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Effective Scheduling of Looking and Talking During Rapid Automatized Naming

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Rapid automatized naming (RAN) is strongly related to literacy gains in developing readers, reading disabilities, and reading ability in children and adults. Because successful RAN performance depends on the close coordination of a number of abilities, it is unclear what specific skills drive this RAN-reading relationship. The current study used concurrent recordings of young adult participants' vocalizations and eye movements during the RAN task to assess how individual variation in RAN performance depends on the coordination of visual and vocal processes. Results showed that fast RAN times are facilitated by having the eyes 1 or more items ahead of the current vocalization, as long as the eyes do not get so far ahead of the voice as to require a regressive eye movement to an earlier item. These data suggest that optimizing RAN performance is a problem of scheduling eye movements and vocalization given memory constraints and the efficiency of encoding and articulatory control. Both RAN completion time (conventionally used to indicate RAN performance) and eye-voice relations predicted some aspects of participants' eye movements on a separate sentence reading task. However, eye-voice relations predicted additional features of first-pass reading that were not predicted by RAN completion time. This shows that measurement of eye-voice patterns can identify important aspects of individual variation in reading that are not identified by the standard measure of RAN performance. We argue that RAN performance predicts reading ability because both tasks entail challenges of scheduling cognitive and linguistic processes that operate simultaneously on multiple linguistic inputs.

Keywords: rapid automatized naming (RAN), eye tracking, sentence reading, task scheduling

In the rapid automatized naming (RAN) task (Denckla & Rudel, 1974) a participant is presented with a grid of familiar stimuli (drawn from sets of letters, numbers, colors, or objects) and must name the stimulus items out loud in order as quickly and accurately as possible. Speed and accuracy on this task are strongly related to future literacy gains by preliterate children (Denckla & Rudel, 1974; Lonigan, Schatschneider, & Westberg, 2008), reading disabilities such as dyslexia (Denckla & Rudel, 1974; Wolf & Bowers, 1999), and reading ability in children, adolescents and adults (Arnell, Joanisse, Klein, Busseri, & Tannock, 2009; Powell, Stainthorp, Stuart, Gardwood, & Quinlan, 2007; Kuperman & Van Dyke, 2011; Swanson, Trainin, Necochea, & Hammill, 2003). Successful performance on the RAN task requires visual recognition of individual stimuli, access to phonological codes and rapid articulation. Sustained attention is required to manage perceptual encoding and vocal execution according to available working memory capacity in order to optimize speed while minimizing interference between successive items. Individual variation in RAN performance could depend on any or all of these cognitive task components as well as the ability to coordinate these processes.

One approach to understanding RAN performance is to explore how it is related to performance on tasks that measure its component cognitive processes. Although RAN appears to be more strongly correlated with oral reading compared with silent reading (Georgiou, Parrila, Cui, & Papadopoulos, 2013; Moll, Fussenegger, Willburger, & Landerl, 2009), articulation rate in tasks involving well-known sequences (e.g., counting to 10) is not typically associated with reading ability (Di Filippo et al., 2005) or with RAN performance (Cutting & Denckla, 2001). The efficiency of other lower-level perceptual and motor processes does appear to contribute to RAN performance (Wolf & Bowers, 1999). For example, slow RAN performance has been found to relate to poor performance on simple visual processing tasks such as visual same/different judgments (Stainthorp et al., 2010). Although performance on phonological processing tasks is highly predictive of reading ability, phonological ability has a low-to-modest relationship to RAN performance (Swanson et al., 2003) and the RAN-reading relation is at least partially independent of phonological processing (Bowers & Newby-Clark, 2002; Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000). Orthographic processing does show some relation to RAN performance (Georgiou, Parrila, & Kirby, 2009; Cutting & Denckla, 2001 for discussion), a pattern that is consistent with stronger prediction of reading ability by the symbolic (letter and digit) RAN tasks than the nonsymbolic (object

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and color) RAN tasks (Kuperman & Van Dyke, 2011; Misra, Katzir, Wolf, & Poldrack, 2004). Nonetheless, object and color RAN tasks also predict reading ability (Denckla & Rudel, 1974) and all of the RAN tasks correlate highly with each other (Arnell et al., 2009; Bowers & Swanson, 1991). As a result, successful RAN performance has been hypothesized to depend on the ability to form strong visual-verbal links in memory (Kirby et al., 2010), which in turn may facilitate rapid lexical access (Georgiou et al., 2009). The items in the RAN task are typically arranged in a way that is similar to how the words in a text are arranged in the reader's language (e.g., left to right for English). This similarity has led to suggestions that in part the RAN is related to reading at least because it provides a sensitive measure of how well the eyes move and attention shifts when processing a sequence of items with this layout (Clarke, Hulme, & Snowling, 2005; Kuperman & Van Dyke, 2011). However, the association between RAN performance and reading is equally strong when RAN items are named in reverse order as in the usual order (Protopapas, Altani, & Georgiou, 2013), a finding that suggests that any contribution of scanning ability to the RAN-reading relation does not depend on the specific pattern of eye movements that has been practiced through reading.

Beyond the task-specific skills required for successful RAN performance, RAN has been considered an indicator of more general cognitive skills. Speed of performance in other complex tasks (e.g., cross out and visual matching tasks) is strongly related to RAN performance (Kail, Hall, & Caskey, 1999), though the RAN-reading relationship persists after controlling for processing speed (Cutting & Denckla, 2001). Measures of visual attention, attentional shifting, and inattention show some relation to RAN or are impaired in populations that show poor RAN performance (Waber, Wolff, Forbes, & Weiler, 2000; Hari & Renvall, 2001; Pham, Fine, & Semrud-Clikeman, 2011) suggesting that RAN tasks provide a measure of executive control (Denckla & Cutting, 1999). The serial nature of the RAN task is important to its relation to reading as discrete naming tasks do not consistently predict reading skill (Bowers, 1995; Georgiou et al., 2013; Perfetti, Finger, & Hogaboam, 1978; Stanovich, 1981) and serial naming tasks discriminate more robustly than discrete naming tasks between dyslexic and nondyslexic readers (Jones, Branigan, & Kelly, 2009). Moreover, serial naming shows a stronger relation to reading after accounting for variation in performance on isolated naming tasks (Logan, Schatschneider, & Wagner, 2011). Serial processing of simultaneously presented stimuli may tap into executive attentional processes involved in the dynamic memory updating and the cognitive suppression of previous responses, as indicated by the relationship between RAN and rapid serial visual presentation (RSVP) tasks (Arnell et al., 2009). Finally, RAN taps working memory as shown by its association with performance on sentence-span (Georgiou, Das, & Hayward, 2008; Swanson & Kim, 2007) and other complex-span tasks (Kuperman & Van Dyke, 2011). In sum, RAN shows relations to performance on a wide variety of tasks, but as reviewed by Kirby et al. (2010), none of these measures can fully explain the RAN-reading relationship, which has been found to persist in studies that have controlled for non-RAN articulation rate, processing speed, phonological short-term memory (STM), phonological awareness, and orthographic processing skill, as well as various measures of attention and memory.

A different approach to understanding RAN performance has been to separately evaluate eye movements and vocalizations as they occur sequentially within the RAN task itself in relation to overall RAN performance. Vocal recordings of RAN can be decomposed into articulation time (AT) and pause time (PT), with the idea that AT depends on the automaticity of making a verbal response once the item has been recognized, while PT reflects preparation processes related to attention, eye movements, and stimulus recognition (Araújo et al., 2011; Clarke, Hulme, & Snowling, 2005; Neuhaus, Foorman, Francis, & Carlson, 2001). However, there is no consistent evidence on whether AT or PT is the better predictor of reading ability (Clarke et al., 2005; Georgiou et al., 2009; Georgiou, Papadopoulos, Fella, & Parrila, 2012), with Georgiou, Papadopoulos, and Kaizer (2014) demonstrating that the two measures share a large amount of variance and that any unique contribution of PT declines with age, though the relative weight of AT and PT during RAN performance in explaining reading skill in children depends on the orthographic consistency of their language's writing system (Georgiou, Aro, Liao, & Parrila, 2015).

Concurrent recordings of participants' vocalizations and their eye movements allow for a fine-grained understanding of how RAN performance is shaped by the coordination of visual and vocal processes. Jones and colleagues have examined RAN eye-voice relationships for individuals with dyslexia and nondyslexic controls using the *fixation-speech interval* (FSI; Jarvilehto, Nurkkala, Koskela, Holappa, & Vierela, 2008; Inhoff, Solomon, Radach, & Seymour, 2011)—the time elapsed between when an item is first fixated and when its articulation begins.[1] In the object RAN task, dyslexic participants showed overall longer FSIs than controls, but visual or semantic similarity between subsequent items led to similar reductions in FSI for both groups (Jones, Branigan, Hatzidaki, & Obregon, 2010). In the letter RAN task, phonological-onset similarity between subsequent items was associated with increased FSI for both dyslexic and nondyslexic participants, suggesting that phonological access was more difficult in the presence of phonologically similar items (Jones, Ashby, & Branigan, 2013; Jones, Obregón, Louise Kelly, & Branigan, 2008). However, although the FSI as a measure seems analogous to simple stimulus-response time, the sequential constraint of the RAN task requires that articulation of earlier items be completed before articulation of the fixated item can begin. As a result, the FSI is very sensitive to the articulation duration of the preceding item(s) and does not provide a straightforward measure of the time needed to generate an item's articulatory output after seeing it.

