



Examining the contribution of RAN components to reading fluency, reading comprehension, and spelling in German

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Abstract

We examined the contribution of rapid automatized naming (RAN) components (articulation time, pause time, and pause time consistency) to reading fluency, reading comprehension, and spelling in a sample of 257 German children (139 boys, 118 girls; $M_{\text{age}} = 5.60$ years, $SD = 0.31$) followed from kindergarten to Grade 1. In kindergarten, children were assessed on measures of RAN (colors and objects), phonological awareness, letter-sound knowledge, phonological short-term memory, and paired-associate learning. Reading fluency, reading comprehension, and spelling were assessed at the end of Grade 1. Hierarchical regression analyses revealed that pause time and pause time consistency continued to predict reading fluency, but not reading comprehension or spelling, after controlling for the effects of the other cognitive skills assessed in kindergarten. Articulation time did not add to the prediction of any literacy skills. These findings support previous research suggesting that, during the early phases of learning to read, pause time holds the key in the relation between RAN and reading fluency.

Keywords Rapid naming · Pause time · Phonological awareness · Reading fluency · Spelling · Reading comprehension

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Introduction

Rapid Automatized Naming (RAN) speed, defined as the ability to name as quickly as possible a sequence of simultaneously presented, highly familiar visual stimuli such as objects, colors, letters, or digits, is a strong predictor of reading ability (see Kirby et al., 2010, for a review). The score in RAN tasks is usually the total time to name all stimuli in an array. However, some researchers have argued that considering only the total time conceals important information about the processes taking place during RAN and suggested that we should further dissect RAN total time into its constituent components (articulation time and pause time) and explore how these components relate to reading (e.g., Araújo et al., 2011; Georgiou et al., 2006; Neuhaus, Foorman, et al., 2001).

The studies that decomposed RAN total time into its constituent components have at least three limitations: First, they have been conducted mostly with school-age children and we do not know if similar results can be obtained before children receive any formal reading instruction. This is of interest because performance in RAN is itself affected by literacy instruction (e.g., Cronin & Carver, 1998). Second, with a few exceptions (see Georgiou et al., 2014; Georgiou, Papadopoulos, et al., 2012; Georgiou, Tziraki, et al., 2013; for studies in Greek), most previous studies on RAN components have been conducted in opaque orthographies such as English. In light of findings showing that RAN may be more strongly related to reading in transparent orthographies than opaque orthographies (e.g., Georgiou et al., 2008c; Mann & Wimmer, 2002), examining the role of RAN components in a transparent orthography like German is important. Finally, only a few studies have examined how RAN components relate to reading comprehension (e.g., Li et al., 2009; Neuhaus, Foorman, et al., 2001) and, to our knowledge, none have examined their relation to spelling. This is important because there is evidence that RAN total time is related to both reading comprehension (e.g., Arnell et al., 2009; Johnston & Kirby, 2006) and spelling (e.g., Savage et al., 2008; Stainthorp et al., 2013). Thus, the purpose of this study was to explore the role of RAN components (articulation time, pause time, and pause time consistency) in reading fluency, reading comprehension, and spelling in a sample of German children followed from kindergarten to Grade 1.

RAN components

Researchers have argued that RAN total time should be dissected into its constituent components of articulation time and pause time (e.g., Georgiou et al., 2006; Neuhaus, Foorman, et al., 2001). Pause time is considered the time needed to access and retrieve information from long-term memory as well as the time to shift from one item to the next in an array. In turn, articulation time reflects the integrity of the stimuli in memory or the automaticity of the response after recognition (Neuhaus, Foorman, et al., 2001). Articulation time and pause time, therefore, capture different processes in RAN performance. To better understand the RAN–literacy relation, it is important to investigate which of these processes is responsible for RAN’s

relation with literacy outcomes. Another score that has been derived from RAN performance (but received much less attention than articulation time and pause time) is the pause time consistency, which is the intra-individual variation in an individual's pause times. According to Neuhaus, Carlson, et al. (2001), pause time consistency measures the consistency of processing efficiency. Das et al. (1994) also argued that variation in pause time may reflect blocks of involuntary rests produced by reactive inhibition during repeated naming.

