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Effects of Reading Ability on Lexically-Informed Letter Perception

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Effects of Reading Ability on Lexically-Informed Letter Perception

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Abstract

Research on perceptual learning for speech shows that lexical information can be used to modify phonological representations. Recent findings suggest that lexically-informed perceptual learning is a domain-general learning mechanism such that lexically-guided learning is also observed in the processing of printed text. The literature on lexically-informed perceptual learning has extensively investigated the nature of the change to the prelexical representation. What this literature has yet to examine, however, is how varying levels of lexical recruitment influence this learning mechanism. Here we examine this question by comparing performance on lexically-guided letter perception between two groups of readers, average readers and advanced readers. The Lexical Quality Hypothesis provides a framework for our hypothesis, which posits that more efficient and richer lexical processing occurs in skilled readers compared to average or impaired readers. Adult monolingual, English readers were assigned to either the average or advanced reading group based on performance of standardized assessments of reading and reading sub-skills. All participants made visual lexical decisions to words and nonwords and then categorized members of an H – N letter continuum. The lexical decision task involved different exposure conditions. Participants in the H-bias group saw an ambiguous grapheme midway between "H" and "N" in H-bias lexical contexts, (e.g., WEIG?), in addition to words with a clear "N," (e.g., REIGN), whereas participants in the N-bias group saw the opposite, (e.g., REIG?, WEIGH). In order to examine the effects of orthographic transparency on perceptual learning, some participants were presented with critical words that had one-to-one letter-to-phoneme correspondences, (e.g., A**H**OY), and different participants did not have such orthographic transparency, (e.g., WEIG**H**). Results indicate that both groups of readers used lexical information to modify letter perception. Strikingly, this learning effect was more robust for the advanced readers compared to the average readers. These results suggest that lexical quality exerts a gradient influence on lexically-informed perceptual learning of letters.

Note

This thesis reflects a working manuscript of a collaborative project conducted with Emily Thompson and Dr. Rachel M. Theodore. Ms. Thompson and I have worked together with respect to study design, data collection, and data analysis. This manuscript will be submitted for publication with authorship shared by all named above. My independent contributions to this project include writing the initial draft and taking the lead on the introduction and discussion sections.

Introduction

Spoken language processing, though rapid and seemingly automatic, involves a complex series of processes in order to derive meaning from the acoustic speech signal. Most models of spoken language processing adopt a hierarchical structure of mapping from sound to meaning such that listeners must activate representations for individual speech sounds before activating larger linguistic units such as words. A major challenge for models of speech perception is describing how stable perception is achieved given that there is no one-to-one mapping between an acoustic event and a given consonant or vowel, and thus for individual words. The goal of the current study is to examine mechanisms that influence how listeners accommodate variability in mapping continuous variability on to representations that convey meaning. Specifically, we examine factors that influence how lexical information is used to modify mapping at a prelexical level of analysis.

Interactive theories such as the TRACE model of spoken word recognition (McClelland & Elman, 1986) claim that prelexical processing is strongly influenced by online feedback from the lexicon. This model is bi-directional, such that there are feed-forward excitatory connections from input to features, features to phonemes, and phonemes to words, as well as top-down feedback excitatory connections from words to phonemes. This framework allows activation at lexical levels to constrain and adjust patterns of activation at phonological levels based on the strength of the signal. For example, when a listener hears a word containing an ambiguous phoneme, the feed-forward component would activate the two phonemes equally, while the top-down component would activate the lexically consistent phoneme and accordingly make a stronger connection. As a result, lexical feedback would have adjusted the phoneme category boundaries. In contrast, Norris and colleagues (2000) suggested a Merge model that builds off of

Shortlist (Norris, 1994) and posits that early stages of word perception are strictly feed-forward in which there is no feedback from the lexicon. This model does, however, acknowledge integration of both prelexical and lexical representations at the ‘decision phase’ in order to determine phonemic identification responses. This concept of on-line lexical feedback continues to be subject of debate in the speech perception literature. Despite this theoretical debate, there is a rich evidence base indicate that lexical information does show striking influences on prelexical processing.

