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Abstract

Individual readers vary greatly in the quality of their lexical representations and consequently in how quickly and efficiently they can access orthographic and lexical knowledge. This variability may be explained, at least in part, by individual differences in exposure to printed language, as practice at reading promotes the development of stronger reading skills. The current eye-tracking experiment tests the hypothesis that the efficiency of word recognition during reading improves with increases in print exposure by determining whether the magnitude of the repetition priming effect is modulated by individual differences in scores on the Author Recognition Test (ART). Lexical repetition of target words was manipulated across pairs of unrelated sentences that were presented on consecutive trials. The magnitude of the repetition effect was modulated by print exposure in early measures of processing, such that the magnitude of the effect was inversely related to scores on the ART. The results show that low levels of print exposure, and thus lower-quality lexical representations, are associated with high levels of difficulty recognizing words and thus with the greatest room to benefit from repetition. Further, the interaction between scores on the ART and repetition suggests that print exposure is not simply an index of general reading speed, but rather higher levels of print exposure are associated with an enhanced ability to access lexical knowledge and recognize words during reading.

Efforts to understand the nature of word recognition during reading have traditionally focused on the characteristics of words or texts that reliably modulate the targeting of saccades or the duration of fixations. For example, a large literature has demonstrated that words that are short, frequent, and predictable are skipped more often and elicit shorter fixation durations compared to words that are long, infrequent, and unpredictable (for reviews, see Clifton et al., 2016; Rayner, 1978, 1998). Although a great deal has been learned about the text-level characteristics that contribute to the relative ease or difficulty of recognizing words during reading, considerably less work has been directed at understanding how variability in cognitive constructs among individual readers contributes to differences in word recognition. Indeed, a complete understanding of the cognitive mechanisms underlying word recognition during reading must not only be able to account for the lexical factors that contribute to this process, but must also account for systematic differences in word recognition among individual readers, including how text-level and individual-level factors interact.

One approach that has proven quite useful in explaining individual differences in reading and language processing involves estimating an individual's level of print exposure, most commonly by administering a recognition test of authors' names. In the Author Recognition Test (ART), originally developed by Stanovich and West (1989), participants are presented with a checklist of author and nonauthor names and are instructed to mark the names they recognize as authors. The underlying assumption is that individuals who read frequently are more likely to have encountered the names of authors compared to those who read less frequently. The ART shows moderate-to-strong relationships with other measures of verbal ability, including vocabulary knowledge (Beech, 2002; Lewellen, Goldinger, Pisoni, & Greene, 1993; Stanovich, West, & Harrison, 1995), reading comprehension (Martin-Chang & Gould, 2008; Stanovich &

Cunningham, 1992), knowledge of spelling (Lewellen et al., 1993; Stanovich & West, 1989), and standardized tests of verbal ability (Acheson, Wells, & MacDonald, 2008; Lewellen et al., 1993; Stanovich et al., 1995). Further, a meta-analysis of studies examining the contribution of print exposure to language development from infancy to early adulthood suggests a causal interdependence among time spent reading, reading skill, and reading enjoyment (Mol & Bus, 2011). That is, more time spent reading (or being read to) at a young age leads to early advancements in reading skill, and thus enhanced reading enjoyment, which in turn leads to more time spent reading, and so on. The idea that practice at reading is a key factor that contributes to reading skill is broadly consistent with Perfetti's *lexical quality hypothesis* (Perfetti, 1985, 2007), which proposes that readers with high levels of linguistic expertise acquire high-quality linguistic representations that allow for low-level knowledge of orthographic forms to be automatically linked to higher-level semantic knowledge, thus contributing to rapid and efficient word recognition during reading.

