information within and between subprocesses. This is captured by speed of processing. Although several studies have verified the role of speed of processing in the RAN–reading relation (e.g., Georgiou, Aro, Liao, & Parrila, 2016; Georgiou, Parrila, & Papadopoulos, 2016), no studies have examined whether speed of processing can explain the RAN–OK relation (particularly when speeded measures of OK are used as outcome measures). Whether speed of processing correlates equally well with both types of OK scores also remains unclear. Georgiou, Parrila, and Kirby (2009), for example, found that speed of processing correlated significantly with OK RTs but not with OK accuracy.

The current study

The purpose of this study was twofold: (a) to examine the relation of RAN (alphanumeric and non-alphanumeric) with different measures of OK (lexical and sublexical; accuracy and RT) and (b) to examine what processing skills may mediate the RAN–OK relation. Examining the RAN–OK relation is obviously important for the discussion around the mechanism underlying the RAN–reading relation (e.g., Georgiou & Parrila, 2013), and that is why we also included measures of reading fluency in our study.

We tested the following three hypotheses:

1. The effects of RAN on reading fluency will be partly mediated by OK (for a similar finding, see e.g., Georgiou et al., 2016; Holland, McIntosh, & Huffman, 2004; Papadopoulos, Spanoudis, & Georgiou, 2016).
2. RAN will be more strongly related to lexical OK than to sublexical OK and will be more strongly related to RT than to accuracy scores of OK (e.g., Georgiou et al., 2009; Powell et al., 2014).
3. All three processing skills will partly mediate the effects of RAN on OK.

Our findings were expected to make two important contributions to the literature. First, we contrasted multiple explanations of the RAN–OK relation, which allowed us to estimate the unique and joint contributions of the examined factors to the RAN–OK relation. Second, we examined the aforementioned relations in a consistent orthography (Spanish). This is important for several reasons. First, because children in consistent orthographies, including Spanish, reach ceiling in reading accuracy soon after they receive formal reading instruction (Seymour, Aro, & Erskine, 2003), reading in these orthographies is operationalized with fluency tasks. Given that reading fluency is predicted by OK (e.g., Georgiou, Parrila, & Papadopoulos, 2008; Rakhlin, Mourgues, Cardoso-Martins, Kornev, & Grigorenko, 2019), we had a unique opportunity to examine whether the already established effects of RAN on reading fluency are mediated by OK. Second, if in consistent orthographies like Spanish every letter corresponds roughly to a phoneme, then unitization may occur at the phoneme level (i.e., strengthening of the letter–sound mapping). In contrast, in opaque orthographies (e.g., English) where digraphs (e.g., *ch, sh*) or trigraphs (e.g., *dge*) determine the pronunciation, a multi-element processing mechanism would need to be employed.

Method

Participants

A total of 114 Grade 3 Spanish-speaking Mexican children (58 girls and 56 boys; M_{age} = 7.9 months, SD = 0.3) participated in the study. They were recruited from three public elementary schools in Cuernavaca city in the State of Morelos, Mexico. The schools are located in different parts of the city and serve mostly middle-class families (based on the location of the schools and on teachers' reports regarding families' socioeconomic status). All children had Spanish as their first and only language and had no formal diagnosis of intellectual, behavioral, or sensory difficulties. Parental and school consent and research ethics approval from the University of Morelos were obtained prior to testing.

Materials

Rapid automatized naming

RAN was assessed with two measures: *digits* (an alphanumeric RAN task) and *objects* (a nonalphanumeric RAN task). Children were asked to name as fast as possible four digits (1, 4, 7, and 9; pronounced as /uno/, /cuatro/, /siete/, and /nueve/ in Spanish) or objects (chair, dog, pencil, and bed; pronounced as /silla/, /perro/, /lápiz/, and /cama/ in Spanish) that were repeated nine times each and arranged in semirandom order in four rows of nine. Before testing, children were asked to name the stimuli in a practice trial to ensure familiarity. A participant's score was the number of items named per second. RAN digits correlated .45 with RAN objects in our sample.