Theoretical explanations of the relationship between RAN and reading

There are several theoretical explanations of why RAN is related to reading (for a review, see Kirby et al., 2010). Four of them are quite popular in the literature. First, some researchers have argued that RAN and reading are related because they both rely on quick access to, and retrieval of, phonological codes from long-term memory (e.g., Torgesen et al., 1997; Wagner & Torgesen, 1987). Second, Bowers and colleagues (e.g., Bowers & Wolf, 1993; Bowers et al., 1999) proposed that RAN predicts reading because it contributes to the development of orthographic knowledge. An alternative hypothesis regarding orthographic knowledge and RAN's relationship to reading has been proposed by Manis et al. (1999). They argued that RAN may partly reflect the ability to form arbitrary connections between a visual stimulus and its name. Third, Kail and Hall (1994) and Kail et al. (1999) argued that RAN and reading are related because they both rely on general processing speed, which is critical in tasks that require integration of information within and between sub-processes. Fourth, some researchers have highlighted the importance of serial processing as the mechanism driving the RAN–reading relationship (e.g., Altani et al., 2020; Georgiou, Parrila, et al., 2013; Protopapas et al., 2018). More specifically, researchers have found stronger relations between RAN and reading tasks of similar format (both discrete or both serial) than dissimilar format (one discrete and one serial) in more experienced readers; in beginning readers, serial RAN was a better predictor of both discrete and serial reading tasks (Altani et al., 2020; de Jong, 2011; Protopapas et al., 2013, 2018). Even though the mechanism underlying the RAN–reading relation is still a subject of debate, the predictive value of RAN total time in reading fluency¹ has been found across different ages (e.g., Vaessen & Blomert, 2010; van den Bos et al., 2002) and languages (e.g., Georgiou et al., 2016; Landerl et al., 2019; McBride-Chang & Kail, 2002; Moll et al., 2014).

RAN components and literacy skills

In general, studies examining the relation of RAN components with reading show that pause time is the main predictor of reading (particularly of reading fluency)

¹ In this paper, we refer to the RAN–reading fluency relation, because, in German, reading fluency measures are typically used. As German is a highly transparent orthography, this leads to ceiling effects in reading accuracy measures (e.g., Landerl & Wimmer, 2008; Landerl, Wimmer, & Frith, 1997).

irrespective of the type of RAN stimuli used (see e.g., Cobbold et al., 2003; and Lervåg & Hulme, 2009, for studies with non-alphanumeric RAN, and see Georgiou et al., 2009; and Neuhaus, Foorman, et al., 2001, for studies with alphanumeric RAN). For example, Georgiou and colleagues (Georgiou et al., 2008a; Georgiou, Tziraki, et al., 2013) found that pause time continued to account for 9–21% of the variance in reading fluency in Grades 1 and 2, even after controlling for general cognitive ability, speed of processing, phonological awareness, phonological short-term memory, or orthographic knowledge. Evidence on the importance of articulation time and pause time consistency is mixed. In regard to articulation time, studies with younger children have shown that it does not predict any reading outcomes (e.g., Cobbold et al., 2003; Georgiou et al., 2006; Neuhaus, Foorman, et al., 2001). In contrast, studies with older children have shown that it predicts reading (particularly reading fluency) (e.g., Georgiou et al., 2009, 2014; Georgiou, Papadopoulos, et al., 2012). In regard to pause time consistency, Neuhaus and colleagues (Neuhaus, Carlson, et al., 2001; Neuhaus, Foorman, et al., 2001) found that RAN Letters pause time consistency was associated with decoding. In contrast, Li et al. (2009) found that RAN Colors, Digits, or Letters pause time consistency was not predictive of reading fluency.

The main goal of reading, however, is to understand the meaning of a text. The easier the access to and retrieval of phonological representations, the fewer resources are spent on this part of reading and more resources can be spent on understanding the meaning of a text (see LaBerge & Samuels, 1974). Not surprisingly, some studies have reported significant correlations between RAN (alphanumeric and non-alphanumeric) total time and reading comprehension (e.g., Arnell et al., 2009; Johnston & Kirby, 2006; Manis et al., 2000). The results for the relation of RAN components with reading comprehension are mixed. For example, Neuhaus, Foorman, et al. (2001) found RAN Letters pause time to be predictive of reading comprehension in first and second graders. In contrast, Li et al. (2009) found that RAN Colors pause time was not predictive of reading comprehension; however, RAN Digits and Letters pause time consistency did predict reading comprehension. These mixed results indicate that the relationship between RAN and reading comprehension still needs further investigation.

Limitations of the studies with RAN components

Most studies on RAN components have focused on school-age children (see e.g., Georgiou et al., 2009, 2014, 2016). In a study with kindergarteners, Georgiou et al. (2006) found that RAN Colors pause time was significantly related with reading accuracy and fluency in Grade 1; however, they did not control for other cognitive skills. Cobbold et al. (2003) also examined younger children and found RAN Objects pause time to predict word-level reading. However, they used a different measure of naming speed in which none of the stimuli were repeated and, similar to Georgiou et al. (2006), did not control for other cognitive skills.