Eye-voice span (EVS)—the number of words that the eyes are ahead of the voice while reading out loud—provides an alternative measure of eye-voice relationships that does not depend on the spoken duration of RAN items. As discussed in Levin and Addis (1979), EVS has long been used in the study of reading and as a tool for assessment and diagnosis of reading deficits. While early

[1] In their articles Jones and colleagues call this measure eye-voice span. We use the term fixation-speech interval in order to avoid confusion with a different, well-established meaning for eye-voice span which we discuss below.

studies indicated that EVS was in the range of eight words for mature readers, more recent studies indicate much shorter averages in the range of two words (Inhoff et al., 2011). EVS increases with age and with reading ability (Anderson & Dearborn, 1952; Buswell, 1921; Tinker, 1965; cited by Levin & Addis, 1979), and individuals with dyslexia show similar levels of impairment in EVS as in other measures of reading skill (De Luca, Pontillo, Primativo, Spinelli, & Zoccolotti, 2013). Within (nondyslexic) readers, EVS is reduced when text is more complex (Buswell, 1921; cited by Levin & Addis, 1979) and appears to vary in accordance with phrase or constituent boundaries (Levin & Addis, 1979). As a result, EVS has been hypothesized to reflect the reader's use of syntactic and semantic information as well as (or in combination with) the temporal interval available for STM (Geyer, 1968; cited by Levin & Addis, 1979). During RAN, eye-voice span can be measured as the number of items that the eyes are fixated ahead of the voice. Pan, Yan, Laubrock, Shu, and Kliegl (2013) found that EVS was a significant predictor of performance on the digit RAN task for typically developing 10-year-old children but not for age-matched children with dyslexia. They interpreted this difference in results as indicating that the *perceptual span*, which determines the region of text surrounding fixation that can be encoded during reading (McConkie & Rayner, 1975; Rayner & Bertera, 1979), is smaller in the dyslexic children than the control children. Similarly, Moll and Jones (2013) have provided evidence that dyslexic readers are less efficient at encoding information beyond the center of fixation than nondyslexic readers during RAN because they are more sensitive to visual crowding in the parafovea. However, eye movements and reading rate during oral reading are less affected by the availability of parafoveal information than silent reading (Ashby, Yang, Evans, & Rayner, 2012). As RAN requires each item to be named out loud, the size or efficiency of readers' perceptual span is unlikely to fully explain individual differences in RAN performance or the RAN-reading relationship.

Eye-voice span during RAN has also been interpreted as a measure of automaticity, or the extent to which the item-to-sound conversion needed for item naming has moved from a resource-demanding to an overlearned, automatic process (but see Georgiou & Stewart, 2013). Pan et al. (2013) observed that differences in EVS between dyslexic and nondyslexic children were greater for digit RAN than the rapid naming of dice surfaces, a task that can be assumed to be much less practiced than naming digits. Hogan-Brown, Hoedemaker, Gordon, and Losh (2014) observed slower RAN naming and lower EVS for participants with ASD compared with age-matched controls. Siblings of individuals with ASD also exhibited lower EVS than controls, but only on letter and digit RAN, the two conditions that are considered most highly automatized. Siblings of individuals with ASD showed similar performance to controls on color and object RANs, which are assumed to be less-automatized naming tasks.

The present work uses EVS and other eye-voice relations as a source of insight into the ways in which component processes are *scheduled* or coordinated in time during RAN performance. Analyses of cognitive processes in terms of scheduling began with applications of mathematical scheduling theory to formal analyses of the organization of cognitive processes (e.g., Schweickert, 1978; Schweickert & Boggs, 1984), where it was argued that scheduling models provide a way of characterizing a very important level of cognitive organization that applies across processing domains. The value of analyzing performance on complex tasks in terms of scheduling is widely recognized in models of dual-task performance (Meyer & Kieras, 1997; Pashler, 1994a) and in extension of those models to performance in tasks—like the RAN—that require speeded responses to individual items in a sequence (Pashler, 1994b). Analyzing the RAN in terms of scheduling naturally incorporates the straightforward notion that having the eyes lead the voice allows upcoming RAN items to be perceptually encoded so that their identities are available when processes of articulatory planning and control are ready to use that information. It further leads to a focus on the fact that this simultaneous processing on successive RAN items must be coordinated in time—scheduled—so that the eyes are sufficiently far ahead of the voice to supply the needed information but not so far ahead that the number of encoded-but-yet-to-be-produced items is too large to be effectively held in working memory. It is likely that the extent to which scheduling constrains performance on RAN tasks depends on the efficiency of the mechanisms that must operate on each individual RAN item, such as those for visual identification, name retrieval and articulatory planning/execution, and also on the efficiency of general mechanisms that directly support scheduling, such as working memory capacity and executive function (Engle, 2002; Kane & Engle, 2003; Miyake & Friedman, 2012). The substantial body of research showing that the RAN-reading relationship survives after controlling for individual variation in the component skills of RAN performance suggests that individual variation in the efficiency of the general mechanisms that support the scheduling of component processes may make an important contribution to the predictive value of the RAN task. By analyzing RAN performance and the RAN-reading relationship in terms of scheduling, this paper aims to provide a framework that can incorporate the specific component processes of the RAN and silent reading as well as address the ways in which these component processes must be coordinated to enable the type of efficient sequential processing that characterizes skilled reading.

During silent reading the eyes provide information about the time course of early orthographic and lexical processes but later processes of lexical integration and comprehension cannot be measured directly, making it difficult to study the ways in which early and later processes of reading and comprehension are coordinated. In contrast, eye movements during the RAN task provide an overt measure of the time course of perceptual encoding of linguistic units, and the acoustic properties of the participants' speech provide information about the time course of subsequent articulatory processes. Thus, the relationship between the eyes and the voice in the RAN task provides information about the scheduling of earlier and later processes that is not available for silent reading. The current research studies a group of skilled readers (college students) in order to determine whether—and how—eye-voice relations in the RAN predict individual differences in RAN performance and in eye movements during silent reading. EVS provided the initial eye-voice measure of interest in the RAN task, but exploration of the data showed the importance of considering the incidence of regressive saccades in explaining individual differences in RAN completion time and in the efficiency of word recognition during silent reading.

Method

Participants

Fifty undergraduates at the University of North Carolina at Chapel Hill participated in the study in exchange for course credit in *Introductory Psychology*. Data from two participants were not usable because of problems with their audio recordings, leaving data for 48 participants for the analyses reported below. All participants had normal or corrected-to-normal vision, and none indicated being colorblind. All participants were naïve to the purpose of the study.

Apparatus

An SR EyeLink 1000 (0.25°–0.5° average accuracy) was used to record eye movements from the participants' dominant eye. All stimuli were presented on a 22-in. Samsung LCD monitor with 120 Hz refresh rate and a resolution of 1,680 × 1,050 at a viewing distance of approximately 22 in. In order to accommodate the maximum visual angle of the eye tracker, stimulus presentation was confined to a 12 in. × 10 in. portion of the screen. During the RAN task, vocal responses were recorded on the PC using a table-mounted microphone with an E-MU 0404 USB amplifier (Creative), and an ASIO sound card. Audio recording began automatically at the beginning of each trial.

RAN Task

Stimuli for the RAN task were taken from the Comprehensive Test of Phonological Processing (CTOPP, Wagner, Torgesen & Rashotte, 1999).[2] Each trial contained an array of 36 items arranged on a grid for four rows and nine columns. There were two trials (A and B) for each of the four RAN types: colors (*blue, red, green, black, brown, yellow*); letters (*s, t, n, a, k, c*); objects (*pencil, star, fish, chair, boat, key*) and numbers (*2, 3, 4, 5, 7, 8*). On each trial, the items on the CTOPP are arranged in a pseudorandom order (with the restriction that no item appears in two consecutive positions) that is fixed for all participants. The B trials reverse the order of the A trials. Each RAN type was preceded by a practice trial containing one instance of each of the six items that would appear for that type of RAN, followed by the A and B trial.

The color items were adjusted slightly from the original source to render them more easily distinguishable on the LCD screen. In addition, the size and spacing of the individual items was adjusted to maximize use of the available room on the display. Areas of interest (AOIs) were assigned to each item by drawing a virtual grid on the array, so that each item's AOI extended from its center to halfway toward its neighboring items. The full RAN grid extended across 31 × 26 degrees of visual angle and each AOI took up approximately 3.5 degrees of horizontal visual angle. Within each AOI, the sizes of the various stimulus items in degrees of visual angle were as follows: color (3 × 4), letters (1 × 1.5), objects (2 × 2.5) and digits (1 × 1.5).

Participants were instructed to name all items in the array as quickly and accurately as possible, naming the items in each row from left to right starting with the top row.

Reading Task

Participants read 10 warm-up sentences and then read a set of 40 sentences that were 10 to 15 words long. The sentences were taken from a larger pool of sentences used for a different study, and were constructed as follows. One-hundred sets of four target words were selected so that each set contained two high frequency and two low frequency words. High and low frequency status was defined within each HF–LF word pair, so that each pair differed by at least one unit of log frequency (SUBTLEXus; Brysbaert & New, 2009). Average log word frequency was 3.24 per 51 million for the HF and 1.81 per 51 million for the LF words. Each four-word set was assigned two different sentence frames, each containing two possible slots for the four words from the set. High and low frequency words were rotated so that each sentence could appear with two HF words, two LF words, or a mix of one HF and one LF word (see Table 1 for an example of a set of sentence frames and target words). The resulting 200 sentences were divided into four lists, so that all sentence frames appeared once in each list, but with different target words across lists. As a result, no target words or sentence frames were repeated within a list. Each list was divided into five blocks of 40 sentences each, resulting in a total of 20 counterbalanced blocks. Each participant in the current experiment was presented only one block of 40 sentences, rotating through the 20 available blocks across participants. The sentences appeared in a different random order for each participant.

