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Oculomotor planning in RAN and reading: a strong test of the visual scanning hypothesis

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Abstract The current study investigates the validity of the visual scanning hypothesis, which posits that rapid automatized naming (RAN) predicts reading skill partly because both require the ability to perform rapid sequential eye-movements. Our data consist of eye-movements collected while 124 young English speaking adults of variable reading skill read passages and performed six modifications of RAN. These modifications isolated articulatory, lexical, oculomotor and attentional task components of RAN. A further requirement for participants was to perform each of the RAN tasks in two directions—the habitual direction of reading (RAN forward) and from right to left and top to bottom (RAN backward). Participants who were better at oculomotor control in RAN-like tasks were better readers regardless of task type or direction. Our most crucial finding is that the explanatory contribution of oculomotor control in the RAN-reading relationship is independent of the practice effect afforded by the habitual direction of visual scanning in reading.

Keywords RAN · Oculomotor control · Visual scanning hypothesis · Reading · Scanning direction

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Introduction

Rapid automatized naming (RAN) is a robust predictor of reading ability across languages, ages, and levels of skill. Performance in this task is typically defined as the time it takes participants to name a series of objects, colored squares and/or alphanumeric characters presented in a grid. RAN has shown remarkable diagnostic utility. It has proven useful in identifying whether at-risk children will develop reading difficulties in children as young as 42-months-of-age (Lyytinen et al., 2006; Snowling, Gallagher, & Frith, 2003). Longitudinal studies following children from kindergarten through the first few primary grades have found correlations between pre-reading RAN scores and 4th grade measures of reading ability as strong as $R^2 = 0.54$ (Badian, McAnulty, Duffy, & Als, 1990). Moreover, Schatschneider, Fletcher, Francis, Carlson, and Foorman (2004) found that RAN letter naming speed in kindergarten explained more of the unique variance in grade 2 reading fluency (0.19) than phonological awareness (0.13) or letter sound knowledge (0.11). Other studies have found similar relationships, even in languages with relatively shallow orthographies such as Italian (Brizzolara et al., 2006; Di Filippo et al., 2005; Franceschini, Gori, & Ruffino, 2012), Finnish (Lyytinen et al., 2006), German (Wimmer, 1993), Norwegian and Swedish (Furnes & Samuelsson, 2011) and Greek (Georgiou, Papadopoulos, Fella, & Parrila, 2012). RAN has also been shown to predict reading abilities in Chinese logographs (Ho, Chan, Tsang, & Lee, 2002) and Japanese phonograms (Wakamiya et al., 2011).

Notably, the predictive value of RAN does not end with adolescence. Van den Bos, Zijlstra, and Spelberg (2002) found a correlation of $r = 0.53$ between word list reading and RAN in Dutch-speaking adults aged 36–65. Similar results have been seen between reading comprehension scores and RAN in adults, with correlations ranging between 0.31 and 0.45 (Arnell, Joanisse, Klein, Busseri, & Tannock, 2009; Swanson, Trainin, Necoechea, & Hammill, 2003). Indeed, Norton and Wolf (2012) have suggested that RAN represents a “microcosm of reading” because both tasks require automaticity of many of the same physical and cognitive processes, including, among many others, attention to the stimulus, retrieval of phonological labels, integration of semantic and conceptual information and articulation (see also Wolf & Bowers, 1999).

One important component of the task missing from Norton and Wolf’s conceptualization is the notion that both tasks require rapid sequential movements across a series of symbols (RAN) or words (reading) and the ability to efficiently and consistently engage and disengage attention from visual stimuli (see also Protopapas, Altani, & Georgiou, 2013a; Protopapas, Altani, & Georgiou, 2013b). The recent “visual scanning hypothesis” (Kuperman & Van Dyke, 2011; Kuperman, Van Dyke, & Henry, 2016) emphasizes this role of oculomotor control as a component process that is shared by RAN and reading.

Many threads of evidence support the claim that the shared demand for efficient planning and coordination of eye-movements is partly responsible for the robust link between RAN and reading performance. Kuperman et al. (2016) directly tested this hypothesis using eye-tracking and novel RAN-like tasks. By asking participants to silently inspect grids containing non-nameable symbols, Kuperman et al. isolated an oculomotor and spatial attentional component shared by RAN and reading. Since processing such grids removes the need for articulation, activation of phonological codes or lexical access in these conditions, the only demand is the one at the core of the visual scanning hypothesis, that is, to engage and disengage attention from visual stimuli while planning rapid sequential movements across a page. These pure oculomotor RAN tasks explained 2–6% of variance in eye-movements during passage reading, and accounted for a substantial share (median 45%) of the total variance accounted for in traditional RAN tasks (Kuperman et al., 2016; for related findings see Doyle, 2005; Onochie-Quintanilla, Defior, & Simpson, 2017).

Further similarities in visual scanning strategies in RAN and reading arise from a comparison of how proficiency affects the use of visual information in one's parafovea. In both RAN and reading, more proficient readers enjoy a greater parafoveal preview advantage of upcoming symbols and words, which facilitates their processing of the previewed word or symbol when it is fixated (for RAN, see Jones, Ashby, & Braningan, 2012; Jones, Obregón, Kelly, & Branigan, 2008; Yan, Pan, Laubrock, Kliegl, & Shu, 2013; for reading, see Choi, Lowder, Ferreira, & Henderson, 2015; Veldre & Andrews, 2014).

Criticism of the visual scanning hypothesis

Despite the corroborating evidence described above, the visual scanning hypothesis faces an important challenge posed by findings of Protopapas et al.'s (2013b) study. At the core of this challenge is the notion of a perceptual span in reading, that is, the field of effective vision, which is known to develop asymmetrically in the direction of reading as a function of reading experience (Blythe, 2014; McConkie & Rayner, 1975; Rayner, 1986; Rayner, Slattery, & Bélanger, 2010; Veldre & Andrews, 2014). This asymmetry affords a right-side parafoveal advantage in languages with the left-to-right direction of reading (in English, 13–14 letters can be processed to the right and only 2–3 to the left of the fixation point, see discussion in Rayner, 1998) and a left-side parafoveal advantage in languages like Hebrew, Arabic, Urdu or Uyghur, which are read from right-to-left (Jordan et al., 2014; Paterson, McGowan, White, Malik, Abedipour, Jordan, 2014; Pollatsek, Bolozky, Well, & Rayner, 1981; Yan et al., 2013). The advantage materializes in the ability to elicit certain (orthographic, phonological and possibly semantic) information about not-yet-fixated visual objects within the perceptual span: this benefit is cashed in when the object is foveated and leads to a reduction in one's processing effort.

