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Eye movements reveal readers' lexical quality and reading experience

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Abstract Two experiments demonstrate that individual differences among normal adult readers, including lexical quality, are expressed in silent reading at the word level. In the first of two studies we identified major dimensions of variability among college readers and among words using factor analysis. We then examined the effects of these dimensions of variability on eye movements during paragraph reading. More experienced readers (who also were higher in reading speed) read words more quickly, especially less frequent words, while readers with higher lexical knowledge showed shorter early fixations, especially for more frequent words. These results suggest that individual differences in reading may reflect differences in the quality of lexical representations and in reading experience, which is a source of lexical quality. In a second study, we controlled the lexical knowledge readers obtained from new words through a training paradigm that varied exposure to a word's orthographic, phonological, and meaning constituents. Training exposure to orthographic and phonological constituents affected first pass reading measures, and phonological and meaning training affected second pass measures. Incomplete knowledge of word components slowed first pass reading times, compared to both more complete knowledge and no knowledge. Training effects were mediated by individual differences, pointing to lexical quality and reading experience—which, combined reflect reading *expertise*—as important in word reading as part of text reading.

Keywords Reading · Individual differences · Eye movements · Vocabulary · Fluency

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Introduction

High quality word representations—those with well specified and strongly linked orthographic, phonological, and morphological/meaning constituents—are both a driver of skilled reading and a consequence of reading experience. Of course, skilled reading comprehension requires much more than word knowledge; but written word identification skill and the word knowledge that supports it are necessary first conditions for fluent comprehension. The high correlations among word level measures and reading comprehension among adults (Hart, 2005; Landi, 2005) as well as children (Nation, 2005) reflect this dependence, which is part of a reciprocal relationship: Lexical knowledge enables comprehension and reading experience strengthens both comprehension and lexical knowledge.

The Lexical Quality Hypothesis assumes that high quality word knowledge consists of strong linkage among the form and meaning constituents of a written word and asserts that this quality allows the rapid meaning retrieval that is needed for comprehension (Perfetti, 2007; Perfetti & Hart, 2001, 2002). Correlational support for the role of the meaning constituent comes from studies that link vocabulary knowledge specifically to reading (beyond listening comprehension) in adult readers (Braze, Tabor, Shankweiler, & Mencl, 2007), that show a consistent linking across development (Verhoeven & Van Leeuwe, 2008), that find an increase with age in the unique variance to comprehension provided by vocabulary at the expense of decoding (Protopapas, Sideridis, Mouzaki, & Simos, 2007), and that show specific effects of vocabulary instruction on reading (Beck, Perfetti, & McKeown, 1982; McKeown, Beck, Omanson, & Perfetti, 1983; Stahl & Fairbanks, 1986). The quality of the orthographic constituent—the precision of spelling knowledge—has been found to affect word identification processes, specifically the effects of orthographic neighbors on primed lexical decisions (Andrews & Hersch, 2010).

An important characteristic of lexical quality is the interconnectedness among word constituents. Factor analyses of scores on a battery of reading tests suggest that two separable components of word knowledge account for the majority of variance among skilled adult readers: form knowledge (orthography and phonology) and meaning knowledge (including text comprehension and vocabulary meanings) (Landi, 2005; Perfetti & Hart, 2002). However, Perfetti and Hart (2002) also found that variance among less-skilled college readers was better explained by 3 factors, with form knowledge separated into two components, orthography and phonology. This suggests that orthographic and phonological knowledge may become more integrated with higher levels skill. Reading skill relies on increasing the strength of connections among word constituents, leading to the unified word representations that define high quality.

Beyond these general associations of word knowledge with reading is the need for more direct observations on the functioning of lexical constituents during moment-to-moment text reading. This, in turn, requires the assessment of individual differences in relevant lexical knowledge and processing. We address both of these in the studies reported below.

Sources of individual differences

There are at least two inter-related sources of individual differences in the quality of lexical representations: (1) the quantity and quality of readers' experiences with text and (2) a reader's ability to acquire lexical knowledge from those experiences.

Reading experience

In the framework of the Lexical Quality Hypothesis, and as modeled by the Word Experience Model (Reichle & Perfetti, 2003), more exposures to words increases the robustness and specificity of the lexical representations, strengthens the connections between learned words and the reader's existing lexical and conceptual knowledge, and strengthens both form–form (orthography–phonology) and form–meaning connections of a word. These factors contribute to making the process of word identification faster and more accurate, enabling fluent comprehension. This role of experience is reflected in the strong link between print exposure and vocabulary knowledge among children (Cunningham and Stanovich, 1991) and adults (Stanovich & Cunningham, 1992; West & Stanovich, 1991). In fact, Stanovich, West, & Harrison (1995) found that print exposure was a better predictor of vocabulary in older adults and college students than was age, even after controlling for working memory, general ability, and education level. Instructional studies, unsurprisingly, find that more exposures to words result in better learning (e.g. Jenkins, Stein, & Wysocki, 1984; McKeown, Beck, Omanson, & Pople, 1985).

Print exposure is a particularly large source of variability among individual readers. These differences start prior to school and with schooling differences have punitive effects on reading and learning when slower readers cannot match the reading required in a classroom session (Biemiller, 1977). With less practice than faster readers, slower readers may fail to achieve the word fluency that comes from experience, which in turn may inhibit the habit of reading that is sustained by skilled readers (Cunningham & Stanovich, 1997).

Ability to learn from experience

The consequences of these skill differences include the degree of benefit achieved from word learning opportunities. More-skilled readers learn more after instruction followed by reading in context than less-skilled readers do from the same instruction and contexts (Jenkins et al., 1984); Nagy, Herman, and Anderson (1985) report a similar trend among average and above average readers.

This pattern appears to hold for adult readers as well. Perfetti, Wlotko, and Hart (2005) taught college students who differed in reading comprehension skill the meanings of very rare words for 50 min. Behaviorally, although both groups started with equally negligible knowledge of the very rare words, the more-skilled comprehenders were more accurate in a post-learning meaning judgment task and showed more evidence of new word learning in their ERP (N400) response to the taught words. The implication is that the ability to take advantage of word learning opportunities depends on the learner's reading skill. Nelson, Balass, and Perfetti (2005) found congruent results in a vocabulary training study in which participants learned word meanings to criterion. Faster learners, despite having fewer exposures to the trained words (by virtue of learning the words with fewer trials), later showed more robust word form knowledge for these words. In addition, ERP data collected after a similar vocabulary training paradigm showed that only the more skilled readers showed a recognition memory effect (the P600) for reading learned words compared to untrained words (Balass, Nelson, & Perfetti, 2010).

By the self-teaching hypothesis (Share, 1995), word learning from independent reading requires readers to be able to re-code the written word into a phonological form to build an orthographic representation of the word. On an item-by-item basis, words eventually become "lexicalized", reducing the reliance on decoding as the means to identification. Learners who are skilled at decoding and establishing high quality phonological representations decoders can acquire more precise orthographic word representations from fewer exposures to the word. The ability to acquire such word representations is also supported by visual-orthographic memory.

These studies establish that individual variability in lexical representations include both the amount of reading experience and skills that allow a reader to benefit from those experiences. Evidence suggests that important skills include decoding ability, orthographic memory, and comprehension ability.

Lexical factors

In addition to reading skill and experience, properties of the words in a text affect moment-to-moment reading, as evidenced through eye movements. Reading difficult text results in elements of the typical "difficult reading pattern": longer fixations, more fixations, shorter saccades, more regressions, and slower reading times. Various properties of words affect moment-to-moment processing demands measured by eye movements. These include word length, predictability, frequency, lexical ambiguity, age of acquisition, subjective familiarity, concreteness, phonological neighborhood size, orthographic neighborhood size and orthographic neighborhood frequency, among other properties (Andrews, 1997; Juhasz & Rayner, 2003; Pollatsek, Perea, & Binder, 1999; Rayner, Sereno, & Raney, 1996; Williams, Perea, Pollatsek, & Rayner, 2006; Yates, Friend, & Ploetz, 2008).

In text reading, these lexical factors reflect not only properties intrinsic to the word, e.g. frequency, morphology, and lexical ambiguity, but also relational factors between the word and the text, e.g. predictability, semantic priming, plausibility in context (Staub and Rayner, 2007). But even "intrinsic" properties can be effectively subcategorized into reader-independent, reader experience-dependent, and reader lexicon-dependent. Thus, word length is context-independent, functional frequency or familiarity is reader-experience dependent, and functional orthographic neighborhood size is dependent on the reader's lexicon. Notice that neighborhood size (and also word frequency) is measured objectively from corpus data without reference to a reader. However, it is the individual's orthographic lexicon and the precision of orthographic knowledge of each word that determines the functional neighborhood for a reader. Indeed, priming effects (inhibition from a word neighbor prime) attributable to neighborhood size depend on the age (experience) of the reader (Castles, Davis, Cavalot, & Forster, 2007). Among adults, these effects depend on the individual's spelling knowledge (Andrews & Hersch, 2010): Better spellers show inhibitory effects from neighbors, whereas facilitatory effects are found in weaker spellers.