The alternative high and low frequency words at a given target location were matched for number of letters, with target words having a mean length of 6.5 letters and a range of five to nine letters. The stimulus sentences were constructed with the goal that the target words would not be predictable. After the main experiment, predictability was assessed using a cloze task in which a separate group of participants was presented with sentence fragments and asked to "continue [each fragment] to create a complete sentence." Sentence fragments were presented up to but not including the first target word (e.g., "Anna forgot her . . .") and in two versions up to but not including the second target word (one version containing the low-frequency first target and one version containing the high-frequency first target, e.g., "Anna forgot her father/cousin did not like . . ."). These three conditions provided measures of the cloze probability of the first target word and of the second target word for the two conditions in which it could appear. These conditions were counterbalanced across groups of participants so that participants only saw each sentence in one of the three conditions. All participants in the cloze task were native speakers of English selected from the same participant pool as those who participated in the eye-tracking portion of the experiment. Cloze data were obtained from 20 to 30 participants for each stimulus. Predictability for the target words was low (mean of 0.78% and 3.23%, respectively for low- and high-frequency

[2] This version of the RAN has been characterized along with the Denckla and Rudel (1974) five-by-ten version as using a traditional format for the RAN grid (Compton, Olson, DeFries, & Pennington, 2002). Performance on an alternative version of the RAN grid with only five items per row is highly correlated ($r = .85$) but may account for more variation in word recognition skill in some populations (Compton et al., 2002).

Table 1
Sample Sentence Frames With Interchangeable High/Low Frequency Target Words

1a.	My thoughtful *father/cousin* gave me some *onions/gourds* from his own garden.
1b.	Anna forgot her *father/cousin* did not like *onions/gourds* until it was too late.

Note. Target words are italicized here but were presented in regular font during the experiment.

words), though this difference was statistically significant, $t(398) = 5.63$, $p < .001$. However, these mean levels of predictability are far below those used in experimental studies that have manipulated predictability of target words. For example, across a number of experiments examining how predictability (or constraint) affects eye movements during reading, the mean cloze values were 64%, 86%, 41%, 64%, and 78% (Balota, Pollatsek, & Rayner, 1985; Rayner & Well, 1996; Rayner, Binder, Ashby, & Pollatsek, 2001). The predictability of individual target words in the current stimulus set ranged from zero to 59% for low-frequency words and zero to 64% for high-frequency words, showing that predictability was not avoided for all 400 target locations in the stimulus set (200 sentences with two target locations each). However, subsidiary analyses to be reported below show that the subset of predictable words had very little effect on the reading data.

Sentences were presented on a single line in black 20-point Times New Roman font on a white background. Despite the use of a proportional font there was no difference in mean physical size of the low-frequency and high-frequency target words (mean of 74.3 pixels for high-frequency words and 74.0 pixels for low-frequency words, $F < 1$). One degree of visual angle spanned approximately three letters (34.3 pixels). Participants were instructed to read for comprehension at a natural pace. Twenty-five percent of the sentences were followed by a true/false comprehension question, which participants answered by pressing a button on a handheld console.

Testing Procedure

Participants were seated in a dimly lit, sound-attenuated room. They completed the sentence-reading task and then the RAN task. During the sentence-reading portion of the study, a chin rest and forehead rest were used to minimize head movements. During the RAN, only the forehead rest was used to allow for movement of the jaw during vocal responses. Both the RAN and the reading experiment began with a 9-point calibration procedure. Average spatial calibration error did not differ with (.46 degrees) and without (.45) the chinrest, $t(47) = .06$, $p > .5$. Each trial began with a fixation point on the left side of the screen, marking the location where the first word of the sentence would appear, or in the upper left corner, marking the location of the first RAN item. The experimenter initiated each trial as soon as the participant established a steady gaze on the fixation point. During the RAN task, subjects advanced to the next trial by pressing a button on a handheld console after naming all 36 items. During the reading portion of the experiment, participants pressed the same button after reading each sentence. Gaze location was monitored throughout the experimental session and recalibrated as necessary.

Results

Analysis Procedures for RAN

Automatic phonetic alignment of the vocal responses was performed using the Penn Phonetics Lab Forced Aligner (Liberman & Yuan, 2008). Subsequently, the onset and offset boundaries output by the automatic alignment procedure were manually edited by two (hypothesis-blind) trained coders based on both the visual waveform and auditory assessment of the response. Errors were identified as any response that deviated from the serial naming of all 36 items, including item-name substitutions, repetitions, skips, self-corrections, and any other type of extraneous speech (e.g., “eh,” “ehm,” and other fillers).

Vocal responses and associated eye movements for the first item and the last items were excluded from all analyses because of difficulties in interpreting eye-movements in relation to those items. As a result, *completion time* is defined as the time between the onset of the second item to the offset of the 35th item on each trial. *Total duration* is the duration of an individual vocal response plus its preceding silence. *Silence duration* is the duration of the interword silence. If there was no silent gap detected in between two subsequent vocalizations, silence duration was coded as zero.

Fixations shorter than 80 ms and within 1 degree of a longer, immediately subsequent fixation were merged with the longer fixation by an automatic procedure in the EyeLink software. Due to track loss no fixations were recorded for a portion of a small number of items (1.02% of all items). These items were excluded from all analyses. EVS was defined as the number of items that the eyes were ahead of the voice at the onset of the vocal response. Vocal responses with an EVS of less than 0 (suggesting that the participant was fixating an item that occurred *before* the currently named item) or more than 5 (suggesting that the participant was looking more than 5 items ahead of the currently named item) were excluded from the analyses (0.43% of all items). Such EVS values deviated substantially from canonical task performance, and were likely due to tracker error and/or erratic, off-task behavior. *Regressions* to previous items were defined as any fixation on an item *after* one or more subsequent items had already been fixated. *Regression rate* is the proportion of fixated RAN items from which there was a regressive eye movement to an earlier item in the sequence. *Skips* were defined as any occasion on which a RAN item was not fixated at all, or not until after the fixation of a later item. *Skipping rate* refers to the proportion of RAN items that were skipped. *Return saccades (RS)* were leftward saccades from near the end of one line toward the beginning of the next line. These long saccades were associated with decreased spatial accuracy; most often resulting in undershoot of the target or *short return saccades (SRS).* As a result, SRSs were often followed by one or more regressive saccades that were *corrections of short returns.*

Table 2
Summary of Vocal Response Measures Across RAN Types

	Completion time (*ms*)	Errors per trial	Duration of vocal response (*ms*)	Duration of silence if present (*ms*)
	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)
Object	21,866 (3,881)	.45 (.552)	433 (52)	265 (98)
Color	19,093 (3,472)	.40 (.447)	410 (48)	219 (76)
Letter	13,826 (3,439)	.32 (.378)	312 (57)	165 (77)
Digit	12,572 (2,996)	.10 (.204)	294 (57)	129 (72)
Mean	16,839 (3,002)	.32 (.245)	362 (48)	194 (66)

Statistical Methods

Analysis of variance was used to assess the statistical significance of differences in the means of these measures across the different types of RAN tasks. Subsequently, linear regression was used to determine whether eye-voice measures could explain individual differences in RAN completion time.

RAN Time and Accuracy

Table 2 shows basic results for vocal performance in the RAN task. Consistent with previous research (Van den Bos, Zijlstra, & lutje Spelberg, 2002; Cronin & Carver, 1998; Denckla & Rudel, 1974; Hogan-Brown et al., 2014; Meyer, Wood, Hart, & Felton, 1998; Misra et al., 2004), average completion time was longer for the object RAN than for the color RAN, $F(1, 47) = 59.3$, $p < .001$, longer for the color RAN than for the letter RAN, $F(1, 47) = 192.9$, $p < .001$, and longer for the letter RAN than for the digit RAN, $F(1, 47) = 38.2$, $p < .001$. The average number of errors per RAN trial was low for these college students, on average showing less than one error per two trials. Accordingly, error rates will not be analyzed further. However, it should be kept in mind that completion time encompasses time spent on erroneous responses, self-corrections and fillers. As such, completion time will be considered a comprehensive measure of RAN performance. Decomposition of the RAN time showed that both the average durations for correctly spoken items and the average durations of silence preceding correctly spoken items were longer for the object RAN than for the color RAN, $F(1, 47) = 24.4$, $p < .001$, $F(1, 47) = 21.2$, $p < .001$, respectively; longer for the color RAN than for the letter RAN, $F(1, 47) = 363.7$, $p < .001$, $F(1, 47) = 27.2$, $p < .001$, respectively; and longer for the letter RAN than for the digit RAN, $F(1, 47) = 21.3$, $p < .001$, $F(1, 47) = 22.0$, $p < .001$, respectively.

Eye Movements and Eye-Voice Span (EVS) During RAN

Qualitatively, the pattern of eye movements during the RAN, shown in Table 3, is broadly similar to the pattern found during reading, a result no doubt of the sequential nature of both tasks. Like most words, most RAN items are fixated at least once; however, occasionally some are skipped, though less frequently than words are skipped during reading (Rayner, 1998). There was a nonsignificant increase in the proportion of items skipped from object to color, to letter, and to digit RAN. In addition, while the eyes generally move forward, they occasionally move backward, though again less frequently in the RAN than is typically observed during reading (Rayner, 1998). Regression rate was higher for the object RAN than for the color RAN, $F(1, 47) = 5.9$, $p = .019$, did not differ for the color and letter RANs, $F(1, 47) < 1$, and was higher for letter RANs than for digit RANs, $F(1, 47) = 7.6$, $p = .008$. Table 3 shows that the proportion of return saccades that landed short of the first item in the row was .58, with no significant differences in the proportion of short returns as a function of RAN type. The proportion of short returns followed by a corrective saccade to the first item in the row was .74. Proportion of short returns that were corrected did not differ between the object and color RANs, $F(1, 37) = 1.2$, $p > .25$, was significantly higher for the color RAN than the letter RAN, $F(1, 37) = 14.9$, $p < .001$, and did not differ significantly between the Letter and Digit RANs, $F(1, 37) < 1$.[3] The finding that corrections of short returns were less common for symbolic (letter and digit) RANs than for nonsymbolic (object and color) RANs suggests that the symbolic RAN items could be recognized more easily without direct fixation than could the nonsymbolic RAN items.