Orthographic knowledge

Two measures of OK were administered: Orthographic Choice (used here as a measure of lexical OK) and Wordlikeness (used here as a measure of sublexical OK). Orthographic Choice was adapted from the work of Cunningham, Perry, and Stanovich (2001) and was administered on a laptop computer. Children were asked to select which of two presented homophones (e.g., *vaso–baso*) was the correctly spelled word by pressing the right or left Ctrl button on the keyboard. There were 3 practice items and 36 test items that were presented one at a time in a counterbalanced order. Both accuracy and RTs were noted. Cronbach's alpha reliability in our sample was .83. Wordlikeness was adapted from the work of Cassar and Treiman (1997) and was also administered on a laptop computer. Children were asked to select the letter string that looked like a real word in Spanish from a pair of pronounceable nonwords (e.g., *moyi–muun*) by pressing either the right or left Ctrl button on the keyboard. There were 3 practice items and 19 test items that were presented one at a time in a counterbalanced order. Both accuracy and RTs were noted. Cronbach's alpha reliability in our sample was .80.

Phonemic awareness

To assess phonemic awareness, we administered a phoneme substitution task. Children were asked to first orally repeat a word provided by the examiner, then replace the initial sound of the word with a new sound (also provided by the examiner), and finally say the new word. For example, the examiner would say, "Say mat (...). Now, take away the first sound from mat and replace it with the /k/ sound. What is the new word?" The task consisted of 2 practice items and 12 test items. The task was discontinued after three consecutive errors, and a participant's score was the total number correct. Cronbach's alpha reliability in our sample was .90.

Speed of processing

To assess speed of processing, we administered the Visual Matching task from the Woodcock–Johnson Tests of Cognitive Ability (Woodcock & Johnson, 1989). Children were presented with 60 strings of digits (e.g., 2, 5, 1, 2, 8, 3) arranged in two columns of 30. Children were asked to circle as fast as possible the two digits in each string that were identical. A participant's score was the total number of correctly completed rows within a 1-min time limit.

Multi-element processing

A computer-based adaptation of the task presented by Onochie-Quintanilla et al. (2017) was used to assess multi-element processing. A three- to five-letter long target was first presented for 2 s in the middle of a laptop computer screen, followed by a 200-ms mask. Two options of equal letter length were then presented on the screen, and children needed to press the right or left Ctrl button on the keyboard to choose the one that matched the target. The stimuli used letters from the Cyrillic alphabet that do not overlap with the Roman alphabet. The task consisted of 3 practice items and 12 test items. A participant's score was the total number correct. Cronbach's alpha reliability in our sample was .84.

Reading fluency

To assess reading fluency, we administered two measures: real word fluency and pseudoword reading fluency. In the real word fluency task, children were asked to read as fast as possible a list of 84 words of increasing difficulty divided into four columns of 21. In the pseudoword fluency task, children were asked to read as fast as possible a list of 48 pseudowords of increasing difficulty divided into three columns of 16. A short 8-word/pseudoword practice list was presented prior to testing to ensure that children understood the requirements of each test. In each task, a participant's score was the total number of words/pseudowords read correctly within a 1-min time limit. A composite score for reading fluency was subsequently created by averaging the *z* scores for real word fluency and pseudoword reading fluency.

Procedure

Trained assistants assessed children individually during school hours in a quiet room at their respective schools. All tasks were administered in one session that lasted approximately 35 min. The computerized tasks (RAN, multi-element processing, and OK) were presented first in random order and lasted about 20 min. Item presentation and RT recordings were controlled by PsychoPy 3.1 experiment generation software (Peirce & MacAskill, 2018). The second part of the session included the paper-and-pencil tasks (phonemic awareness and speed of processing), which were also presented in random order and lasted about 10 min. Children were allowed a 5-min break in between sessions. Testing took place from October to December of the school year (i.e., 2–4 months after the beginning of the academic year in Mexico).