Likewise, externally defined word frequency measures are only estimates of how frequently an individual reader encounters a word. Without a connection to the reader's experience, objective frequency can be a misleading as an indicator of experience in lexical processing. Reduced frequency effects for more skilled readers (e.g. Kuperman & Van Dyke, 2011) may reflect the functional frequency (familiarity) gains that come from more reading, a gain more detectable for low frequency words given the nonlinear relation between objective frequency and word processing. This line of reasoning leaves few factors that are actually "intrinsic". Some factors are "knowledge" factors (dependent on an individual's knowledge, lexicon, or experience), and some are as Staub and Rayner (2007) proposed, "relational" factors that depend on the context in which they appear.

Thus, although corpus measures (e.g. word frequency or number of neighbors) are useful as proxies for reading experience or word knowledge, they are limited when the focus is on individual differences. In fact, subjective measures that directly tap experience judgments, such as familiarity ratings, can be more successful in showing relationships to reading processes (Gernsbacher, 1984; Kacinik, Shears, & Chiarello, 2000). Individual readers' (1) actual experiences, (2) ability to learn from their experiences, and (3) resulting word knowledge are quite variable, and these differences are a good starting point in understanding individual differences in reading skill among adult readers. As Kuperman and Van Dyke (2011) point out, "efficient word recognition is not simply about linguistic characteristics of words, but rather about linguistic characteristics of *particular* words *as learned by particular individuals.*"

The present studies

Building on previous research, we assume that any observed reading behavior at the word level is a joint product of the properties of words in the text being read and the reader's current knowledge of these words. Our studies, comprising two factor analyses and two experiments, examine how individual differences in reading and an individual's knowledge of specific words show their effects in moment-to-moment reading processes. Factor analyses aimed to identify the structure of individual reader differences in word knowledge and reading skill and to identify the structure of word differences on relevant lexical dimensions. Rather than choosing a single dimension or individual (perhaps correlated) tests to define reading skill, we took a data-driven approach to defining functionally distinct dimensions of variability.

The goal of Experiment 1 was to characterize how the dimensions of individual variability defined in the factor analysis contributed to differences in word reading behavior. This was achieved by tracking readers' eye movements while they read paragraphs for meaning and analyzing patterns for individual words and individual readers. This allowed us to examine not only the overall effects of reading ability, but also the interaction between reading ability and lexical characteristics, both intrinsic and knowledge-dependent. We hypothesized that both reading experience and lexical knowledge would be predictors of efficient reading. We expected that readers with a high degree of reading experience would build strong and well-connected word representations, even for low frequency and rare words. Readers with well developed lexical knowledge should be better at decoding unfamiliar words quickly and may have more unitized representations of words they have encountered several times. Thus individual differences along these dimensions should predict fixation times.

The goal of Experiment 2 was to characterize the relationship between word knowledge (orthographic, phonological, and meaning components) and reading behavior more directly, avoiding proxies for measures of word knowledge such as frequency or familiarity ratings. This was achieved by employing a rare-word training paradigm to control which components of word knowledge a reader acquired (orthographic, phonological, and/or meaning) and the quality of that knowledge (by varying number of exposures). We hypothesized that form-related components of knowledge would affect early, first-pass fixations. In particular, orthographic word knowledge may help readers predict the identifiability of a word, thus affecting the decision to make an eye movement following the first fixation. In contrast, we expected meaning knowledge to affect later eye-movements and total fixation durations, which reflect the processing required to retrieve the meaning of the word and integrate it into the context provided by the text. Because different readers vary in how effectively they can learn from exposures to words, we also accounted for the individual skill differences identified in the factor analysis.

Experiment 1

Methods

Participants

Thirty-five native English-speaking adults with normal or corrected-to-normal vision and no diagnosed reading disability took part in this experiment. Participants were paid a small fee for their participation.

Materials

Stimuli consisted of 68 paragraphs obtained from internet sources with some slight modifications for clarity. Paragraphs ranged from 80 to 119 words, with a mean of 95 words per paragraph. A norming study was conducted to ensure that the paragraphs were of average difficulty and were fairly homogenous in their difficulty level.

Norming study Each paragraph was rated for difficulty by 33 native English speakers who received course credit. Participants read the paragraphs on paper and used a 7-point scale (ranging from 1 to 7) to rate the difficulty. The scale was anchored by 1 "very easy" and 7 "very difficult" with 4 as "average". These were defined as follows: *Very easy*: A very easy passage is well below your level of reading ability. It can be completely understood with minimal effort. *Average*: An average passage matches your normal level of reading difficulty. You can read the passage at a normal pace and understand the text. *Very difficult*: A very difficult passage is beyond your normal level of reading difficulty. You might need to spend a long time on the passage, re-read the passage, or read effortfully to understand the text. You may feel you need more surrounding context to understand the passage.

The mean paragraph rating was 3.24 (SD = 0.59), below "average difficulty", with a range of 2.21–4.54.

Eye tracking

Eye movements were monitored from the right eye using an Eyelink 1000 eyetracker with a sampling rate of 1000 Hz. We used a standard 9 point full-screen calibration before each participant began reading. A center point only calibration was used between each trial, and a full 9-point calibration was re-conducted as necessary throughout the experiment. Following raw data collection, vertical drift was corrected using the Eyelink Data Viewer software. Trials in which the calibration was appreciably off-target were removed. In addition, any fixations less than 50 ms within 0.5 character spaces of another fixation were merged.

Procedure

Paragraphs were presented to readers in a randomized order. A True/False comprehension question with feedback was given following each of the paragraphs to ensure that participants stayed focused on reading the passages for meaning. Participants were instructed to read each paragraph once for meaning, and to press a mouse button when they were finished reading. When a True/False question appeared after reading the paragraph, participants used the left mouse button to indicate "true" and the right mouse button to indicate "false", corresponding to the side of the screen on which the choices "true" and "false" appeared. The total duration of the experiment depended on the participant's speed, generally about 1 h.

Dependent variables

For words that were not initially skipped, the following fixation durations were computed:

First fixation duration is the duration of the first fixation on a word. *Refixation duration* is the cumulative duration of any additional fixations made on the first pass reading of the word (before the reader has moved their eyes off of the word). *Gaze Duration* is the cumulative duration of all first pass fixations (the sum of the first fixation duration and refixation durations). *Re-reading duration* is the cumulative duration of any fixations made on the word after the eyes have moved off the word (forward or backwards). *Total viewing time* is the sum of all fixations on the word. Log transforms were applied to each of the duration measures to normalize the distributions.

In addition to measuring the durations of fixations, we assessed the probability of skipping the word, the probability of refixating the word on the first pass, and the probability of re-reading the word after the first pass reading. Additionally, for words that were initially skipped, the probability of looking back at the word versus never viewing the word was measured.

Independent variables

Measures of individual differences The individual difference variables were scores along five factors derived from a factor analysis of a large database of adult (college student) participants who had taken a battery of reading tests. The battery of tests included an orthographically based test of phonological analysis (PhAT), the Raven's Progressive Matrices with a 15 min time limit (Raven, 1960), a modified Author Recognition Test (Stanovich & West, 1989) in which some of the foils (e.g. published psychologists) were replaced with names that were more clearly non-authors, the Nelson–Denny Comprehension Test (Nelson & Denny, 1973), Form E (Brown, Bennett, & Hanna, 1981) with a 15 min time limit, the vocabulary portion of the Nelson–Denny reading test (Brown et al., 1981) with a 7.5 min time limit, the Real Word Test in which participants marked words on a list which sound like real words (pseudohomophones). This test included items from Olson, Wise, Conners, Rack, & Fulker (1989) and the addition of more difficult items. Similarly, there was a recognition spelling test with items adapted from (Olson et al., 1989) with the addition of more difficult items, some of which were obtained from the Baroff Spelling Test (Perfetti & Hart, 2002). The final assessment was the Adult Reading History Questionnaire (ARHQ) based on Lefly and Pennington's (2000) modification of Finucci, Isaacs, Whitehouse and Childs (1982), Finucci, Whitehouse, Isaacs and Childs (1984) questionnaire to which we added a question about internet reading to our version of the ARHQ. Instead of computing a single score, we scored the ARHQ along several dimensions revealed by a factor analysis of the individual questions.

Factor analyses results

Individual difference factors

We performed a PCA with Varimax rotation on all test sub-scores for 1450 participants who had completed the battery of tests. Five factors were extracted which collectively accounted for about 60 % of the variance (23.4, 13.4, 9.3, 7.3, and 6.1 % respectively).