Researcher William F. Ganong (1980) was the first to show online lexical influences on ambiguous speech tokens. His findings showed that listeners shifted phonetic category boundaries based on lexical context. In other words, listeners had a tendency to shift their phonetic categories in order to accommodate the lexical constraints of their language. A line of recent research has extended this concept, investigating the persisting effects of lexically-conditioned shifts in phonetic perception, termed ‘perceptual learning in speech’ (Norris et al., 2003). Perceptual learning in speech is a domain general mechanism that allows a listener to take systematic variation in the acoustic speech signal and map it onto a stable phonemic category (Goldstone 1998). Norris and colleagues (2003) exposed Dutch listeners to an ambiguous fricative midway between /f/ and /s/. The critical manipulation during the training phase was that group one heard this ambiguous sound in a condition where lexical recognition would only occur if they perceived it as /f/ (i.e., in Dutch words like “witlof”) while group two heard it in a condition where lexical recognition would occur if perceived as an /s/ (i.e., in Dutch words like “naaldabos”). Following this manipulation, listeners categorized sounds along a continuum between /□f/ and /□s/. Results indicated that listeners shifted or “retuned” their fricative categorization given their biasing condition. That is, listeners exposed to /f/ biased conditions categorized more sounds on the test continuum as /f/ and vice versa. These results support Ganong's (1980) claim, suggesting that listeners' ability to adjust preexisting phonemic categories depends on lexical content. Norris et al. (2003) posit that listeners adjusted their phonetic boundaries to facilitate word recognition and that this adjustment would make future recognition of words containing those sounds faster.

Various studies have adapted Norris et al.'s (2003) paradigm to investigate perceptual learning effects for talker specificity (Eisner & McQueen, 2005; Kraljic & Samuel, 2005, 2006), temporal manipulations (Kraljic & Samuel, 2005), and generalization to related sounds (Kraljic & Samuel, 2006) and to new words (McQueen et al., 2006). Eisner and McQueen (2004) suggest that perceptual adjustments are highly specific to segmental information (phonetic contrasts) and talker identity. In contrast, results from Kraljic and Samuel (2005) support the notion that perceptual categories are dynamic and flexible. In their study, listeners were exposed to an ambiguous token half way between /s/ and /□/ and tested for perceptual learning on two continua, one in the same voice during exposure, and one in a novel voice. A new dimension was studied in which half of the listeners were tested immediately after exposure while the other half engaged in a 25-minute intervening task. Results show reliable generalization across speakers (findings consistent with later study by Karljic & Samuel, 2006) and a robust perceptual learning effect given such a delay, indicating that learning does not fade over time. Studies also show that such adjustments generalize to related sounds (Kraljic & Samuel, 2006) and new words (McQueen et al., 2006). Listeners were initially exposed to an ambiguous sounds between /d/ and /t/ and performed a lexical decision task. To test whether perceptual learning occurs at a phonemic level or a more abstract featural level, the second task involved all listeners labeling items on a /b/ to /p/ continuum. Results show a perceptual learning effect for the stop consonants, thus indicating generalization to new phonemes. McQueen et al. (2006) adapted Norris et al.'s (2003) paradigm and exposed listeners to novel minimal pairs that could be a word with either /f/ or /s/ (e.g. *knife-nice*). Listeners interpreted the minimal pairs differently depending on their training condition, indicating perceptual learning about speech sounds extends to novel words. These results provide further support of Norris et al.'s (2003) claim that training on ambiguous phonemes in lexically biased contexts lead to adjustments to prelexical representations.

Recent findings by Norris et al. (2006) suggest that lexically-informed perceptual learning is a domain-general learning mechanism such that lexically-guided learning is also observed in the processing of printed text. In this study, participants made visual lexical decisions to words and nonwords based on their biasing condition, and then categorized an N-H letter continuum that systematically varied by manipulating the diagonal line in "N". The lexical decision task involved different exposure conditions: Participants in the H-bias group saw an ambiguous letter "?", midway between N and H, in H-bias lexical contexts (e.g., "WEIG?") in addition to words with a clear N (e.g., REIGN), whereas participants in the N-bias group saw the reverse (e.g., REIG?, WEIGH). Results showed that the N-bias group categorized more of the test continuum as N than did the second group, while the control group, who saw the ambiguous token in nonword contexts, exhibited no such effects. Thus, lexical information can mediate sublexical processes for not only speech perception (Norris et al., 2003), but also letter perception. Indeed, many findings point to a shared network for speech and print processing (Pugh et al., 2013). This is supported by findings indicating phonological processing in an auditory modality is predictive of future reading abilities (Johnson et al., 2009; Vellutino et al., 2004). Van Orden (1987) was one of the first researchers to show that visual print activates the same speech representations as an auditory signal (e.g. ROWS primes ROSE). Moreover, neuroimaging findings show a circuitry for reading that overlaps with brain regions necessary for speech processing, some of which are regions that are sensitive to perceptual learning (Myers & Mesite, 2014).