Protopapas et al. (2013b) have theorized that the asymmetry of the perceptual span during reading transfers to RAN tasks. Moreover, they argue that the oculomotor and spatial-attentional link between RAN and reading would only be observed if both tasks are performed in the highly-practiced direction of reading. According to their directional hypothesis, only in RAN forward tasks can readers fully utilize their practiced attentional and oculomotor strategies, including the parafoveal advantage granted by the skewed perceptual span. If RAN were to be administered in the backward direction—right-to-left and bottom to top, with a right-ward sweep at the end of each grid line—the RAN-reading link would be broken. Because all readers of Greek (or English) are equally unpracticed in backward-directed oculomotor control, they would lose all parafoveal advantage, and thus correlations between RAN backward and reading would be expected to be weaker than the correlations between RAN forward and reading.

To test this idea, Protopapas et al. (2013b) had 107 Greek children complete both traditional RAN (RAN forward) and an experimental version of RAN backward, naming each item in the grid from right to left. The outcome they observed was opposite to their prediction. RAN backward was either equally or more strongly correlated with word reading fluency and passage reading fluency than RAN forward (word: backward $r = 0.61$ vs forward $r = 0.70$; passage: backward $r = 0.35$ vs forward $r = 0.26$). That the unpracticed direction did not attenuate the predictive power of RAN for reading led the authors to reject the directional scanning hypothesis and to conclude that oculomotor control and its related attentional demands cannot be a factor in the relationship between RAN and reading.

Protopapas et al.'s interpretation is open to several points of criticism. First, equally strong correlations between reading behavior and performance in two directions of RAN do not necessarily signify that oculomotor or spatial-attentional control plays no role in the RAN-reading relationship. They may only imply that oculomotor control is an equally strong (or an equally weak) underlying component of this relationship, and that its share in explaining variability is not at all affected by the scanning direction. Suppose, for instance, that the change in direction adds a penalty to the efficiency of oculomotor control in RAN backward, because of a weaker parafoveal preview or other factors. If the penalty is constant for all saccades directed backwards or for subsequent fixations, then indices of oculomotor control of RAN backward and forward would produce identical correlations with indices of reading effort. Mathematically, adding a constant to one term in a correlation does not alter the correlation magnitude.

Second, the argument of Protopapas et al.'s study relies on an assumption that visual scanning in RAN would demonstrate the same skewness of perceptual span as reading would. Yet unlike reading, individuals do not spend a lifetime learning how to process RAN-like grids of symbols in either direction. It is thus plausible that the backward direction of visual scanning would not disrupt the oculomotor and perceptual patterns of grid scanning as much as it would disrupt reading (Afsari, Ossandón, & König, 2016; Inhoff, Pollatsek, Posner, & Rayner, 1989).

Finally, the visual scanning hypothesis makes a specific claim that directionality is irrelevant for whether the RAN-reading relationship can be observed. Kuperman et al. (2016, p. 184) 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". Thus, the equality of RAN forward and RAN backward as predictors of reading performance reported by Protopapas et al. (2013b) are not problematic for the visual scanning account.

Protopapas et al. (2013b) reveal an important deficit in the current body of empirical evidence for the RAN-reading relationship, and specifically its shared oculomotor component. Our goal is to extend our understanding of this relationship by offering a new test of the visual scanning hypothesis. Here, we manipulate the direction of visual scanning in RAN tasks and examine within subjects whether a change in direction affects the strength of a correlation between eye-movements in RAN and in passage reading for comprehension. We contrast forward scanning of grids of symbols in the direction of reading (left-to-right, and top-to-bottom) with backward scanning (right-to-left, bottom-to-top), as proposed by Protopapas et al. (2013b). We further isolate the unique contribution of oculomotor control by manipulating the nature of the task (reading aloud, silent reading, or visual inspection) and the nature of elements in RAN grids (letters, digits or non-nameable symbols), see below. If the visual scanning hypothesis holds, indices of oculomotor control in RAN will be reliable and substantial co-determinants of variability in eye-movements during reading, regardless of directionality of visual scanning. We predict—in line with reports on compound spatial biases in non-reading visual tasks (see review in Afsari et al., 2016)—that scanning direction will have little influence on oculomotor control during RAN tasks, especially in the "oculomotor" conditions with non-nameable symbols. In this paper and our prior work (Kuperman et al., 2016) we use the term "oculomotor control" in the same sense as it is used in research of eye movements in reading, that is, as ballistic eye movement patterns that are driven by cognitive and attentional demands of a task that requires rapid and efficient orchestration of multiple physiological and psychological processes. We view these higher-level demands as critical for eye-movements even in the most stripped-down RAN-like conditions that we study.

We conducted a large-scale eye-tracking experiment in which participants completed a battery of RAN tasks in both the forward and backward direction, as well as reading passages for comprehension. We decided to change the direction of RAN scanning rather than the direction of reading (as in Afsari et al., 2016; Inhoff et al., 1989) to avoid the ecologically questionable disruption of reading as an overlearned activity. Apart from the critical manipulation of direction, this study follows the design of Kuperman et al. (2016), where RAN grids and instructions are manipulated to incrementally isolate component processes of RAN, see Table 1 for the list of processes. These RAN-like manipulations enable us to pin down the unique contribution of oculomotor conditions and of other components to individual variability in reading behavior, across scanning directions. They also allow for establishing differences and similarities in how scanning direction affects oculomotor, perceptual and cognitive components that RAN shares with reading.

As in Protopapas et al. (2013b), we expect correlations between reading and RAN backward to be no weaker than those between reading and RAN forward. Contrary to predictions of Protopapas et al., we expect oculomotor conditions to show a reliable and substantial contribution to the RAN-reading correlations, both in the backward and forward conditions.

Table 1 Conditions and the RAN components they represent

Condition	Articulation	Activation of phonological codes	Retrieval of lexical information	Oculomotor coordination
1. Letter-/Digit-Aloud	+	+	+	+
2. Letter-/Digit-Silent	–	+	+	+
3. Different-Silent	–	–	–	+

Letter-/Digit-Aloud is conventional RAN

Method

Participants

Eighty-six undergraduate students (73 female) between 17 and 27 years-of-age participated for partial course credit: one participant was removed due to excessive signal loss.[1] This cohort was recruited through the departmental participant pool. Additionally, 64 (21 female) non-college-bound readers between 18 and 30 years of age participated for monetary compensation ($15 an hour). This cohort was recruited through classified ads posted on recruitment websites and by word of mouth. In this cohort, we only considered 39 non-college-bound readers who completed both the RAN and GORT passage reading tasks (others completed a sentence reading task instead of passage reading) and whose recordings were not subject to signal loss. None of the participants had been diagnosed with learning or cognitive impairments, and all had normal or corrected-to-normal vision and self-reported as native speakers of English. Performance of the undergraduate and non-college-bound cohorts on eye-movement and acoustic measures in RAN tasks (see below) was statistically indistinguishable (all t tests yielded $p > 0.05$), and so we opted for considering the 124 participants jointly as a single cohort.