The first factor, which we characterize as related to reading experience, captured speed measures, text exposure, and an ARHQ subscore reflecting reading attitude, book reading, and reading speed loading on this factor. The second factor, which we characterize as lexical knowledge, reflects decoding, word recognition, and spelling skills. We use "lexical" for this factor not as a contrast to sublexical, but to capture the clear involvement of lexical knowledge that is partly dependent on sublexical skills. Loading on this factor were the real word test (lexical decisions that include low familiarity words and spelling foils), a orthographic-phonological analysis test that manipulates whole words (the PhAT), and the spelling tests. The third factor includes the Nelson–Denny accuracies and the Raven's accuracies (with a negative loading from the Raven's speed, indicating a speed-accuracy tradeoff for that test), which we characterize as an "accuracy focus" factor. Students scoring highly on this factor had high levels of accuracy regardless of their speed, indicating that they worked at a pace that enabled them to maintain high accuracy. The last two factors, which turn out to be the least useful in explaining eye-movement data, were primarily based on ARHQ test subscores: Factor 4 combines items referring to learning, memory, and reading problems. Factor 5 is characterizes as a "Casual Reading" dimension, based on items assessing the frequency of magazine, newspaper, and internet reading. This factor accounts for the least variability.

We used the factor analysis to compute five factor scores for each of the participants in our study, based on test score weightings from the large-sample factor analysis. The five dimensions are: reading experience, lexical knowledge, accuracy focus, learning and memory, and casual reading.

Although the factor scores are centered and follow a normal distribution over the whole population of participants included in the factor analysis, these scores were re-centered for the subset of participants who participated in Experiment 1 so that the zero point represented the experimental sample mean. Trial number was also centered and included as an independent variable.

Lexical factors for words in the experimental texts

The following ten lexical properties were obtained from the English Lexicon Project database for 1167 of the words appearing in the paragraphs: number of syllables, number of phonemes, length, orthographic neighborhood size, phonological neighborhood size, log frequency of the orthographic neighbors, log frequency of the phonological neighbors, number of morphemes, bigram frequency by position, and log HAL frequency (Balota et al., 2007). Many of these variables are highly correlated (e.g., number of syllables and number of phonemes) and are thus not suitable for use together as predictors. Rather than eliminating a subset of the variables because of their collinearity, we conducted a PCA with Varimax rotation to compute meaningful, orthogonal dimensions along which words vary. This procedure, which allows a fuller use of word data, is appropriate here because assigning specific influences of co-varying lexical properties was not the goal of the experiment.

About 90 % of the variance could be accounted for by reducing the ten lexical properties to six factors, and these 6 factors were highly interpretable: The first factor is a word length factor that included the number of syllables, number of phonemes, and number of letters. The second factor reflected the number of neighbors, with high loadings from both the number of orthographic neighbors (differing by one letter) and the number of phonological neighbors (differing by one phoneme). The third factor was a neighborhood frequency factor and had high loadings from both the orthographic and phonological neighborhood frequency measures (reflecting how frequent a word's neighbors are on average). The final three factors had high loadings from only one measure each: number of morphemes, mean bigram frequency by position, and log HAL frequency, respectively. These 6 orthogonal factors (corresponding to length, number of neighbors, neighborhood frequency, number of morphemes, bigram frequency, and frequency) were used as independent variables predicting eye movements.

The factors from both the individual reader differences and the lexical attributes factor analyses were used in the modeling of eye tracking results reported below.

Eye tracking results

Data analysis

Data for reading times were analyzed using Linear Mixed Effects Regression (LMER) analyses (Baayen, 2008; Baayen, Davidson, & Bates, 2008). Because our independent variables are scores along dimensions produced by factor analyses and because our dependent variables are often transformed to fit a linear model, it can be difficult to interpret the meaning of the values of the coefficients. For example, a coefficient of 0.05 for the effect of word length on log total viewing time means that for every increase of 0.05 standard deviations along the word length factor, there is a corresponding increase of 1 in the log total viewing time rather than measured viewing time.

The benefit of the LMER is that it includes subjects, words, and paragraphs as random factors in a single analysis. For all models, only the intercept was allowed to vary by the random factors, with the exception that the slope of trial number was allowed to vary by subject to account for any practice or fatigue effects (with no random correlation term between the intercept and trial number slope). Slopes were allowed to vary only via fixed effect interactions of interest—further allowing the slopes to vary by random effects would probably overfit the model, as evidenced by the failure of these models to converge in a reasonable number of iterations.

The models were fit using restricted maximum likelihood. *p* values were obtained based on highest posterior density confidence intervals computed using Markov chain Monte Carlo (MCMC) sampling with 10,000 iterations (see Baayen, 2008, p. 270). This avoids anti-conservative *p* values that can arise from use of the *t* statistic with the upper bound of degrees of freedom.

Probabilities of skipping, refixating, and re-reading (binary coded variables) were analyzed with mixed-effects logistic regression, which uses a logit transformation of the binary dependent variable. Again, intercepts for these models were allowed to vary by the subjects, words, and paragraphs as random factors. The slope for trial number was allowed to vary by subject to account for fatigue or practice effects. *p* values for this set of models were computed using the Wald Z statistic.

Results for lexical factors

All estimated model coefficients for both lexical factors and individual difference factors are summarized in Table 1.

Initially viewed words

The total viewing time was affected by all lexical factors. As expected, shorter, more frequent words with many frequent neighbors and fewer morphemes were read more quickly than longer, less frequent words. Of note is the relationship between the bigram frequency factor and total viewing time. Total viewing time was longer for words with higher bigram frequencies. This effect may reflect the information value of a letter sequence, with lower bigram frequencies being more informative for the word's identity. This is the case especially in low frequency words (Broadbent & Gregory, 1968).

Total viewing times depend on the combination of fixation durations and the probabilities of refixating. Each of the lexical factors contributed reliably to both the probability of refixating the word on the first pass and the probability of re-reading the word. Thus, a clear way that these lexical factors have an effect on viewing times is by increasing or reducing the number of fixations on a word.

Another way that lexical factors contribute to longer total viewing times is by modulating the durations of fixations, including the first fixation duration, refixation durations, and re-reading durations. Results show some differences in which fixation durations are affected by each factor. Word length, neighborhood size, and word frequency affected fixation durations across the board. The frequency of the neighbors affected the first fixation duration, but not re-fixation durations or re-reading durations. Bigram frequency affected refixation durations, but not first fixation durations or re-reading durations. The number of morphemes in a word affected re-reading durations, but not first-pass fixation durations.

Each of the lexical factors affect gaze duration, so the combination of effects on the first fixation durations, the probability of refixating, and the refixation durations (all the first pass measures) indicate that all of these lexical factors are important in modeling first pass reading behavior.

Skipping

All the lexical factors also predicted whether a word would be skipped. Again, the directions of these effects were as expected (shorter, frequent words were skipped more often), and again, it was the lower bigram frequency words that were more likely to be skipped. For words that were initially skipped, all of the lexical factors contributed to predicting whether the word would then be later reviewed (vs. skipped completely). More difficult words (those with longer lengths, lower frequencies, more morphemes, higher bigram frequencies, etc.) were more likely to be re-read after being initially skipped.

Table 1 Experiment 1 model coefficient estimates

	Initially viewed words							Skipped words	
	TVT	P(Refix)	P(Reread)	FFD	Refix	GD	Reread	P(Skip)	P(Reread)
Intercept	5.454***	−2.571***	−1.811***	5.267***	5.101***	5.322***	5.372***	−0.076	−1.029***
Trial number	−0.001*	−0.003**	−0.005***	0.000	−0.001	0.000	0.000	0.001	−0.005***
Lexical factors									
Length	0.054***	0.252***	0.113***	0.016***	0.020***	0.040***	0.040***	−0.346***	0.268***
Neighbors	−0.031***	−0.188***	−0.079***	−0.008**	−0.017**	−0.022***	−0.014*	0.216***	−0.182***
Neighbor freq	−0.022***	−0.118***	−0.072***	−0.007**	−0.007	−0.014***	−0.004	0.189***	−0.099**
Morphemes	0.035***	0.209***	0.097***	0.004	0.009	0.023***	0.014**	−0.250***	0.182***
Bigram freq	0.017***	0.122***	0.047*	0.002	0.013*	0.011***	0.006	−0.094***	0.096***
Frequency	−0.041***	−0.177***	−0.059**	−0.018***	−0.037***	−0.032***	−0.016**	0.225***	−0.216***
Individual differences									
Expertise	−0.062**	−0.246***	−0.241**	−0.025	−0.049*	−0.037*	−0.027	0.212***	−0.337***
Lexical	−0.046	−0.214**	−0.131	−0.029	−0.026	−0.038	−0.041	0.157*	−0.154
Accuracy focus	0.060*	0.097	0.376***	0.020	0.036	0.024	0.034	0.122	0.269*
Learning/memory	−0.022	0.010	−0.095	−0.010	−0.018	−0.011	−0.030	0.052	−0.119
Casual reading	0.001	−0.064	−0.014	0.004	0.005	0.001	−0.008	0.080	−0.004
Interactions									
Expertise × lexical	−0.040	−0.144	−0.050	−0.015	−0.007	−0.021	−0.037	−0.071	−0.200
Expertise × acc focus	0.017	0.181*	0.217*	−0.009	0.017	0.002	−0.019	−0.030	0.226
Neighbor freq × expertise	0.000	−0.015	−0.027*	−0.002	0.010	0.000	0.003	−0.009	0.018
Frequency × expertise	0.004**	−0.014	−0.005	−0.001	0.000	0.002	0.003	−0.003	−0.002
Bigram freq × expertise	−0.002	0.005	0.013	−0.002	−0.004	−0.003*	−0.001	0.007	0.006
Frequency × lexical	0.000	−0.002	0.001	−0.003*	−0.004	−0.001	0.003	0.003	−0.028***