Response times

RT data were collected for Orthographic Choice and Wordlikeness. The RT represents the time interval between the appearance of the stimulus on the computer screen and the time children made their decision by pressing the right or left Ctrl button on the keyboard. The calculation of the mean RTs was completed in five steps. First, to reduce the possibility of confounding accuracy with RT (e.g., better performers having slower RTs because of trying harder items), we selected items in each task where at least 70% of our sample answered correctly. Second, the RT data across the selected items were cleaned from the responses that were incorrect. Third, any responses below 200 ms and above 8000 ms were removed as anticipation errors (values <200 ms) or machine errors (values >8000 ms). Fourth, responses that were 2 standard deviations below or above the individual's mean (after the first three steps were completed) were removed as outliers. In total, 18.97% of the RTs in Orthographic Choice and 21.45% of those in Wordlikeness were removed. Finally, a new mean was calculated and used in all analyses.

Statistical analysis

To examine the possible mediators of the RAN–OK relation, we performed a series of mediation analyses using Mplus Version 8 (Muthén & Muthén, 2017). First, separate mediation models using either phonemic awareness, multi-element processing, or speed of processing as a possible mediator were constructed separately for each RAN task and OK measure (see Fig. 1 in Results). Second, multiple mediation models were constructed in which only those mediator variables that predicted the OK measures were included (see Figs. 2 and 3 in Results). Nonsignificant paths were eliminated one at a time to evaluate a more parsimonious model with fewer paths. The fit of each model was assessed using a set of fit indices: the chi-square value, the comparative fit index (CFI), the Tucker–Lewis index (TLI), the root mean square error of approximation (RMSEA), and the standardized root mean square residual (SRMR). A nonsignificant chi-square value, CFI and TLI values above .95, an RMSEA value below .06, and an SRMR value below .08 indicate a good model fit (Kline, 2015).

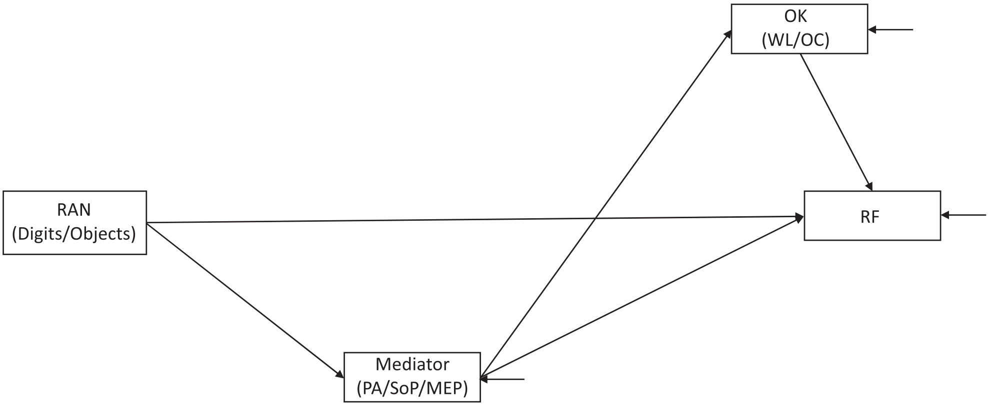

Fig. 1. Separate mediation models exploring the mediating role of phonemic awareness (PA), speed of processing (SoP), and multiple-element processing (MEP) in the rapid automatized naming (RAN)–orthographic knowledge (OK) relationship. WL, Wordlikeness; OC, Orthographic Choice; RF, reading fluency.

Finally, to test the mediated effect of RAN on OK and reading fluency, we used a bias-corrected bootstrapping technique (Hayes & Scharkow, 2013) with 5000 resamples to establish confidence intervals (CIs) for the mediated effects. If a bootstrapped CI does not include zero, there is a 95% probability that the effect is significant (Preacher & Hayes, 2008).