Figure 1 shows the proportion of articulation onsets on which the eyes led the voice by zero, one, or two or more items. For all four RAN types the modal EVS was one item, occurring for 75.9% of the articulations averaged across RAN types but showing lower values of 72.5% and 65.6% for the letter and digit RANs respectively. These decreases in frequency of the modal EVS are attributable to a greater incidence of longer EVSs (two-or-more items) for the letter and digit RANs. Table 3 shows the mean EVS for all RANs and for each RAN separately. Mean EVS did not differ significantly for the object and color RANs, $F(1, 47) < 1$, but was lower for the color RAN than for the letter RAN, $F(1, 47) = 6.4$, $p = .015$, and lower for the letter RAN than for the digit RAN, $F(1, 47) = 53.8$, $p < .001$.

[3] When collapsed across RAN types all 48 participants had nonzero rates of short return saccades but only 38 participants had nonzero rates of short return saccades for every RAN type. The proportion of short returns that are corrected cannot be calculated for conditions where there are no short returns, and for this reason Table 3 shows the mean results for proportion of short returns that are corrected for those 38 participants who had nonzero rates of short returns for all RAN types, and this accounts for the reduced degrees of freedom reported for tests between these RAN types on this measure. Performing these tests in a pairwise fashion increases the number of participants included in each analysis but does not change the pattern of results: object versus color (means of .84 and .83), $t(43) = .26$, $p = .80$; color versus letter (means of .85 and .64), $t(43) = 4.22$, $p < .001$; and letter versus number (means of .66 and .62), $t(39) = .72$, $p = .47$.

Table 3
Summary of Eye Movement Measures Across RAN Types

	Skipping rate	Regression rate	Proportion short return saccades	Proportion of short returns corrected	EVS
	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)
Object	.047 (.026)	.085 (.058)	.53 (.31)	.83 (.26)	.95 (.13)
Color	.057 (.037)	.067 (.034)	.58 (.28)	.84 (.22)	.94 (.14)
Letter	.084 (.059)	.072 (.060)	.65 (.31)	.66 (.37)	1.01 (.22)
Digit	.097 (.059)	.055 (.059)	.58 (.36)	.62 (.38)	1.23 (.31)
Mean	.071 (.034)	.070 (.042)	.58 (.24)	.74 (.25)	1.03 (.16)

Note. Skipping rate refers to the proportion of items that did not receive a first-pass fixation. Regression rate refers to the proportion of fixated RAN items from which there were regressive eye movements to earlier items in the sequence. Proportion short return saccades refers to the proportion of return saccades that undershot the target RAN item (the first item on the new line). Proportion of short return saccades corrected refers to the proportion of short returns that were corrected by a regressive saccade aimed towards the original target of the return saccade.

Figure 2 shows eye-voice traces for individual trials in the letter RAN for three participants. Hypotheses about the ways that eye-voice relations contribute to RAN performance were generated by examining such traces. Comparison of the top and middle panels of Figure 2 illustrates a consistent difference wherein completion time decreased as EVS increased (e.g., the trial from Participant 15 had greater average EVS and shorter completion time than did the trial from Participant 37). This relationship was found previously by Pan et al. (2013) for typically developing 10-year-olds but not for those with dyslexia. Further exploration of these data showed that RAN performance was also affected by regression rate—the likelihood that the eyes move backward to an earlier item; this effect can be seen in the bottom panel of Figure 2 where Participant 29 has a long completion time and frequent regressive saccades. A straightforward interpretation of the pattern shown by Participant 29, and by other similar participants, is that having the eyes ahead of the voice facilitates RAN performance as long as the eyes are not so far ahead as to require regressing to an earlier item in order to avoid confusion. Below we test this interpretation by examining how EVS and the rate of regressive saccades interact in predicting individuals' RAN completion time and by examining the local impact of regressive saccades on the vocal duration of RAN items.

An initial series of linear regression models was performed in order to evaluate the extent to which individual variation in average RAN completion time across RAN types could be predicted from EVS and regression rate.[4] Collapsing across RAN types provides a stable measure of RAN performance, as shown by the high test–retest reliability for participants' completion times (r = .95, R^2 = 0.90), EVS (r = .88, R^2 = 0.78), and regression rate (r = .78, R^2 = 0.60). As noted above, the pattern of regressive saccades is strongly influenced by the line position of the item because of corrective regressions that occurred following return saccades at the end of the line. This pattern of eye movements related to line returns likely causes the relationship between the eyes and the voice to differ for the central items of a row and for the peripheral items at both ends of a row. Accordingly, statistical analysis of the relationship of RAN performance and reading to RAN eye-voice relations was performed separately for central (columns 3–7) and peripheral items (columns 1–2 and 8–9), with the exception that columns 1 and 2 of the first row and columns 6 through 9 of the final (fourth) row were excluded from all analyses because they exhibited distinctive eye-voice patterns associated with the beginning and the end of the trial.

Table 4 shows the results of linear regression models that predict RAN completion time for the RANs based on EVS (Model 1) and on both EVS and regression rate (Model 2); these models were assessed separately using eye-voice measures from central and peripheral items. For Model 1, the relationship between EVS and completion time fell short of statistical significance for central items but was highly significant for peripheral items. For Model 2, regression rate was a significant predictor of completion time for both central and peripheral items. Further, adding regression rate to the model strengthened the relation between EVS and completion time as compared to Model 1 where EVS was the sole predictor. Prediction was strongest for eye-voice measures taken from peripheral items, where they accounted for 48% of the variance in completion time. The stronger prediction for eye-voice measures taken from peripheral items suggests that this pattern is particularly important when coordinating vocal responses around long return saccades. Participants who were able to keep the eyes consistently ahead of the voice across line breaks achieved faster RAN times than those who did not.

More generally, the results of these initial linear-regression models support the interpretation that having the eyes lead the voice facilitates RAN performance as long as the eyes do not lead by so much that regressive saccades are required in order to avoid confusion. This interpretation was tested by examining the immediate effects of regressive saccades on eye-voice relations and on the durations of RAN items. As in the determination of EVS (see above), the onset of vocalization of a RAN item is used as the

[4] Our initial explorations of individual differences also examined the different types of RAN tasks separately. Those exploratory analyses showed some tendency for stronger relations between the eye-voice measures and RAN completion time for the symbolic (letter and digit) RANs than for the nonsymbolic (object and color) RANs. However, this tendency was not consistent across measures and the results did not provide a compelling indication about whether the observed patterns reflected true differences between the RANs or whether they simply reflected variation due to sampling error given the quantity of data collected for each participant on each RAN type. Accordingly, our modeling of individual differences uses participants' results averaged across the four RAN types.

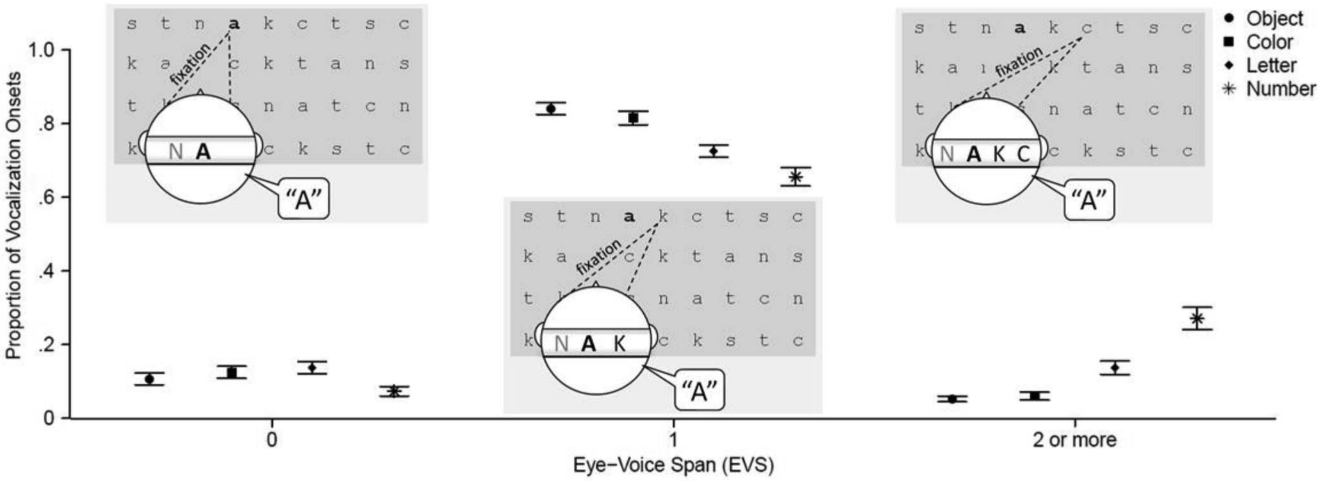

Figure 1. Average proportion of vocalization onsets with an EVS of 0, 1, or 2 or more across RAN types.

temporal landmark for determination of eye-voice relations. A regressive saccade was deemed to have occurred *during* a RAN item if it occurred after the onset of vocalization of that item and before the onset of vocalization of the next item. Identifying the concurrent RAN item in this way provides a rough measure of the temporal relation between the regressive saccade and the vocalization sequence. This temporal relation can be refined by dividing regressive saccades into *final* and *nonfinal* regressions. For final regressions, the regressive saccade was the last saccade that occurred during the concurrent RAN item; its landing position determined the fixation location at the onset of the vocalization of the next RAN item. For nonfinal regressions, the regressive saccade was followed by a progressive saccade before the onset of vocalization of the next RAN item; this means that there was a regression–progression sequence during the concurrent RAN item. Because the vast majority of regressive saccades in the RAN data were followed immediately by a progressive saccade (94.2%), the difference between final and nonfinal regressions is matter of timing with respect to the spoken sequence of RAN items. The relationship of regression condition (final regression, nonfinal regression or no regression) to eye-voice measures and to the durations of nearby RAN items was evaluated in order to provide an indication of how regressive eye movements affect RAN performance within a RAN sequence.