Table 1 continued

	Initially viewed words							Skipped words	
	TVT	P(Refix)	P(Reread)	FFD	Refix	GD	Reread	P(Skip)	P(Reread)
Bigram freq × lexical	0.000	0.012	−0.009	0.001	0.004	0.001	−0.006	0.009	−0.007

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Results for individual differences

Initially viewed words

Total viewing times for non-skipped words were associated with two of the five individual difference factors: the experience factor and the accuracy focus factor. High experience factor was associated with shorter total viewing times. Higher scores on the accuracy focus factor, which reflected accuracies on the Nelson-Denny tests as well as scores on the non-verbal intelligence test, were associated with longer total viewing times. Additionally, lexical knowledge was associated at a marginal level of reliability ($p < 0.08$). In addition, the word frequency effect was modulated by reading experience; more experience reduced the effect of frequency (see Fig. 1).

These effects on total viewing times stem from individual differences in fixation durations and probabilities of refixating. Those with more experience ($p < 0.001$) and better lexical knowledge ($p < 0.01$) showed a lower probability of refixating words after the first fixation. An experience x accuracy focus interaction indicated that the experience effect was stronger for the low accuracy focus readers ($p < 0.05$). Lower accuracy focus/lower experience readers were the most likely to refixate, but low accuracy/high experience readers were least likely to refixate. The latter group may represent careless readers (for this experimental situation) who prefer to read the text quickly at the expense of accuracy.

The probability of re-reading words shows a similar pattern. Those with more reading experience were less likely to re-read ($p < 0.01$) and those more focused on accuracy were more likely to re-read ($p < 0.001$). An interaction ($p < 0.05$) shows that it is primarily the low accuracy/high experience (fast inaccurate) readers who show a low probability of re-reading (see Fig. 2). There is also an interaction between neighborhood frequency and experience ($p < 0.05$): More experienced readers show a greater advantage (less probability of re-reading) for high

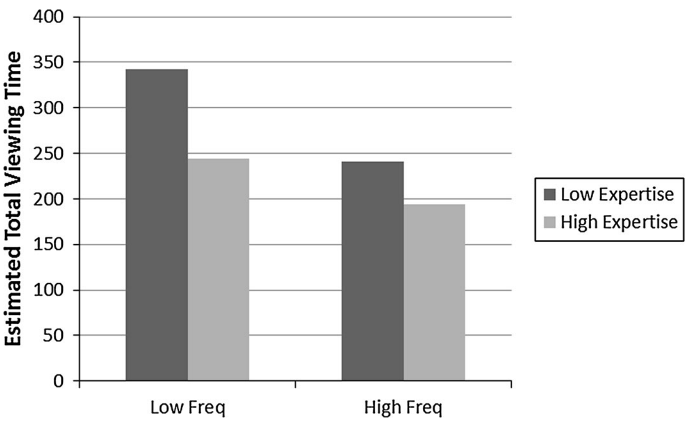

Fig. 1 Interaction between reader expertise and word frequency on total viewing time. Graph of model predictions for the bounding data values illustrating the interaction between reader expertise and word frequency. Predictions are back-transformed from log fixation durations for display in ms

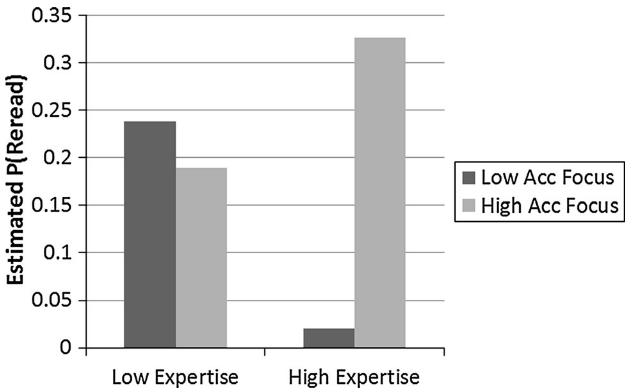

Fig. 2 Interaction between reader expertise and reader accuracy focus on probability of re-reading. Graph of model predictions for the bounding data values illustrating the interaction between reader expertise and accuracy focus

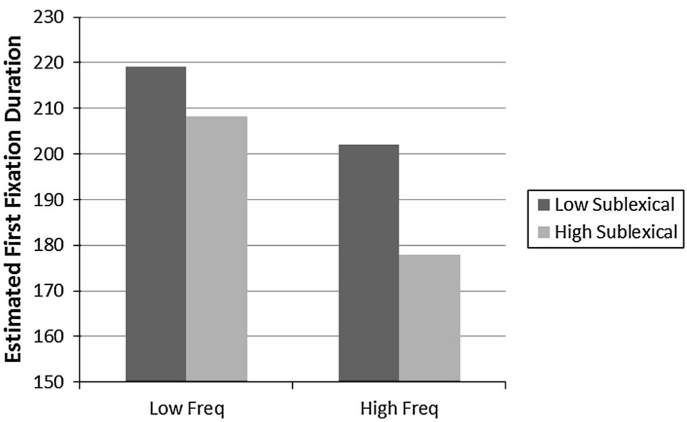

Fig. 3 Interaction between readerlexical knowledge and word frequency on first fixation durations. Graph of model predictions for the bounding data values illustrating the interaction between lexical knowledge and word frequency. Predictions are back-transformed from log fixation durations for display in ms

neighborhood frequency words, and thus a greater overall neighborhood frequency effect.

In addition to refixating and re-reading, individual differences were present in the durations of fixations. For first fixation durations, readers with strong lexical knowledge showed a greater advantage (shorter durations) for high-frequency words, and thus a larger frequency effect ($p < 0.05$) (see Fig. 3). More experienced readers had shorter refixation durations, and shorter total gaze durations, especially for high bigram frequency words (p's < 0.05). Whereas the bigram frequency effect was modest for experienced readers, the less-experienced readers had longer gaze durations for high bigram frequency words (interaction $p < 0.05$). There were no significant individual differences in re-reading durations.

Skipping

Readers with more experience ($p < 0.001$) and better lexical knowledge ($p < 0.05$) were more likely to skip words. Once a word had been skipped, readers with more experience were also less likely to go back and read the word ($p < 0.001$). Readers with lower scores on the accuracy factor were less likely to go back to re-read the skipped words ($p < 0.05$). Furthermore, lexical knowledge interacted with word frequency in re-reading skipped words: Higher lexical knowledge benefitted readers only for higher frequency words—higher lexical knowledge was associated with less re-reading of more frequent words ($p < 0.001$).

Discussion

The results of the eye-tracking experiment show that, in addition lexical factors, eye movement and fixation durations varied with individual differences defined by factor scores derived from off-line reading-related tasks. These individual effects included (1) widespread main effects of reading experience (a factor reflecting experience, attitude, and speed), (2) interactions between reading experience and frequency-related measures, (3) early effects of lexical knowledge, (4) later effects of an accuracy focus factor, and (5) interactions between the experience and accuracy focus factors on refixations.

The factor analysis allowed the variability among normal college readers (based on a variety of reading related tasks and self-report assessments) to be described along five dimensions, the first three of which were associated with the moment-to-moment reading measured in eye movements. The most important factor for these measures was the experience factor (based on attitudes about reading, amount of reading, and speed of reading) how much reading they tended to do, and the speed of reading. Readers with more experience showed faster reading by skipping more words, refixating less often, doing less re-reading, and having shorter refixation durations when they did refixate.