Materials

Manipulations of RAN tasks

Materials consisted of variations on the RAN task designed to deconstruct RAN in such a way as to enable us to examine the contributions of lexical access and activation of phonological codes, articulation, oculomotor control and attentional cues as predictors of reading ability (see Table 1). Condition 1 *Letter-/Digit-Aloud*

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[1] Performance of this cohort in RAN forward (but not RAN backward) conditions and passage reading is reported as Study 2 in Kuperman et al. (2016). Due to differences in aggregation (reading eye-movements are averaged by participant in this study, rather than by both a participant and text complexity) and trimming, minor differences in descriptive statistics may be observed between present analyses and those in Kuperman et al. Our analysis with different types of data trimming showed identical critical patterns.

was expected to require all 5 of the processes under investigation, because participants were instructed to name alphanumeric symbols out loud. In Condition 2 *Letter-/Digit-Silent*, participants silently named the symbols allowing us to assess the contribution of articulation.

Condition 3 *Different-Silent* presented grids with different non-nameable symbols instead of letters or digits for silent visual inspection. A comparison between Conditions 2 and 3 identified the contribution of a phonological representation that linked to some (nameable) visual objects in RAN grids but not others (non-nameable ones). In Condition 4 *Identical-Silent*, letters and digits were replaced by the *same* non-nameable symbol. The motivation for this condition was to remove attentional cues afforded by diverse visual materials and isolated the role of ballistic movements in predicting reading performance. However, it is not clear whether this condition achieves the desired effect because it does not offer visual anchors for guiding the successive movements, and may not provide sufficient exogenous reasons to keep progressing across a grid where all symbols are identical. For completeness, we provide descriptive statistics for this Identical-Silent condition but forgo a direct comparison between this and other conditions. A test of the role that attentional cues play over and above the basic oculomotor control is relegated to future research. The final manipulation required participants to perform each of these tasks in two directions. In RAN forward tasks participants fixated on symbols from left-to-right and from the top-line to the bottom-line. In RAN backward, participants started at the bottom right symbol and fixated from right-to-left and from the bottom-line to the top-line. This manipulation allows us to test predictions related to scan direction, as well as evaluate the efficacy of RAN backward in comparison to conventional RAN in predicting reading ability. RAN tasks were presented first and followed by the reading task.

Passage reading

For quantifying individual patterns of natural text reading, we selected passages 8-11 from the Grey Oral Reading Test (GORT-IV; 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 5 multiple choice comprehension questions (part of the standard GORT instrument): see Supplementary materials S1 for further details.

Reading experience

We used the Author and Magazine Recognition Tests (ART and MRT; Acheson, Wells, & MacDonald, 2008) to evaluate variability in readers' exposure to print. Each test consists of 30 names of existing fiction writers or magazine titles and 30 foils, that is, names of non-writers or non-existing magazine titles. Participants are instructed to only mark actual authors/titles. Their score increases by 1 for each correct response and decreases by 1 for each incorrect response. Due to a software error, the tests were administered to all 39 community-pool participants, and only 20 university students, to a total of 59 (48% of the participant pool). Since analyses with ART and MRT tests produced near-identical results, in what follows we only report analyses with the ART, which is a more commonly used test (Moore & Gordon, 2015).

Variables

RAN naming times 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 based on recordings taken during the RAN eye-tracking task. Because we used grids of different sizes (4 × 9 and 5 × 10 symbols), an average naming time per symbol and per participant was calculated across the two grids and used in further analyses.

Eye-movements in RAN-like tasks were represented by three measures: total viewing time (TVT; the sum of all fixations on a symbol in the RAN grid), regression rate (RR; the likelihood of a saccade from the fixated symbol in the direction opposite to the direction of visual scanning), and skipping rate (SR; the likelihood of not fixating a symbol in a grid). These measures reflect both the individual consistency of visual scanning (gauged as skipping rate), its speed (total viewing time) and its efficiency in maintaining the direction of scanning (regression rate). A symbol in the grid was considered the unit of analysis for RAN-tasks.

We also considered amplitudes of saccades landing on a symbol to evaluate the quality of saccadic targeting. The same eye-movement measures (TVT, RR, and SR) were analyzed in GORT tasks as indices of word recognition effort: with word as the unit of analysis. We considered a word skipped if it was not fixated even once; and the total viewing (fixation) time factored in all fixations on all non-skipped word, regardless of the reading pass. Since passage reading for comprehension was our task, eye-movements to individual words also likely reflected some higher-level syntactic, semantic, and discourse-level influences. We did not attempt to remove these influences statistically, opting instead for behavioral measures of word recognition as they emerge in ecologically valid contexts as opposed to oft-studied recognition of isolated words. Additionally, we gauged the effort of processing an entire text passage by considering the total passage reading time (PRT; the time period between the presentation of the text on a screen and the participant's pressing of the key that completed that presentation). Comprehension accuracy was defined as the number of correct responses to questions following each text. Individual variability in reading experience was measured by the score on the ART and MRT.

Results and discussion

The unit of eye-movement analysis for the RAN conditions was a single symbol in a grid: a letter, digit, or shape. The original data pool had 144,979 data points. After trimming (described in Supplementary materials S2) the remaining data pool contained 97,857 data points (67% of the original pool). Due to hardware failure, speech production during Letter- and Digit-Aloud tasks was only recorded for 88 participants (eye-movements were recorded for all participants): correlations with naming times reported below were based on this subset of participants. Descriptive statistics of all RAN measures is reported in Supplementary materials S3.

Analysis 1: comparisons between conditions in RAN-like tasks

We used mixed-effects linear regression models (Bates, Maechler, Bolker, & Walker, 2015) for comparing eye-movement behavior between RAN-like tasks in each separate study. Where necessary, we also fitted models to subsets of the data from specific tasks to evaluate statistical reliability of the critical effect of direction. In this analysis, we used trial-level unaggregated data. All models were initially fitted with the maximum random effects structure and then trimmed down to a set of random effects whose removal led to a significant decrease in the model's goodness of fit, as indicated by the log-likelihood model comparison (Bates et al., 2015). After fitting each model, we removed outliers (i.e., data points with absolute standardized residuals exceeding 2.5) and re-fitted the model again. All analyses involving mixed-effects modeling in this paper were made using the library lmerTest (Kuznetsova, Brockhoff, & Christensen, 2015) for the R statistical software package (R Core Team, 2014): Satterthwaite's approximation for denominator degrees of freedom was used in the estimation of p values. We reported and visualized estimations of critical effects based on regression models using the library *effects* (Fox, 2003). We also used Bayesian model comparison in cases where null effects are theoretically important, using functions implemented in the BayesFactor library for R.