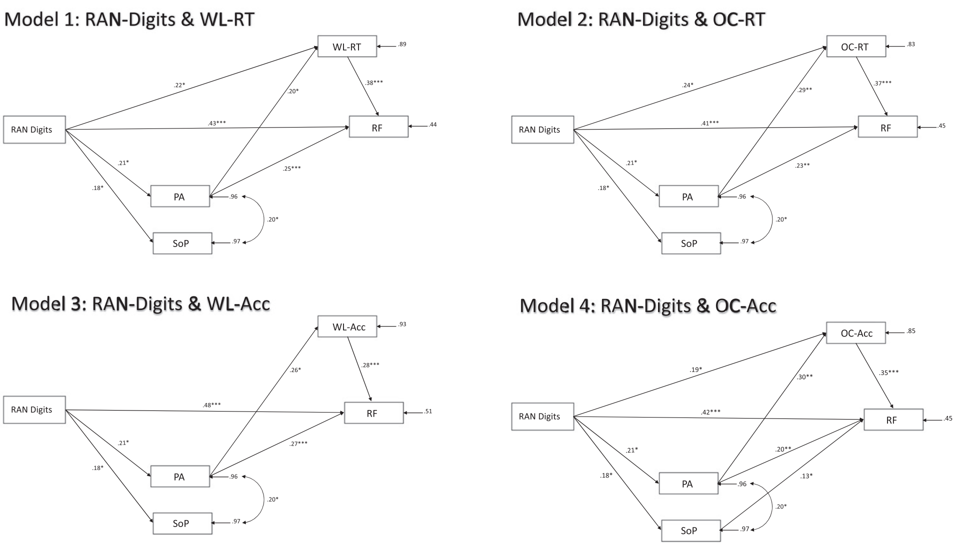

Fig. 2. Parallel multiple mediation models exploring the role of phonemic awareness (PA) and speed of processing (SoP) in the rapid automatized naming (RAN) digits–orthographic knowledge relationship. Coefficients are presented in standardized form. OC, Orthographic Choice; WL, Wordlikeness; RF, reading fluency; Acc, accuracy; RT, response time. Fit indices are as follows: Model 1: $\chi^2(2) = 2.95$, $p = .23$, comparative fit index (CFI) = .99, Tucker–Lewis index (TLI) = .96, root mean square error of approximation (RMSEA) = .07, 90% confidence interval (CI) = .00–.21, standardized root mean square residual (SRMR) = .04; Model 2: $\chi^2(2) = 2.73$, $p = .26$, CFI = .99, TLI = .97, RMSEA = .06, 90% CI [.00, .20], SRMR = .03; Model 3: $\chi^2(3) = 3.64$, $p = .30$, CFI = .99, TLI = .98, RMSEA = .04, 90% CI [.00, .17], SRMR = .04; Model 4: $\chi^2(1) = 0.33$, $p = .57$, CFI = 1.00, TLI = 1.00, RMSEA = .00, 90% CI [.00, .21], SRMR = .01. *$p < .05$; **$p < .01$; ***$p < .001$.