Besides, studies investigating how RAN components relate to spelling are still missing. The studies that examined the relation of RAN total time with spelling have

produced mixed findings. Some studies have found RAN total time to be a significant predictor of spelling (e.g., with alphanumeric RAN: Stainthorp et al., 2013; with non-alphanumeric RAN: Fricke et al., 2016; with combined alphanumeric and non-alphanumeric RAN: Preßler et al., 2014), while others did not (e.g., with alphanumeric RAN: Nikolopoulos et al., 2006; with non-alphanumeric RAN: Landerl & Wimmer, 2008; with combined alphanumeric and non-alphanumeric RAN: Babayiğit & Stainthorp, 2010). In addition, some studies found RAN to be predictive of spelling only under specific circumstances. For example, Furnes and Samuelsson (2011) found alphanumeric RAN to predict spelling before controlling for phonological awareness and Georgiou, Torppa, et al. (2012) found RAN Colors to predict spelling in Greek and English, but not in Finnish. In view of these conflicting results using the RAN total time, examining the contribution of RAN components to spelling performance might provide some further insights into the relation between RAN and spelling.

Finally, even though some studies have examined the role of RAN components in reading across languages varying in orthographic consistency (e.g., Georgiou et al., 2008b, 2015), most studies on RAN components have been conducted in English (e.g., Georgiou et al., 2006, 2009; Neuhaus, Carlson, et al., 2001; Neuhaus, Foorman, et al., 2001). To our knowledge, only one study with kindergarten children has examined the role of RAN components on literacy skills in a consistent orthography (i.e., Greek). Georgiou, Tziraki, et al. (2013) found that pause time was a stronger predictor of reading fluency than articulation time and that pause time remained a significant predictor even after controlling for speed of processing and working memory. Although there are several studies in German examining the relation of RAN with literacy skills (e.g., Fricke et al., 2016; Landerl & Wimmer, 2008; Landerl et al., 2019; Moll et al., 2014; Schmitterer & Schroeder, 2019), to our knowledge, none has explored the role of RAN components.

The present study

This study aimed to examine the relation of RAN components—articulation time, pause time, and pause time consistency—with reading fluency, reading comprehension, and spelling in a sample of German children followed from kindergarten to Grade 1. Furthermore, in this study, we examined the relationship of RAN components with literacy skills after controlling for the effects of phonological awareness (PA) and letter-sound knowledge (LSK), which, along with RAN, are the most important predictors of learning to read (Hulme & Snowling, 2013). Additionally, phonological coding in working memory (also known as phonological short-term memory; PSTM) is considered an integral component of phonological processing (Wagner & Torgesen, 1987) and, for this reason, we controlled for its effects as well. Finally, visual-verbal Paired-Associate Learning (PAL), defined as the ability to establish connections in memory between a given visual stimulus and a verbal response, was found to be related to reading performance (e.g., Horbach et al., 2015; Hulme et al., 2007). In view of Manis et al. (1999) theoretical account that RAN may partly reflect the ability to form arbitrary connections between the visual

stimulus and its name, examining the effects of RAN components on reading and spelling after controlling for the effects of PAL is important.

Based on the findings of previous studies examining the relation between RAN components and reading (e.g., Georgiou et al., 2006, 2009, 2015; Georgiou, Tzi-raki, et al., 2013; Li et al., 2009; Neuhaus, Carlson, et al., 2001; Neuhaus, Foorman, et al., 2001), we hypothesized that:

1. Pause time, but not articulation time, would predict reading fluency, even after controlling for other cognitive skills (i.e., phonological awareness, phonological short-term memory, letter-sound knowledge, and PAL). Whether or not this pattern would also apply to reading comprehension and spelling was examined in an exploratory manner.
2. Pause time consistency would explain a significant amount of variance in reading fluency and reading comprehension.

Method

Participants

Our sample consisted of 257 German kindergarten children (139 boys, 118 girls) in the area of Frankfurt am Main that were followed until the end of Grade 1. These children were tested in RAN and the other predictors at the beginning of the last kindergarten year ($M_{\text{age}} = 5.60$ years, $SD = 0.31$) and about two years later in literacy measures at the end of Grade 1 ($M_{\text{age}} = 7.41$ years, $SD = 0.30$). The assessments were part of the larger project TRIO and this subsample consists only of children who were assessed at the end of Grade 1. Parental and school consent was obtained prior to testing.