RAN: the overall effect of direction on saccades and fixation times

One of our goals is to identify which oculomotor or perceptual aspects of saccadic planning and execution in RAN are affected by directionality of scanning. First, we tested whether there was an overall penalty to the speed of performing RAN tasks in the backward direction. Models fitted to RAN total viewing times in both cohorts—with direction as the critical main effect and grid type and symbol position in line as control variables—answered this question in the negative. A total of 10 models were fitted (5 tasks × 2 cohorts). Direction-related differences in viewing times were negligibly small (within 6 ms) and statistically unreliable in either cohort (models not shown), see descriptive statistics in Supplementary materials S3, Table B3 and B4. Thus, planning a saccade in the atypical direction did not take longer on average than the same planning in the direction of reading.

One other possible influence of the direction of scanning is less accurate targeting and implementation of saccades in the less practiced direction. Across RAN-like tasks, we examined distributions of amplitudes of the incoming saccade into an interest area containing a symbol. F tests, conducted for each of the five RAN-like tasks, did not reveal a systematic difference in targeting accuracy between the forward and backward scanning direction. Additional Bayesian analyses revealed moderate to strong support for the null hypothesis in all five comparisons (all BFs $< 1/3$; see below for a detailed explanation of the method).

RAN: effect of scanning direction between tasks

Since the most intriguing patterns were observed in eye-movement latencies, (i.e., total viewing times), we concentrated on these measures rather than regression or skipping rates. We fitted a linear mixed-effects model to total viewing time with a critical interaction between direction (forward vs backward) and task (see Table B1 in Supplementary materials S1 for the six tasks), and also grid type (5 × 10 or 4 × 9) and symbol position in line as control variables: see Tables B5–B6 in Supplementary materials S4 for model specifications. Symbol position in line was coded in the direction of scanning: that is, leftmost symbols were first in forward conditions and last in the backward conditions. Figure 1 summarizes predicted total viewing times for all tasks: see also Table B7 in Supplementary materials S4.

In the forward scanning direction, conditions requiring silent recognition of alphanumeric symbols (Letter- and Digit-Silent) came with reliably shorter inspection times than pure oculomotor conditions (Different-Silent; all ps < 0.05). In RAN forward, the range of differences between mean viewing times in all silent tasks was on the order of 40 ms. When reading-aloud tasks were included, the range of differences in viewing times between conditions was around 60 ms. This is at least partly due to articulation demands. In the backward direction of scanning, total viewing times were much more uniform across tasks, such that the range of differences between their means in silent tasks reduced from 40 ms in RAN forward to about 25 ms in RAN backward.

Importantly, in oculomotor (Different-Silent) and read-aloud conditions, total viewing times did not change reliably (at the 0.05 level) when performed in the backward versus forward direction (all Bayes Factor values $< 1/3$, see below). At the same time, alphanumeric grids (Digit- and Letter-Silent) came with a processing penalty when scanned backwards as indicated by the significantly longer viewing times (e.g., Digit-Silent: 379 vs 341 ms; all ps < 0.05, models not shown).

We went beyond the analyses of the central tendencies in RAN conditions and charted the effect of direction on task-specific total viewing times across an entire range of symbol positions in the grid, see Fig. 2. Positions are labeled in the direction of scanning, e.g. position 2 is near the left edge in forward RAN conditions and near the right edge in backward ones the first and last positions in each grid were trimmed out (see above). Figure 2 demonstrates that the progression of the eyes through a grid of text followed similar patterns across the directions of scanning or reading skill. The forward direction of scanning came with a near-constant advantage in viewing times over the backward direction, in most positions of the Digit-Silent and Letter-Silent grids. We also note that in pure oculomotor conditions, a substantial speed-up was associated with going from the first symbol in line to the last one, regardless of whether the saccades were launched left-to-right or right-to-left.

Interim summary

Analysis 1 demonstrated that the habitual direction of reading had little influence on oculomotor parameters of forward and backward scanning in RAN. These

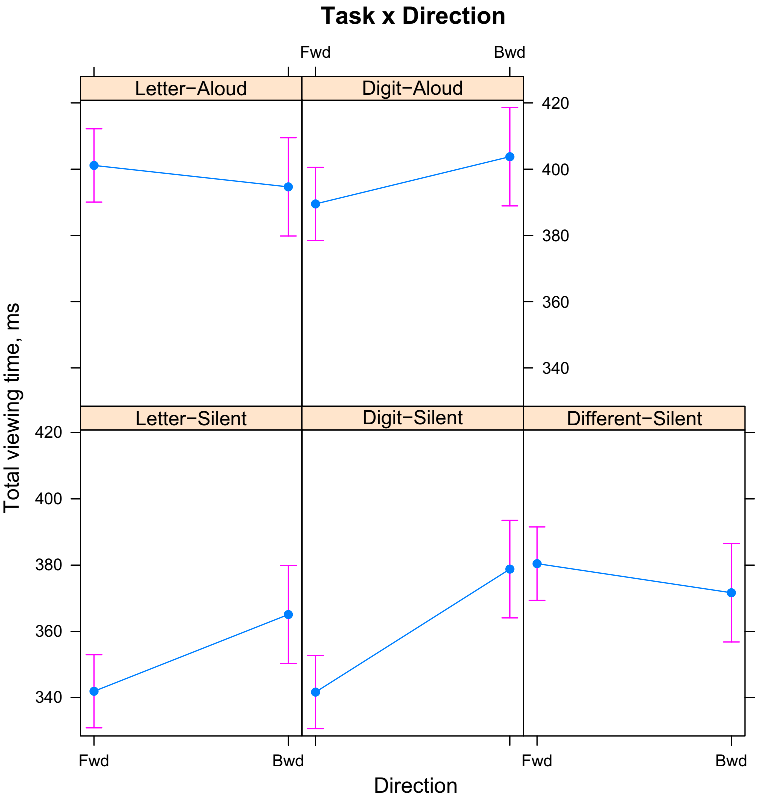

Fig. 1 Model-estimated mean total viewing times for each task and direction of visual scanning. Error bars stand for 1 SE

parameters were solely determined by the directional demands of the current task. Thus, no substantial influence of direction was observed in the precision of saccadic targeting of symbols in the grids, or in fixation times in oculomotor conditions (Different-Silent) or reading-aloud conditions (Letter- and Digit-Aloud). In the Letter-Aloud and Digit-Aloud conditions, naming times did not vary as a function of scanning direction either (all ps > 0.1 in two-sample t tests corrected for multiple comparisons). This null effect is intriguing, since the parafoveal preview in the direction of reading grants some processing advantage to the forward vs backward condition. That the Aloud conditions do not reflect this “forward” advantage in either naming times or fixation times likely means that the advantage is nullified by the eye-voice lag: even if the visual recognition of a symbol is faster in the direction of reading, the eye has to prolong its fixation on the symbol to allow the voice to catch up, regardless of direction.[2]

The only perceptible effect of direction was the inflated total viewing times in those RAN backward conditions that required silent recognition of alphanumeric

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[2] We thank an anonymous reviewer for this suggestion.