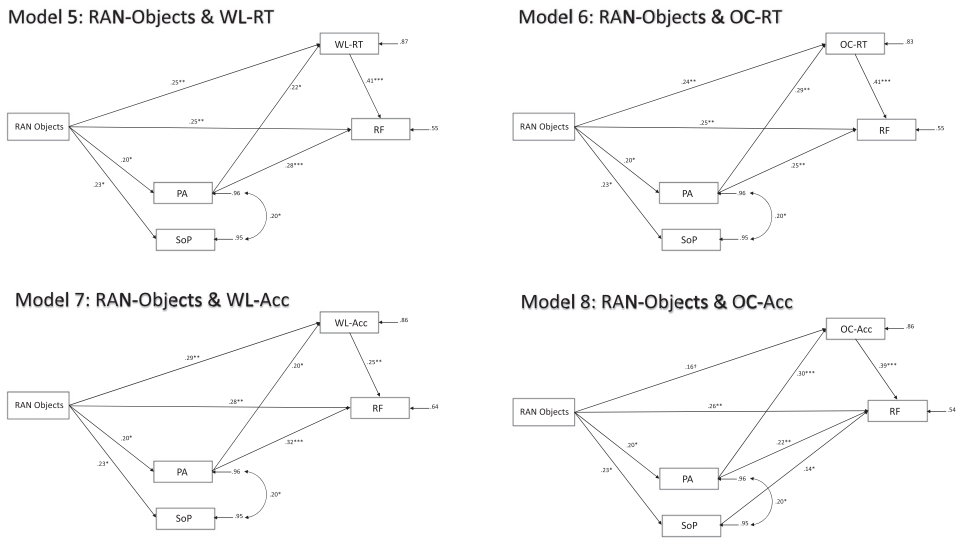

Fig. 3. Parallel multiple mediation models exploring the role of phonemic awareness (PA) and speed of processing (SoP) in the rapid automatized naming (RAN) objects–orthographic knowledge relationship. Coefficients are presented in standardized form. OC, Orthographic Choice; WL, Wordlikeness; RF, reading fluency; Acc, accuracy; RT, response time. Fit indices are as follows: Model 5: $\chi^2(2) = 2.55$, $p = .28$, comparative fit index (CFI) = .99, Tucker–Lewis index (TLI) = .97, root mean square error of approximation (RMSEA) = .05, 90% confidence interval (CI) = .00–.20, standardized root mean square residual (SRMR) = .04; Model 6: $\chi^2(2) = 2.40$, $p = .30$, CFI = 1.00, TLI = .98, RMSEA = .04, 90% CI [.00, .20], SRMR = .03; Model 7: $\chi^2(2) = 2.42$, $p = .30$, CFI = .99, TLI = .97, RMSEA = .04, 90% CI [.00, .20], SRMR = .03; Model 8: $\chi^2(1) = 0.39$, $p = .53$, CFI = 1.00, TLI = 1.00, RMSEA = .00, 90% CI [.00, .21], SRMR = .01. †$p = .06$; *$p < .05$; **$p < .01$; ***$p < .001$.

Results

Preliminary data analysis

Table 1 presents the descriptive statistics for all the measures used in the study. An examination of the distributional properties of the measures showed that the skewness and kurtosis values were in the acceptable range (Kline, 2015). We identified only one univariate outlier in Wordlikeness RT whose score was 3 standard deviations above the group mean, and we replaced that score with a value equal to the next highest non-outlier score plus 1 unit of measurement (Tabachnick & Fidell, 2012). The winsorized data were used in all subsequent analyses.

Table 2 presents the correlations among all variables. Both RAN tasks correlated significantly with the OK measures, with the exception of a nonsignificant correlation between RAN digits and Wordlikeness accuracy. In addition, both RAN tasks and OK measures correlated significantly with reading fluency.

The mediators of the RAN–OK relation

Before constructing the multiple mediation models, we first tested separate mediation models that included either phonemic awareness, speed of processing, or multi-element processing as a single mediator in the relations among RAN, OK, and reading fluency (Fig. 1). The results showed that whereas multi-element processing was predicted by RAN, it did not predict OK or reading fluency in any of the models. Thus, we left out multi-element processing from the final models. The results of these analyses are available on request from the corresponding author.

Fig. 2 presents the multiple mediation models for the relations among RAN digits, OK, and reading fluency, and Table 3 presents the results of the mediation analyses. Because speed of processing failed

Table 1
Descriptive statistics.

	M	*SD*	Min	Max	Skewness	Kurtosis
RAN objects[a]	0.93	0.20	0.42	1.49	−.12	.13
RAN digits[a]	1.50	0.29	0.92	2.14	−.01	−.59
SoP (max = 60)	19.1	4.1	8	28	−.52	.24
MEP (max = 12)	8.3	1.8	3	12	−.93	.75
PA (max = 12)	7.5	4.0	0	12	−.74	−.91
OC Acc (max = 36)	24.4	4.6	13	33	−.29	−.75
OC RT[b]	3.9	1.2	1.7	7.4	.59	.27
WL Acc (max = 18)	14.5	2.8	6	18	−.70	−.07
WL RT[b]	3.8	1.6	1.7	10.7	.70	−.36
WRF (max = 84)	42.8	13.2	13	69	−.32	−.82
NWRF (max = 48)	24.1	6.5	6	43	.00	.03

Note. N = 114. RAN, rapid automatized naming; SoP, speed of processing; MEP, multiple-element processing; PA, phonemic awareness; OC, Orthographic Choice; Acc, accuracy; RT, response time; WL, Wordlikeness; WRF, word reading fluency; NWRF, nonword reading fluency.
[a] Number of items named per second.
[b] In seconds.