Measures

Rapid automatized naming (RAN)

To assess RAN we administered two non-alphanumeric tasks: colors and objects. Children were asked to name as fast as possible five objects (ice, ball, dog, tree, and fish) or colors (black, red, yellow, green, and blue) that were repeated 4 times each and arranged in two rows of 10 (items adapted from Preßler et al., 2014). A child's score was the total time to name the stimuli in each card. We also recorded the children while naming the stimuli to be able to extract the RAN components (see below for details). The internal consistency was McDonald's $\omega = .84$ for the mean articulation times in RAN Objects and Colors, McDonald's $\omega = .83$ for the mean pause times, and McDonald's $\omega = .30$ for the mean pause time consistency, respectively.

Paired-associate learning (PAL)

A computerized paradigm (adapted from Horbach et al., 2015; see also Ehm et al., 2019) was used in which three symbols (triangle, square, and circle) were paired with three syllables (/pa/, /ma/, and /ta/). The symbols were presented separately in the middle of a 14.1-inch screen. At first, the symbol-syllable-pairs were introduced to the children. In the learning phase, the children were asked to name the symbols and received corrective feedback for their responses. Each symbol was presented 10 times while the same symbol was never presented twice in direct succession. Immediately after the learning phase, the retrieval phase started in which children were again asked to name the symbols, but they did not continue to receive feedback. Each item was presented 4 times in an alternating but fixed order. The retrieval phase was automatically stopped after seven errors. The scores were the number of correctly named symbol-syllable-pairs (max during learning phase = 30; max during retrieval phase = 12). The internal consistency of both tasks was McDonald's $\omega = .83$. The composite score for PAL was calculated by averaging the z scores of the two tasks.

Phonological awareness (PA)

To assess PA, a rhyming task was administered. A target word was orally presented to the children. At the same time, the children were shown three or four pictures of objects, one of which rhymed with the target word. Afterward, the target word was orally presented another time and the children were asked to point to the corresponding rhyming object in the booklet. There were three practice trials and 16 test trials. The score was the number of correctly identified rhyme words (max = 16). The internal consistency was McDonald's $\omega = .79$.

Letter-sound knowledge (LSK)

LSK was assessed with a task comprising 12 common German letters (E, N, I, R, A, T, S, H, D, U, L, and C). The letters were presented separately on a white sheet of paper and the children were asked to name each presented letter. German is a consistent orthography: the names of vowels correspond to their sound; the names of consonants usually incorporate the corresponding letter sounds either as initial phoneme (D, H, and T) or as final phoneme (L, M, R, and S); the consonant name of C, however, is inconsistently related to the sound of C. Thus, providing either the letter sound or the letter name was considered correct. The score was the number of correctly named letters (max = 12). The internal consistency was McDonald's $\omega = .91$.

Phonological short-term memory (PSTM)

PSTM was assessed using two forward span tasks (words and digits) of the computerized and adaptive Working Memory Test Battery for Children Aged Five to Twelve Years (AGTB 5–12; Hasselhorn et al., 2012). Children were presented with

a sequence of monosyllabic, high-frequency nouns or digits (1 to 9) and were asked to orally repeat the sequence in the same order as presented. The stimuli were presented every 1.5 s with no stimuli appearing twice in one sequence. Both tasks consisted of 10 trials presented in 5 testing blocks and were adaptive. The first testing block consisted of 2 items. If the child reproduced the sequence correctly, the sequence length was increased by 1 item. If the child reproduced the sequence incorrectly, the sequence length decreased by 1 item (or stayed at the 2-item sequence). For the next four testing blocks, the sequence length was no longer adjusted after each trial but in a more conservative way. If the child reproduced both trials of a testing block correctly, the sequence length in the next testing block was increased by 1 item. If the child reproduced one of two trials of a testing block correctly, the sequence length remained the same. If the child reproduced both trials incorrectly, the sequence length was decreased by 1 item. The score is based on the mean performance in the last 8 trials. Children received a score corresponding to the span length for each correctly recalled sequence. Children received a score corresponding to the span length minus 1 item for each incorrectly recalled sequence. The maximum score in both tasks was 5.5 points. The internal consistency for both tasks was McDonald's $\omega = .84$. The composite score for PSTM was calculated by averaging the two mean values from both tasks.

Reading fluency

A standardized German reading fluency measure was administered (Differenzierter Lesetest – Dekodieren; DiLe-D; Paleczek et al., 2018). The measure consisted of two subtests: word reading and nonword reading. In both subtests, 157 words were presented on a white sheet of paper and children were asked to read out loud as many words/nonwords as possible within a one-minute time limit. The score was the number of words/nonwords read correctly. The internal consistency for the word and nonword reading task was McDonald's $\omega = .94$. The composite score for reading fluency was calculated by averaging the z scores of the two tasks.