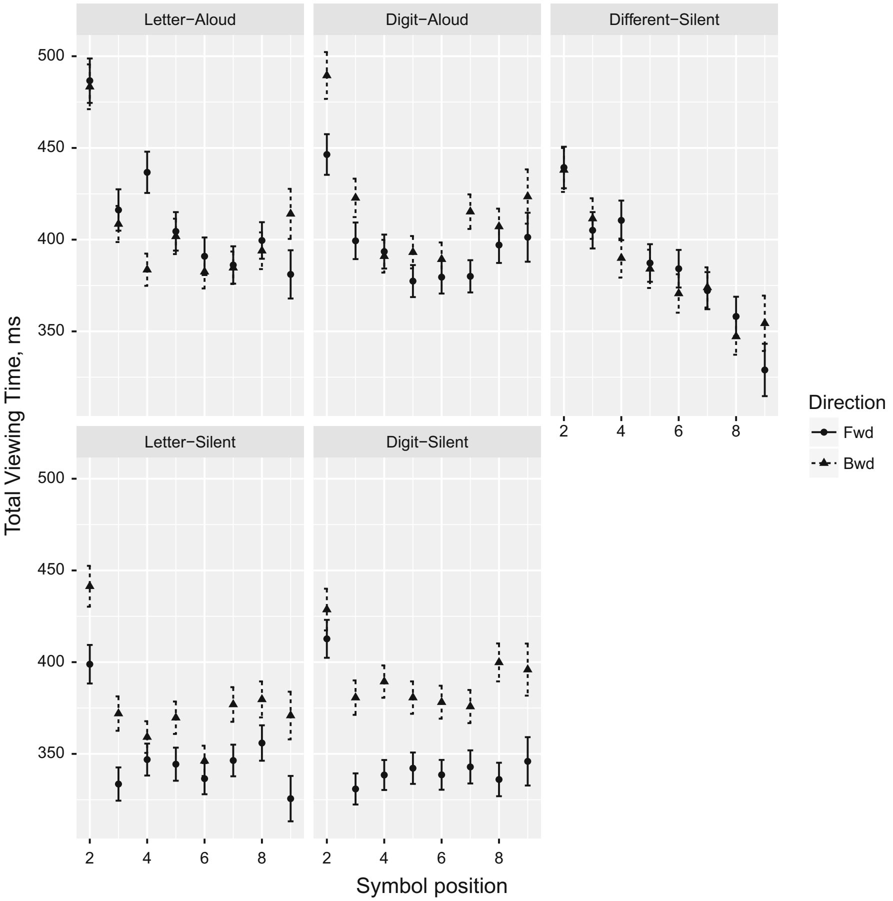

Fig. 2 Total viewing times for RAN-like tasks, presented across the range of symbol position in the grid and broken down by direction of scanning

symbols (Letter- and Digit-Silent), as compared to the respective forward conditions. This inflation is conceptually consistent with Protopapas et al.'s (2013a, b) proposal that the backward scanning direction robs proficient readers of the parafoveal advantage associated with the asymmetrical perceptual span arising from practice reading in a particular direction. In backward scanning, the preview of nameable shapes like digits or letters may be attenuated, and so their recognition when foveated may be more effortful as compared to the forward condition, where parafoveal preview benefit is cached in. Protopapas et al.'s interpretation is also consistent with the observation that direction has no effect on viewing times in oculomotor conditions. Indeed, the loss of parafoveal preview would not affect the processing of non-nameable shapes, because they do not require recognition. An important additional observation that we make here is that scanning direction had no effect on either total viewing times in other conditions requiring symbol identification (Letter- and Digit-Aloud) or naming times in RAN. While a higher quality of a parafoveal preview (afforded by the forward but not the backward direction) should, under a directional proposal, translate into a stronger preview benefit and decreased processing effort, no evidence of such advantage is found. In other words, the scanning direction did not affect the core component of the visual scanning hypothesis, that is, the oculomotor characteristics of grid scanning in RAN-like tasks. The non-directional nature of the RAN-reading link is therefore supported by the evidence. Further investigation of how task demands, including change in direction of scanning, affect eye-movements will require use of specialized moving-window techniques for determining perceptual span boundaries (McConkie & Rayner, 1975).

As we argued above, the additional cost incurred to the silent recognition of alphanumeric symbols in RAN backward does not necessarily influence how strongly these RAN conditions predict reading behavior, or whether their influence is different from that observed during RAN forward. Analyses 2 and 3 address these questions directly.

Analysis 2: GORT passage reading and its correlations with RAN

This analysis presents data from the passage reading task and reports correlations between reading and RAN performance across directions and tasks. The units of analysis for the eye-movement data recorded during reading of GORT passages were the word and the passage. Overall, 86 university students completed silent reading of GORT passages, generating a pool of 52,295 observations, and 45 non-college-bound students generated a pool of 27,756 observations. After trimming (described in Supplementary materials S2), eye-movement measures to words were averaged by participant. Furthermore, the number of correct responses to comprehension questions was calculated for each participant. Finally, for each participant we calculated the mean passage reading time: since all participants read all passages, we did not norm the data by the number of words in a passage. The aggregated measures yielded 124 data points. Table B2 in Supplementary materials S3 reports descriptive statistics of all reading eye-movement measures.

Correlations of RAN behavior and reading behavior

Both eye-movements in RAN tasks and eye-movements and comprehension scores in GORT were aggregated by participant. Table 2 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. *p* values are reported after a family-wise correction (applied using the *p.adjust* function of the *base* package of the *R* statistical software, R Core Team, 2014): See Supplementary materials S3 for details.

Most of the correlations that retained statistical significance after the family-wise correction were observed between durational eye-movement measures, that is, word and passage reading times in GORT and symbol viewing times in RAN-related tasks. Invariably, longer symbol viewing times came with inflated times for recognizing a word in text or reading an entire text. Most of these correlations were

Table 2 Correlations between individual performance in RAN-like tasks and GORT passage reading