Previous work examining the relationship between print exposure and word recognition has primarily relied on single-word presentation paradigms, as in the lexical decision task (Chateau & Jared, 2000; Lewellen et al., 1993; Sears, Campbell, & Lupker, 2006; Sears, Siakaluk, Chow, & Buchanan, 2008; Unsworth & Pexman, 2003). This work has generally shown that not only do individuals with higher levels of print exposure make faster and more accurate lexical decisions, but they also access lexical information more efficiently, as revealed by smaller word-frequency effects compared to individuals with lower levels of print exposure. More recent studies have begun to relate performance on the ART to measures of eye-movement behavior during reading. For example, Moore and Gordon (2015) showed that higher ART scores were associated with shorter gaze durations (i.e., first-pass reading time on a word), as well as reduced word-frequency effects. In addition, Choi, Lowder, Ferreira, and Henderson (2015) used a gaze-contingent moving-window paradigm to show that higher ART scores (as well as higher scores on other measures of verbal ability) were associated with a larger perceptual span during reading. That is, readers with higher levels of print exposure were more efficient at extracting parafoveal information from the right of the currently fixated word.

The current experiment tests the hypothesis that the efficiency of word recognition during reading improves with increases in print exposure by determining whether the magnitude of the *repetition priming effect* is modulated by individual differences in ART scores. Within the context of word recognition, repetition priming refers to facilitation in the processing of a word when that word has been encountered previously. Although repetition-priming effects have traditionally been studied within the context of list-learning paradigms (e.g., Jacoby & Dallas, 1981; Scarborough, Cortese, & Scarborough, 1977; Tulving & Schacter, 1990) or masked-priming word-identification paradigms (e.g., Bodner & Masson, 2001; Forster & Davis, 1984, 1991), a growing body of work in the eye-movement literature has demonstrated that repetition of a word facilitates processing during the natural reading of text (Choi & Gordon, 2013; Gordon, Plummer, & Choi, 2013; Ledoux, Gordon, Camblin, & Swaab, 2007; Lowder, Choi, & Gordon, 2013; Liversedge, Pickering, Clayes, & Branigan, 2003; Traxler, Foss, Seely, Kaup, & Morris, 2000). This facilitation has been explained as resulting from enhanced lexical retrieval processes, as repetition effects have been shown to be larger for words that are more difficult to access. For example, Lowder et al. (2013) demonstrated enhanced repetition priming for low-frequency as compared to high-frequency words, suggesting that repetition aids the process of lexical access such that the more-difficult-to-find, low-frequency words benefit more from repetition than do the easier-to-find, high-frequency words.

Our study's focus on eye-tracking methodology and print exposure offers several advantages over previous investigations of individual differences in visual word recognition. First, most of the previous work examining individual differences in priming effects has relied on the lexical decision task (e.g., Andrews & Hersch, 2010; Andrews & Lo, 2012; Tan & Yap, 2016; Yap, Tse, & Balota, 2009), in which participants are required to make a metalinguistic judgment about the target stimulus. Thus, performance on this task inherently reflects decision-related processes in addition to the more theoretically relevant process of lexical retrieval. In contrast, the eye-tracking paradigm does not require any explicit judgment about the target word, and thus has the advantage of more accurately reflecting word-recognition processes as they occur during reading. Second, this previous work has tended to focus primarily on individual differences related to vocabulary knowledge and spelling ability and has not considered the role of print exposure. In particular, Andrews and colleagues (Andrews & Hersh, 2010; Andrews & Lo, 2012, 2013) have argued that spelling ability is a particularly powerful construct for indexing individual differences in lexical quality. Although this may be true, the bulk of this evidence comes from experiments that relate performance on spelling tests to performance on the lexical decision task, which is potentially problematic given that the lexical decision task itself can be viewed as a type of spelling test. In contrast, the task demands reflected by the ART (i.e., to identify author names) and the eye-tracking task (i.e., to read naturally) are conceptually distinct from one another. Finally, the design of the current experiment contributes to the important goal of replicating key findings across a range of different methodological approaches by testing whether individual differences in priming effects that have been reported in lexical decision paradigms also emerge in an eye-tracking paradigm.