Table 2
Pearson correlations among experimental measures.

Variable	1	2	3	4	5	6	7	8	9	10
1. RAN objects		.46**	.23*	.23*	.20*	.22*	−.30**	.32**	−.29**	.42**
2. RAN digits			.18	.16	.21*	.25*	−.30**	.15	−.25**	.57**
3. SoP				.21*	.23*	.05	−.21*	.10	−.21*	.27**
4. MEP					.25*	.23*	−.24*	.17	−.18	.21*
5. PA						.34**	−.34**	.26*	−.27**	.44**
6. OC Acc							−.45**	.41**	−.37**	.53**
7. OC RT								−.18	.67**	−.57**
8. WL Acc									−.44**	.42**
9. WL RT										−.55**
10. RF										

Note. N = 114. RAN, rapid automatized naming; SoP, speed of processing; MEP, multi-element processing; PA, phonemic awareness; OC, Orthographic Choice; Acc, accuracy; RT, response time; WL, Wordlikeness; RF, reading fluency.
* $p < .05$.
** $p < .01$.

to predict the OK measures, we did not calculate the indirect effects of RAN on OK through speed of processing. The results showed that RAN digits predicted speed of processing (β = .18) and phonemic awareness (β = .21), and it also had an indirect effect on both accuracy and RT in Orthographic Choice and Wordlikeness through phonemic awareness (see Table 3). RAN digits also had a direct effect on both OK measures (βs = .19–.22) except the accuracy in Wordlikeness. In addition, RAN digits had an indirect effect on reading fluency through the effects of phonemic awareness and OK.

Fig. 3 presents the models for the relations among RAN objects, OK, and reading fluency. The results showed that RAN objects predicted speed of processing (β = .23) and phonemic awareness (β = .20), and it also had an indirect effect on both accuracy and RT in Orthographic Choice and Wordlikeness through phonemic awareness (see Table 3). RAN objects also had a direct effect on both OK measures (βs = .24–.29), except the accuracy in Orthographic Choice, over and above the effects of all other variables (see Fig. 3). Finally, RAN objects had an indirect effect on reading fluency through the effects of phonemic awareness and OK.

Table 3
Indirect effects of RAN on orthographic knowledge and reading fluency.

Path	Estimate	BC bootstrapped 95% CI
RAN digits → PA → OC Acc	.064	[.012, .146]
RAN digits → PA → OC RT	.055	[.011, .136]
RAN digits → PA → WL Acc	.048	[.003, .149]
RAN digits → PA → WL RT	.041	[.003, .114]
RAN objects → PA → OC Acc	.063	[.007, .148]
RAN objects → PA → OC RT	.054	[.007, .136]
RAN objects → PA → WL Acc	.041	[.001, .134]
RAN objects → PA → WL RT	.039	[.001, .116]
RAN digits → OC Acc → RF	.068	[.016, .129]
RAN digits → OC RT → RF	.083	[.014, .160]
RAN digits → WL Acc → RF	-.027	[−.016, .078]
RAN digits → WL RT → RF	.069	[.002, .143]
RAN objects → OC Acc → RF	.068	[.001, .140]
RAN objects → OC RT → RF	.090	[.028, .164]
RAN objects → WL Acc → RF	.071	[.020, .144]
RAN objects → WL RT → RF	.090	[.013, .180]
RAN digits → PA → OC Acc → RF	.022	[.005, .056]
RAN digits → PA → OC RT → RF	.020	[.004, .055]
RAN digits → PA → WL Acc → RF	.013	[.001, .041]
RAN digits → PA → WL RT → RF	.015	[.001, .046]
RAN objects → PA → OC Acc → RF	.025	[.004, .062]
RAN objects → PA → OC RT → RF	.022	[.003, .059]
RAN objects → PA → WL Acc → RF	.010	[.000, .038]
RAN objects → PA → WL RT → RF	.016	[.001, .049]

Note. RAN, rapid automatized naming; BC, bias-corrected; CI, confidence interval; PA: Phonemic Awareness; OC: Orthographic Choice; WL: Wordlikeness; RF: Reading Fluency; Acc: accuracy; RT: Response Time.