Reading comprehension

Reading comprehension was measured using two subtests of a standardized German reading comprehension test (Ein Leseverständnistest für Erst- bis Siebtklässler – Version II; ELFE II; Lenhard et al., 2017). The first subtest measured reading comprehension of sentences. Children were presented with a total of 36 sentences that were missing a word and were then asked to choose the word (among five options) that would best complete the meaning of the sentence. All options in a given sentence belonged to the same part of speech. The sentences differed in length and complexity. The children had three minutes to complete the task. The score was the number of correctly identified words. The second subtest measured reading comprehension of texts. Children were presented with short texts and after silently reading each text, they were asked to answer multiple-choice questions. In total, there were 17 texts and 26 multiple-choice questions. Text complexity and length varied with a minimum length of 12 words and a maximum length of 74 words.

In each multiple-choice question, children had to choose the correct answer among four options. The children were given 7 min to complete as many questions as they could. The internal consistency of the two tasks was McDonald's $\omega = .86$. The composite score for reading comprehension was calculated by averaging the z scores of the two tasks.

Spelling to dictation

Spelling was assessed using the Würzburger Rechtschreibtest für 1. und 2. Klassen (WÜRT 1-2; Trollenier, 2014). Children were asked to write down the missing word in a sentence that was dictated to them. The dictated words could be divided into three categories: (a) words that could be spelled the way they sound, (b) words for which the spelling could be deduced from rules by reflection, and (c) words with orthographic particularities, which could not be deduced but should be learned by heart. The tester would first say the word out loud, then say the word within the sentence and, finally, repeat the word. The sentences were incorporated into four short stories. The score was the number of words written correctly across the four stories (max = 36). The internal consistency was McDonald's $\omega = .89$.

Procedure

Testing at the first measurement point was done in daycare centers ($n = 24$) and children were tested individually in three sessions on three different days. RAN was administered in the first session. PAL and LSK were administered in the second session. PA was administered in the third session. The reading and spelling tasks were administered in children's respective schools ($n = 32$) at the end of Grade 1. Reading comprehension and spelling were administered in one session. The children were tested in groups in the last two measures. Children's reading fluency was tested individually in another session. All tests at both measurement points were administered by trained university students.

Processing of the RAN sound files

The entire naming process was digitally recorded with the Audacity® program (version 2.1.2; Audacity Team, 2016) via a laptop microphone. Separate sound files were recorded for the RAN Object and Colors task. The program PRAAT (version 6.0.36; Boersma & Weenink, 2017) was used to differentiate between the RAN total time and the individual pauses and articulation times. RAN total time was measured in seconds and the RAN components were measured in milliseconds. If the audio contained a lot of background noise, a noise reduction was carried out in Audacity.

The identification of the individual pauses and articulations was first performed by PRAAT by using a volume threshold of -30 dB. Volumes higher than -30 dB were automatically recognized and marked as articulations. Volumes below the

threshold were classified as pauses. If the evaluator noticed problems with the automatic identification of pauses and articulations, the threshold was adjusted.

The classifications by PRAAT were afterward checked manually. Cleaning of the RAN components took place following the procedure developed by Georgiou et al. (2006). Therefore, the data check was carried out in two steps: First, the evaluator listened to the entire audio recording to identify the categories error, correction, skip, or noise. Depending on the category, the evaluator then proceeded to data cleaning.

In this study, the articulation time was defined as the mean of all correctly verbalized articulation times that were not preceded by a skipped stimulus. There were 20 possible articulation times for both the RAN Objects and Colors task, indicating that no cleaning for errors, corrections, skips, or noises took place. Across the 5020 possible articulations in the RAN Objects task (251 participants \times 20 stimuli), 53 instances of cleaning took place (1.06%). Across the 5060 possible color naming articulations (253 participants \times 20 stimuli), 97 instances of cleaning took place (1.92%). The pause time in this study was defined as the mean of all pause times between two correctly verbalized articulations. The end of the line pause time after item 10 was excluded to prevent end of the line scanning to influence the score. There were 18 possible pause times for both the RAN Objects and Colors task, indicating that no cleaning for errors, corrections, skips, or noises took place. Across the 4518 possible pauses in the RAN Objects task (251 participants \times 18 pauses), 217 instances of cleaning took place (4.80%). Across the 4554 possible pauses in the RAN Colors task (253 participants \times 18 pauses), 357 instances of cleaning took place (7.84%). In the following analyses, only the cleaned articulation and pause times were used. Finally, pause time consistency was defined according to Li et al. (2009) as the standard deviation of pause times divided by the mean of pause times. Again, the end of the line pause time after item 10 was excluded.