In the current eye-tracking-while-reading experiment, we systematically manipulated whether a target word was repeated or new across pairs of unrelated sentences and collected ART scores from each of our participants. If readers with low print exposure have lower-quality lexical representations than readers with high print exposure, then they should also experience greater difficulty accessing words during reading. For that reason, readers with low print exposure should have a greater capacity to benefit from lexical repetition and should therefore show larger repetition-priming effects.

Method

Participants

Forty-eight students at the University of North Carolina at Chapel Hill participated in this experiment in exchange for course credit. They were all native English speakers and reported normal or corrected-to-normal vision.

Materials and Design

Sixteen pairs of sentences were constructed (see Example 1). The first of each pair served as the prime-bearing sentence (1a), whereas the second served as the target-bearing sentence (1b). Thirty-two proper names were chosen to serve as prime and target words. Proper names were used because they can easily be placed in different sentence positions without the lexical-semantic constraints associated with content words, and because they can be counterbalanced across prime and target positions. In addition, previous work indicates that the initial stages of word recognition operate similarly for proper names and common nouns (Valentine et al., 1991, 1993; Van Petten et al., 1991). Finally, our own previous work has demonstrated robust repetition-priming effects with proper names (Gordon et al., 2013; Ledoux et al., 2007; Lowder et al., 2013). The names that were chosen were drawn from a database containing the names of all first-year undergraduate students who entered UNC over a five-year period. All names were low-frequency, defined as appearing in the corpus four or five times. Names were between five and eight characters in length. Two names of the same length and gender were assigned to each pair of sentences, and different versions of the sentences were created by allowing each name to alternately serve as prime and target in repeated and new conditions (see Example 1). One version of each item was assigned to one of four counterbalanced lists, such that no participant saw more than one version of each item, and such that all participants received 16 prime-bearing and 16 target-bearing sentences with half containing a repeated target and half containing a new target. In addition, there were 124 filler sentences representing a variety of structures. Every sentence was followed by a true-or-false comprehension question. The comprehension question that followed experimental items never contained a proper name.

(1a) Prime: The TV was on all night even though [Selena/Blythe] had fallen asleep very early.
(1b) Target: Yesterday morning, I made sure to thank [Selena/Blythe] for the Christmas gift.

Author Recognition Test

Participants completed a recently updated version of the ART (Moore & Gordon, 2015). The test contains a list of 130 names: 65 are the names of real authors, and 65 are names that do not refer to authors (foils). The names are presented in alphabetical order. Participants are instructed to mark only the names that they know to be authors and are told that the score is penalized for marking non-authors. The score is calculated as the number of authors correctly selected minus the number of foils incorrectly selected.

Procedure

Eye movements were recorded with an EyeLink 1000 system (SR Research), which was calibrated at the beginning of each session and recalibrated throughout the session as needed. A headrest and chinrest were used to minimize head movement. At the start of each trial, a fixation point was presented near the left edge of the computer screen. Once the participant's gaze was steady on this point, the experimenter pressed a button that presented the sentence. After reading the sentence, the participant pressed a button on a handheld console, which replaced the sentence with a true-false comprehension question. Participants pressed one button to answer "true," and a different button to answer "false." Mean comprehension-question accuracy was 96%. After the participant answered the question, the fixation point for the next trial appeared.

Participants were first presented with four of the filler sentences. After this warm-up block, the remaining sentences were presented in a different random order for each participant while preserving the critical order of the prime-target pairs. In other words, each prime sentence was always immediately followed by its corresponding target sentence (with an intervening comprehension question). Following the eye-tracking portion of the experiment, participants completed the ART.