Condition	Measure	Forward					Backward				
		TRT	RR	SR	Score	PRT	TRT	RR	SR	Score	PRT
1. Letter-Aloud	TVT	0.46**	0.05	− 0.21′	− 0.11	0.47**	0.46**	0.06	− 0.21′	− 0.01	0.45**
	RR	0.37**	0.19	0.03	− 0.02	0.33**	0.07	0.07	0.09	0.06	0
	SR	− 0.3**	− 0.05	0.26**	0.13	− 0.22′	− 0.24*	− 0.11	0.2*	0.03	− 0.11
2. Digit-Aloud	TVT	0.5**	0.11	− 0.28*	− 0.08	0.52**	0.47**	0.04	− 0.23′	− 0.04	0.5**
	RR	0.34**	0.2	− 0.02	− 0.03	0.33**	0.37**	0.15	− 0.14	0.03	0.36**
	SR	− 0.26**	0.01	0.3**	0.13	− 0.18	− 0.17′	− 0.11	0.19*	− 0.04	− 0.04
3. Identical Symbol-Silent	TVT	0.34**	0.13	− 0.1	− 0.05	0.28**	0.36**	0.18	0.02	− 0.11	0.24**
	RR	0.15	− 0.12	− 0.03	− 0.06	0.17	− 0.17′	− 0.16	0.12	0.11	− 0.11
	SR	− 0.24*	− 0.16	0.24*	0.09	− 0.14	− 0.29**	− 0.26*	0.14	0.12	− 0.15
4. Different Symbol-Silent	TVT	0.26**	0.16	− 0.03	− 0.11	0.2*	0.42**	0.19	− 0.09	− 0.07	0.34**
	RR	0.18′	0	0.01	0	0.11	0.13	0.15	0.02	0.01	0.1
	SR	− 0.26**	− 0.16	0.26**	0.14	− 0.19	− 0.23*	− 0.12	0.13	0.05	− 0.11
5. Letter-Silent	TVT	0.43**	0.1	− 0.1	− 0.05	0.43**	0.43**	0.04	− 0.05	− 0.06	0.37**
	RR	0.22*	0.27*	0.13	0.01	0.15	0.15	0.06	0.12	− 0.1	0.07
	SR	− 0.24*	− 0.01	0.29**	0.13	− 0.15	− 0.18′	− 0.13	0.36**	− 0.01	− 0.15
6. Digit-Silent	TVT	0.44**	0.08	− 0.1	− 0.11	0.42**	0.54**	0.08	− 0.13	− 0.14	0.48**
	RR	0.45**	0.28*	0.04	− 0.17	0.36**	− 0.3**	− 0.09	0.15	0.12	− 0.16
	SR	− 0.19*	0.04	0.43**	0.08	− 0.19	− 0.41**	− 0.17	0.25*	0.1	− 0.25′
7. Letter-Aloud	PT	0.38**	− 0.02	− 0.12	− 0.17	0.36**	0.52**	0.12	− 0.21′	− 0.08	0.53**
8. Digit-Aloud	PT	0.48**	0.08	− 0.28*	− 0.1	0.52**	0.54**	0.09	− 0.2′	− 0.12	0.55**

TVT total viewing time, *TRT* total reading time, *RR* regression rate, *SR* skipping rate, *PRT* passage reading time, *PT* production time

$^{**}p < 0.01$, $^{*}p < 0.05$, $^{\prime}p < 0.1$

in the moderate-to-strong range for both directions of visual scanning, with a median correlation coefficient r at 0.45. Correlations of this magnitude are in line with the strong correlations (in the range of $r = [0.5–0.6]$) that are routinely found in the literature about the RAN-reading relationship (see Protopapas et al., 2013b and references therein). The correlation tables provide evidence that eye-movements and naming times in RAN are consistent and reliable predictors of reading times, across the two directions of reading. We also note that none of the independent variables, including the conventional naming times, were predictive of GORT comprehension scores, suggesting that an individual's performance in RAN had little effect on offline indices of reading comprehension.

Individual variability in reading

We also examined the potential modulating role of reading experience in the RAN-reading relationship in 59 participants from our pool (for descriptive statistics see Table B2 in Supplementary materials S3). To this end, we first correlated ART scores (indicative of individual exposure to print; Acheson et al., 2008) with reading eye-movement measures and, separately, with all eye-movement measures in forward and backward RAN tasks. While correlations between ART and total reading time for the word and the passage were moderate, negative in polarity, and reliable ($r = -0.40$ and -0.46, both $ps < 0.01$), none of the RAN measures correlated with individual exposure to print (all $ps > 0.05$ both before and after family-wise correction). Thus, more experienced readers read faster (see Moore & Gordon, 2015) but had no advantage over less experienced ones in scanning the RAN grids, regardless of direction or specific task. This dissociation is consistent with the idea that reading practice does not transfer over to at least some of the component skills of RAN.

As the next step, we fitted a series of linear multiple regression models with eye-movement measures from passage reading as dependent variables and a critical interaction of individual ART score and their RAN eye-movement measures. By-participant averages of eye-movement measures were used, and so the regression models included no by-participant or by-item random effects. No model showed a reliable interaction between ART and RAN as predictors of reading behavior, even before the family-wise correction for multiple comparisons. The null effect was observed across all RAN conditions, both scanning directions, and all combinations of RAN and GORT eye-movement measures.

To verify this finding using a larger data pool with greater statistical power, we pooled together all participants in the present study that we had ART scores for ($N = 59$) and all participants from Kuperman et al.'s (2016) Study 1 ($N = 65$): pooled $N = 124$. We fitted regression models described above to all tasks that overlapped between these two cohorts of participants, that is, Letter- and Digit-Silent, Letter- and Digit-Aloud, and Identical-Silent all performed in a forward direction. This pooled cohort of participants replicated the null result: in no model, did the ART × RAN interaction reliably predict reading behavior. Also, one's exposure to print predicted faster reading times for a word and a passage, but had no bearing on RAN inspection times (models available on request). We conclude that—in the age group and spectrum of ability that we consider—the relationship between RAN and reading is equally strong for readers across the range of proficiency.

Analysis 3: hierarchical regressions

This series of analyses addresses two questions: the role of oculomotor conditions in predicting individual variability in reading for comprehension, and the differences in this predictive role that are caused by directionality of RAN-like tasks.

The role of oculomotor conditions

Our experimental variations were developed to assess the relative contribution of different motor, perceptual and cognitive components (see Table 1). We expected more inclusive RAN tasks (i.e., tasks with a larger number of components overlapping with reading) to show more affinity with reading behavior. We predicted that tasks with letters and digits have stronger correlations with reading behavior than the pure oculomotor conditions (with grids of non-nameable symbols), because the former conditions require symbol recognition and lexical access, much like reading does. Critically, we predicted that the most stripped-down, pure oculomotor (Different-Silent) condition in both directions of reading will explain a non-trivial amount of variance in reading behavior and will account for a substantial portion of the variance that RAN tasks are able to explain.

We used hierarchal regression models to analyze contributions of the conditions of interest. A total of eight sets of models were fitted, crossing 2 levels of RAN direction (forward vs backward), 2 types of alphanumeric RAN symbols (Digit vs Letter) and 2 dependent variables (total viewing time on the word or passage reading time in GORT silent reading for comprehension). To give an example, one set estimated the amount of variance explained by total viewing time in the oculomotor RAN forward Different-Silent task in total viewing word time during GORT reading, and compared this amount to the variance explained by the intercept-only model at its Step 1. Step 2 in that model set added total viewing time from the Digit-Silent forward condition, to estimate the contribution of lexical access over and above oculomotor control. Step 3 added total viewing time from the Digit-Aloud forward condition, and evaluated the contribution of articulation to explaining variance in GORT total word reading times. Other model sets varied in whether they zoomed in on the backward direction and/or Letter conditions. We also report for each step the percentage of variance that oculomotor RAN conditions account for out of the total variance explained by more inclusive RAN tasks. Table 3 presents hierarchical models for each direction of visual scanning separately.