Viewed collectively, the literature on lexically-informed perceptual learning has shown that lexical information is a domain-general learning mechanism that helps listeners resolve ambiguity in both the spoken and written signals and leads to changes in prelexical representations. Moreover, these studies have extensively investigated the nature of the change to the prelexical representation. What this literature has yet to examine, however, is how varying levels of lexical recruitment influence this learning mechanism. That is, findings to date indicate that lexical information is necessary for this type of perceptual learning – this learning does not occur when the ambiguous stimuli are presented in nonwords – but there has been no investigation that examines how graded levels of lexical recruitment systematically influence learning effects at the prelexical level.

Here we examine this question by comparing performance on lexically-guided letter perception between two groups of readers, average readers and advanced readers. There is a rich literature demonstrating that reading ability is influenced to a large degree by lexical recruitment. The Lexical Quality Hypothesis (Perfetti & Hart, 2002) suggests that skilled reading depends on high quality lexical representations. According to this model, lexical quality depends on experience with words, which in turn determines accuracy and fluency of word identification (Perfetti, 2007). A lexical representation is considered high in quality if it contains orthographic, phonological, and semantic information sufficient to identify a word. If a lexical representation is specific and redundant, its retrieval is more likely to be automatic and reliable. Reliability suggests that multiple encounters with a given word tend to produce a lexical representation that consists of coherent orthographic, phonological, and semantic information. Through repeated exposure of a given word, these representational features are believed to “bind” together into a coherent, secure, and well-specified lexical representation. Thus, lexical quality is inherently contingent on experience with words because a skilled reader has more experience with words than a less skilled reader (Perfetti, 2007).

Braze and colleagues (2007) extended this hypothesis, suggesting that robust word knowledge facilitates printed word recognition when the print signal is weak. They investigated reading skills in a group of adolescent and young adults spanning a wide range of reading ability. In particular, they examined whether vocabulary knowledge accounts for variance in reading comprehension, as predicted by Perfetti and Hart (2002). Results indicated that vocabulary is a strong predictor of reading comprehension, suggesting that vocabulary knowledge should play an important role in accounting for individual differences in reading comprehension (Braze et al., 2007). Based on these findings, Braze and colleagues (2007) posit that top-down influences on comprehension, such as the quality of lexical representations, are critical when the bottom-up influences (e.g., mappings from print to lexicon) are compromised. According to this view, print is inherently weaker than its speech counterpart. This is because mappings from print to lexicon are less practiced than those of speech to lexicon and the print signal lacks information provided by co-articulation of speech sounds, prosody, non-linguistic context, and speaker affect. Braze and colleagues (2007) support the LQH, stating that readers with robust connections among semantic and phonological features have an advantage when dealing with the inherently weaker print signal, compared to a reader whose lexical connections are impoverished. Another way this disparity manifests is that skilled readers show faster lexical decisions compared to poor readers (Katz et al., 2012). This supports the notion that stronger mutually supporting connections between correlated features allow for quick lexical access, whereas impoverished connections yield slower and more laborious access.

These theories are consistent with the *Matthew Effect* outlined by Stanovich (1986), which highlights individual differences in reading ability. Colloquially, the *Matthew Effect* is the notion that "the rich get richer, the poor get poorer." This theory outlines how individuals with poor reading skills read less, and consequently continue to be less proficient readers. Similarly, good readers continue to read more, and thus continue to become more and more proficient readers. Consequently, a larger and larger disparity develops between poor and good readers. When analyzed through the lens of the LQH, it is clear that continuous exposure to reading builds stronger and stronger connections between orthographic, phonological, and semantic mappings, which in turn leads to a specified and coherent lexical representation. Alternately, inconsistent exposure to reading tasks would impede development of well-specified, coherent lexical representations.