Analysis

Analysis of the eye-tracking data focused on seven standard eye-movement measures that reflect a range of processing stages (Rayner, 1998). *Skipping rate* is the proportion of trials in which a target word is not fixated at all or is only fixated after a subsequent word has been fixated. *Single-fixation duration* is the average across trials of the durations of the initial first-pass fixations on a word, provided that the word received only one first-pass fixation. *First-fixation duration* is the average of the durations of the initial, first-pass fixations on a word, regardless of the total number of first-pass fixations. *Gaze duration* is the average of the sum of all first-pass fixations on a word. These four measures are thought to reflect the earliest stages of word recognition, including processes of perceptual encoding and lexical access. *First-pass regression rate* is the proportion of trials on which a first-pass fixation on a word is followed by a regressive saccade rather than a progressive saccade. *Regression-path duration* (also called *go-past time*) is the sum of all fixations beginning with the initial fixation on a word and ending when gaze is directed away from the region to the right. Thus, regression-path duration includes time spent rereading earlier parts of the sentence before the reader is ready to move to the right of the target word. First-pass regression rate and regression-path duration are thought to reflect processes involved in integrating a word with earlier parts of the sentence. *Rereading duration* is the sum of all fixations on a word that are not included in gaze duration. Unlike the other measures, rereading duration contains zeroes (i.e., trials where the word was not refixated after first-pass reading). This measure is thought to reflect later stages of processing, including any lingering difficulty associated with integrating the word with the rest of the sentence.

An automatic procedure in the EyeLink software combined fixations that were shorter than 80 ms and within one character of another fixation into one fixation. Additional fixations shorter than 80 ms and longer than 1,000 ms were eliminated. In addition, means and standard deviations were computed separately for each dependent measure within the repeated and new conditions. Reading times that were greater than 2.5 standard deviations from the condition mean were eliminated. This procedure affected 2.6% of the data.

The data were analyzed using mixed-effects models in the lme4 package (Bates, Maechler, & Bolker, 2012) in R. Fixed effects included the experimental factor of repetition (new versus repeated), ART score (mean-centered), and the repetition-by-ART interaction. Subjects and items were entered as crossed random effects, including maximally appropriate random intercepts and slopes. In cases where the model failed to converge, the random-effects structure was sequentially simplified until convergence was achieved (Barr, Levy, Scheepers, & Tily, 2013). For fixation duration measures (single-fixation duration, first-fixation duration, gaze duration, regression-path duration, and rereading duration), linear mixed-effects regression models were fit using the lmer function, which provides the regression coefficient (*b*), standard error (*SE*), and *t*-value of the coefficient. For fixation probability measures (skipping rate and first-pass regression rate), logistic mixed-effects regression models were fit using the glmer function, which provides the regression coefficient, standard error, and *z*-value for the coefficient. Effects were considered significant when the absolute value of *t* or *z* was 2 or greater.

Results

ART scores

There was substantial variability in ART scores across participants, with a minimum score of 1 and a maximum score of 44. The mean was 16.73, the standard deviation was 9.91, and the median was 14.

Eye movements

Mean values for all eye-movement measures are presented in Table 1. Results of the mixed-effects analyses are presented in Tables 2 and 3. Main effects of repetition were observed in measures of single-fixation duration, gaze duration, regression-path duration, and first-pass regression rates, with repeated targets elicited shorter reading times and fewer regressions compared to new targets. Main effects of ART score were observed in measures of single-fixation duration, first-fixation duration, gaze duration, and regression-path duration, with higher levels of print exposure being associated with shorter reading times. In addition to these main effects, we observed significant repetition-by-ART interactions in single-fixation duration, first-fixation duration, and gaze duration. These effects are depicted graphically in Figure 1 with ART scores binned into thirds for purposes of illustration. For all three measures, the effect of repetition was robust for readers with lower ART scores and became smaller as ART score increased, such that for the highest ART scorers, the effect was absent altogether.

