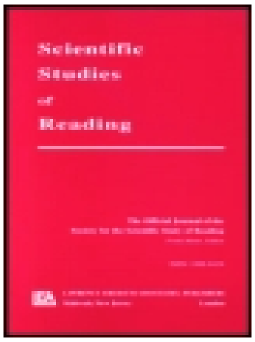

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Eye-movement control in RAN and reading

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ABSTRACT

The present study examined the *visual scanning hypothesis*, which suggests that fluent oculomotor control is an important component underlying the predictive relationship between Rapid Automatized Naming (RAN) tasks and reading ability. Our approach was to isolate components of saccadic planning, articulation, and lexical retrieval in 3 modified RAN tasks. We analyzed 2 samples of undergraduate readers (ages 17–27). We evaluated the incremental contributions of these components and found that saccadic planning to nonlinguistic stimuli alone explained roughly one third of the variance that conventional RAN tasks explained in eye movements registered during text reading for comprehension. We conclude that the well-established predictive role of RAN for reading performance is in part due to the individual ability to coordinate rapid sequential eye movements to visual nonlinguistic stimuli.

The Rapid Automatized Naming (RAN) task is one of the best predictors of concurrent and later reading ability. In the standard version of the task, a participant is shown a grid of common objects, colors, or alphanumeric symbols and is asked to name (say out loud) each item in the grid as quickly as possible. The speed at which a participant is able to name all of the items in the grid is highly correlated with his or her reading ability (Aarnoutse, van Leeuwe, & Verhoeven, 2005; Bowers & Swanson, 1991; Georgiou, Parrila, & Kirby, 2009; Georgiou, Parrila, & Liao, 2008; Hu & Catts, 1998; Oakhill & Cain, 2012; Schatschneider et al., 2004; Tan, Spinks, Eden, Perfetti, & Siok, 2005; Wolf, 1991; Wolf & Bowers, 1999; for a review, see Norton & Wolf, 2012). Correlations as high as r = .55 have been observed between kindergarten performance in RAN and second-grade decoding (Bowers & Swanson, 1991). Moreover, this predictive relationship appears to remain through adulthood, with correlations as high as r = .53 for adults ages 36 to 65 (Van den Bos, Zijlstra, & Lutje Spelberg, 2002). In addition, studies have suggested that 60% to 75% of individuals with reading disabilities exhibit RAN deficits (de Groot, van den Bos, Minnaert, & van der Meulen, 2015; Katzir, Kim, Wolf, Morris, & Lovett, 2008; Waber, Forbes, Wolf, & Weiler, 2004; Wolf et al., 2002). These strong relationships, which hold across languages (Georgiou, Aro, Liao, & Parrila, 2015; Georgiou et al., 2008; Moll et al., 2014; Tan et al., 2005), together with the clinical efficiency of the task itself, which takes less than 5 minutes to administer, make understanding the causal underpinnings of the RAN–reading association a significant goal.

Much research in this direction has examined specific components of the RAN task. Wolf and Bowers (1999, p. 418; see also Wolf & Denckla, 2005) enumerated seven subcomponents that are required for letter-naming:

> a) attentional processes to the stimulus; b) bihemispheric visual processes responsible for feature detection, visual discrimination, and pattern identification; c) integration of visual features and pattern information with stored orthographic representations; d) integration of visual and orthographic information with stored

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> phonological representations; e) access and retrieval of phonological labels; f) activation and integration of semantic and conceptual information with all other input; and g) motoric activation leading to articulation. (p. 2)

The connection to phonological processing (components d–e) has received much attention, with some suggesting that RAN should be understood as an index of a core phonological processing deficit (e.g., Pennington, Cardoso-Martins, Green, & Lefly, 2001; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997; Wagner, Torgensen & Rashotte, 1994). Others have examined the connection to orthographic processes (components c–d), suggesting that RAN deficits indicate weakness in orthographic-phonologic associations (e.g., Bowers & Newby-Clark, 2002; Compton, Olson, DeFries, & Pennington, 2002; Wimmer, Mayringer, & Landerl, 2000). Still other studies have focused on visual aspects of the task (e.g., Compton, 2003; Jones, Branigan, & Kelly, 2008; Moll & Jones, 2013), whereas others have examined articulatory components (e.g., Georgiou, Papadopoulos, Fella, & Parrila, 2012; Neuhaus, Foorman, Francis, & Carlson, 2001; Obregón, 1994).

An alternative approach has embraced the complexity of the task, conceptualizing RAN as a "microcosm or mini-circuit of the later developing reading circuitry" (Norton & Wolf, 2012; p. 430). On this view, RAN is predictive because it involves so many of the linguistic and perceptual processes involved in reading, including accessing phonological, orthographic, and semantic representations, integrating visual information and allocating working memory. Thus, one's performance in the RAN task is an index of the ability to coordinate these multiple cognitive processes efficiently and accurately (Norton & Wolf, 2012; Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000).

The current study returns to the componential approach to investigate a component of RAN that was not explicitly articulated in the Wolf and Bowers's letter-naming model and has received little direct attention: the role of oculomotor control. This component also incorporates elements of the holistic approach advocated by Wolf and colleagues through the idea of coordination; oculomotor control requires the coordination of low-level motor planning with the higher level cognitive processes of word recognition. However, by investigating coordination at the level of eye movements, rather than between cognitive processes more generally, we are able to directly connect the RAN task to natural reading. Thus, we test the hypothesis that a substantial component of the predictive power of RAN comes through the fact that it is the only major reading skill assessment to incorporate the same oculomotor programming required in text reading (Kuperman & Van Dyke, 2011), namely, the ability to rapidly program saccades as the eyes move across the printed page. This hypothesis is related to the idea that RAN is predictive of reading because both require serial processing (Georgiou, Parrila, Cui, & Papadopoulos, 2013). However, we are interested specifically in participants' ability to coordinate rapid and sequential eye movements across the RAN grid, and across the written page. Evidence supporting the importance of seriality in the RAN–reading association comes from studies showing that when each to-be-named item is shown individually (discrete RAN), instead of being presented serially, the RAN–reading relationship is reduced or nonexistent (e.g., Bowers & Swanson, 1991; Jones, Branigan, & Kelly, 2009; Logan, Schatschneider & Wagner, 2011; Stanovich, 1981; Torgesen, Wagner, & Rashotte, 1994; Wagner, Torgensen, Laughon, Simmons, & Rashotte, 1993; Wagner et al., 1994). Here, we suggest that seriality alone is not the key factor, as processing visual information in a text passage or in a RAN grid crucially involves the ability to direct the eyes through the material. We refer to this hypothesis as the *visual scanning hypothesis* (cf. Protopapas, Altani, & Georgiou, 2013).