The current study examines lexically-guided perceptual learning of letters in two groups of unimpaired readers, average and advanced readers, who perform near the middle and the top of the normal distribution on reading assessments, respectively. To assess the effects of reading ability on perceptual learning of letters, we adapted a similar paradigm of Norris et al.'s study (2006). Both groups of readers were randomly assigned to a biasing condition (i.e., H or N) in which critical words contained an ambiguous letter between upper case H and N in lexically biased contexts. For example, participants in the H-bias conditions saw this ambiguous grapheme in H-bias lexical contexts (e.g., WEIG?) in addition to words with clear "N" (e.g., REIGN); the N-bias group saw the opposite (e.g., REIG?, WEIGH). In order to examine the effects of orthographic transparency on perceptual learning, some participants were presented with critical words that had one-to-one letter-to-phoneme correspondences (e.g., A**H**OY) and some did not (e.g., WEIG**H**). (Due to the default orthographic transparency in English, note that all N items had a one-to-one letter-to-phoneme correspondence.) Findings examining influences of orthographic transparency between the letter and sound on reading ability have shown significant differences across languages. Research done in Dutch (de Jong & van der Leij, 1999, 2002) German (Landerl & Wimmer, 2008), and Italian (Di Filippo et al., 2005) languages, which are languages with a high grapheme-phoneme correspondence, suggest that reading development depends more strongly on naming speed than on phonological awareness. The main problem of poor readers in phonologically transparent orthographies is extremely low reading fluency, despite having high reading accuracy (Wimmer et al., 2000; Wimmer & Mayringer, 2002). In contrast, the relationships between spoken and written language become more complex in languages like English where there is an inconsistent mapping of phonemes to graphemes (e.g., the word "phone"). Research suggests that early phonological deficits seem to have a more persistent negative influence on children's literacy development (Landerl & Wimmer, 2008). Findings for English-speaking children show that deficits in phonological awareness have been linked to deficits in phonological decoding (Vellutino et al., 2004). This discrepancy motivated us to consider this variable in the present study.

All participants made visual lexical decisions to words and nonwords based on their assigned biasing condition, and then categorized members of an H-N letter continuum that systematically varied by manipulating the horizontal line in "H". For both groups of readers, our primary analyses concerned the effects of (1) biasing condition, (2) reading group, (3) orthographic transparency on perceptual learning of letters. Previous studies have shown that a learning effect (e.g., H-bias group is more likely to categorize an ambiguous H-N test continuum as “H”) does not occur if the ambiguous grapheme is presented in the context of nonwords, suggesting that lexical information can mediate sublexical processes (Norris et al., 2003). Moreover, other work shows a graded influence of lexical activation based on lexical quality (Perfetti and Hart, 2002; Perfetti, 2007). This leads us to the hypothesis that graded lexical quality will exert a gradient influence on lexically-informed perceptual learning of letters. If high-quality lexical representations observed in skilled readers lead to advanced learning effects, then perceptual learning effects will be greater compared to average readers. A failure to observe this graded effect of lexical information on perceptual learning would suggest that the role of lexical recruitment in this learning mechanism operates as a threshold effect, and not a gradient one.

Methods

Participants

Seventy-two native monolingual speakers of American English (18 males and 54 females) between the ages of 18 – 35 were recruited from the University of Connecticut community to participate in the experiment. Half of the participants were randomly assigned to the low orthographic transparency condition (n = 36) and half of the participants were randomly assigned to the high orthographic transparency condition (n = 36). Within each of the orthographic transparency groups, half were randomly assigned to either the H-bias (n = 18) or N-bias training condition (n = 18). All participants provided informed consent according to protocol approved by the University of Connecticut Institutional Review Board and were either paid or received partial course credit for their participation. Reponses to questionnaires developed in our laboratories confirmed that participants had no history of speech, language, hearing, or reading disorders. All participants passed a pure tone hearing screen on the day of testing, administered at 20 dB for octave frequencies between 500 Hz and 4000 Hz.

Participants were assigned to the average or advanced reading group based on performance for a standardized assessment battery of reading sub-skills and reading comprehension (shown in Table 1). Specifically, a composite reading score was calculated for each participant (defined as mean percentile across the reading assessments) and a median split based on this measure determined the participant grouping. The median split was performed within each biasing condition (i.e., H-bias or N-bias) separately for each of the orthographic transparency conditions. Mean percentile was 61 (*SD* = 9) for the average readers and 78 (*SD* = 5) for the advanced readers, which represent statistically distinct distributions ($t_{70} = -10.26$, $p < 0.001$, $d = -2.335$). As shown in Table 1, this grouping adequately characterized performance between the groups for each of the components on which it was based. All participants also completed the *Test of Nonverbal Intelligence - Fourth Edition* (TONI-4), as shown in Table 1.