Table 1

Mean eye-movement measures on target word as a function of repetition condition

	Fixation duration measures (ms)					Probability measures	
Condition	SFD	FFD	GZD	RPD	Rereading	Skipping	Regressions
New	214	214	246	310	111	.18	.19
Repeated	200	201	221	247	100	.21	.10

Note. SFD = single-fixation duration; FFD = first-fixation duration; GZD = gaze duration; RPD = regression-path duration

Table 2
Results of mixed effects analyses for fixation duration measures

Parameters	SFD			FFD			GZD			RPD			Rereading		
	b	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*	*b*	*SE*	*t*
(Intercept)	210.21	4.68	**44.90**	209.32	4.74	**44.21**	273.13	6.54	**36.27**	300.42	15.46	**19.43**	103.24	12.39	**8.33**
Repetition	-11.18	5.21	**-2.15**	-9.61	5.06	-1.90	-20.84	7.54	**-2.76**	-59.06	13.81	**-4.28**	-13.53	15.46	-0.88
ART	-22.97	6.36	**-3.61**	-21.44	6.24	**-3.43**	-33.67	8.60	**-3.92**	-42.15	15.56	**-2.71**	-12.44	17.51	-0.71
Repetition × ART	17.59	6.09	**2.89**	12.30	5.55	**2.22**	14.88	7.23	**2.06**	19.25	14.23	1.35	-3.51	15.93	-0.22

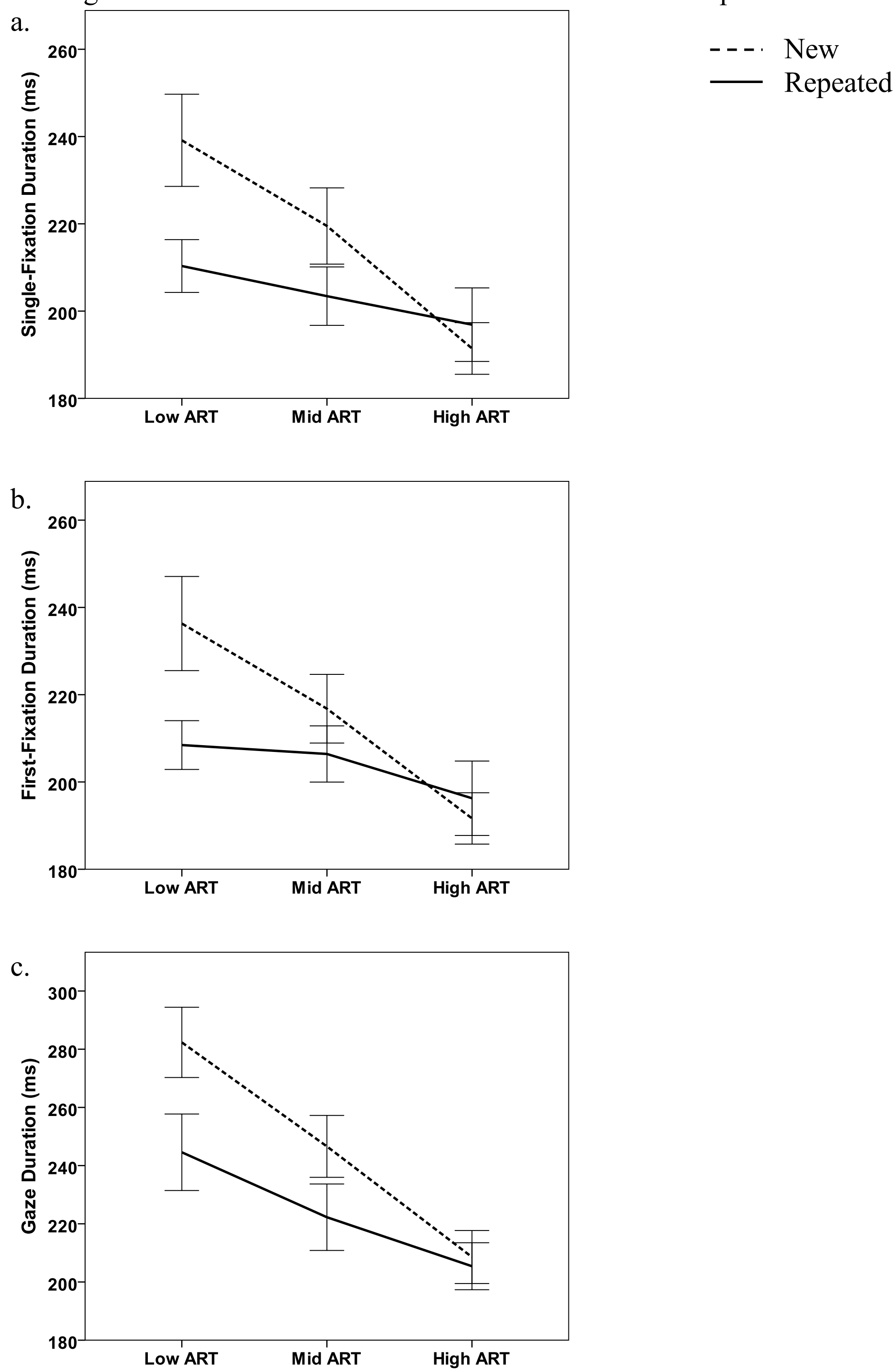
Note. ART = Author Recognition Test; SFD = single-fixation duration; FFD = first-fixation duration; GZD = gaze duration; RPD = regression-path duration; statistically significant effects are indicated in boldface