Some evidence in support of this view is already available from the eye-movement literature. Previous research has revealed that RAN naming times correlate with individual differences in eye movements during word or sentence reading. Longer naming times in RAN tend to come with more fixations per word, smaller saccades, and increased refixation rates, as well as more frequent regressive saccades (Adler-Grinberg & Stark, 1978; Eden, Stein, Wood, & Wood, 1994; Elterman, Abel, Daroff, Dell'Osso, & Bornstein, 1980; Hawelka & Wimmer, 2005; Jones et al., 2009; Lefton, Nagle, Johnson, & Fisher, 1979; Martos & Vila, 1990; Rayner, Slattery, & Bélanger, 2010). A specific connection with eye movements and RAN was observed by Kuperman and Van Dyke (2011), who found that RAN naming times were a strong predictor of *all* aspects of the per-word eye-movement record during sentence reading, accounting for even more variance than length and frequency of individual words. Additional evidence comes from a study by Doyle (2005), who found significant positive correlations ($.32 < r < .59$) between RAN performance and the percentage of fixations and regressions during paragraph reading. Finally, studies that have examined eye movements during the RAN task have found that they are analogous in many aspects to those registered during reading. For instance, eye-movement patterns in both tasks reveal systematic reductions in the uptake of foveal and parafoveal information in less proficient (including dyslexic) versus typical readers in both English and Chinese (for RAN, cf. Jones, Ashby, & Braningan, 2013; Pan, Yan, Laubrock, Shu, & Kliegl, 2013; Yan, Pan, Laubrock, Kliegl, & Shu, 2013; for reading, see Veldre & Andrews, 2014). These reductions are thought to cause (a) increased difficulty of visually inspecting and recognizing the fixated target (i.e., word or symbol); (b) lack of efficiency or accuracy in planning a saccade to the upcoming target, which leads to longer reading times and refixations of that target when it is foveated; and (c) lower quality parafoveal preview of the upcoming target, which attenuates pre-activation of orthographic and phonological features of the target, thus impeding recognition. The preceding studies demonstrate similarities in the nature of oculomotor control and visual uptake between RAN and reading and lend support to the hypothesis that visual scanning constitutes an important component of the RAN–reading relationship.

To investigate this hypothesis further, we recorded eye movements during text reading and in conventional RAN tasks requiring rapid naming of letters and digits. We then estimated the amount of variance each RAN task explains in eye movements observed in a naturalistic reading task. The novel contribution of the current project is several-fold. First, our target population was that of (presumably) proficient university student readers, rather than commonly studied populations of children, clinical populations, or lower literacy adults. As we expect this population to exhibit vast and (over-)trained reading experience, potential deficiencies of oculomotor control, lexical access, or decoding are expected to be minor. Also, unlike most previous studies of the RAN–reading relationship, we used silent text reading for comprehension rather than single-word naming as our task, and our dependent measure was eye movements during silent reading rather than naming latencies, durations, or pauses between productions.

Our most significant contribution is the use of several new experimental RAN-like tasks, which were designed to strip away many of the aforementioned components that Wolf and Bowers (1999) associated with RAN. We conducted two studies with a largely overlapping design, which are reported jointly. Table 1 summarizes the experimental conditions in both studies, as well as the components that their execution requires. The table also specifies which conditions occurred in each study.

Table 1. Conditions and the RAN components they represent, as implemented in Studies 1 and 2.

Condition	Articulation	Activation of phonological codes	Retrieval of lexical information	Oculomotor coordination	Attentional cues	Implemented in
1. Letter-/Digit-aloud (conventional RAN)	+	+	+	+	+	Study 1 and 2
2. Letter-/Digit-silent	—	+	+	+	+	Study 1 and 2
3. Different-silent	—	—	—	+	+	Study 2 only: Nonlinguistic non-nameable symbols
4. Identical-silent	—	—	—	+	—	Study 1: Asterisks Study 2: A non-nameable shape

Conventional rapid naming of letters and digits in Condition 1 (letter-/digit-aloud) was administered while eye movements were recorded. This condition was expected to engage all critical components of RAN, including oculomotor control, retrieval of orthographic codes, their decoding into phonological codes, and speech planning and production. Tasks in Condition 2 (letter-/digit-silent) presented participants with the same kind of letter or digit grids as used in standard RAN and Condition 1, but the instruction was to read the symbols *silently* rather than name them. This manipulation stripped away the need to articulate the items in the grid and in contrast with Condition 1 aimed at isolating the role of speech production as a predictor of reading ability. Study 2 adopted a further modification to this condition, which contained *different* non-nameable symbols as items (Condition 3: different-silent): The instruction was to visually (and silently) inspect every symbol. The rationale for this manipulation was to create a spatial arrangement of visual stimuli that would elicit the same kind of ballistic oculomotor patterns as other RAN grids but would eliminate the need for articulation, or retrieval of phonological codes. The contrast between Conditions 2 and 3 would highlight the unique role of retrieval of phonological labels and articulatory planning (though not execution) in the RAN–reading relationship. Of importance, the amount of variance explained by the different-silent condition would indicate the unique role of oculomotor control in codetermining eye movements in passage reading. The presence of Condition 3 (different-silent) is then the critical difference between our Study 1 and Study 2. Finally, Condition 4 (identical-silent) only differed from Condition 3 different-silent in that it used *identical* non-nameable symbols in the grid. We were interested in whether this condition, which required the same ballistic movements but provided weaker attentional cues than other RAN conditions, would be as predictive of eye movements in reading as Condition 3 different-silent. Again, the amount of variance explained by this condition would isolate the contribution of oculomotor control to reading behavior, whereas its contrast with letter/digit tasks in Condition 2 would show the unique contribution of linguistic information.