The experience factor also modulated frequency-related effects. For word frequency, the experience advantage in lower total viewing times was particularly evident for lower frequency words. This result suggests that with increased reading experience, the functional frequency of "low frequency" words becomes sufficiently high to produce fluent word processing, an observation consistent with Kuperman and Van Dyke (2011). Reading experience interacted also with bigram frequency in predicting gaze duration. The bigram frequency effect (longer gaze duration for higher bigram frequencies) was reduced for more-experienced readers. Notice that the bigram frequency effect is opposite that of word frequency, probably reflecting the cost of activation of more word neighbors on the way to word identification. Thus, greater experience is associated with less cost of neighborhood activation. This is consistent with the assumption that fully specified orthographic representations, a dimension of lexical quality, allow a more rapid access to a specific orthographic spelling with less interference from similarly spelled neighbors, as observed by Andrews and Hersch (2010) for skilled readers who were also good spellers. The orthographic lexicon of an expert reader with fully specified orthographic representations would be characterized by strong inhibitory links between similarly spelled words. Stronger inhibitory links would reduce bigram effects, which could be affected by parafoveal preview (White, 2008).

High experience readers showed a greater effect of neighborhood frequency on rereading—fewer refixations for words from neighborhoods with higher frequency words. Large neighborhood sizes and high frequency neighbors may especially facilitate the recognition of low frequency words by boosting activation via form-related words (Andrews, 1989, 1992; Sears, Hino, & Lupker, 1995). Stronger inhibitory links arising form more precise spelling representations may again be the key. More experienced readers, with more exposure to all words in a neighborhood, establish stronger inhibitory links among the words. This reduces the effect of neighborhood related variables on both fixation durations and the need for re-reading.

The Lexical knowledge factor, reflecting more specific word knowledge and orthographic and phonological skill was associated with shorter first fixation durations for more-frequent words and fewer refixations on the first pass. Readers with high lexical knowledge were also more likely to skip words and less likely to go back to read more-frequent words. Thus, even among generally skilled college readers, lexical knowledge vary in ways that are related to reading processes. Perhaps surprisingly, lexical knowledge affected processing speed for frequent words more than infrequent words. This may be evidence that high levels of exposure to words causes them to become "unitized," a shift that results in word identification processes that are less dependent on sublexical features and more dependent on familiarity based lexical retrieval. Our finding here is consistent with Spieler and Balota (2000), who found that older readers (with more exposure to words) showed these larger frequency effects.

The accuracy focus factor (reflecting accuracy rate on standardized tests of comprehension, vocabulary, and non-verbal reasoning that have time pressures that lead to uncompleted tests) captures a dimension of reading skill that may be generally less visible in studies of individual differences. Accuracy focus was associated with longer total reading times. Just as accuracy focus readers strive for accuracy over speed in test taking, they also read a text at a rate consistent with accurate comprehension. They do more re-reading and refixating on the first pass, although these differences interact with the experience. Readers high in experience and low in accuracy focus are especially unlikely to re-read or re-fixate. Such readers may be able to focus on accuracy when task engagement is high but not in situations of low-stakes experimental assessments.

Only these three factors of experience, lexical knowledge, and accuracy focus were associated with reading measures. The final two factors derived from reading questionnaires, which we characterized as a learning/memory factor and casual reading factor, showed no effect in reading measures. In contrast to the result for casual reading, self-assessed book reading (part of the Experience factor) was associated with reading measures.

In summary, the first study, which combined a factor analysis of reading-related measures from 1450 college students with an eye-tracking experiment with participants from this same population, identified both individual differences and lexical factors that play a significant role in reading. Strong lexical knowledge was associated with early (first fixation and first-pass) reading measures, especially for more-frequent words and a trend toward reduced total viewing times. Those with more reading experience and thus more reading experience had shorter total viewing times, with fewer re-fixations, shorter re-fixation times, and less re-reading. Accuracy focus proved to be a factor in reading, with higher accuracy focus associated with longer total viewing times, reflecting more refixating and re-reading. Readers with low accuracy focus who were also more expert (fast and experienced) showed especially low re-fixating and re-reading.

We emphasize that any study that links individual difference measures to reading processes can only show the effects allowed by the original individual difference measures. Given the measures we used for this purpose, there are at least three important dimensions of individual differences in reading behavior: specific reading-related skills, reading experience, and a reading strategy for accuracy.

Experiment 2 more directly examined the link between word knowledge and reading behavior at the single word level by controlling word knowledge experimentally through a rare word vocabulary training paradigm.

Experiment 2

Experiment 2 aimed to determine the contributions of each of the three lexical constituents (orthography, phonology, and meaning) to reading as measured in the eye movement record. To establish variation in constituent knowledge, we controlled the exposure to the written (orthographic), spoken (phonological) and meaning information available to learners for rare, unknown words in a vocabulary training paradigm. Controlling the information available on these dimensions should affect the quality of lexical representations, even if learners had access to translation procedures to provide missing information: Given orthography, learners can generate phonology; given phonology, learners can generate spellings. These recoding procedures should be especially available to learners with high lexical knowledge and associated sublexical routines. However, by not providing direct information on spelling and pronunciations, we lower the likelihood that a learner establishes fully specified representations. By observing eye movements when participants read sentences containing these newly taught words, we could determine how incomplete specifications of word constituents affect reading behavior and the extent to which individual differences modulate these effects.

Methods

Participants

35 adult native English speakers with no diagnosed reading disability and with normal or corrected-to-normal vision were recruited to participate for payment.

Materials and apparatus

180 rare words were chosen from a set of words rated for familiarity and meaning knowledge by 30 participants receiving course credit for their participation. Each of these ratings was completed using a 7-point scale ranging from "unfamiliar" to "familiar" for the familiarity rating, and from "not at all" to "completely" for how well the definition was known. Words were chosen to have low familiarity and meaning ratings. The mean familiarity was 2.18 (ranging from 1.33 to 3.00), and the mean meaningfulness was 1.78 (ranging from 1.17 to 2.96). Words with extremely low familiarity and meaning scores were not chosen because they appeared very unusual and non-wordlike.

All words were either 7 or 8 letters long to reduce the chance of skipping during reading. Words were divided into 18 lists of 10 words each, balanced for mean word length and part of speech. These word lists were assigned to a 6 (training condition) $\times$ 3 (number of exposures) training design. The six training conditions were the following combinations of orthography (O), phonology (P), and meaning (M): O, P, OP, OM, PM, and OPM (every possible combination except the impossible meaning only). Completely untrained words were not included, because a pilot study showed highly inflated looking times on untrained rare words in context, with as many as 20 refixations of a word. This suggested that participants attempted to recall whether the word had been taught, rather than reading the word normally. By omitting an untrained condition, we aimed to increase normal reading behavior. Words appeared one, three, or five times during the training. A partial Latin square design rotated the word lists through the experimental conditions, resulting in six versions of the experiment. Eye movements were monitored using an Eyelink 1000 eyetracker in the same way as Experiment 1.

Procedure

Training Presentation of experimental words was randomized across conditions within subjects. Conditions that included orthography displayed the word written in lowercase letters. Conditions with phonology displayed a speaker icon, which disappeared when a recording of the word's pronunciation was played over the computer speakers. Conditions including meaning showed a brief definition for the word. To minimize variability in the amount of exposure each participant had to the words, training was not self-paced. Instead, words in each condition were presented for enough time for participants to be able to briefly study the information. The conditions with more information were presented for longer durations. The display times for each condition were as follows: O: 3000 ms, P: 4000 ms (1000 ms before the sound played + 3000 ms of a blank screen after), OP: 5000 ms (2000 ms before the sound played + 3000 ms after), OM: 7000 ms, PM: 7000 ms (2000 ms before the soundplayed + 5000 ms after), OPM: 9000 ms (2000 ms before the sound played + 7000 ms after).

To ensure attention during training, probe questions, tailored to the specific condition, followed a random 10 % of trials. Words that were trained with multiple knowledge components were followed by a question about just one of the components given. Questions included:

- Orthography: What letter did the previous word begin with?
- Orthography: What letter did the previous word end with?
- Phonology: How many syllables were there in the word?
- Phonology: Did the word start with a vowel or consonant sound?
- Meaning: Is the meaning a thing, action, or description? (Participants were instructed that these choices correspond to nouns, verbs, and adjectives.)

Prior to training, participants were given seven practice words by the experimenter to become familiar with the pacing and question probes. One of the seven practice words was presented twice, and one, three times to represent the mix of single and multiple exposures that would occur in training. (This fact was also explicitly described by the experimenter). Three of the example words were also followed by example probe questions.

Participants were encouraged to take breaks as needed before proceeding forward from probe questions. The total time spent in training was approximately 1.5 h.

Eyetracking Following training, participants read one sentence per trained word while their eye movements were monitored. Sentences did not span more than one line of text. The trained words were never the first or last word in a sentence, nor did they appear before a comma or other punctuation. Each sentence was followed by a True/False comprehension question to encourage reading for meaning. The experimenter was in the room with the participant for the whole session. Calibration procedures and eye-tracking details were the same as for Experiment 1.

Dependent variables

Dependent variables were computed in the same manner as in Experiment 1, except that skipping measures were not computed. By choosing longer target words, we ensured that few target words were skipped.