Given that the median split of the composite reading score (and thus assignment to the average versus advanced reading groups) was done within each of the four conditions created by crossing bias and orthographic transparency, we conducted an analysis in order to confirm that the composite score of the average and advanced reading groups was equivalent across these conditions. Composite reading score was submitted to between-subjects ANOVA with the factors of reading group (average versus advanced), bias (H-bias versus N-bias), and orthographic transparency (low versus high). The ANOVA showed a robust main effect of reading ability, ($F_{1,64} = 101.50$, $p < 0.001$, $^{2}_{p} = 0.613$), with composite reading score for the advanced readers higher than that of the average readers. Critically, there were no main effects of bias, ($F_{1,64} = 0.21$, $p < 0.651$, $^{2}_{p} = 0.003$), or orthographic transparency, ($F_{1,64} = 0.81$, $p < 0.372$, $^{2}_{p} =$ 0.012), nor were there any interactions among reading group, bias, and orthographic transparency ($p > .150$ in all cases).

Stimuli

Test stimuli. Stimulus creation followed the methods outlined in Norris et al. (2006). One set of test stimuli were created for use with participants in all training groups. Four sets of training stimuli were created, one for the H-bias and N-bias conditions for each of the orthographic transparency groups. We describe each in turn.

The final test stimuli consisted of a 5-step continuum ranging from more N-like letters to more H-like letters. This continuum is shown in Figure 2. The test stimuli were drawn from a continuum ranging from “N” to “H” that was created using the Helvetica Light font in size 43.

This continuum was constructed by systematically rotating the horizontal line of the H in equal steps of 3 degrees using the Keynote software such that the degree of the line ranged from 360 (unambiguous H) to 309 degrees (unambiguous N). In order to determine which five tokens would be used in the primary experiment, the 18 steps of the continuum were submitted to pre-testing.

Participants for the pre-test were 20 monolingual English adults who did not participate in the primary experiment. Ten randomizations of the 18 steps were presented visually on a computer monitor and participants were directed to identify each letter as either H or N by pressing an appropriately labeled button on a response box. Participants were seated approximately 50 cm from the screen, and the letters displayed on the monitor were 7 mm high. Each trial consisted of four displays, presented sequentially each for 250 ms including a fixation screen (..), a blank screen, the continuum step to be identified; and a masking symbol (@). Figure 1 shows percent H responses across the 20 participants for each of the 18 steps of the continuum. We selected the five consecutive tokens from the ambiguous region for use as test stimuli in the primary experiment. In addition, the most ambiguous step with an angle of 336 degrees was used as the ambiguous grapheme in the training stimuli, as described below.

Training stimuli. Four sets of training stimuli were created, one for each of the H-bias and N-bias groups for the low and high orthographic transparency conditions. Each set consisted of 420 printed items, 210 real words and 210 nonwords. These items are shown in the Appendix. Of the 210 real words, 60 served as critical “H” items, 60 served as critical “N” items, and 90 served as filler items. Different critical items were used in the low and high orthographic transparency conditions in order to differentially manipulate orthographic transparency. Note that most of the N critical items were used in both transparency conditions, given the relationship between the letter N and /n/ for English, but that most of the H-critical items were different in the two conditions. All critical items contained only one example of the respective critical letter. The filler words and the nonwords contained no examples of either critical letter. All critical stimuli ranged from four to nine letters in length. The critical letter could appear in the initial, medial, or final position of the word. Stimuli containing the critical letters (H or N) were matched in total length, position of the critical letter, and in similar combinations of immediately neighboring letters in both words (e.g., HARP and NAVY). All items were printed words in the Helvetica Light font in size 43.