To sum up, we examine the relationship between individual variability in eye-movement behavior in RAN-like tasks and naturalistic passage reading to reveal the relative contributions of oculomotor factors and linguistic information in passage reading. Of critical interest was whether characteristics of individual oculomotor control in RAN would independently account for a substantial portion of RAN variability in text reading, and thus corroborate the role of visual scanning in the RAN–reading relationship.

Studies 1 and 2

In two studies, we estimated contributions of all major components of the RAN task to behavioral indices of silent reading for comprehension. Study 1 has one important limitation in that its baseline oculomotor-control condition (identical-silent) is implemented with identical symbols (asterisk) in the RAN grid. The absence of varying attentional cues might be argued to elicit a different, *voluntary* kind of eye movements in that condition rather than the *involuntary* (i.e., caused by external visual stimuli) eye movements elicited during RAN or reading. This may both lower the magnitude of the effect of oculomotor processing on RAN and reading performance and render the comparison across RAN-like tasks inadequate. Study 2 remedies this limitation with a new condition (different-silent) where a set of *different* non-nameable symbols is presented in the grid. Because of their similar design, the methods and most of the results of Studies 1 and 2 are presented jointly.

Methods

Participants

A total of 151 undergraduate students between 17 and 27 years of age participated for partial course credit: 65 (54 female) participants in Study 1 and 86 (73 female) participants in Study 2. None of the participants had been diagnosed with learning or cognitive impairments, and all had normal or corrected-to-normal vision. No language requirement was applied during the data collection. However, this analysis excludes two participants who started acquiring English only at age 4. Eye-movement records were unusable for an additional 11 participants because of excessive signal loss or accidental loss of stored data. The resulting pool contained 138 participants (53 in Study 1, including 42 female, and 85 in Study 2, including 72 female).

Materials

Materials consisted of our variations on the RAN task, as just described in Table 1. See online supplementary materials S1 for further details of materials and procedures. For quantifying individual patterns of natural text reading, we selected Passages 7–11 from the Gray Oral Reading Test (GORT; Wiederholt & Bryant, 2001) to be read silently for comprehension. Passage 4 was used as a practice trial for all participants. Following each passage, participants read and answered five multiple choice comprehension questions (part of the standard GORT instrument). RAN tasks were presented first followed by the reading task for all participants. Materials and procedure of Study 2 are identical to those of Study 1, with a few exceptions, as described in S1 of the supplementary materials.

Variables

Table 2 describes the eye-movement dependent measures used in both Studies 1 and 2. Comprehension accuracy was assessed by the number of correct responses to questions following each text. Conventional RAN naming times were available from recordings taken during the RAN eye-tracking task. These were calculated as the duration of the acoustic signal from the onset of the first symbol production to the end of the articulation of the last symbol in the grid.

Results and discussion

RAN: eye movements

The unit of eye-movement analysis for the RAN conditions was a single symbol in a grid: a letter, digit, asterisk, or shape. After data trimming (described in S2 of the supplementary materials) the pool of observations consisted of 12,057 data points in Study 1 and 39,933 in Study 2. See Table 3 (rows 1–5) for descriptive statistics of all eye-movement variables in the studies. Due to hardware failure, speech production during Letter- and Digit-Aloud tasks was recorded for only 49 participants in Study 2 (eye movements were recorded for all participants): Correlations with naming times reported next were based on this subset of participants. In further analyses, eye movements in RAN were aggregated by participant.

As expected, reading-aloud conditions showed longer total viewing times than their silent counterparts in Studies 1 and 2, consistent with the well-established finding that demands of

Table 2. Eye-movement dependent measures.

Variable name	Method of calculation	Interpretation
Total viewing time	Summed duration of all fixations landing on a target	Total amount of cognitive effort of recognizing a target.
Regression rate	Binary indicator of whether the participant looked back after fixating a target	How consistently the participant maintains forward movement through the grid.
Skipping rate	Binary indicator of whether a target is skipped or fixated	How consistently the participant fixates on targets in a serial fashion.

Note. A *target* refers to either a symbol (in the Rapid Automatized Naming tasks) or a word (in the reading task).

Table 3. Descriptive statistics of aggregate eye-movement measures during Rapid Automatized Naming grid inspection and naming, text reading, and comprehension scores.

		Study 1					Study 2				
Condition	Measure	Min	Max	Mdn	M	SD	Min	Max	Mdn	M	SD
1. Letter-aloud	TVT, ms	55	958	295	334.58	58.13	51	999	364	406.35	182.32
	RR	0	1	0	0.07	0.26	0	1	0	0.09	0.29
	SR	0	1	0	0.06	0.23	0	1	0	0.07	0.26
2. Digit-aloud	TVT, ms	55	966	350	380.46	66.95	53	995	360	389.73	161.23
	RR	0	1	0	0.09	0.29	0	1	0	0.1	0.3
	SR	0	1	0	0.06	0.25	0	1	0	0.09	0.29
3. Identical symbol-silent	TVT, ms	53	983	311.50	345.94	180.30	52	997	338.5	369.44	174.28
	RR	0	1	0	0.14	0.34	0	1	0	0.11	0.31
	SR	0	1	0	0.36	0.48	0	1	0	0.24	0.43
4. Different symbol-silent	TVT, ms						58	997	362	390.42	175.03
	RR						0	1	0	0.11	0.31
	SR						0	1	0	0.14	0.35
4. Letter-silent	TVT, ms	56	981	272	309.16	150.45	52	996	308	347.24	158.85
	RR	0	1	0	0.07	0.26	0	1	0	0.09	0.28
	SR	0	1	0	0.08	0.26	0	1	0	0.1	0.3
5. Digit-silent	TVT, ms	51	997	283	319.59	53.04	55	996	309	345.3	156.12
	RR	0	1	0	0.09	0.28	0	1	0	0.08	0.27
	SR	0	1	0	0.10	0.30	0	1	0	0.11	0.31
6. Letter naming time (per symbol)	Production time, s	0.22	0.76	0.34	0.36	0.09	0.26	0.77	0.41	0.43	0.1
7. Digit naming time (per symbol)	Production time, s	0.25	0.64	0.39	0.40	0.08	0.26	0.57	0.42	0.42	0.07
8. GORT	TVT, ms	214.20	709.70	372.37	389.32	94.35	190.31	795.89	392.21	406.2	103.34
	RR	0.02	0.40	0.14	0.15	0.07	0	0.43	0.16	0.17	0.07
	SR	0.04	0.54	0.21	0.22	0.09	0	0.66	0.19	0.2	0.1
9. Comprehension score	Answers correct	0	5	4	3.54	1.29	0	5	3	3.34	1.27