Table 3 revealed several patterns of interest. Step 1 in all hierarchical regression models indicated that oculomotor conditions did explain substantial and statistically significant amounts of variance in total word reading times and passage reading times in both directions: mean amounts of variance explained by the Different-Silent condition in word and passage total reading times was 10%.

Table 3 Hierarchical regression models testing contributions of components of RAN

Dependent variable	Predictors added	R^2	ΔR^2	p value	Predictors added	R^2	ΔR^2	p value
		Forward RAN				Backward RAN		
Model 1: GORT								
TVT								
Step 1	Different-Silent TVT	0.07	0.07	0.003	Different-Silent TVT	0.17	0.17	< 0.001
Step 2	Digit-Silent TVT	0.18	0.11	0.001	Digit-Silent TVT	0.3	0.13	< 0.001
Step 3	Digit-Aloud TVT	0.27	0.09	< 0.001	Digit-AloudTVT	0.33	0.03	0.03
R^2 ratio Step 1/Step 2		0.39				0.57		
R^2 ratio Step 1/Step 3		0.26				0.52		
Model 2: GORT								
PRT								
Step 1	Different-Silent TVT	0.04	0.04	0.026	Different-Silent TVT	0.11	0.11	< 0.001
Step 2	Digit-Silent TVT	0.17	0.13	< 0.001	Digit-Silent TVT	0.23	0.12	< 0.001
Step 3	Digit-Aloud TVT	0.3	0.13	< 0.001	Digit-Aloud TVT	0.29	0.06	0.002
R^2 ratio Step 1/Step 2		0.24				0.48		
R^2 ratio Step 1/Step 3		0.13				0.38		
Model 3: GORT								
TVT								
Step 1	Different-Silent TVT	0.07	0.07	0.003	Different-Silent TVT	0.17	0.17	< 0.001
Step 2	Digit-Silent TVT	0.19	0.12	0.001	Digit-Silent TVT	0.23	0.13	< 0.001
Step 3	Digit-Aloud TVT	0.25	0.06	0.003	Digit-Aloud TVT	0.29	0.03	0.03
R^2 ratio Step 1/Step 2		0.37				0.74		
R^2 ratio Step 1/Step 3		0.28				0.59		
Model 4: GORT								
PRT								
Step 1	Different-Silent TVT	0.04	0.04	0.025	Different-Silent TVT	0.11	0.11	< 0.001
Step 2	Digit-Silent TVT	0.19	0.15	< 0.001	Digit-Silent TVT	0.16	0.05	0.012
Step 3	Digit-Aloud TVT	0.24	0.05	0.003	Digit-Aloud TVT	0.25	0.09	< 0.001

Table 3 continued

Dependent variable	Predictors added	R^2	ΔR^2	p value	Predictors added	R^2	ΔR^2	p value
		Forward RAN				Backward RAN		
R^2 ratio Step 1/Step 2		0.21				0.69		
R^2 ratio Step 1/Step 3		0.17				0.44		

Models broken down by direction (Forward vs Backward) and dependent variable [word or symbol's Total Viewing Time (TVT) vs Passage Reading Time (PRT)]

As expected, Step 2 showed that eye-movements in the Digit-Silent and Letter-Silent conditions were stronger predictors of eye-movements in passage reading (mean amount of variance explained at Step 2 by Digit-Silent = 22% and by Letter-Silent = 19%) than in the oculomotor conditions. This was expected since these tasks incorporated attentional cues and phonological representations similar to those implicated in reading. Step 3 further revealed that eye movements in the most inclusive RAN-Aloud tasks were the most predictive (mean amount of variance explained at Step 3 by Digit-Aloud = 30% and by Letter-Aloud = 26%).

Importantly, eye movements in oculomotor conditions accounted for a hefty portion of all variance explained by RAN tasks in reading behavior: an average of 35% of variance explained by the most inclusive Digit- or Letter-Aloud tasks and 46% of variance explained by the Digit- or Letter-Silent task. These findings indicate that oculomotor control was a substantial independent contributor to reading for comprehension across the spectrum of reading ability. This dovetails well with the predictions of the visual scanning hypothesis.

We also found that RAN eye-movements were consistently stronger predictors of the word's total reading time than passage reading time, a finding in line with Protopapas et al. (2013b). The total reading time for a word taps into the real-time effort of word recognition in context, while the total reading time for the passage is more remote from individual words and reflects the difficulty of processing the linguistic, inferential and topical structure of an entire passage. We acknowledge that a comparison with Protopapas et al.'s (2013b) data should be treated with caution because their study considered words in isolation while ours looked at word recognition in the ecologically valid context of the passage.

The role of directionality

In two series of hierarchical regression models we tested whether eye-movements registered in the RAN forward and backward tasks were different in their ability to predict passage reading behavior. In one series of models, we examined whether RAN backward explained variance over and above RAN forward in total reading times and passage reading times in GORT reading, and in another series we examined the reverse. Specifically, Step 1 in one series of models contained total viewing times from one forward task (e.g., forward Different-Silent), and Step 2 added total viewing times from the respective backward counterpart as a predictor to the model (e.g., backward Different-Silent). In a second series of models, the order of adding backwards and forwards tasks was reversed. A gain in the amount of variance explained would indicate whether the predictor added at Step 2 accounted for any unique variance and whether a direction-driven change in one's performance was a substantial contributor to individual variability in reading for comprehension.

Since statistical significance does not convey the amount of support for null effects (e.g., when a tests fails to reject the null hypothesis), we also conducted Bayesian analyses for each model comparison. We report the Bayes Factor that quantifies the amount of support for the alternative hypothesis. To this end, we calculated the Bayesian Information Criterion (BIC) value for each regression model, using the BIC function in the base distribution of R, and used the following transformation proposed by Masson (2011) to translate the difference in BICs of the compared models into a Bayes Factor (BF):

$$\mathrm{BF} = e^{(\mathrm{BIC}_2 - \mathrm{BIC}_1)/2},$$

where BIC_1 and BIC_2 are BIC values for the two models under comparison. As a rule of thumb, a Bayes Factor over 3 indicates moderate support, and over 6 indicates strong support for the alternative hypothesis (i.e., that the variable at Step 2 explains additional variance), while values below 1/3 show moderate and below 1/6 show strong support for the null hypothesis (e.g., variable added at Step 2 does not explain unique variance).

We selected three tasks for comparison: the oculomotor Different-Silent condition, and the more inclusive Digit-Silent and Digit-Aloud conditions (which routinely explained more variance in reading measures than their Letter-based counterparts). Table 4 shows six models (3 predictors × 2 orders of steps) that have word total reading time (GORT TVT) as a dependent variable. Models using passage reading time showed qualitatively identical results and are not presented here.