Independent variables

Four of the five factors derived from the factor analysis of Experiment 1 were the individual difference measures. (We omitted the casual reading factor, because it explained the least variability in the factor analysis and showed no effects in Experiment 1). Although the Learning/Memory also showed no effects in Experiment 1, we included it here because Experiment 2 is a learning task). Factor scores were re-centered for Experiment 2 participants to make zero the mean for experimental sample. Lexical factors were not included in these models, because all words were of equal length (7–8 letters) and were very low frequency, unknown words. Trial number was included to account for fatigue or practice effects. The number of exposures was also included as a numeric variable.

To assess the contribution of each lexical constituent to reading behavior, the data were combined across training conditions to isolate a specific constituent, as follows (with the tested constituent underlined).

- Orthography: P and PM versus OP and OPM (orthographic training)
- Phonology: O and OM versus OP and OPM (pronunciation training)
- Meaning: O and P and OP versus OM and PM and OPM (definition training)

A single factor with three levels (OP, OM, PM) examined the effects of orthography and phonology training when each was combined with a second constituent. A separate factor examined meaning training (OPM + PM + OM vs. OP + P + O).

Interactions We were interested in whether individual differences modulated the effects of the training conditions, specifically testing the hypothesis that readers with greater experience or lexical knowledge show greater influence from the training on reading. In addition, interactions between the training conditions and the number of exposures should reveal training effects that might become more pronounced with more exposures. Thus several interactions were tested: experience × orthography/phonology training, experience × meaning training, experience × number of exposures, lexical knowledge × orthography/phonology training, lexical knowledge × meaning training, lexical knowledge × number of exposures, learning/memory × number of exposures, orthography/phonology training × number of exposures, and meaning training × number of exposures.

Results

Data for reading times were analyzed using Linear Mixed Effects Regression (LMER) as in Experiment 1. All estimated model coefficients and p values are summarized in Table 2. Results are discussed in terms of patterns present in the fitted model.

Main effects of training

Orthographic training produced only one effect, a trend toward longer first fixation durations ($p < 0.06$). Meaning training showed no main effect. However, phonology training resulted in a higher probability of refixating the word on the first pass ($p < 0.05$) and (in part because of that effect) longer gaze durations ($p < 0.05$). The number of training exposures showed effects on several measures: fewer refixations ($p < 0.05$) re-readings ($p < 0.05$), shorter gaze duration ($p < 0.01$), and less total viewing time ($p < 0.001$). Training effects, however, interacted with both individual difference measures and the number of exposures. These interactions are described below for each training component.

Table 2 Experiment 2 model coefficient estimates

	TVT	P(Refix)	P(Reread)	FFD	Refix	GD	Reread
Intercept	6.160***	−0.029	−0.883***	5.505***	5.523***	5.916***	5.721***
Trial number	−0.002***	−0.003***	−0.008***	0.000	−0.002***	−0.001***	−0.002***
Training factors							
No orthography	0.027	−0.089	0.214	−0.030	0.014	−0.034	0.113
No phonology	−0.026	−0.384*	−0.048	−0.018	0.024	−0.070*	0.061
No meaning	0.011	−0.151	−0.079	0.014	0.063	0.003	0.098
# Exposures	−0.032***	−0.080*	−0.104*	−0.005	−0.022	−0.023**	−0.013
Individual differences							
Expertise	−0.038	−0.034	−0.108	−0.044	−0.002	−0.031	−0.016
Lexical	−0.260***	−0.626**	−0.560*	−0.078**	−0.191**	−0.211***	−0.103
Learning/memory	−0.145*	−0.392*	−0.419	−0.032	−0.091	−0.112*	−0.010
Accuracy focus	0.085	0.036	0.404*	0.039	0.045	0.043	−0.040
Interactions							
Expertise × orthography	−0.009	0.020	0.047	0.019	−0.031	0.008	−0.071
Expertise × phonology	0.003	−0.002	0.063	0.024*	−0.019	0.014	−0.048
Expertise × meaning	0.029*	−0.035	0.179**	0.009	0.024	0.008	0.002
Orthography × lexical	−0.011	0.052	−0.098	0.017	0.011	0.025	−0.026
Phonology × lexical	−0.023	0.084	−0.190*	0.026*	−0.037	0.032*	−0.016
Meaning × lexical	0.020	0.082	0.027	0.003	0.006	0.017	0.017
Expertise × # exposures	−0.003	−0.012	−0.018	−0.004	0.005	−0.004	0.021*
Lexical × # exposures	0.007	0.030	−0.008	−0.004	0.015*	0.007	−0.003
# Exposures × learning/memory	0.002	−0.010	0.012	0.005	−0.002	0.000	−0.013
Orthography × # exposures	0.022*	0.077	0.002	0.008	0.037*	0.029**	−0.018
Phonology × # exposures	0.011	0.104*	0.020	0.000	0.007	0.020*	−0.016

Table 2 continued

	TVT	P(Refix)	P(Reread)	FFD	Refix	GD	Reread
Meaning × # exposures	0.007	0.047	0.044	−0.005	−0.002	0.003	−0.007

* $p < 0.05$; * $p < 0.01$; *** $p < 0.001$

Orthography

Exposure to the written form of the word during training suggested different effects for high and low experience readers on first fixation durations (interaction, $p < 0.06$). Readers with less experience showed increases in first fixations following orthographic training. This increase tended to allow reduced re-reading times for low experience readers ($p < 0.07$ for the interaction). Thus, general orthographic training effects were absent for high experience readers, but affected lower experience readers by increasing first fixation durations and decreasing subsequent re-reading times (See Fig. 4).

The effect of increasing exposures was limited to Orthographic learning which reduced reading times on a number of measures: shorter duration of first-pass refixations ($p < 0.05$), gaze durations ($p < 0.01$), and the total viewing times ($p < 0.05$), which are shown in Fig. 5. Conditions without orthography (P and PM) produced no exposure effect.

Thus, the general pattern was that all readers were sensitive to orthographic training, in that increased orthographic exposure affected three different duration measures beyond first fixation. Individual differences emerged in the general effects of orthographic training, which tended to increase first-fixation, allowing shorter re-reading durations of lower experience readers, but not higher experience readers.

Phonology

Information about word pronunciation during training resulted in an interesting pattern: reading was often less efficient (longer fixation durations and more

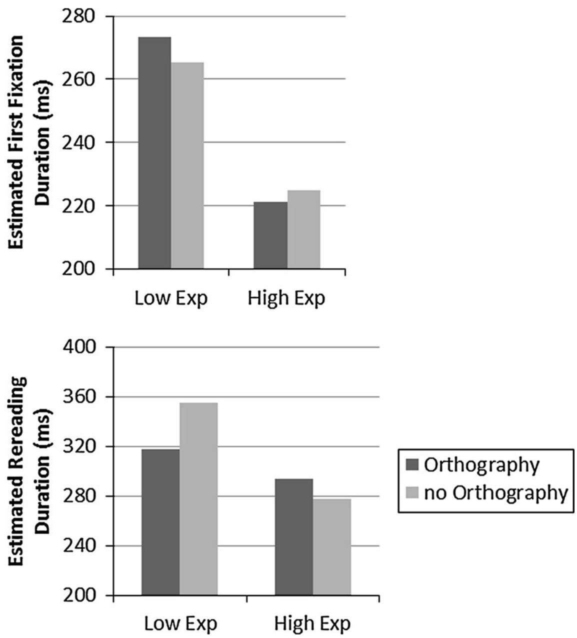

Fig. 4 Interaction between orthography training and reader expertise. Model predictions for the bounding expertise values illustrating the interaction effect: less expert readers show longer first fixation durations but shorter rereading durations with orthographic training. Predictions are back-transformed from log fixation durations for display in ms

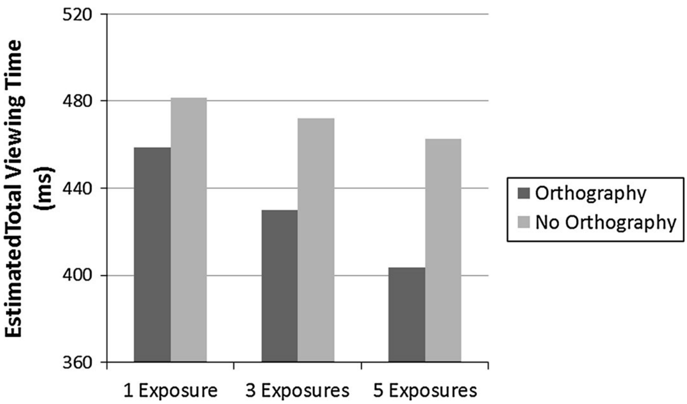

Fig. 5 Effect of orthography training on total viewing time. Model predictions illustrating the interaction between orthographic training and number of training exposures. Predictions are back-transformed from log total viewing times for display in ms

fixations), but only when there were fewer training exposures or when the reader's skill was low on some dimension. The decrease in efficiency tended to disappear or reverse with more training and for readers of higher skill. This pattern held across a number of measures.