Results

Preliminary data analysis

Table 1 presents the descriptive statistics for all measures. An examination of the distributional properties of the measures revealed some problems. The RAN pause time, reading fluency, and reading comprehension were substantially skewed and a log transformation was performed to normalize their distribution. The RAN articulation time and pause time consistency were moderately skewed and a square-root transformation was performed. The transformed data were used in all subsequent analyses.

Table 2 shows the correlations between the RAN components, the other cognitive predictors assessed prior to school entry, and the reading and spelling measures. RAN pause time had small to moderate correlations with all literacy measures (r s ranged from $-.21$ to $-.33$). RAN articulation time, however, had weak and mostly non-significant correlations with reading and spelling. Finally, RAN pause time

Table 1 Descriptive statistics for all measures

	<i>n</i>	<i>M</i>	<i>SD</i>	Min	Max	Skew	Kurtosis
RAN objects							
Total time ^a	251	25.11	6.51	12.87	63.09	1.70	5.44
Articulation time ^b	251	489.69	109.17	253.65	794.14	0.39	-0.32
Pause time ^b	251	709.12	298.74	214.64	2067.73	1.34	2.77
Pause time consistency	251	0.57	0.19	0.18	1.34	1.13	1.68
RAN colors							
Total time ^a	253	26.08	7.53	12.25	52.10	0.97	1.12
Articulation time ^b	253	553.70	115.63	304.83	866.81	0.33	-0.17
Pause time ^b	253	668.51	330.90	74.58	2432.73	1.32	3.21
Pause time consistency	253	0.67	0.23	0.21	1.46	0.90	1.01
Phonological awareness (max = 16)	244	8.85	3.68	1	16	-0.15	-0.81
Letter-sound knowledge (max = 12)	253	4.56	4.12	0	12	0.62	-1.03
PSTM							
Words (max = 5.5)	253	2.73	0.64	1.00	4.38	-0.44	0.74
Digits (max = 5.5)	250	2.83	0.66	1.00	4.75	-0.17	0.60
PAL							
Learning phase (max = 30)	250	12.54	7.37	0	30	0.27	-0.78
Retrieving phase (max = 12)	208	6.14	3.47	1	12	0.20	-1.11
Reading fluency							
Words (max = 157)	244	22.30	13.85	0	81	1.17	1.95
Nonwords (max = 157)	243	16.23	8.26	1	39	0.33	-0.47
Reading comprehension							
Sentence (max = 36)	257	5.67	4.13	0	19	0.90	0.58
Text (max = 26)	256	3.23	3.05	0	13	1.09	0.54
Spelling (max = 36)	249	14.56	7.65	0	32	-0.14	-0.67

RAN rapid automatized naming, PSTM phonological short-term memory, PAL paired-associate learning

^aMeasured in seconds

^bMeasured in milliseconds

consistency was only moderately correlated with RAN articulation time ($r = .40$) and had a weak correlation with RAN pause time ($r = -.26$).

Hierarchical regression analyses

Hierarchical regression analyses were conducted to examine whether the RAN components continue to predict reading fluency, reading comprehension, and spelling after controlling for other predictors (PA, LSK, PSTM, and PAL). PA, LSK, PSTM, and PAL were entered as a block in the first step of the regression equation, followed by the RAN components (entered interchangeably at step 2 of the regression equation). We also ran a model in which RAN total time

Table 2 Correlations between all measures

	1	2	3	4	5	6	7	8	9	10	11
1. RAN total time		.36**									
2. RAN articulation			.85**	-.07	-.19**	-.25**	-.31**	-.23**	-.36**	-.30**	-.36**
3. RAN pause				.40**	-.10	-.13*	-.20**	-.05	-.03	-.13*	-.11
4. RAN pause consistency					-.14*	-.14*	-.20**	-.17*	-.33**	-.21**	-.25**
5. PA					-.10	-.03	-.05	.07	.15*	.01	.02
6. LSK						.21**	.32**	.16*	.230**	.36**	.35**
7. PSTM							.31**	.40**	.33**	.43**	.47**
8. PAL								.20**	.30**	.33**	.29**
9. Reading fluency									.27**	.30**	.36**
10. Reading comprehension										.71**	.67**
11. Spelling											.64**

RAN rapid automatized naming, PSTM phonological short-term memory, LSK letter-sound knowledge, PA phonological awareness, PAL paired-associate learning