Note. TVT = total viewing time; RR = regression rate; SR = skipping rate; GORT = Gray Oral Reading Test.

articulation slow down silent reading and may also slow down oculomotor scanning to maintain a fairly short distance between the fixed word and the articulated one (e.g. Inhoff, Solomon, Radach, & Seymour, 2011; Pan et al., 2013). The identical-silent condition showed signs of increased processing effort compared with the other silent RAN conditions, as indicated by longer reading times and more frequent regressions. Particularly strong was the effect on skipping rate, showing an average of 36% of asterisks skipped in Study 1 and 24% in Study 2, as compared to 8% or 11% letters or digits skipped, respectively, in each study during silent RAN performance. We attribute this less controlled progression through the grid of asterisks to the absence of strong attentional cues provided by the varied content of typical RAN grids. This is consistent with the interpretation of Rayner and Fischer (1996), who suggested that lexical material (which we interpret as including letters and digits) affords top-down cues for where to move the eyes (for alternative explanations, see Nuthmann & Engbert, 2009; Vitu, O'Regan, Inhoff, & Topolski, 1995). The finding of more effortful processing in the absence of linguistic cues has also been observed in the literature using the Landolt circles paradigm (Günther et al., 2012), where participants are looking for an open circle in a string of closed circles. Similar results are observed in *z*-string reading, a paradigm in which participants read sentences with every letter replaced with a *z* symbol, such that a sentence *I wish you a Happy Birthday* yields a string *Z zzzz zzz z Zzzzz Zzzzzzz* (Nuthmann & Engbert, 2009; Rayner & Fischer, 1996; Vitu et al., 1995; see also Hutzler, Kronbichler, Jacobs, & Wimmer, 2006, for similar task).

RAN: naming times

Naming times were defined as the time between the first and last articulations of symbols in a grid. Because the read-aloud grid of letters was 5 × 10, and that of digits 4 × 9, for parity we calculated the average naming time per symbol per participant in each grid. Table 3 (rows 6 and 7) reports the distribution of naming times in the letter-aloud and digit-aloud conditions, respectively, in Studies 1 and 2.

Text reading

The unit of analysis for the eye-movement data recorded during reading of GORT passages was the word. After trimming (see S2 of the supplementary materials for details), eye-movement measures were averaged by participant and text. Furthermore, the number of correct responses to comprehension questions was calculated for each participant and each text. Table 3 (row 8) reports distributions of total viewing time, regression, and skipping rates, whereas row 9 in Table 3 reports the distributions of correct answers to comprehension questions in Studies 1 and 2. Eye-movement measures and comprehension scores were averaged by participant and text.

Correlations of RAN behavior and reading behavior

Table 4 reports coefficients for all Pearson correlations that pitted eye movements and naming times in RAN-like tasks against eye movements and comprehension scores in GORT passage reading in Studies 1 and 2. The p values are reported after a family-wise correction of the respective p values (applied using the *p.adjust* function of the *base* package of the *R* statistical software, R Core Team, 2014). See S3 of the supplementary materials for details.

The direction of the correlations was consistent across all measures: longer reading times, and higher regression or skipping rates in RAN-related tasks led to longer reading times and regression or skipping rates in text reading. To take an example from Study 1, considering only the asterisk

Table 4. Pearson's correlations of eye-movement measures and naming times recorded in RAN-related tasks with eye-movement measures and comprehension scores obtained in text reading.

		Study 1				Study 2			
Condition	Measure	GORT TVT	GORT RR	GORT SR	GORT score	GORT TVT	GORT RR	GORT SR	GORT score
1. Letter-aloud	TVT	0.28**	0.03	−0.19**	−0.09	0.34**	0.06	−0.12	−0.09
	RR	0.14*	0.07	−0.21**	−0.06	0.17**	0.15*	0.06	0.08
	SR	0.12	−0.04	0.10	−0.03	−0.11	0.03	0.18**	0.08
2. Digit-aloud	TVT	0.23**	0.05	−0.17*	−0.14†	0.43**	0.15†	−0.15†	−0.09
	RR	0.07	0.01	0.04	−0.05	0.12†	0.18**	0.07	0.07
	SR	−0.04	−0.11	0.16*	−0.02	−0.02	0.07	0.24**	0.08
3. Identical symbol-silent	TVT	0.15*	−0.14	−0.15*	−0.15†	0.24**	0.09	−0.06	0.01
	RR	0.21**	0.24**	−0.12	−0.09	0.11†	−0.09	−0.05	−0.07
	SR	0.07	0.00	0.06	−0.08	0.06	−0.07	0.16**	0.02
4. Different symbol-silent						0.21**	0.10	0.00	−0.05
						−0.08	0.05	0.10	0.08
						−0.06	−0.05	0.21**	0.08
5. Letter-silent	TVT	0.26**	0.03	−0.15*	−0.11	0.37**	0.09	−0.05	−0.01
	RR	0.16*	0.09	−0.05	0.01	0.14*	0.29**	0.2**	0.13
	SR	0.19*	−0.13	0.04	−0.03	0.03	0.07	0.2**	0.07
6. Digit-silent	TVT	0.3**	0.04	−0.24**	−0.13†	0.37**	0.07	−0.04	−0.1
	RR	0.26**	0.13	−0.05	0.00	0.21**	0.23**	0.06	−0.04
	SR	0.12	−0.09	0.18*	−0.06	−0.03	0.10	0.40**	0.04
7. Letter-aloud	Production time	0.21**	0.07	−0.2**	−0.11	0.24**	0.01	−0.06	−0.10
8. Digit-aloud	Production time	0.18**	0.09	−0.13*	−0.15′	0.27**	0.16†	−0.07	−0.15†