Table 3
Results of mixed effects analyses for fixation probability measures

	Skipping			Regressions		
Parameters	*b*	*SE*	*z*	*b*	*SE*	*z*
(Intercept)	-1.81	0.23	**-7.85**	-1.53	0.17	**-9.13**
Repetition	0.19	0.19	0.97	-0.76	0.25	**-3.07**
ART	0.09	0.20	0.46	-0.07	0.16	-0.41
Repetition × ART	0.27	0.20	1.37	-0.04	0.26	-0.15

Note. ART = Author Recognition Test; statistically significant effects are indicated in boldface

Figure 1
Mean single-fixation duration (a), first-fixation duration (b), and gaze duration (c) for repeated and new targets as a function of Author Recognition Test (ART) group. ART scores are binned in thirds: Low ART includes scores of 10 or less, Mid ART includes scores between 11 and 18, and High ART includes scores of 19 and above. Error bars represent standard error of the mean.



Discussion

The research reported here combined eye-movement measures from a repetition-priming paradigm and participants' scores on the Author Recognition Test to determine whether the efficiency of word recognition during reading improves with increases in print exposure. Results showed significant repetition effects in eye-tracking measures associated with early stages of lexical access (single-fixation duration, gaze duration) as well as later stages of integration (regression-path duration, first-pass regressions). In addition, higher ART scores were associated with shorter reading times in measures of single-fixation duration, first-fixation duration, gaze duration, and regression-path duration. Crucially, the magnitude of the repetition effect was modulated by print exposure in measures of single-fixation duration, first-fixation duration, and gaze duration, such that the repetition effect was robust for readers with lower ART scores and absent altogether for readers with higher ART scores. The results have implications for research on individual differences in reading and sentence processing as well as the basic mechanisms underlying word recognition during reading.

The ART is generally considered a reliable estimate of an individual's exposure to printed language (Stanovich & West, 1989), and therefore serves as a good indicator of how much reading practice an individual has had (see Mol & Bus, 2011; Moore & Gordon, 2015). Reading practice then is believed to promote high-quality linguistic representations that serve to strengthen the associations between low-level knowledge of word forms and higher-level knowledge of word meanings (Perfetti, 1985, 2007). The current results are consistent with this idea in showing that readers with lower levels of print exposure display an enhanced capacity to benefit from lexical repetition in measures that reflect the earliest stages of word recognition. Thus, the pattern suggests that greater amounts of reading practice as reflected in higher scores on the ART are associated with high-quality linguistic representations that support rapid and efficient word recognition during reading. Further, the results highlight the ART as a useful measure for better understanding individual variability in reading and language processing (see also Choi et al., 2015; Moore & Gordon, 2015). That is, the ART is not simply an index of reading speed, but rather higher scores on the ART are associated with an enhanced ability to access lexical knowledge during reading.