Models in Table 4 show an inconsistent picture with respect to which direction of scanning has advantage over another in predicting total word reading time, or passage reading time (not shown). On the one hand, the backward scanning direction accounted for much additional variance in both word- and passage-level reading times over and above the contribution of the forward direction in Different-Silent and Digit-Silent conditions (see ΔR^2 and $\mathrm{BF} > 6$) in Models 1 and 2 (left). Conversely, individual performance in the forward scanning direction in Diffierent-Silent and Digit-Silent conditions (Models 1 and 2 right) did not add anything to the contribution of the backward scanning direction: all $\mathrm{BFs} < 1/3$, indicating moderate to strong support for the null hypothesis in this model comparison test.

On the other hand, in the Digit-Aloud condition the situation was reversed. RAN forward explained a substantial and well-supported additional variance in the word- and passage-level reading times over and above RAN backward (all $\mathrm{BFs} > 3$; see Model 3 right for word-level analysis). Yet RAN backward explained no additional variance and this null effect was strongly supported by the Bayesian factor test (0.18; Model 3 left for word-level analysis).

Table 4 Hierarchical regression models testing contributions of scanning direction

Dependent variable	Predictors added	R^2	ΔR^2	p value	Bayes factor$_{10}$	Predictors added	R^2	ΔR^2	p value	Bayes factor$_{10}$
Model 1: GORT TVT										
Step 1	Different-Silent forward	0.07				Different-Silent backward	0.17			
Step 2	Different-Silent backward	0.18	0.11	< 0.001	216.35	Different-Silent forward	0.18	0.01	0.39	0.15
Model 2: GORT TVT										
Step 1	Digit-Silent forward	0.18				Digit-Silent backward	0.28			
Step 2	Digit-Silent backward	0.28	0.10	< 0.001	210.71	Digit-Silent forward	0.28	0.00	0.89	0.09
Model 3: GORT TVT										
Step 1	Digit-Aloud forward	0.27				Digit-Aloud backward	0.23			
Step 2	Digit-Aloud backward	0.27	0.0	0.248	0.18	Digit-Aloud forward	0.27	0.04	0.006	4.45

Models test the contributions of one scanning direction over and above another scanning direction to explain variance in word total reading times

Thus, across all models and conditions, neither scanning direction has shown a clear advantage over the other direction. We interpret this inconsistency as another piece of evidence against the proposed directional nature of RAN-reading link. We conclude—in line with the finding of Protopapas et al. (2013b) for other tests—that eye-movements registered in either RAN forward or RAN backward tasks are similarly predictive of the eye-movement control in reading. That is, one's ability to move eyes in a rapid, efficient manner through a grid of visual objects correlates with reading performance, regardless of the grid's scanning direction.

General discussion

The goal of the present study was to examine the role of oculomotor control in RAN as a predictor of eye-movements in reading. We pursued this goal through a test of the visual scanning hypothesis, i.e., the hypothesis that the relationship between RAN and reading is partly due to a shared demand for efficient oculomotor control (Clarke, Hulme, & Snowling, 2005; Kuperman et al., 2016; Kuperman & Van Dyke, 2011; Logan, Schatschneider, & Wagner, 2011). To this end, we created RAN-like tasks to parametrically vary the number of components shared with reading, from oculomotor coordination to lexical access and activation of phonological codes (Table 1), and instructed participants to perform these tasks in the habitual direction of reading in English and the opposite direction. Because the visual scanning hypothesis is not direction-specific (see discussion in Kuperman et al., 2016), reading behavior should be predicted equally well by any task that requires planning and coordination of rapid sequential saccadic movements. Thus, finding a discrepancy between the predictive power of RAN forward versus RAN backward would argue against the hypothesis in question: no such discrepancy was observed in our data.

Our analyses resulted in two novel sets of findings. First, we are now able to characterize the impact that scanning direction has on the processing of RAN grids within-participants. Despite a colossal advantage in the amount of practice with forward vs backward scanning in reading, readers did not show a consistent delay in planning and launching their saccades when moving their eyes backward in the RAN grid. The only substantial penalty to backward scanning, compared to its forward counterpart, was an inflation of viewing times in grids with letters and digits, in both more and less proficient readers and in silent scanning only. We speculate that the inflation was due to a reduction in the ability of readers to use their perceptual span in backward conditions, and a concomitant decrease in the parafoveal preview benefit. Critically, however, individual performance in pure oculomotor conditions was stable across scanning directions suggesting that the oculomotor machinery that an individual possesses enables precise and fast planning and implementation of saccades across a grid of symbols in all directions. This observation obtained from hierarchical regression models and also analyses of individual differences demonstrates that the oculomotor component of RAN is not affected by the amount of practice that the individual has with reading or by linguistic features like phonological representation. Thus, despite its similarity to reading, spatial biases in RAN-like tasks do not show the same flexibility as reported, for instance, in bilingual studies of left-to-right and right-to-left languages (Jordan et al., 2014; Paterson et al., 2014; Pollatsek et al., 1981) and in studies of reading in a non-habitual direction (Inhoff et al., 1989). In terms of the direction-driven distribution of visual attention, RAN falls in with non-reading visual tasks (see Afsari et al., 2016).

Our second set of results is perhaps the most intriguing finding. Eye-movements registered in RAN backward tasks were as strong or stronger co-determiners of eye-movements in RAN, as compared to their forward counterparts. These findings lead us to the following conjecture. Even though both alphanumeric RAN and reading make use of parafoveal preview (see among others Jones et al., 2008, 2012; Yan et al., 2013; Veldre & Andrews, 2014), one's ability to use parafoveal preview is *not* a factor that is responsible for the robust RAN-reading relationship. The evidence so far is consistent with the visual scanning hypothesis that the oculomotor and spatial-attentional demands shared by RAN and reading are confined to the ability to plan and coordinate rapid sequential movements and to engage and disengage visual objects when moving the eyes across a page, no matter in what direction.

Moreover, our findings shed light on the criticism raised by Protopapas et al. (2013b). We confirm their observation of an equally strong relationship between reading and backward RAN, in comparison to its forward counterpart. Yet we additionally show that this equality does not imply that the role of oculomotor control is negligible in terms of total viewing time. On the contrary, across scanning directions eye-movements in pure oculomotor RAN conditions explained both a substantial (10% or more) and statistically reliable amount of variance in eye-movements during passage reading. It also accounted for a big chunk of the total variance that more inclusive RAN tasks explained in reading (about 40%).

In sum, our results demonstrate that the change in direction does not have an appreciable effect on either the speed or accuracy of oculomotor control during RAN, nor does it affect the strength of association between RAN and reading for comprehension. Crucially, in line with the visual scanning hypothesis, adults who were better at controlling eye-movements during RAN were better at reading, regardless of scanning direction or task type. These findings lend support to the notion that oculomotor and spatial ability is an important irreducible component of the link between RAN and reading, and the direction-specific experience does not contribute to this link.

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