The first column of data in Table 5 shows the relation between regression classification and the maximum by which the eyes moved ahead of the voice during the concurrent RAN item (*maximum lead*). For analyses over all RAN regions a highly significant relation was observed, $F(2, 86) = 17.3$, $p < .001$, with the mean of the maximum lead being lower for vocalizations that were not concurrent with a regression as compared with the average maximum lead during vocalizations concurrent with either of the two regression classifications, $t(43) = 7.45$, $p < .001$, and with the mean of the maximum lead being lower for nonfinal regressions as compared with final regressions, $t(43) = 2.82$, $p = .007$.[5] The finding that regressions are associated with *higher* maximum eye-voice leads is consistent with the argument that regressive saccades occur because the eyes have gotten too far ahead of the voice. In addition, there was a highly significant relationship between regression classification and duration of the current RAN item, $F(2, 86) = 55.0$, $p < .001$, with shorter durations when there was no regression as compared with the average of the two regression classifications, $t(43) = 9.46$, $p < .001$, and longer durations for nonfinal regressions as compared to final regressions, $t(43) = 5.49$, $p < .001$. When the peripheral RAN items were considered alone, the same statistical pattern was observed, $F(2, 80) = 24.2$, $p < .001$, with smaller maximum eye-voice leads when there were no regressions as compared with when there were regressions, $t(40) = 6.12$, $p < .001$, and with maximum leads being smaller for nonfinal as compared with final regressions, $t(40) = 4.23$, $p < .001$. Durations for peripheral RAN items varied significantly with regression classification, $F(2, 80) = 28.2$, $p < .001$, again with shorter durations when there was no regression as compared with the average of the two regression classifications, $t(40) = 6.96$, $p < .001$, and longer durations for nonfinal regressions as compared with final regressions, $t(40) = 4.42$, $p < .001$. For central RAN items, the relationship between the mean of the maximum lead and regression pattern was not significant, $F(2, 50) < 1$. The absence of a significant effect of regression classification on EVS for the central items considered alone may be due to the small number of regressive saccades. Nonetheless, durations for central RAN items varied significantly with regression classification, $F(2, 50) = 23.4$, $p < .001$, again with shorter durations when there was no regression as compared to the average of the two regression classifications, $t(25) = 6.59$, $p < .001$, and longer durations for nonfinal regressions as compared to final regressions, $t(25) = 2.62$, $p = .015$.

The remaining data in Table 5 show the relationships between regression classification, mean EVS and the duration (vocalization

[5] The degrees of freedom are reduced for in statistical tests for differences as a function of the two different types of regressions because only 44 of 48 participants showed both types of regressions. Fewer participants showed both types of regressions when analyses were restricted to peripheral items and fewer still showed both types of regressions for central items where the overall rate of regressions was substantially lower.

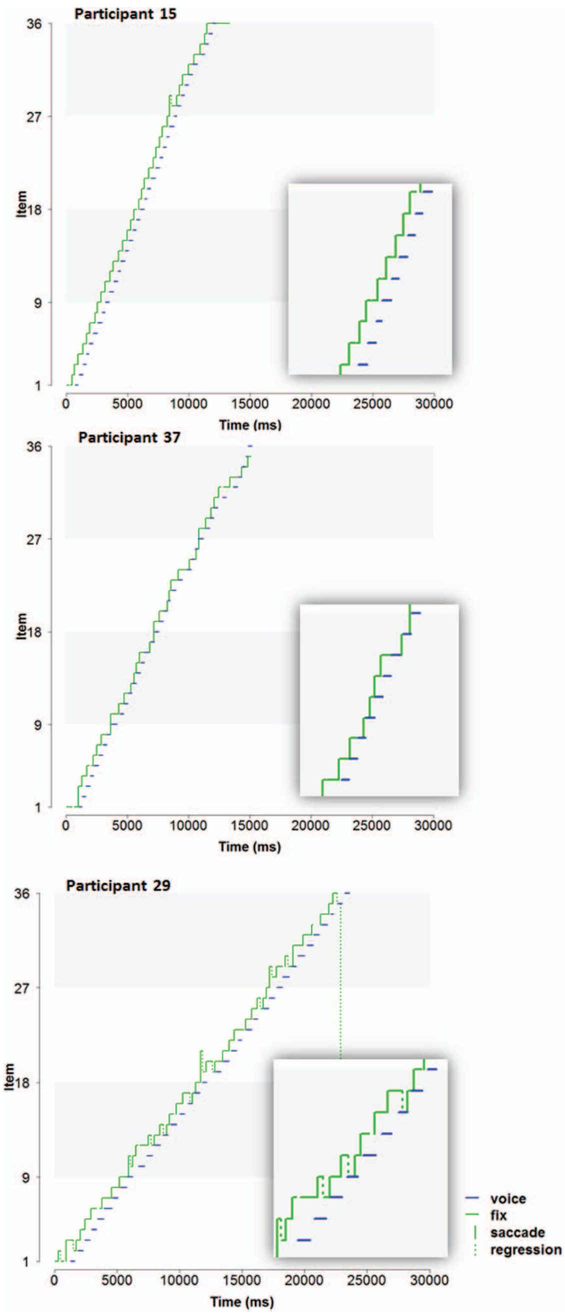

Figure 2. Eye-voice traces for individual trials of the letter RAN for three participants. The position in terms of RAN items (vertical axis) across time (horizontal axis) is shown with green lines for the eyes and blue lines for the voice. The insets provide a blow-up of the pattern for RAN items 10 through 18. EVS (measured in number of RAN items) is indicated by the magnitude of the vertical gap between the green and blue lines. Participant 15 (top panel) has a large average EVS; it can be seen that at the onset of vocalizing an item the eyes are almost always fixating on a RAN item that is one or two ahead. Participant 37 (middle panel) has a smaller average EVS and it is apparent that at times the voice catches up to the eyes, so that at the onset of vocalizing an item the eyes are fixating that same item. Participant 29 (bottom panel) often has a substantial lead of the eyes over the voice but has frequent regressive saccades that bring the eyes back to an earlier item. See the online article for the color version of this figure.

plus following silence) of the RAN item following the RAN item being spoken over the interval in which regression classification was assessed ("next RAN item"). Over all RAN regions, mean EVS for the next RAN item varied significantly by regression type, $F(2, 86) = 99.6$, $p < .001$. Mean EVS was higher when there was no regression as compared to the mean of the two regression classifications, $t(43) = 7.73$, $p < .001$, but it is apparent from the pattern of EVS that this difference is entirely due to a substantial reduction in mean EVS when the regression was the final saccade before the next vocalization compared with when it was nonfinal, $t(43) = 10.57$, $p < .001$. The duration of the next RAN item was significantly related to regression type, $F(2, 86) = 7.54$, $p = .001$, with a nonsignificant trend for shorter durations when there was no regression than when there was, $t(43) = 1.81$, $p = .08$, and with shorter durations when the regression was nonfinal as compared with when it was final, $t(43) = 3.03$, $p = .004$. The patterns of differences and statistical significance for analyses on the peripheral and central RAN items were very similar to those for the overall analyses. Peripheral RAN items showed a significant relation between regression type and mean EVS, $F(2, 80) = 25.6$, $p < .001$. EVS was higher when there was no regression compared to when there was, $t(40) = 2.49$, $p < .05$, an effect that was due to the reduction in EVS when the regressive saccade was final compared to when it was nonfinal, $t(40) = 6.00$, $p < .001$. Duration of the next RAN item was significantly related to regression type, $F(2, 80) = 6.75$, $p < .01$, with a nonsignificant trend for longer durations when there was no regression compared with when there was, $t(40) = 1.75$, $p = .09$, but significantly shorter durations when the regression was nonfinal compared with when it was final, $t(40) = 2.96$, $p < .01$. Central RAN items also showed a significant relation between regression type and EVS, $F(2, 50) = 119.5$, $p < .001$. EVS was higher when there was no regression compared with when there was, $t(25) = 10.97$, $p < .001$, and again this effect was due to the reduction in EVS when the regressive saccade was final compared with when it was nonfinal, $t(25) = 10.92$, $p < .001$. Duration of the next RAN item was significantly related to regression type, $F(2, 50) = 4.0$, $p < .05$. While there was no overall difference in duration when there was a regression compared with when there was not, $t(25) = 1.71$, $p = .1$, in cases where there was a regression, duration of the next RAN item was significantly shorter when the regression was nonfinal compared with when it was final, $t(25) = 2.11$, $p < .05$.

The manner in which different types of regressions are related to the time course given by local measures of RAN performance is readily interpretable in terms of the task demands. For cases of nonfinal regressions, the regressive saccade is followed by a forward saccade before the onset of vocalization for the next RAN item. These additional saccades are associated with longer durations for the concurrent RAN items as compared with when there is no regression or when there are final regressions. However, the additional forward saccade advances the eyes so that the EVS for the next RAN item is close to the modal value of one (see Figure 1) and very similar to the EVS found when there is no regression at all. The duration of the RAN item following nonfinal regressions is no longer than for RAN items following cases where there was no regression at all, which can be taken as an indication that the disruption in processing associated with the regression has been resolved by that point and that normal processing has been resumed. The time course is quite different for cases where the

Table 4
Model Fits for RAN Completion Times as a Function of EVS (Model 1) and of EVS and Regression Rate (Model 2)

	Central items			Peripheral items		
	B	*SE*	*t*	*B*	*SE*	*t*
Model 1						
EVS	−4.73	2.70	−1.75	−6.33	1.97	−3.21**
R^2		.06			.18	
Model 2						
EVS	−5.34	2.43	−2.19*	−6.99	1.60	−4.37***
Regr	49.13	14.23	3.45**	17.10	3.38	5.04***
R^2		.26			.48	

* $p < .05$. ** $p < .01$. *** $p < .001$.

regression is the final saccade before the onset of the next RAN item. As discussed, the duration of the current RAN item is longer than when there was no regression, but it is shorter than for cases of nonfinal regressions where there was an additional forward saccade. However, having a final regressive saccade affects the following RAN item in such a way that the modal EVS (one item) is achieved for less than half of the items. In addition, the duration of the RAN item following final regressions is longer than those following nonfinal regressions, indicating that the processing disruption associated with the regression has not yet been resolved and is continuing to affect performance.