Note. Rapid Automatized Naming (RAN) measures are averaged per participant, Gray Oral Reading Test (GORT) eye-movement measures are averaged per participant per text, and GORT comprehension scores per text. TVT = total viewing time; RR = regression rate; SR = skipping rate.

†$p < .10$. *$p < .05$. **$p < .01$.

Table 5. Pearson's correlations of total viewing times recorded in Rapid Automatized Naming–related tasks.

	Letter-aloud	Digit-aloud	Identical-silent	Different-silent	Letter-silent	Digit-silent
Letter-aloud	—	0.62/0.78	0.55/0.57	0.21	0.85/0.6	0.82/0.62
Digit-aloud		—	0.41/0.40	0.39	0.57/0.78	0.60/0.69
Identical-silent			—	0.71	0.68/0.57	0.67
Different-silent				—	0.55	0.53
Letter-silent					—	0.82/0.84
Digit-silent						—

Note. All correlations were significant at the .05 level after the family-wise adjustment. Except for the different-silent condition only available in Study 2, all correlations are reported as *a/b*, where *a* is the correlation in Study 1 and *b* in Study 2. Condition Different-silent is present only in Study 2.

grids (identical-silent), which is the most stripped down version of the RAN task, longer viewing times predicted that participants were slower in reading texts ($r = .15$, $p < .05$). In addition, making more regressions also came with a higher regression rate in text reading ($r = .24$, $p < .01$). Taking the data all together, it is clear that more efficient performance in any of the RAN tasks was associated with more efficient oculomotor behavior in reading. Magnitudes of correlations were in the weak to moderate range $|r| \leq .43$ in both studies, including the correlations with the accepted measure of RAN naming time assessed for the entire grid. This may appear at odds with the strong correlations (often in the range $r = [0.5–0.6]$) that are routinely found in the literature. We discuss this in the General Discussion section.

We also calculated correlations among the different RAN-like tasks; see Table 5. In the interest of space, we report only correlations between total viewing times in all tasks. These and other (unreported) correlations strongly suggest a relationship between the oculomotor control demonstrated in RAN when it is devoid of linguistic content (inspecting a grid of asterisks) and when symbols are recognized and their orthographic and phonological codes retrieved. Across Studies 1 and 2, strong positive correlations ($r > .5$) were observed between all eye-movement measures in all RAN tasks that required silent reading (digit-, letter-, identical and different-silent). Correlations between oculomotor silent (identical- and different-) and reading-aloud tasks were mostly in the moderate range ($.2 < r < .5$), whereas correlations between silent and reading-aloud digit and letter conditions were in the strong range, $r > .57$. All correlational patterns hold true or become somewhat stronger even when RAN and GORT eye movements are aggregated by participant (as opposed to the aggregation by participant and by text for GORT; see S2 of the supplementary materials).

Hierarchical regression models: Study 1

Our RAN conditions are incremental in that more inclusive tasks incorporate all of the cognitive and physiological requirements of the less advanced tasks (see Table 1). Thus, we never expect that a less inclusive task (e.g., one that requires a specific kind of oculomotor control) explains more variance in reading behavior than a more inclusive task (e.g., one that additionally requires lexical access and symbol decoding). The critical question then is whether a less inclusive task explains a significant/substantial amount of variance in text reading behavior, and not whether it outperforms a more inclusive task. Thus, it is expected that tasks that implement pure oculomotor activity (e.g., identical-silent) would show weaker correlations with reading behavior, and explain less variance in reading behavior, than the tasks (e.g., letter- and digit-silent) that additionally share with reading the need to access the mental lexicon and convert orthographic representations into phonological ones. In a series of hierarchical regression models we tested (a) whether oculomotor-control conditions independently explain a significant amount of variance in reading behavior and (b) whether those conditions accounted for a substantial portion of variance explained by more advanced RAN-like tasks.

Step 1 in all models estimated the amount of variance explained by any eye-movement measure (e.g., total viewing time, regression, or skipping rate) in the most stripped down RAN task (identical-silent) as a predictor of any of the eye-movement measures of GORT passage reading.

This amount is compared to the amount of variance by an intercept-only regression model fitted to the same measure in the GORT eye-movement record and indicates whether the oculomotor component explains any variance beyond random noise. In addition, Study 2, Step 2 added the same measure from the different-silent condition. Steps 2a, 2b, and 2c in Study 1 (Table 6) and Steps 3a, 3b, and 3c in Study 2 (Table 7) add as predictors the chosen eye-movement measure as observed in the letter-silent condition, digit-silent condition, or in both conditions, respectively. The hierarchical regression models report the amount of variance explained at each step and its comparison with the amount of variance explained at the previous step. Thus, a significant gain in variance at Steps 2a–c as compared to Step 1 (Study 1) and Steps 3a–c compared to Step 2 in Study 2 would indicate a to-be-expected outcome: that RAN tasks that require processing linguistic information explain additional variance in reading behavior. Finally, at Steps 3a, 3b, and 3c in Study 1 (Table 6) and Steps 4a, 4b and 4c in Study 2 (Table 7) we added predictors of the same eye-movement variable from the letter-aloud, digit-aloud, or both conditions. The comparison of Steps 3a, b, and c with Step 2c in Study 1 and Steps 4a, b, and c with Step 3 in Study 2, identified the role of speech production and fluency in codetermining eye-movement measures and comprehension in reading.