* $p < .05$; ** $p < .01$

Table 3 Coefficients of hierarchical regression analyses predicting literacy measures

Step	Variable	Reading fluency		Reading comprehension		Spelling	
		β	ΔR^2	β	ΔR^2	β	ΔR^2
1	PA	.147*	.18**	.253**	.29**	.194**	.29**
	LSK	.211**		.271**		.311**	
	PSTM	.175*		.161*		.106	
	PAL	.102		.127		.184*	
2	RAN total time	-.254**	.06**	-.122	.01	-.180**	.03**
2	RAN articulation	.025	<.01	<.001	<.01	-.013	<.01
2	RAN pause	-.228**	.05**	-.097	.01	-.101	.01
2	RAN pause consistency	.184**	.03**	.063	<.01	.032	<.01
2	RAN pause	-.228**	.05**	-.097	.01	-.101	.01
3	RAN pause consistency	.125	.01	.037	<.01	<.001	<.01
2	RAN pause consistency	.184**	.03**	.063	<.01	.032	<.01
3	RAN pause	-.188**	.03**	-.086	.01	-.101	.01

PA phonological awareness, RAN rapid automatized naming, PSTM phonological short-term memory, LSK letter-sound knowledge, PAL paired-associate learning

* $p < .05$; ** $p < .01$

was entered in the regression equation at step 2 to examine if the RAN components were accounting for a similar amount of unique variance in the outcome measures as RAN total time. The results are shown in Table 3. In Table 4 (see “Appendix”), we also display the results of hierarchical regression analyses in which we examined the effects of RAN components (entered at step 2 of the regression equation) after controlling for PA, PSTM, LSK, and PAL (entered one at a time at step 1 of the regression equation).

The results of Table 3 indicated first that RAN total time accounted for more unique variance in reading fluency and spelling than any of the RAN components. Second, RAN pause time and pause time consistency accounted for unique variance only when predicting reading fluency. Specifically, after controlling for PA, LSK, PAL, and PSTM, RAN pause time explained 5% of unique variance and pause time consistency 3% of unique variance in reading fluency. However, the effects of pause time consistency (entered at step 3 of the regression equation) on reading fluency disappeared after controlling for PA, LSK, PAL, and PSTM (entered at step 1) and RAN pause time (entered at step 2). None of the RAN components explained unique variance in reading comprehension and spelling. PA, LSK, and PSTM emerged as significant predictors of reading comprehension, whereas PAL did not. In turn, PA, LSK, and PAL emerged as significant predictors of spelling, whereas PSTM did not.

Discussion

This study aimed to extend previous work on RAN and literacy acquisition across different languages by examining the role of RAN components also in reading comprehension and spelling in a sample of German children followed from kindergarten until Grade 1. We first hypothesized that pause time, but not articulation time, would explain additional variance in reading fluency after controlling for other cognitive skills such as PA, PSTM, LSK, and PAL. The relationship between the RAN components and reading comprehension and spelling was evaluated in an exploratory manner. The results confirmed our hypothesis concerning reading fluency and were in line with those of previous studies (e.g., Georgiou et al., 2006, 2008a; Georgiou, Tziraki, et al., 2013). Pause time continued to predict reading fluency, but not reading comprehension or spelling, even after controlling for PA, PSTM, LSK, and PAL. This has important theoretical implications. More specifically, assuming RAN pause time reflects the speed of access and retrieval of phonological representation from long-term memory (Torgesen et al., 1997), it should contribute to both reading and spelling because both require quick access to phonological representations. Likewise, if RAN and reading were related because both rely on the efficiency of speed of processing, then pause time should predict reading fluency and comprehension equally well because our comprehension task was also timed. Instead, our findings seem to support the theoretical proposition that RAN captures the ability of an individual to simultaneously process multiple items when they appear in serial format (i.e., while articulating an item, one has already access to the phonological representation of the following item, and has previewed the next item). This ability would be particularly important for reading fluency, but not for reading comprehension or spelling. Reading comprehension and spelling tasks do not involve processing of items in serial order.