The substantially better fits that were obtained with both regression rate and EVS (Model 2) as compared with EVS show that regression rate is an important predictor of RAN completion time. Further, inclusion of regression rate strengthened the predictive relationship between EVS and completion time, which suggests that not accounting for regressions suppressed that relationship. The finding (see Table 5) that RAN items have longer durations when they coincide with regressive saccades suggests that including regression rates improves model fits through this direct association with longer durations on specific RAN items. While that is likely true to some extent, the low overall regression rate suggests that the contribution of regression rate to model fit might also be based on processes beyond those that are observed locally in the form of increased vocal duration during or shortly after a regressive saccade. To test this possibility, the models using EVS and regression rate to predict total RAN completion time were rerun, but the outcome measure of total RAN completion time was replaced by the average duration (vocalization plus following silence) of RAN items that did *not* coincide with or immediately follow a regressive saccade. As seen in Table 6, regression rate continued to make substantial contributions to eye-voice models of RAN performance even when the outcome measure did not include RAN items whose durations were directly affected by regressive saccades. This suggests that regressive saccades are both a direct indication of a disruption in smooth processing during the RAN task and also an indirect indication of the individual's susceptibility to processing disruptions that do not result in this overt behavior.

Reading: Analysis Procedures and Word-Recognition Results

Fixations shorter than 80 ms and within 1 degree of a longer, immediately subsequent fixation were merged with the longer fixation by an automatic procedure in the EyeLink software. Reading times for the two target words in each sentence were analyzed according to several standard measures of eye movements during

Table 5
Relations Between Regression Classification, Maximum Lead (the Maximum Number of Items the Eyes Moved Ahead of the Voice During the Concurrent RAN Item), Duration of the Concurrent RAN Item (Vocalized RAN Item During Which the Regressive Saccade Occurred), EVS (Number of Items the Eyes Were Ahead of the Voice at the Onset of the Next RAN Item) and Vocal Duration of the Next RAN Item for all RAN Regions Combined and When Assessed Separately for Central and Peripheral RAN Items

		Measure			
		Maximum lead	Duration current RAN item	EVS	Duration of next RAN item
	Regression type	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)
All RAN regions	None	1.89 (.192)	546 (101)	.89 (.193)	503 (91)
	Nonfinal	2.03 (.179)	903 (264)	.97 (.192)	489 (107)
	Final	2.25 (.470)	701 (230)	.45 (.290)	566 (154)
Peripheral regions	None	1.90 (.275)	567 (118)	.90 (.276)	545 (118)
	Nonfinal	2.04 (.177)	900 (319)	.99 (.212)	477 (111)
	Final	2.43 (.621)	661 (278)	.63 (.370)	554 (167)
Central regions	None	1.88 (.173)	569 (113)	.88 (.173)	518 (92)
	Nonfinal	1.93 (.360)	926 (248)	.88 (.323)	511 (131)
	Final	1.92 (.245)	782 (275)	.09 (.168)	634 (298)

Table 6

Model Fits for Average Duration (Vocalization Plus any Following Silence) of RAN Items for Which There Were no Regressive Saccades During the Vocalization of That Item or the Preceding Item

	Central items			Peripheral items		
	B	*SE*	*t*	*B*	*SE*	*t*
Model 1						
EVS	−142.36	76.77	−1.85	−203.63	54.59	−3.73**
R^2		.07			.232	
Model 2						
EVS	−157.43	71.33	−2.21*	−220.45	45.89	−4.80***
Regr	1220.38	416.96	2.93**	439.50	97.01	4.53***
R^2		.22			.47	

Note. Fits are shown for the participants' eye-voice span (Model 1) and for their eye-voice span and their regression rate (Model 2) as measured when the RAN items associated with regressions were included.
* $p < .05$. ** $p < .01$. *** $p < .001$.

reading. *Skipping rate* is the proportion of occasions on which a word did not receive a first-pass fixation, meaning that the word was never fixated or that it was only fixated after the eyes had already gone beyond the word. Skipping rate is affected both by oculomotor factors (e.g., saccade overshoot) and ease of processing a word in the parafovea to the right of fixation (Choi & Gordon, 2013, 2014; Gordon, Plummer & Choi, 2013; Rayner, Sereno, & Raney, 1996; Vitu, O'Regan, Inhoff, & Topolski, 1995). *Gaze duration* is the sum of all first-pass fixations on a target word, starting when the eyes first enter the word's region and ending when the eyes exit the region either to the left or the right; it is generally regarded as the most appropriate eye-movement measure of word recognition (Inhoff, 1984; Morris, 1994; Rayner, 1998). *First-pass regression rate* is the proportion of occasions on which the first-pass fixations on a target word are followed by a regressive eye movement to an earlier region of text; it is thought to reflect difficulty in integrating the target word into the evolving sentence meaning and in some instances correction for an earlier mistargeted saccade (Frazier & Rayner, 1982; Rayner, Sereno, Morris, Schmauder, & Clifton, 1989).

Mean accuracy on the postsentence comprehension questions was 95% ($SD = 6.0$); no participants' data were excluded from analyses due to poor question-answering performance. Table 7 shows eye tracking during reading results for the target words as a function of word frequency (high vs. low). Skipping rate was greater when the target word was high frequency as compared with low frequency, $F_1(1,47) = 8.9$, $p < .01$, $F_2(1,199) = 9.6$, $p < .01$. Gaze duration was shorter for high- than for low-frequency words, $F_1(1,47) = 27.3$, $p < .001$, $F_2(1,196) = 25.6$, $p < .001$. First-pass regression rate was lower for high- than for low-frequency words, $F_1(1,47) = 5.5$, $p < .05$, $F_2(1,196) = 7.3$, $p < .01$.[6]

RAN Performance and Word Recognition During Reading

Table 8 presents regression analyses that show how different facets of RAN performance predict skipping rate, gaze duration and first-pass regression rate during reading and the effects of word frequency on those measures. For each reading measure, models were evaluated using total RAN completion time (the standard RAN measure) and for the two eye-voice models (Model 1: EVS only; Model 2: EVS and regression rate) applied separately to the central and peripheral RAN items.

Readers' average skipping rate was not predicted by RAN time, a null effect that is consistent with the results of a large scale study conducted around the same time as the current study and using similar materials, with the difference that the RAN task was presented on paper and completion time was measured with a stopwatch (546 readers, Gordon, Moore, Choi, Hoedemaker, & Lowder, under review). Of the eye-voice models, only Model 2 applied to the central RAN items showed a significant relation to skipping rate, with higher EVS associated with more skipping. The effect of word frequency on skipping rate was not significantly related to any of the models of RAN performance.

Readers' average gaze duration declined significantly with their RAN time, a relationship that was also observed in Gordon, Moore, Choi, Hoedemaker, and Lowder (under review) and Kuperman and Van Dyke (2011). Eye-voice Models 1 and 2 both showed significant prediction of gaze duration when applied to central RAN items. Of note, Model 2 (including both EVS and regression rate) accounted for 22% of the variance in gaze duration as compared to the 11% accounted for by the standard measure of RAN completion time. The effect of word frequency on gaze duration was not related significantly to RAN completion time, again consistent with Gordon et al. (under review). However, all of the eye-voice models showed significant relations such that a greater EVS was associated with a smaller effect of frequency on gaze duration. This relationship was strongest for models fit to the central items, with Models 1 and 2 accounting for 17% and 19% of the variance, respectively.

[6] The results change little when the analyses were restricted to the less predictable words as shown in Table A1 where the eye movement results are presented after progressively more stringent criteria are used to exclude the more predictable words (Cloze ≥ 0.25, ≥ 0.10 and > 0). The effects of frequency remain significant both by participants and items under all three exclusion criteria. Further exclusion by the various criteria did not substantially alter the measures at the level of individual participants, as can be seen from the correlations between participants' results with the full set of items and when items were excluded by the various criteria. These high correlations indicate that individual differences in these measures are robust across different criteria for excluding items due to predictability.

Table 7
Summary of Eye-Movement Measures on High- and Low-Frequency Target Words During Sentence Reading

	Skipping rate	Gaze duration	FP regression rate
High-frequency words	.154	250	.149
Low-frequency words	.119	272	.183

Note. FP = First-pass.

Readers' average first-pass regression rate increased significantly with their RAN time, once again showing the same results as in Gordon et al. (under review). All of the eye-voice models also showed significant relations to first-pass regression rate: Greater EVS was associated with lower rates of first-pass regressions and greater RAN regression rate was associated with higher first-pass regression rates in reading. The effect of frequency on first-pass regression rate was not predicted significantly by any of the measures of RAN performance. The models of average first-pass regression rate show three notable features: First, first-pass regression rate was related to the standard measure of RAN completion time as strongly, or more strongly, than to the eye-voice models. Second, first-pass regression rate was predicted equally well by eye-voice models based on central and peripheral RAN items. Finally, within the eye-voice models the statistical relationship of EVS and number of RAN regressions to first-pass regressions appeared equally strong.

Discussion

The scheduling (coordination in time) of eye movements with naming was investigated in relation to individual variation in RAN performance. Across all RAN types, the modal EVS was one item, with symbolic RANs showing greater average EVS than nonsymbolic RANs. Across individuals, as well as RAN types, greater average EVS was associated with faster RAN performance and this relationship was strengthened when the rate of regressive eye movements was included in the statistical models. Together EVS and regression rate accounted for a quarter (central items) to almost half (peripheral items) of the individual variation in RAN completion times indicating that good coordination of eye-voice relations is particularly important across line breaks. This pattern of results suggests that fast RAN performance is facilitated by having the eyes far enough ahead of the voice that upcoming items can be encoded for vocalization in quick succession, but that progressive eye movements are scheduled in such a way that they do not get so far ahead as to cause confusion and require regressive eye movements. Furthermore, regression rates were predictive of RAN speed on items that were not directly affected by regressive saccades, suggesting that an individual's tendency to make regressive eye movements serves as an indicator of their susceptibility to processing disruptions even if such disruptions do not always lead to overt changes in behavior. RAN was related to performance on a separate sentence reading task, such that participants with faster RAN completion times showed shorter gaze durations and lower first-pass regression rates during silent reading. Although RAN completion time is conventionally used as the primary indicator of RAN performance, the eye-voice models better accounted for the variation in eye movements during reading. The full eye-voice model accounted for more variance in gaze duration than RAN completion time, and EVS (but not completion time or regression rate) was significantly related to the effect of word frequency, so that participants with larger average EVS showed smaller effects of frequency. RAN completion time and the eye-voice models accounted for equal proportions of variance in regression rate, but the eye-voice model revealed that this relationship results from both EVS and regression rate during the RAN.