For the critical items, separate versions were created for use in the H-bias and N-bias conditions. Specifically, the Keynote software was used to replace the original H or N in each of these words with the ambiguous grapheme determined by the stimuli pre-test. Thus, there were two versions of the critical items, one that had the unambiguous critical letter and one that replaced this letter with the ambiguous grapheme. Stimuli for the H-bias group consisted of the ambiguous versions of the H-critical items and the unambiguous versions of the N-critical items. Stimuli for the N-bias group consisted of the unambiguous H-critical items and the ambiguous versions of the N-critical items. The 90 filler words and 210 nonwords were identical across the biasing conditions and for the low and high orthographic transparency conditions. Figure 3 shows an example of the critical items for the H-bias and N-bias training groups.

Procedure

The experiment was completed in a sound-attenuated booth. A flat screen computer monitor was used for presenting the visual stimuli and participants made their responses using a button box. Participants were seated approximately 50 cm from the screen, and the stimuli displayed on the monitor were 7 mm in height. All listeners completed a training phase followed by a test phase.

During training, the 420 words for the particular training group were presented in a randomized order and listeners completed a visual lexical decision task. Participants were directed to decide as quickly and accurately as possible whether each letter string constituted a real English word. Responses were made by pressing a button on a response box that was labeled either “YES” or “NO.” All “YES” responses were made with the dominant hand, with button assignment counterbalanced within each biasing condition. Each word appeared on the monitor screen for 1500 ms or until the participant responded, and there was an interval of 925 ms between trials. All subjects were given a short break halfway through the training phase.

Immediately following the lexical decision task, participants completed the test phase. Each phases consisted of six randomizations of the five steps of the test continuum. Participants were asked to categorize each visual stimulus as either “N” or “H” as quickly as possible by pressing an appropriately labeled button. Button assignment was counterbalanced within each biasing condition. Each trial consisted of an ordered sequence of images presented on the main computer screen. Each trial consisted of four displays, each presented for 250 ms with no intermediate delays: fixation points (..); a blank screen; the letter shape; and a masking symbol (@). The next trial began 825 ms after the participant made a response. Before completing the test experiment, all subjects completed 10 practice trials.

Results

Training

Performance during training was measured in two ways. First, we considered mean percent correct lexical decisions for the 420 items presented during training. Figure 4 shows mean lexical decision accuracy for words and nonwords for each of the two reading groups. As expected, performance for both groups for both the words and nonwords was near ceiling. These values were submitted to a mixed ANOVA with the between-subjects factor of reading group (average versus advanced) and the within-subjects factor of item type (word versus nonwords). The ANOVA showed no main effect of reading group, ($F_{1,70} = 0.065$, $p = 0.800$, $^{2}_{p} = 0.001$), indicating that accuracy on the lexical decision task did not differ between the average and advanced readers. The ANOVA did show a significant main effect of item type, ($F_{1,70} = 6.177$, $p = 0.015$, $^{2}_{p} = 0.081$), with accuracy for the nonwords slightly higher than that for the real words. There was no interaction between reading group and item type, ($F_{1,70} = 0.584$, $p = 0.447$, $^{2}_{p} = 0.008$).

Second, we analyzed training performance in terms of reaction time to correct responses. Figure 5 shows mean reaction time in milliseconds for the average and advanced readers for each item type. These values were submitted to a mixed ANOVA with the between-subjects factor of reading group (average versus advanced) and the within-subjects factor of item type (word versus nonwords). Consistent with previous research, responses to words were faster than responses to nonwords, ($F_{1,70} = 148.448$, $p < 0.001$, $^{2}_{p} = 0.680$). Critically, we also observed a main effect of reading group, ($F_{1,70} = 5.962$, $p = 0.017$, $^{2}_{p} = 0.078$), with responses for the advanced readers faster compared to those of the average readers. Thus, consistent with the lexical quality hypothesis, those who performed higher on the standardized measures of reading and reading sub-skills were able to make faster lexical decisions compared to those who scored lower. There was no interaction between item type and reading group, ($F_{1,70} = 0.816$, $p = 0.369$, $_p^2 = 0.012$).

Test

Performance at test was measured in terms of percent H responses, which was calculated separately for each token of the test continuum by collapsing across the six repetitions of each degree presented during the test phase. Mean percent H responses was submitted to ANOVA with the within-subjects factor of degree of the test continuum and the between-subjects factors of reading group (average versus advanced), training bias (H-bias versus N-bias), and orthographic transparency (low versus high). The results of the ANOVA showed no main effect of orthographic transparency, ($F_{1,64} = 0.535$, $p = 0.467$, $_p^2 = 0.008$), nor did orthographic transparency interact with any other factor ($p > 0.050$ in all cases). Thus, it does not appear that the lexical influence on letter perception was mediated by the letter-to-sound correspondence of the stimulus items.