We selected for analysis those pairs of eye-movement measures from RAN and GORT reading that revealed the strongest role (i.e., the largest correlation coefficients) of the most inclusive RAN conditions, letter- and digit-aloud. Tables 6 and 7 report hierarchical regression analyses for GORT total viewing time as a function of RAN total viewing time and regression rate; GORT regression rate as a function of RAN regression rate, and GORT skipping rate as a function of RAN total viewing time.

Hierarchical models presented in Table 6 and Table 7 revealed that the total amount of variance that even the most inclusive RAN tasks explained in the eye-movement measures registered during reading

Table 6. Hierarchical models for selected eye-movement measures in Rapid Automatized Naming and reading observed in Study 1.

Dependent variable	Predictors added	R^2	ΔR^2	p
Model 1: GORT TVT				
Step1	Identical-silent TVT	0.023	0.023	0.017
Step 2a	Letter-silent TVT	0.071	0.048	< 0.001
Step 2b	Digit-silent TVT	0.095	0.062	< 0.001
Step 2c	Letter-silent TVT + Digit-silent TVT	0.098	0.065	< 0.001
R^2 ratio Step 1/Step 2c	23%			
Model 2: GORT RR				
Step 1	Identical-silent RR	0.059	0.059	< 0.001
Step 2a	Letter-silent RR	0.061	0.002	> 0.1
Step 2b	Digit-silent RR	0.063	0.004	> 0.1
Step 2c	Letter-silent RR + Digit-silent RR	0.063	0.004	> 0.1
R^2 ratio Step 1/Step 2c	93%			
Model 3: GORT SR				
Step 1	Identical-silent TVT	0.024	0.024	.016
Step 2a	Letter-silent TVT	0.024	0.000	> 0.1
Step 2b	Digit-silent TVT	0.058	0.034	0.003
Step 2c	Letter-silent TVT + Digit-silent TVT	0.058	0.034	0.006
R^2 ratio Step 1/Step 2c	41%			
Model 4: GORT TVT				
Step1	Identical-silent RR	0.043	0.043	0.001
Step 2a	Letter-silent RR	0.060	0.017	0.041
Step 2b	Digit-silent RR	0.088	0.045	< 0.001
Step 2c	Letter-silent RR + Digit-silent RR	0.088	0.045	0.003
R^2 ratio Step 1/Step 2c	49%			

Note. The following are reported: The dependent variable of the model, predictors added at each step, amount of variance explained (R^2), increase in the amount of explained variance associated with the step (ΔR^2), and statistical significance of the increase. Also reported is the ratio of variance explained by the oculomotor condition and cumulative variance explained by all Rapid Automatized Naming conditions. TVT = total viewing time; GORT = Gray Oral Reading Test; RR = regression; SR = skipping rates.

Table 7. Hierarchical models for selected eye-movement measures in RAN and reading observed in Study 2.

Dependent variable	Predictors added	R^2	ΔR^2	p
Model 1: GORT TVT				
Step 1	Identical-silent TVT	.060	.060	< .001
Step 2	Different-silent TVT	.062	.002	.346 (< .001)
Step 3a	Letter-silent TVT	.138	.076	< .001
Step 3b	Digit-silent TVT	.143	.081	< .001
Step 3c	Letter-silent TVT + Digit-silent TVT	.151	.089	< .001
Step 4a	Letter-aloud TVT	.167	.016	.013
Step 4b	Digit-aloud TVT	.197	.046	< .001
Step 4c	Letter-aloud TVT + Digit-aloud TVT	.197	.046	< .001
R^2 ratio Step 2/Step 3c	41%			
R^2 ratio Step 2/Step 4c	31%			
Model 2: GORT RR				
Step 1	Identical-silent RR	.009	.009	.082
Step 2	Different-silent RR	.016	.005	.132 (.071)
Step 3a	Letter-silent RR	.112	.096	< .001
Step 3b	Digit-silent RR	.073	.057	< .001
Step 3c	Letter-silent RR + Digit-silent RR	.128	.112	< .001
Step 4a	Letter-aloud RR	.128	.000	.930
Step 4b	Digit-aloud RR	.129	.001	.490
Step 4c	Letter-aloud RR + Digit-aloud RR	.129	.001	.752
R^2 ratio Step 2/Step 3c	13%			
R^2 ratio Step 2/Step 4c	12%			
Model 3: GORT TVT				
Step 1	Identical-silent RR	.012	.012	.041
Step 2	Different-silent RR	.027	.015	.024 (.010)
Step 3a	Letter-silent RR	.054	.027	.002
Step 3b	Digit-silent RR	.092	.065	< .001
Step 3c	Letter-silent RR + Digit-silent RR	.096	.004	< .001
Step 4a	Letter-aloud RR	.100	.00	.245
Step 4b	Digit-aloud RR	.097		.632
Step 4c	Letter-aloud RR + Digit-aloud RR	.100		.508
R^2 ratio Step 2/Step 3c	28%			
R^2 ratio Step 2/Step 4c	27%			
Model 4: GORT SR				
Step 1	Identical-silent SR	.01	.01	.079
Step 2	Different-silent SR	.027	.017	.019 (< .001)
Step 3a	Letter-silent SR	.036	.009	.093
Step 3b	Digit-silent SR	.097	.070	< .001
Step 3c	Letter-silent SR + Digit-silent SR	.097	.070	< .001
Step 4a	Letter-aloud SR	.107	.010	.078
Step 4b	Digit-aloud SR	.123	.026	.002
Step 4c	Letter-aloud SR + Digit-aloud SR	.123	.026	.012
R^2 ratio Step 2/Step 3c	28%			
R^2 ratio Step 2/Step 4c	22%			

Note. The following are reported: The dependent variable of the model, predictors added at each step, amount of variance explained (R^2), increase in the amount of explained variance associated with the step (ΔR^2), and statistical significance of the increase. The p-value of the increase in step 2 is given in parentheses. Also reported is the ratio of variance explained by the oculomotor Rapid Automatized Naming (RAN) conditions and cumulative variance explained by all RAN conditions. GORT = Gray Oral Reading Test; total viewing time (TVT), regression (RR) and skipping rates (SR).

was fairly small, ranging between 5.8% and 19.7%. We discuss this further in the General Discussion section. As expected, the bulk of variance in reading behavior was explained by the independent contribution of lexical symbol processing in letter- and digit-silent conditions over and above the oculomotor demands of the RAN task (Study 1, Step 2; Study 2, Step 3). Of interest, processing of digits consistently predicted more variance in RAN than that of letters; see the General Discussion section.