For first fixation durations, the effects of pronunciation exposure were moderated by readers' experience and lexical knowledge. More experienced readers and readers with high lexical knowledge showed either no effect or shorter durations with pronunciation training. Such training produced slower first fixations durations for readers with either less experience or weaker lexical knowledge,

Pronunciation training increased the probability of refixating words on the first pass and also increased gaze durations. However, the gaze duration effect was limited to readers with lower lexical skills. Moreover, the phonology training effect on refixations decreased with increasing exposures during training. This same interaction held for gaze durations, which were higher for phonology training with few exposures, but decreased with more exposures.

Finally, phonological training reduced the probability of re-reading (second pass reading), but only for readers with low lexical knowledge. Readers with stronger lexical knowledge showed low levels of re-reading across all conditions.

Overall, phonology training—in particular a single exposure to a word's pronunciation—tended to slow the initial reading of a word (longer first fixation durations, more first-pass fixations, and increased gaze durations) for readers lower in reading experience or lexical knowledge. However, these first pass costs of minimal pronunciation exposure tended to be compensated by less re-reading the later, thus leaving total viewing times unaffected by phonology exposure.

Because of the apparent interactions among phonology training, training exposures, and individual differences, we added this three-way interaction to the regression models. This three-way interaction was significant for the probability of refixation, gaze duration, probability of rereading, and total viewing times.

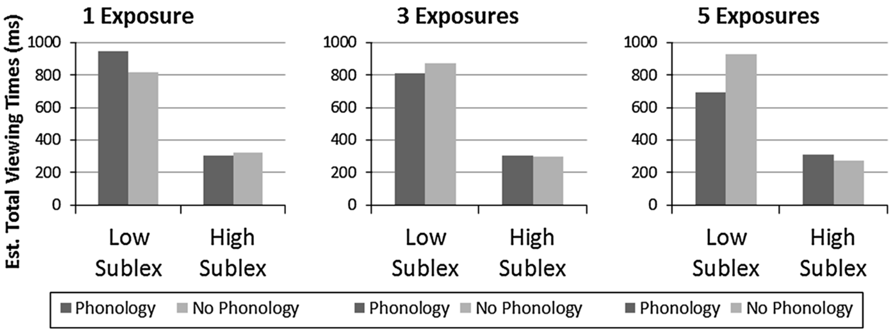

Fig. 6 Effects of phonology training andlexical knowledge on total viewing time. Graph of model predictions for the boundinglexical knowledge values illustrating the interaction effect. Predictions are back-transformed from log total viewing times for display in ms

Consistent with the results reported above, readers with higher lexical knowledge were faster overall and showed little effect of the phonology training. Readers with lower lexical knowledge showed a slow-down with phonology training after one exposure, but by five exposures they showed a benefit of phonology. This three-way interaction is shown for total viewing time in Fig. 6, which also demonstrates the general trend of the findings for phonology training.

Meaning

Meaning training significantly affected the probability of re-reading, but did not affect any of the first pass measures of reading. The direction of the effect, similar to the pattern for phonology training, depended on the reader's experience score. Lower experience readers were more likely to re-read when a word's meaning had been exposed during training. In contrast, more-experienced readers were less likely to re-read when meaning was trained. Total viewing times also showed a similar pattern, but with the effect restricted to higher experience readers, who showed reduced total viewing times with the meaning exposure (see Fig. 7).

Individual differences

Experience

Unlike in Experiment 1, a reader's score on the experience (Experience/Speed) dimension had limited effects on reading behavior for trained words. Meaning exposure reduced re-reading and total viewing times more for higher experience readers compared with lower experience readers, who tended to show the opposite effect. One additional effect was an experience interaction with the number of training exposures on re-reading times. Only the less experienced readers showed reductions in re-reading durations with more meaning exposure.

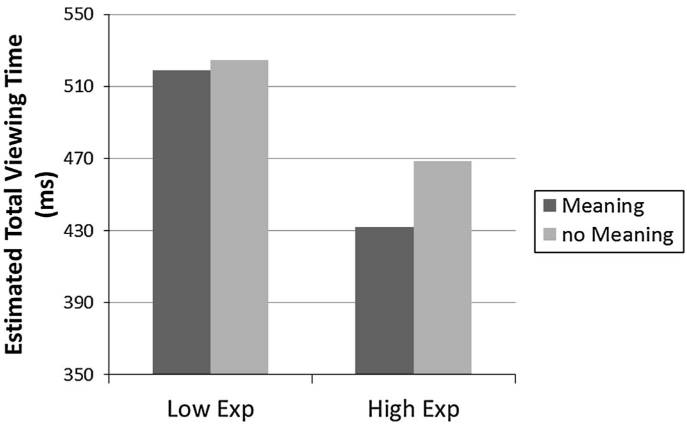

Fig. 7 Effects of meaning training and reader expertise on total viewing time. Model predictions illustrating the interaction between meaning training and reader expertise. Predictions are back-transformed from log total viewing times for display in ms

Lexical knowledge

Lexical knowledge seemed to be the most important individual difference factor. Besides the multiple interactions between lexical knowledge and phonology training, stronger lexical knowledge was associated with shorter first fixation durations, fewer refixations, shorter refixation durations, shorter gaze durations, less re-reading, and shorter total viewing times.

Learning/memory

Learning/memory interactions with specific training conditions were not included in the model, but readers who self-reported better learning and memory skills showed fewer refixations, shorter gaze durations, and shorter total viewing times. This effect may reflect better learning and memory of the target words and was independent of the number of training exposures.

Accuracy focus

Readers showing lower levels of accuracy showed less re-reading, consistent with assumption that readers who trade off accuracy for speed in assessments also do this in reading.

Discussion

The eye tracking results suggest that the availability of partial word knowledge has distinctive effects on reading behavior that depend on the knowledge source. These distinctive effects appear to be temporally distributed. When readers have been exposed to the orthographic form of the word, they show effects on the durations of first pass fixations, including the first fixation, and sometimes the duration of re-reading fixations. However, orthographic exposure did not affect the re-fixating or re-reading. When readers were exposed to the pronunciation of a word, the effects were on both first fixation durations and the relative frequency of refixations and re-readings, and a consequent effect on gaze durations. By contrast to these broad effects of pronunciation, exposure to the word's meaning had an effect only on the probabilities of re-reading. This pattern suggests that—for partial knowledge of a word—form information is the most important determiner of first pass reading, with meaning training becoming important in determining re-reading behavior.

However, the effects of partial knowledge depended on reader characteristics. Readers with lower lexical knowledge were slowed by the addition of phonology training in their first fixation durations, probability of re-reading, and gaze durations. Less experienced readers were also slowed by the additional pronunciation training in their first fixation durations.

The number of exposures was also a factor. With few exposures to the pronunciation, the probability of refixating was high and gaze durations were longer, but both were reduced following more exposures to the pronunciation. This effect may reflect the degree to which the pronunciation has been lexicalized, i.e. attached reliably to the word's orthographic form or meaning. With a single pronunciation exposure prior to sentence reading, the appearance of the written word may evoke an episodic memory trace based on the single training presentation of its pronunciation. With more exposures of its pronunciation, the written word and its phonology become integrated as lexical knowledge. This lexicalization procedure may take longer for readers with lower lexical knowledge. Of course, even without exposure to pronunciation, a reader's encounter with the word in a sentence should initiate decoding procedures that yield some approximation to the correct pronunciation—which, because the word is completely unfamiliar, is unknown to the reader and thus is not followed by a verification process. In contrast, a single prior exposure to the correct pronunciation may be present competition to the decoding routine. Readers of lower skill especially may decode the word in a way that is a mismatch with the exposed pronunciation. Accessing episodic traces or producing mismatches between generated and learned pronunciations would lead to the slowing effects we observed. Sufficient additional exposures to the pronunciation of a word would establish the phonological representation so that it is accessible from the written word form.

These results are consistent with the framework of the Word Experience Model (Reichle & Perfetti, 2003) in which word knowledge is built from the accumulation of individual experiences. Increasing exposures lead to high overlap of core features of form and meaning across repeated instances, leading to lexicalization, and integrated representation of form and meaning features. The current study suggests that within the word experience framework, more skilled readers may be able to establish context-independent representations with fewer exposures to words than less skilled readers require by making better use of each exposure. This is consistent with ERP markers of episodic memory (P600) and semantic memory (N400) observed following a similar training paradigm (Perfetti et al., 2005; Balass et al., 2010). Strong episodic traces should allow episodic recall of a particular experience to occur quickly and accurately, and it should also allow a shift from episodic recall toward a more context-independent knowledge of the word.