Eye-Voice Relations in the RAN

Figure 3 shows how the relationship in time between looking at a RAN item and saying it determines the degree to which successive RAN items are processed in parallel. These schematic timelines adopt a representation (simultaneous activity on separate items) that has been used extensively in models of how component processes are scheduled during dual-task performance (e.g., Meyer & Kieras, 1997; Pashler, 1994a) and in extensions of those models to serial performance (e.g., Pashler, 1994b). Within each panel time goes from left to right and progress through a sequence of RAN items goes from top to bottom. EVS is shown by the dashed vertical lines; it is the number of items by which the eyes lead the voice at the onset of vocalization of a RAN item (one for the sequence in the top and two for the sequence in the bottom). Comparison of the top and bottom panels of Figure 3 shows that as EVS increases so does the number of RAN items that are processed simultaneously. Thus, while the RAN is a serial task at the level of goals (the items must be said in the correct order), efficient performance is achieved by processing more than one item at a time so that relevant information about downstream items is available without delay when needed by the articulatory system. However, as can be seen in Figure 3, the efficiency of processing downstream items brings with it a requirement that the advance information about items and the order of those items must be accurately stored in working memory until it is used by the articulatory system. This model of RAN performance is consistent with the Protopapas, Altani, and Georgiou (2013) proposal that developmental changes in RAN performance are driven primarily by an increased ability to process RAN items in a cascaded manner, such that multiple subsequent RAN items are processed simultaneously as they are passed through a "pipeline" of different stages of processing. As pointed out by Protopapas et al. (2013), such parallel processing of successive items benefits from the automatization of processes concerned with individual items (visual processing, articulation) but also requires adequate executive control to schedule and monitor the processing of multiple items in parallel processing cascades.

Of course, the memory representations shown in Figure 3 are not fully fleshed out. It is possible that processing each item requires multiple steps (e.g., perceptual encoding, maintenance and articulatory encoding) and therefore that the processing of each item requires storage of multiple representations rather than the single representation shown in Figure 3. Thus, by showing a one-to-one relationship between EVS and the number of items stored in memory Figure 3 may underestimate the rate at which the demand for memory storage increases with EVS. Certainly, the memory loads of one or two items shown in Figure 3 would not of themselves be expected to tax the working memory capacity of college students (Cowan, 2001; Luck &

Table 8
Model Fits for Reading Measures as a Function of Total RAN Completion Time (Total Time) and Separately as a Function of EVS (Model 1) and EVS and Regression Rate (Regr, Model 2)

					Central items			Peripheral items		
	B	*SE*	*t*		*B*	*SE*	*t*	*B*	*SE*	*t*
Prop. words fixated				Model 1						
Total time	.01	.01	1.38	EVS	−.17	.09	−1.96	−.09	.07	−1.29
R^2		.04		R^2		.08			.04	
				Model 2						
				EVS	−.18	.09	−2.03*	−.10	.07	−1.38
				Regr	.50	.47	1.07	.19	.14	1.39
				R^2		.10			.08	
Prop. words fixated—frequency effect				Model 1						
Total time	.00	.00	−.09	EVS	.01	.08	.13	−.01	.06	−.20
R^2		.00		R^2		.00			.00	
				Model 2						
				EVS	.01	.08	.12	−.01	.06	−.15
				Regr	.01	.42	.03	−.10	.12	−.81
				R^2		.00			.02	
Gaze duration				Model 1						
Total time	4.47	1.90	2.35*	EVS	−92.91	35.54	−2.61*	−49.68	28.86	−1.72
R^2		.11		R^2		.13			.06	
				Model 2						
				EVS	−97.47	34.11	−2.86**	−52.01	28.67	−1.81
				Regr	416.59	184.40	2.26*	77.51	58.26	1.33
				R^2		.22			.10	
Gaze duration—frequency effect				Model 1						
Total time	1.16	1.41	.82	EVS	−74.25	24.49	−3.03**	−51.27	19.56	−2.62*
R^2		.01		R^2		.17			.13	
				Model 2						
				EVS	−75.80	24.50	−3.09**	−50.85	19.79	−2.57*
				Regr	141.41	132.44	1.07	−13.77	40.21	−.34
				R^2		.19			.13	
FP regression rate				Model 1						
Total time	.01	.00	3.65**	EVS	−.16	.08	−2.14*	−.14	.06	−2.42
R^2		.23		R^2		.09			.11	
				Model 2						
				EVS	−.17	.07	−2.43*	−.15	.06	−2.69*
				Regr	1.02	.39	2.62*	.28	.11	2.44*
				R^2		.21			.22	
FP regression rate—frequency effect				Model 1						
Total Time	−.00	.01	−.21	EVS	.00	.09	.01	.02	.07	.33
R^2		.01		R^2		.00			.00	
				Model 2						
				EVS	−.00	.10	−.01	.02	.07	.24
				Regr	.19	.56	.35	.18	.16	1.15
				R^2		.00			.03	

Note. FP = First-pass.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Vogel, 1997). Furthermore, individual differences in working memory capacity may affect scheduling efficiency during RAN performance because of the task's simultaneous demands on memory storage and processes of attention control or executive function (Engle, 2002; Kane & Engle, 2003; Miyake & Friedman, 2012), a possibility that awaits investigation.

Regression models that only included EVS had some ability to predict RAN completion time, but both overall model fit and the strength of the relationship between EVS and RAN completion time increased when the rate of regressive eye movements was included in the model. As discussed previously, a plausible explanation of this pattern is that regressive eye movements are an indication that the eyes got too far ahead of the voice, with the consequence that a regression was needed for the purpose of confirming or correcting the items stored in memory. Support for this view comes from the finding that on average the extent to which the eyes led the voice was greater before regressive saccades than progressive saccades (see Table 5). On this account, performance was best for those participants who were able to keep their eyes sufficiently far ahead that downstream items could be encoded and made available for articulatory processing but not so far ahead that they lost track of intermediate items or item order.

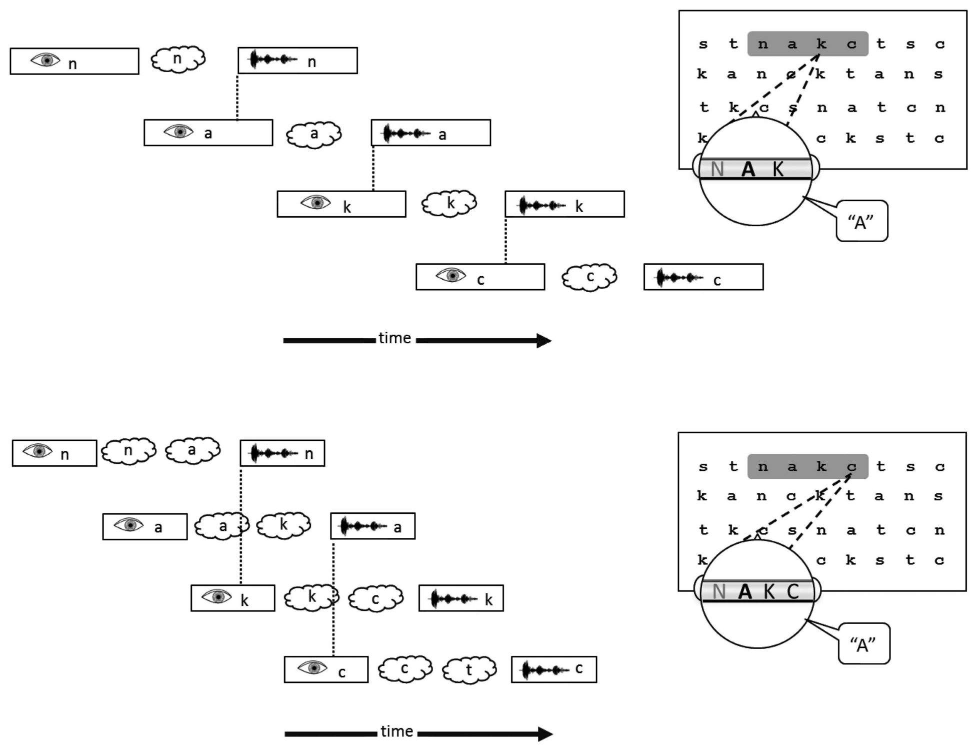

Figure 3. Schematic timeline showing eye-voice relations across items during the RAN, as well as the memory requirements that are imposed when the eyes leave an item before articulation of the item begins. The top panel illustrates an EVS of one while the bottom panel illustrates an EVS of two. EVS is given by the difference in RAN items of the eyes and voice at the onset of vocalizing an item and is shown by the dashed vertical lines. An EVS of one (as in the top panel) occurs when at the onset of vocalizing an item (the left edge of the voice rectangle) the eyes are already fixating the next item; this relation between the eyes and the voice requires that a single RAN item be stored in memory (as indicated by the thought cloud). An EVS of two (as in the bottom panel) occurs when the eyes are already fixating two items ahead at the onset of vocalization; this relation between the eyes and the voice requires that two items must be stored in memory.

However, including regression rate with EVS improved the fit of eye-voice models even for the prediction of individual variation in RAN times that excluded RAN items whose durations were directly affected by regressive saccades (see Table 6). As noted above, this suggests that the rate of regressive saccades is an observable indication of an individual's susceptibility to disruptions in smooth sequential processing even on occasions where those disruptions do not result in a regressive saccade.