Crucially, the models showed that the identical-silent oculomotor condition (Step 1) explained 2%–6% of the variance in eye-movement measures during text reading. This contribution was consistently significant and explained a substantial proportion of the total variance that RAN performance accounted for. This proportion ranged from 13% (Model 2 in Table 7) to 93% (Model 4), with a median of 45%.

We also reported (in parentheses in Table 7) the comparison between the model in Step 2 with the intercept-only model to test whether oculomotor conditions explained nonrandom variance when considered jointly. Furthermore, in Study 2, a comparison of Steps 1 and 2 indicated the role of attentional cues provided by the diverse (vs. identical) visual stimuli.

We note that the model with GORT regression rate as a function of RAN regression rate showed the weakest performance of the oculomotor RAN conditions in Study 2 (1.6% of explained GORT variance in Step 2 and 12% of total GORT variance explained by all RAN tasks). Yet the same model was the one where the oculomotor condition showed the strongest performance in Study 1 (5.9% of explained GORT variance in Step 1 and 93% of total GORT variance explained by all RAN tasks). This suggests that the specific relationship between regression rates in RAN and GORT is less stable than others and should not be overinterpreted.

General discussion

The present study aims at identifying factors responsible for the widely acknowledged role of RAN as a strong predictor of reading ability, across ages, skill and ability levels. We examined the visual scanning hypothesis, which suggests that a key ability underlying RAN predictivity is the need to rapidly engage and disengage visual stimuli in a consistent and efficient fashion—just as is required when reading natural texts (Kuperman & Van Dyke, 2011). To test this hypothesis, we implemented incremental RAN conditions, with each successively more complex grid including all cognitive demands that were required in the more basic ones. Demands of the RAN-like tasks ranged from basic oculomotor control in grids presenting non-nameable identical (Studies 1 and 2) or different (Study 2) shapes, to an additional demand to retrieve orthographic codes for letters or digits and decode them into phonological codes, to planning and execution of speech production of those letters or digits (Table 1).

We do recognize that compared to RAN–reading correlations typically reported in the literature, those reported here are relatively weak. For example, Protopapas et al. (2013) observed that digit forward–RAN accounted for 37% of variance in word reading fluency. We believe this apparent discrepancy stems from both our choice of population and task. It is not surprising that our sample, which represents the higher end of the skill continuum, shows overall lower correlations between RAN and reading tasks. More important, however, it is not surprising that processes subserving single symbol recognition (including oculomotor coordination) explain less variance in our text reading task than in a word reading task. Indeed, in our data the average amount of variance explained by the total of all RAN-related read-silent conditions was 8% (Mdn = 9.2%) across Studies 1 and 2, which is on par with the amount of variance that RAN naming times explained in text reading fluency in Protopapas et al., namely, 7% explained by digit-forward and 6% by digit-backward RAN. The reasons for the magnitude difference in relation to word and text reading tasks are important to understand so that the RAN–reading relationship can be interpreted more meaningfully. We suggest that it arises from two sources. First, it must be recognized that text reading is more remote from the demands of RAN than is single word recognition, as it requires many additional processes, such as syntactic and discourse-level processing, inferential logic, world knowledge, working memory, and so on. This task complexity will necessarily reduce the amount of variance associated with RAN. On the flip side, RAN and word naming tasks have shared components that are not inherently present in text reading (i.e., articulation), and these will serve to inflate the magnitude of that relationship. Crucially for the current study, however, the factors likely responsible for our low-magnitude correlations are orthogonal to our goal, which is to establish whether the oculomotor component of RAN would play a significant role in the RAN–reading relationship, precisely during natural text reading. In support of this, we observed consistently strong correlations between eye movements recorded in oculomotor-only conditions and in the more inclusive silent RAN tasks (all $rs > .5$, all $ps < 0.05$ after family-wise correction). This pattern reveals a substantial shared component between the RAN conditions: we argue that this component is the ability to efficiently coordinate rapid serial eye movements over a grid. The finding is consistent with our previous work, which revealed RAN to be a ubiquitous predictor of per-word eye-movement measures during sentence reading, explaining more variance than linguistic variables like word length and frequency (Kuperman & Van Dyke, 2011). It confirms our speculative account of those initial results, which pointed to the fact that RAN is the only major reading skill assessment to incorporate the same oculomotor programming required in text reading.

Although the current data provide support for the visual scanning hypothesis, we acknowledge a recent criticism of this idea. Protopapas et al. (2013) coined the phrase "visual scanning hypothesis" to summarize findings and interpretations of Clarke et al. (2005), Logan et al. (2011), and Kuperman and Van Dyke (2011). Protopapas et al. further proposed that the visual scanning hypothesis implicates "overlearned, automatized procedures effecting left-to-right-then-down control" (p. 2) as a predictive factor in the relation between RAN and reading fluency. Consequently, they argued that a backward RAN condition (scanning right to left, bottom to top) would negate the visuo-oculomotor advantage that proficient readers may have, because more and less proficient readers would be equally unexperienced with coordinating serial eye movements in the direction opposite to that of reading. Thus, the correlation between backward RAN and reading should be significantly reduced if the visual scanning hypothesis were correct. In fact, they found that correlations between reading fluency and naming times in the standard and in the backward versions of the task were equally strong. This finding, along with null effects observed for manipulations of presentation format (rows vs. columns) and other arguments, led them to conclude that directionality (automatized or not) is irrelevant for the RAN–reading relationship.