Secondly, we hypothesized that pause time consistency would explain a significant amount of variance in both reading fluency and reading comprehension. This hypothesis was partly confirmed because pause time consistency predicted only reading fluency. Similar to Li et al. (2009), RAN pause time consistency did not explain any additional amount of variance in reading fluency when RAN pause time was controlled for. In contrast to our hypothesis, pause time consistency did not predict reading comprehension. A possible explanation might be the way we calculated our score in pause time consistency. While the measure of consistency was adapted from Li et al. (2009) and was defined as the degree of intraindividual variability in pause times ($SD/mean$), in the present study cleaning of the RAN components was done according to Georgiou et al. (2006) and, in addition, the end of the row pause time was excluded. Li et al. (2009) only found the predictive relationship of RAN pause time consistency on reading comprehension for alphanumeric RAN tasks and not for non-alphanumeric RAN (like the ones we used in this study). As formal reading instruction in Germany starts in primary school, children in this study were not expected to be highly familiar with alphanumeric stimuli and therefore only non-alphanumeric stimuli were used. The results that

RAN pause time consistency in non-alphanumeric RAN tasks is not significantly related to reading or spelling fits the findings of previous studies and indicates that RAN pause time consistency might only be a significant predictor of literacy skills if the stimuli are similar (i.e., alphanumeric: letters and numbers).

Although the focus of this study was on RAN, it is worth commenting also on the importance of the other predictors of reading/spelling, especially since RAN components did not predict reading comprehension and spelling. The present analyses revealed that PA and LSK were predictive of all reading and spelling outcomes, while PSTM emerged as an additional predictor of reading comprehension and PAL of spelling. Again, these findings appear to be in line with the findings of previous studies in German (e.g., Landerl & Wimmer, 2008; Landerl et al., 2019; Schmitterer & Schroeder, 2019) and other transparent orthographies (e.g., de Jong & van der Leij, 1999; Lepola et al., 2005; Lervåg et al., 2009; Manolitsis et al., 2009).

Our study has some limitations worth noting. In general, the children in our sample attained slightly lower mean scores in the standardized literacy tests in comparison to the normative samples of the tests. Although the scores were still within the range of expected variation between samples, our results may not generalize to children with relatively higher scores. Second, we used non-alphanumeric RAN tasks because we assessed children in kindergarten and not all children are familiar with letters and digits. Third, although processing speed has been argued to explain the RAN–reading relationship (Kail & Hall, 1994), we did not assess processing speed in this study. Finally, our study was correlational and any effects do not imply causation.

Conclusion

The results of this study showed that RAN pause time assessed in kindergarten was predictive of reading fluency at the end of Grade 1 in a German-speaking sample even after controlling for phonological awareness, letter-sound knowledge, phonological short-term memory, and paired-associate learning. These findings suggest that pause time holds the key in understanding the relationship with reading fluency. Thus, in an attempt to better understand the RAN–reading relationship it may be worthwhile dividing the total RAN total time into pause time and articulation time. Further research should explore the role of RAN components (particularly letter and digit naming) in reading and spelling over a longer developmental span.

Appendix

See Table 4.

Table 4 Coefficients of hierarchical regression analyses predicting literacy measures including only one other predictor in the first step

Step	Variable	Reading fluency		Reading comprehension		Spelling	
		β	ΔR^2	β	ΔR^2	β	ΔR^2
1	PA	.252**	.06**	.388**	.15**	.350**	.12**
2	RAN articulation	-.014	<.01	-.094	.01	-.082	.01
2	RAN pause	-.280**	.08**	-.138*	.02*	-.173**	.03**
2	RAN pause consistency	.162*	.03*	.053	<.01	.017	<.01
1	LSK	.333**	.11**	.428**	.18**	.465**	.22**
2	RAN articulation	-.035	<.01	-.094	.01	-.074	.01
2	RAN pause	-.248**	.06**	-.122*	.02*	-.166**	.03**
2	RAN pause consistency	.133*	.02*	.012	<.01	.007	<.01
1	PSTM	.302**	.09**	.340**	.12**	.300**	.09**
2	RAN articulation	<.001	<.01	-.081	.01	-.062	<.01
2	RAN pause	-.271**	.07**	-.119	.01	-.195**	.04**
2	RAN pause consistency	.186**	.03**	.038	<.01	.050	<.01
1	PAL	.256**	.07**	.298**	.09**	.362**	.13**
2	RAN articulation	.005	<.01	-.066	<.01	-.047	<.01
2	RAN pause	-.307**	.09**	-.170*	.03*	-.204**	.04**
2	RAN pause consistency	.172*	.03*	.008	<.01	.034	<.01

PA phonological awareness, RAN rapid automatized naming, PSTM phonological short-term memory, LSK letter-sound knowledge, PAL paired-associate learning

* $p < .05$; ** $p < .01$

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Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

Ethics approval Ethics approval was obtained from the ethics committee of the DIPF | Leibniz Institute for Research and Information in Education (Rostocker Straße 6, 60323 Frankfurt am Main, Germany).

Consent to participate Parental informed written consent to participate was obtained for all children prior to testing.

Consent for publication All authors have approved the manuscript and agree with its submission.

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