The manner in which eye-voice patterns and RAN completion time varied across RAN types is consistent with individual-differences evidence about how eye-voice relations contribute to RAN performance. As is typically found, RAN completion time decreased from object to color to letter to digit RAN (Van den Bos et al., 2002; Cronin & Carver, 1998; Denckla & Rudel, 1974; Hogan-Brown et al., 2014; Meyer, Wood, Hart, & Felton, 1998; Misra et al., 2004). Average EVS was significantly lower for the object and color RANs than for the letter RAN, which was lower than for the digit RAN. Average regression rate was higher for the object than for the color and letter RANs, which were higher than for the digit RAN. These differences between symbolic and non-symbolic RANs suggests that the processing stream from encoding to articulation functions more smoothly and is less susceptible to interitem interference for the letter and digit RANs than for the object and color RANs (see Figure 1). A stronger association between items and their names for the symbolic compared with the nonsymbolic RANs is one possible contributor to this difference though it is likely that other factors (e.g., visual complexity and inherent phonetic length of RAN items) also contribute. The greater EVS for the digit as compared with the letter RAN may occur because college students would typically be expected to encode letters during the recognition of words (where letter names play little or no role) while digits are more likely to be encoded or spoken aloud individually. Thus, the steps of perceptual encoding, name retrieval, and articulatory planning may work more efficiently for digits than for letters, with visually perceived digits rapidly converted into articulatory codes with fewer opportunities for memory interference than occur for letters or for nonsymbolic visual stimuli. This account is consistent with the idea that good RAN performance occurs when naming is automatic (Hogan-Brown et al., 2014; Norton & Wolf, 2012; Pan, Yan, Laubrock, Shu, & Kliegl, 2013), but needs to be evaluated in tasks that independently control factors other than the strength of the item-name association.

Eye-voice relations in the RAN for the college students tested in this study showed variation in a small range around a very consistent core pattern (i.e., the EVS of one item that was found for 75.9% of RAN items across all four types of RAN task). The mean magnitude of the EVS is quite similar to those of Pan et al. (2013), who report that their groups' means for EVS in the digit RAN were .81 for dyslexic 10-year-olds ($SD = .25$) and 1.1 for control 10-year-olds ($SD = .27$). For the adults in the current study mean EVS in the digit RAN was 1.23 ($SD = .31$). In the Pan et al. (2013) study the correlation between RAN completion time and EVS was not significant for the dyslexic 10-year-olds, but for the control 10-year-olds these two measures were negatively correlated (i.e., faster RAN time associated with larger EVS), as was the case for the adults in the current study. The small differences in EVS between the groups in these two studies show an orderly relation to diagnostic status (dyslexic vs. control) and education level (fifth graders vs. college students). Pan et al. (2013) interpret their results as indicating that the visual attention span is smaller in the dyslexic children than the control children. The current finding that the strength of the association between EVS and completion time increased when number of regressive eye movements was added to the model (see Table 4) indicates that regression rate had a suppressive effect on the relationship between EVS and completion time. Therefore, absence of a relationship between EVS and completion time for Pan et al.'s (2013) dyslexic group could be due to suppression of the relationship between EVS and completion time by frequent disruptions of parallel processing of the sort indicated by regressive saccades. The extent to which eye-voice relations in other populations (e.g., very young children) are similar to those found here remains an open question.

RAN Performance and Skilled Reading

The results of this study show that variation in RAN completion time predicted variation in eye-movement measures of lexical processing by skilled readers (see also Gordon et al., under review). For measures of early word-recognition processes predictions from the eye-voice model of RAN performance were better than predictions based on RAN completion time alone. Predictions for measures of early word recognition were stronger using the eye-voice models for central rather than peripheral RAN items, an outcome that is unsurprising given that the reading study was designed to provide information about recognition of words that were not near the edges of a line. For eye-movement measures of later lexical processing predictions from the eye-voice model and RAN completion time were similar.

With respect to early word-recognition processes, both RAN completion time and eye-voice relations for central RAN items were significantly related to mean gaze duration, though the eye-voice relations accounted for a greater share of variance (22% vs. 11%). Eye-voice relations for central RAN items were significantly related to first-pass skipping and to the effect of word frequency on gaze duration, but RAN completion time was not significantly related to either measure. This pattern is consistent with the findings of the larger study (Gordon et al., under review) where RAN completion time was significantly related to mean gaze duration but not to the effect of frequency on gaze duration or to skipping rate.

The finding that eye-voice relations in the RAN were a better predictor than RAN completion time for these first-pass measures of early word recognition suggests that eye-voice relations have the potential to provide new insight into the cognitive processes that allow for efficient word recognition during reading. It is possible that this efficiency is found in the actual operation of word-recognition mechanisms, but it seems more likely that it is due to the efficiency with which a reader coordinates early word-recognition processes with rapid first-pass eye movements (e.g., the L1 familiarity check in the EZ Reader model; Pollatsek, Reichle, & Rayner, 2006; Reichle, Rayner, & Pollatsek, 2003, which is affected by word frequency and determines gaze duration) and to the efficiency with which information gained by those early word-recognition processes is used at subsequent levels of comprehension. Our interpretation of the RAN-reading relationship in adults is consistent with Protopapas et al.'s (2013) proposal that the relationship between RAN and reading across development may be explained by changes in developing readers' ability to process subsequent items in parallel. Reading entails processing of input at many different levels of abstraction ranging from the processing of visual features, through different levels of word recognition and the integration of meaning across sentences. The manner in which the characteristics of text influence eye movements during reading is consistent with the idea that processing of words occurs faster at lower levels, such as gauging whether a word is familiar, than at higher levels, such as integrating a word's meaning with an emerging discourse representation (Gordon et al., 2013; Lowder, Choi, & Gordon, 2013; Rayner, 1998). For reading to be efficient, these processes must be scheduled so that the ones that are early and quick are completed by the time that their output is needed, but that these early levels do not get so far ahead of the slower processes that their connection to the larger goal of comprehension is lost with the result that reading becomes mindless (McVay & Kane, 2012; Rayner & Fischer, 1996).

With respect to later lexical processing, slightly over 20% of the individual variation in first-pass regression rate during reading was accounted for by RAN completion time, a relationship that was also found in the larger study (Gordon et al., under review). The additional finding that the two components of the eye-voice model, EVS and regressions rate, predict first-pass regression rate during reading offers insight into why this RAN–reading relationship is observed. The finding that increased rate of regressions in the RAN predicts increased rate of first-pass regressions during reading is consistent with findings showing individual consistency in eye-movement characteristics across tasks (Henderson & Luke, 2014). That is, participants who are more likely to make regressive eye movements in the RAN are more likely to make them during reading. While this finding provides some support for the idea that the RAN–reading relation occurs because both tasks tap the same ability to control eye movements (Clarke et al., 2005; Kuperman & Van Dyke, 2011; see Protopapas et al., 2013 for discussion), the finding that increased EVS in the RAN predicts decreased rate of first-pass regressions during reading does not involve a straightforward correspondence of eye movements across the two tasks.

EVS reflects a process in which the eyes are advanced through a sequence so that perceptual encoding can be initiated for upcoming stimuli while processing of earlier items is ongoing. RAN and other reading-aloud tasks allow measurement of both eye and vocal position, with the distance between them giving the span over which processing is taking place. In silent reading the timing of perceptual encoding can be measured reasonably directly by eye position but far less information is available about the timing of processing at higher levels such as selection of word meaning and the integration of meanings within and across sentences. On this interpretation, both RAN performance and silent reading require scheduling of processes that occur simultaneously on a sequence of items and the RAN task is a useful predictor of reading because it indicates the efficiency with which the individual achieves this type of scheduling.

Conclusion

Performance on the RAN task has been shown to be strongly related to reading skill, the acquisition of literacy, and reading disorders. Yet the reasons for its success have been elusive. The analyses of eye-voice relations reported here show that successful performance in the RAN task requires that rapid eye movements and slower articulation be scheduled (coordinated in time) so that the eyes are sufficiently ahead of the voice to allow preparation for upcoming RAN items but not so far ahead as to strain memory for the correct order of the items. It is argued that silent reading also involves coordination of processes that occur at different rates and that this common scheduling challenge is an important factor in the predictive success of the RAN task.

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(*Appendix follows*)

Appendix

Eye Movement Results With Analysis Restricted to Less Predictable Words

Table A1
Stimulus Characteristics and Reading Measures After Exclusion of Items Using Progressively More Stringent Criteria

Cloze exclusion	WF	Cloze (proportion of items excluded)	Skipping rate	Gaze duration	FP regression rate
$\geq .25$	HF	.0318 (.022)	.154 (r = .998)**	250 (r = .994)***	.122 (r = .939)**
	LF	.0052 (.005)	.119 (r = .999)††	272 (r = .999)†††	.161 (r = .972)††
$\geq .10$	HF	.0105 (.101)	.156 (r = .990)**	249 (r = .989)***	.123 (r = .919)**
	LF	.0033 (.019)	.118 (r = .996)††	273 (r = .998)†††	.162 (r = .972)†
$> .00$	HF	.0000 (.324)	.147 (r = .922)*	251 (r = .954)***	.123 (r = .847)**
	LF	.0000 (.115)	.114 (r = .984)†	273 (r = .990)††	.165 (r = .969)†

Note. The value in parentheses after the mean cloze proportion is the proportion of items excluded by the criterion indicated for that row. The r values in parentheses after each reading measure are the correlation between participants' performance when no items were excluded and when items were excluded using the predictability criterion shown for that row. WF = Word frequency; FP = First-pass; HF = High frequency; LF = Low frequency.
* $p < .05$. ** $p < .01$. *** $p < .001$ for frequency effect as tested by participants. † $p < .05$. †† $p < .01$. ††† $p < .001$ for frequency effect as tested by items.

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