We agree with the conclusions of Protopapas et al. but disagree with their suggestion that these findings provide evidence against the visual scanning hypothesis. We argue that the visual scanning hypothesis—as defined here and envisioned in the publications that are credited with the hypothesis—can easily accommodate Protopapas et al.'s findings. We maintain (a) that a substantial part of the variance shared by RAN and text reading is due to the shared requirement for coordinating rapid sequential eye movements in recognition of visual objects and (b) that an individual's ability to meet this demand in an efficient and consistent way requires both cognitive control and motor coordination, both of which lead to better performance in RAN-like tasks and in text reading. Crucially, the question of directionality of visual scanning and how automatized it may be as a result of reading experience is orthogonal to the visual scanning hypothesis. We predict that better performance in any task requiring orchestration of rapid sequential eye movements would correlate with better text reading, including counterdirected or vertical inspection of RAN-like grids or symbol/word lists.[1] Hence, we believe that the Protopapas at al. findings of equally strong correlations between text reading fluency and forward and backward RAN conditions can rather be interpreted as support for the visual scanning hypothesis. Moreover, although the current article does not manipulate scanning direction, we do demonstrate that RAN tasks implemented in the direction of reading reveal a noticeable independent role of oculomotor control, at least for skilled adult readers.

In conclusion, the current results present evidence in favor of the visual scanning hypothesis—the idea that a significant component underlying the RAN–reading relationship is the ability of the RAN task to index participants' fluency and skill at moving their eyes sequentially across a printed page. Our data further point to the important role that linguistic knowledge has in directing eye movements. We found that eye movements were less efficient (longer fixations, higher regression, and skipping rates) in the absence of linguistic cues. This observation is notable given the relative paucity of linguistic information available in the typical RAN task (limited to only letter or digit form cues for the to-be-produced phonological forms.) We take this as reflective of the broader importance that linguistic knowledge has in directing saccades during natural reading, where cues may range from lexical (e.g., word frequency, orthographic or phonological neighborhood) to contextual (e.g.,

[1]It is worth mentioning that of the three articles that Protopapas et al. credit with the visual scanning hypothesis, only one mentions the direction of reading as a possible factor in the RAN–reading relationship (Logan et al., 2011).

predictability of a word in a given context, syntactic role in the sentence, or referential status in a discourse). Indeed, several models of eye movements explicitly incorporate a role for linguistic knowledge in directing attention or saccade planning and execution during reading (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle, Rayner, & Pollatsek, 2003). The implication of the current results is that the predictability of RAN can best be understood as stemming from the task's ability to simultaneously account for variance associated with programming eye movements during reading and the ease with which readers incorporate linguistic knowledge into those calculations.

Our primary findings are in support of a significant contribution of oculomotor control to the RAN–reading association; however, three other findings in the current data deserve mention. First, the digit-silent condition consistently showed stronger correlations with, and explained more variance, in text reading than the letter-silent condition, even though texts contained alphabetic, not numeric, material. We link this observation to the more complex nature of phonological representations associated with digits than with letters: Specifically they can be monosyllabic ("one") or bisyllabic ("seven"). Even though speech production was not required in letter- and digit-silent conditions, speech planning is known to be ongoing even in silent reading (Abramson & Goldinger, 1997; Ashby & Clifton, 2005; Breen & Clifton, 2011).

Second, our hierarchical modeling revealed a negligible role of read-aloud RAN tasks in predicting text reading behavior. This may be expected given the silent character of text reading and points to the unsuitability of using name-aloud tasks as predictors of *text* reading ability. As noted earlier, it is important to be aware that the shared articulatory component in standard RAN tasks and in word naming tasks will support high correlations between the two; however, this correlation should not be interpreted as indicative of an equally strong relationship between standard RAN and text reading ability.

Finally, no RAN condition, however inclusive, showed a significant correlation with comprehension scores that gauge the reader's understanding of the entire passage. This suggests that the RAN–reading relationship is at its strongest when online processes of word recognition are considered but has little bearing on higher order inferential processes of building discourse-level representations of the passage, at least not for the highly proficient population tested here. This finding is consistent with our overall conclusion, which is that a significant proportion of the variance shared between RAN and reading is associated with the ability to rapidly engage and disengage visual stimuli in a consistent and efficient fashion during online text reading.

Conclusion

The observed patterns confirmed the overall connection between RAN and reading. More efficient performance in processing any version of the RAN grid (e.g., shorter fixations, fewer regressions or skips) predicted more efficient eye-movement behavior in text reading (cf. Table 3). Most significant for the visual scanning hypothesis, however, is that correlations between oculomotor-only RAN conditions with text reading behavior were of the same polarity and similar (generally, weaker) magnitude than the correlations between more inclusive RAN conditions and text reading behavior; see Table 5. The hierarchical regression analysis further revealed that oculomotor conditions (identical-silent in Study 1, or jointly identical- and different-silent in Study 2) accounted for 2% to 6% (M = 3.5%) of variance in reading-for-comprehension eye movements, whereas the maximum amount of variance that the most inclusive RAN tasks explained in reading eye movements ranged between 6% and 20% (M = 10.7%). These oculomotor contributions were significant in all models. The contributions of conditions that implemented letter or digit recognition additionally accounted for an average of 9.2% (maximum = 10%) and were significant. Evidence for the role of articulation is mixed and largely points at the negligibly small contribution of this component to explaining variance in natural reading (M and Mdn < 1%). Although these figures appear small, weighed against the total variance that all the RAN conditions explained in GORT eye movements, they are considerable: The oculomotor conditions accounted for an average of 34.5% (*Mdn* = 39.5%) of this total. Given the statistical reliability and the relative size of the contribution from oculomotor-only conditions, we conclude that planning and coordinating eye movements is an important factor in explaining the RAN–reading relationship, even in the absence of linguistic information. Specifically, these findings highlight the importance of a readers' ability to engage and disengage visual stimuli in a sequence of rapid serial movements—a skill that is critical for successfully reading natural texts.

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