Discussion

The purpose of this study was to examine the relation of RAN with different measures of OK (lexical and sublexical; accuracy and RT) and to examine what processing skills may account for their relation. This is important in light of the attention that OK has received as a significant predictor of reading fluency in different languages (e.g., Georgiou et al., 2008, 2016; Inoue, Georgiou, Muroya, Maekawa, & Parrila, 2017; Lervåg et al., 2009; Liu et al., 2017; Rakhlin et al., 2019).

Prior to examining the relations of RAN with OK, we tested whether OK was indeed mediating (at least partly) the effects of RAN on reading fluency. Obviously, this is a necessary step because if OK was found not to mediate the effects of RAN, then we would have had no good reason to examine the RAN–OK relations more closely. Our findings confirmed our expectation (see Hypothesis 1) and extend those of previous studies in both alphabetic orthographies (e.g., Georgiou et al., 2009, 2016; Papadopoulos et al., 2016) and nonalphabetic orthographies (e.g., Liao et al., 2015; Liao, Georgiou, & Parrila, 2008). Even though the purpose of our study was not to examine the reason why RAN is related to reading fluency, our findings clearly show (as has been shown already in previous studies; e.g., Cutting & Denckla, 2001; Georgiou et al., 2016; Holland et al., 2004; Papadopoulos et al., 2016) that different processing skills may mediate the relation between RAN and reading fluency.

Next, our findings showed that, with one exception, RAN (alphanumeric and nonalphanumeric) correlated significantly with all measures of OK. However, the correlations were rather weak (−.30 to .33) and were lower than the average weighted correlation reported in Swanson et al.'s (2003) meta-analysis (r = .41). A possible explanation for this difference may be that Swanson et al.'s correlation was a weighted correlation derived from a small number of studies (n = 21) conducted mostly in English.

In contrast to our second hypothesis, there were no substantial differences between the RAN–lexical OK and RAN–sublexical OK correlations. We also found no substantial differences between the RAN–OK accuracy and RAN–OK RT correlations (even though in all instances the correlations with

OK RT measures were slightly higher).[3] This suggests that speed alone is not the reason why RAN relates to OK, an argument that is further supported by the fact that speed of processing did not mediate their relation (see Figs. 2 and 3).

The fact that RAN contributed similarly to lexical and sublexical OK is interesting from a theoretical point of view. Manis et al. (1999) argued that RAN taps into children's ability to process the whole orthographic representation of a word as a single unit (i.e., children must form arbitrary connections between the visual stimuli in RAN tasks and their names in the same way as they must learn the pronunciations of irregular/exception words). Clearly, our findings do not support this theoretical proposition. However, we acknowledge that our finding may partly reflect the nature of the orthography our participants were learning to read (i.e., Spanish). According to the psycholinguistic grain size theory (Ziegler & Goswami, 2005), children may be using different grain size units in reading depending on the orthographic consistency of their language. In Spanish (a consistent orthography), children might not necessarily rely on whole-word orthographic representations to read words correctly, and sublexical OK may be sufficient (see Acha, Laka, & Perea, 2010; Gagl, Hawelka, & Wimmer, 2015; Goswami, Gombert, & de Barrera, 1998). This, in turn, may have given rise to the RAN–sublexical OK relation.