In summary, we highlight three major results: (1) Partial knowledge controlled through training of unfamiliar rare words affects readers' eye movements when they later read those words in sentences. Form information primarily affects first pass eye movements and meaning information affects re-reading. (2) Readers' skills determine how their word experience shapes their reading behavior: a "rich get richer" pattern is evident in which skilled, experienced readers show more facilitation than less experienced readers from the same number of exposures to words. (3) Exposure to written and spoken word forms initially slow first fixation durations and increase first pass refixations, but later decrease the amount of re-reading. This pattern may indicate that the trained form information triggers an episodic retrieval on the first encounter with the word, and that its trained lexical form becomes available to serve subsequent word-to-text integration without rereading. Without prior form exposure, readers may initially skim the word to avoid disruption to reading, but then later must re-read it.

General discussion

Using individual difference measures derived from a factor analysis of assessments of a large sample of college students, the present studies demonstrate some of the ways that reading skill, including lexical knowledge, are reflected in eye movements during reading. Even among a group of skilled college readers, there is variability in reading related skills, including lexical knowledge and experience, that is systematic enough to predict on-line reading behaviors. The dimensions of individual differences that were important included two prominent factors that capture reading experience and word knowledge. The experience factor included of assessments of reading experience, attitudes toward reading, and word processing speed. This factor predicted on-line reading measures obtained during normal reading of short texts of modest difficulty, adapted from internet sources. When they read these texts, more experienced readers skipped more words, refixated less often and with shorter durations, and did less re-reading. A second factor, characterized as lexical knowledge, captured readers' performance on various reading related subtests (decoding, word recognition, spelling, and orthographic-phonological analysis). Readers with more lexical knowledge had shorter first fixation durations for higher frequency words and were less likely to re-fixate words during the first pass. Third, we were able to identify a factor not often considered in the structure of reading skills, a focus on accuracy. This factor reflects accuracy rates on timed standardized tests on which failures to complete the tests are common. This accuracy focus factor, perhaps surprisingly, proved to capture reading behaviors in a way consistent with the assumption that performing with a high accuracy standard is a stable individual difference characteristic: Readers with high accuracy-focus tended to have longer reading times, including more frequent re-fixations.

Experience in reading both develops expertise and reflects it. A reader's self reported amount of book reading, but not magazine or internet reading, was associated with more efficient reading behavior. That this experience factor couples reading speed with reading experience reflects the outcome of reading experience on reading efficiency. This relationship of experience and efficiency, we suggest, is mediated through the acquisition of high quality word representations that develops largely from sufficiently frequent and effective word reading experiences.

Beyond the general experience factor and its reflection in eye movements during normal reading, we emphasize the role of this factor in learning. The ability of the reader to benefit from a learning experience depends on the reader's current word knowledge and reading skill, and also the reader's motivation and attention. By focusing on encounters of unfamiliar words, our second experiment examined how the eye movements of readers of different lexical knowledge and experience handled the challenge of incomplete and recently acquired information about a word's form and meaning.

Readers tended to engage in re-readings of these unfamiliar words rather than dwell on them on their initial encounters. These refixations may be the first stage in acquiring word representations, as suggested by Williams and Morris (2004), who found similar results when they observed adult readers learning words from context. Unfamiliar words that were later correct on a forced-choice meaning test were read more quickly on the first pass, but more slowly on the second pass than words that were later incorrect on the test. The authors attribute the increased re-reading duration to the process of connecting the unfamiliar word with the meaning inferred from the informative text following the word. Quicker first pass readings reflect a metacognitive sense that there was little knowledge concerning the word form. The general results of our Experiment 2 are consistent with this suggestion, while additionally showing specific effects of partial knowledge of pronunciation or spelling (with and without meaning).

Partial knowledge—very low lexical quality—for a still unknown word leads to more processing time when the word is first encountered. More fixations and longer fixations are needed to obtain the word's meaning for the given context. However, the reader's emerging familiarity with the word allows a metacognitive expectation that the meaning is forthcoming with more processing. Which particular fixations are increased depends on which parts of the word representations are weak—orthographic and phonological information affect first pass fixations, and phonological and meaning information affect re-reading times. This finding corroborates priming experiments describing the time-course of activation of different components of knowledge during reading, and extends those findings by verifying that the degree of knowledge of each of these components (controlled through a training paradigm) also affects reading on a similar time-course. Thus, both orthographic and phonological information are accessed quickly, with semantic information retrieved as lexical access occurs (Lee, Rayner, & Pollatsek, 1999; Perfetti, Bell, & Delaney, 1988; Perfetti & Bell, 1991; Rayner, Sereno, Lesch, & Pollatsek, 1995).

Learning new words and lexicalizing them—converting them from episodic experiences to lexical entries–varies with reader expertise and with the quantity and quality of word exposures. Beyond the conclusion that more skilled readers are more effective word learners (e.g. Balass et al., 2010; Nelson et al., 2005; Perfetti et al., 2005), our study of the dimensions of reading skill suggest found that dimension of experience, specific lexical and sublexical knowledge, and performance strategies (accuracy-focus) influenced the use made in reading of partial knowledge of unfamiliar words.

Readers with greater experience and expertise are quicker to use orthographic, phonological, and meaning knowledge in reading. Whether this use reflects lexicalization or only a more effective use of episodic memory is not clear. In either case, familiarity with words and their sublexical structures must play a role. More experience means more exposure to more words and thus to spellings, pronunciations, and meanings.

Readers with strong lexical knowledge are more quickly able to use, specifically, spoken word information to improve the quality of lexical representations. Nelson et al. (2005) found that faster learners depend less on the modality in which a word was learned for later recognition. Faster learners were better than slower learners at recognizing a word that they had only heard during training when they later saw the written word. Such use of the spoken word may reflect an ability to create a spelling representation of the word as it is pronounced as well as the ability to decode the word when it is presented visually, producing a match with its stored phonology. Assuming that the faster learners of Nelson et al. had better lexical knowledge explains both why they needed fewer exposures to learn a word and their lower dependence on being tested in the same modality. As in Nelson et al. (2005), our readers with strong lexical knowledge could effectively link the pronounced word to the written word, establishing a more robust lexical representation and allowing the written word to be more quickly identified in reading. Regardless of training condition, those readers with strong lexical knowledge were more fluent readers of all of the newly learned target words. Lexical knowledge seems to result not only in more highly unitized representations of frequent words, as shown in Experiment 1, but also allows readers to more efficiently turn a few exposures to word forms into accessible representations.

Reading expertise

It is noteworthy that individual differences in lexical and sublexical knowledge and experience matter even among a population of college students. We suggest that the individual difference factors that emerge in our analyses add up to a characterization of reading *expertise*—built on a foundation of lexical and sublexical knowledge and strengthened through experience.

Although a continuing role for experience through adulthood may seem obvious, one might expect its effect to be nonlinear and even thresholded. That is, a certain amount of experience is required to build expertise, but at some point the marginal gains of additional experience reduce and disappear—similar to the logarithmic function of word frequency on word processing. Although our approach did not allow information in a precise functional relation between the quantity of experience and eye tracking measures, we can suggest that motivated practice in reading (choosing to read beyond academic assignments) continues to be a driving force in reaching and maintaining high levels of reading expertise. This experience couples (in our study) and lexical knowledge to characterize a reading expertise that, like all expertise, is a matter of high volume practice (Ericsson, Krampe, & Tesch-Römer, 1993). Although expertise research in more complex domains emphasizes the role of intentional practice, skills that have a large perceptual component engage routines (e.g. word identification) that become increasingly automated with the specific intention to gain skill.

Lexical quality is part of reading expertise, both a mediator and a consequence of experience. The development of stable representations of pronunciations and spellings that are tightly bonded with meaning features is enabled largely through literacy experiences, especially reading words in texts, with additional boosts from targeted practice in spelling and vocabulary instruction. Increasingly well specified word representations, in turn, allow rapid retrieval of word meanings from written forms and thus lead to more overall reading efficiency, and thus more reading experience. As we saw in Experiment 1, readers with more experience are faster, more efficient readers, especially for less-frequent words. Readers with strong lexical knowledge are also more efficient because their knowledge of word forms, both phonological and orthographic, allows faster word identification, relatively free from neighborhood competition, on the first fixation on a word. Expertise allows more efficient identification of both low frequency and high frequency words, although the effects for high frequency effects are subtle, detectable more readily in eye-tracking than other measures.

Adding the picture of expertise is the demonstration (Experiment 2) that controlling lexical quality exposes the continuing role of reading expertise (experience and lexical knowledge) in acquiring new lexical knowledge. How prior exposure to orthographic, phonological and semantic knowledge for an unfamiliar word influences reading the word depends on individual differences in experience and lexical knowledge.

Thus, lexical quality and, more generally, reading expertise are reflected both in reading and in word learning. Knowledge of words and practice at reading them builds a reading expertise that affects reading of ordinary words also affects how readers make use of exposure to incomplete lexical knowledge for unfamiliar words.

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