The results also add to previous demonstrations of repetition priming during the natural reading of a text (Choi & Gordon, 2013; Gordon et al., 2013; Ledoux et al., 2007; Lowder et al., 2013; Liversedge et al., 2003; Traxler et al., 2000) and provide new insights into the mechanisms underlying these effects. As we have argued previously (see Lowder et al., 2013), the finding that repetition-priming effects during reading persist even when several words intervene between the prime and target suggests that these effects do not stem from the residual activation of orthographic or phonological representations between prime and target, as has been posited to explain repetition priming in masked word-identification paradigms (see Forster & Davis, 1984; Grainger & Jacobs, 1996). Importantly, the current experiment further suggests that repetition-priming effects during reading do not stem from higher levels of discourse interpretation. Whereas previous reading studies have demonstrated repetition priming with prime and target words inserted in the same sentence, the current experiment showed evidence for repetition priming across pairs of unrelated sentences that could not be interpreted together as part of a coherent message. This makes it difficult to explain our effects in terms of facilitation at the discourse-level representation. Instead, the results are most readily explained as resulting from enhanced lexical retrieval processes.

Some have argued that repetition priming effects are best explained in terms of episodic memory mechanisms (e.g., Bodner & Masson, 2001). According to this account, the initial encounter with the prime creates a representation in episodic memory that is then retrieved to facilitate processing of the target. This might suggest, then, that readers with lower levels of print exposure benefited more from lexical repetition because they were more likely than readers with higher levels of print exposure to rely on episodic memory. However, given that the first-pass eye-tracking measures we report are thought to reflect the earliest stages of word recognition rather than processes related to episodic memory (e.g., Clifton, Staub, & Rayner, 2007), we do not believe a memory-based account can explain our pattern of results. This highlights a key advantage to our use of eye tracking in the current study as compared to the lexical-decision task used in most word-recognition priming studies. The first-pass reading-time measures that showed significant repetition-by-ART interactions ranged between 200 and 250 ms (see Table 1), whereas lexical decision times tend to range between 500 and 600 ms (e.g., Andrews & Lo, 2013; Tan & Yap, 2016; see Hoedemaker & Gordon, 2014, in press, for discussion of how the long response times in manual lexical-decision tasks affect patterns of semantic priming). The much shorter durations of eye-tracking measures compared to lexical decision latencies supports our assertion that the repetition effects we observed reflect lexical retrieval processes rather than mechanisms related to episodic memory.

Methodological differences between eye tracking and lexical decision might also explain an apparent inconsistency between our results and the results of Tan and Yap (2016). Tan and Yap showed an interaction between masked repetition priming effects and verbal ability (measured by vocabulary and spelling tests) such that the magnitude of the repetition priming effect was larger for participants who scored *higher* on these measures of verbal skill. In this experiment (and other experiments like it), the prime was presented very briefly (40 ms), making processing of the prime difficult, whereas the target was presented until a response was made. This suggests that higher levels of verbal ability in a masked priming experiment are helpful for efficiently detecting a rapidly presented prime stimulus, which aids subsequent processing of the target. In contrast, lower levels of verbal ability in the current eye-tracking experiment were associated with a greater degree of difficulty recognizing words during natural reading, and thus repetition of a word was most likely to be beneficial for these readers.

In conclusion, this work represents an important step toward understanding how variability in print exposure contributes to basic processes of word recognition during reading. These results also support the notion that repetition-priming effects during reading reflect facilitation in lexical search, rather than facilitation at the level of perceptual encoding or discourse interpretation. Whereas our previous work shows that the words that are most difficult to access are the ones that benefit most from repetition (Lowder et al., 2013), the current work shows that the individual readers who find it most difficult to access words during reading are the ones who benefit most from repetition.

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