The third goal of this study was to examine the possible mediators of the RAN–OK relation, and to do this we contrasted the role of three candidate processing skills (multi-element processing, phonemic awareness, and speed of processing). Our findings showed that, irrespective of RAN task used or OK outcome, only phonemic awareness mediated the effects of RAN on OK. However, in all models, the mediation was partial given that RAN continued to predict OK directly. This is in line with the finding of previous studies showing that RAN explained unique variance in OK over and above the effects of phonemic awareness (e.g., Lervåg et al., 2009; Manis et al., 2000; Mesman & Kibby, 2011). The fact that phonemic awareness mediated (at least partly) the effects of RAN on OK can be explained by the self-teaching hypothesis (Share, 1995, 2004), according to which word-specific orthographic representations are acquired primarily as a result of the self-teaching opportunities provided by the phonological recoding of novel letter strings. For phonological recoding to take place, an individual must quickly access and retrieve the phonological representations of graphemes in words. This fits nicely with the description of RAN as a measure of the speed of access to phonological representations in long-term memory (e.g., Wagner & Torgesen, 1986). On the basis of these findings, we argue here that RAN might be playing the role of a gatekeeper: On the one hand, performance in RAN below a certain threshold level may harm the efficiency of phonological recoding, which then impairs the development of lexical or sublexical OK. On the other hand, performance in RAN above a threshold level might not necessarily come with added benefits for phonological recoding (see Bowers, 2001, for a similar argument).

Interestingly, neither multi-element processing (used here to capture the unitization process) nor speed of processing explained the RAN–OK relation. In terms of the former, our findings suggest that the unitization process proposed by Bowers and Wolf (1993) is not visual but rather phonological (as Share's [1995] theory would suggest). Two pieces of evidence from previous studies support this explanation. First, Bowers et al. (1999) showed that children with a RAN deficit performed equally as well as children with no deficits when asked to recall four-letter real words (e.g., *come, like*) and pronounceable pseudowords (e.g., *kile, meft*) but performed more poorly when asked to recall four-letter unpronounceable nonwords (e.g., *tnws, ncdk*). This suggests that children with a naming speed deficit did not have a problem in accessing the orthographic representation of an existing short high-frequency word or a short pseudoword that was created by changing only one of the letters in real words but did have difficulty in accessing the phonological representations of individual letters that are then used to encode orthographic patterns. Second, Martens and de Jong (2006) showed that "CaSe MiXiNg," a condition where the alternate use of lowercase and uppercase letters distorts multiletter features within words, impaired children's reading speed but did not affect their RAN performance. However, again we acknowledge that our finding could be due to the language of our study. If in con-

[3] Applying Hotelling's t test for dependent correlations also revealed no significant differences between the accuracy and RT correlations with the RAN tasks.

sistent orthographies every letter corresponds roughly to a phoneme, then unitization may occur at the phoneme level (i.e., strengthening of the letter–sound mapping). As Gagl et al. (2015) showed, children learning to read a consistent orthography may read words fluently not necessarily by recognizing them as whole units but rather by retrieving the sounds of the individual letters in words more quickly, which then allows blending to take place at a faster pace. In regard to speed of processing, our findings replicate those of previous studies in which speed of processing was found to be weakly related with OK (e.g., Georgiou et al., 2009; Papadopoulos et al., 2016). In contrast to RAN and reading, it is possible that OK is a more modular process and does not require efficient integration of information within and across multiple subprocesses.

Some limitations of the current study are worth noting. First, our study was correlational, and any relations reported here do not imply causation. Second, we collected data from Grade 3 Spanish-speaking students, and our findings might not generalize to other grade levels or languages. As mentioned earlier, future studies should explore the relation of RAN with lexical and sublexical OK across different grade levels. Third, we administered single measures for the potential mediators of the RAN–OK relation. Although these measures are considered to be "traditional" measures of phonemic awareness, speed of processing, and multi-element processing, future studies should try to replicate our findings using more than one task of these processing skills. Finally, our multi-element processing task was a two-alternative forced-choice recognition task and not a production task. This may have allowed some children to guess what the correct answer was (even though the mean performance on this task was above chance level). Future studies should try to replicate our findings using a production task.

To conclude, our study builds on previous studies (e.g., Loveall et al., 2013; Manis et al., 2000; Mesman & Kibby, 2011; Onochie-Quintanilla et al., 2019) showing that RAN and OK are related (albeit weakly) and that their relation is partially mediated by phonemic awareness. In view of these findings, we conclude that OK is not a viable explanation of the RAN–reading relation (for a similar argument, see Georgiou et al., 2016; Shum & Au, 2017). If OK results from a unitization process, then that process is not visual but rather phonological–visual, where the phonological component may be critical for success.

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