Figure 6 shows percent H responses across the five degrees presented in the test continuum. Four functions are shown, two for the average readers (H-bias and N-bias) and two for the advanced readers (H-bias and N-bias). Consider first performance for the average readers. The H-bias average readers showed more H responses at test compared to the N-bias readers, indicating that lexical information during training influenced performance at test, with H responses patterning with respect to the bias condition. Now consider performance for the advanced readers. These readers too showed a learning effect, with performance for the H-bias group displaced towards more H responses compared to the N-bias group. Strikingly, the magnitude of displacement between the two training conditions is greater in the advanced readers compared to the average readers. Indeed, the ANOVA described above showed a main effect of training condition, with more H responses in the H-bias compared to the N-bias training condition, ($F_{1,64} = 117.977$, $p < 0.001$, $^2_p = 0.648$). However, the ANOVA revealed a reliable interaction between reading ability and training condition, ($F_{1,64} = 13.004$, $p < 0.001$, $^2_p = 0.169$). This interaction is shown in Figure 7. Results of independent t-tests showed that for the N-bias condition, there were fewer H responses for the advanced compared to the average readers, ($t_{34} = -3.234$, p = 0.003, $d = -1.109$), and that for the H-bias condition, there were more H responses for the advanced compared to the average readers, ($t_{34} = 1.975$, p = 0.056, $d = 0.677$). This pattern confirms the learning effect was larger in the advanced compared to the average readers.

As expected, the ANOVA showed a main effect of degree, ($F_{4,256} = 28.190$, $p < 0.001$, $^2_p = 0.306$), such that H responses increased as the degree of the test continuum became more appropriate for the natural H letter. There was no interaction however between degree and training condition, ($F_{4,256} = 0.959$, $p = 0.431$, $^2_p = 0.015$), or degree and reading group, ($F_{4,256} = 1.157$, $p = 0.330$, $^2_p = 0.018$), indicating that the effect of training condition and reading group extended throughout the test continuum and was not limited to the ambiguous token used during training. None of the three-way interactions or the four-way interaction was statistically reliable ($p > 0.250$ in all cases).

One additional analysis was performed in order to examine whether the effects of reading ability on perceptual learning would be observed if we considered reading ability as a continuous variable, instead of the categorical grouping (i.e., average versus advanced readers) that we used in the primary analysis. To do so, we calculated linear correlations between the composite reading score and percent H responses separately for the 36 participants in each of the H-bias and

N-bias training conditions. These correlations are shown in Figure 8. As can be observed in this figure, reading ability did show a correlation with performance at test. Specifically, there was a significant positive correlation between reading ability and percent H responses in the H-bias group (*r* = 0.364, *p* = 0.029) and a significant negative correlation between reading ability and percent H responses in the N-bias group (*r* = -0.596, *p* < 0.001)[1]. These correlations confirm that reading ability exerts a gradient influence on lexically-informed letter perception such that the learning effect is stronger for those who perform higher on standardized measures of reading and reading sub-skills.

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[1] As shown in Table 1, the two reading groups showed a difference in their performance on the TONI – 4, with the advanced readers performing slightly higher compared to the average readers. This difference was not specifically recruited nor was performance on this measure included in the composite reading score. In order to confirm that performance at test was not due to this difference in nonverbal intelligence, we correlated percent H responses and percentile on the TONI – 4 separately for the H-bias and N-bias participants. Unlike the composite reading score reported in the main text, there was no correlation between nonverbal intelligence and percent H responses for either the H-bias (*r* = 0.020, *p* = 0.906) or N-bias training group (*r* = -0.220, *p* = 0.198). Thus, the difference in performance on the TONI – 4 is not related to performance at test.

Summary and Conclusions

A growing body of research indicates that individuals can use lexical information in order to dynamically adjust the mapping to prelexical representations for both auditory (Ganong, 1980; Norris et al., 2003) and visual signals (Norris et al., 2006). Norris and colleagues (2006) found that experimental groups identified letters on an N-H continuum based on prior exposure to an ambiguous grapheme in lexical contexts. In contrast, control groups, who saw the ambiguous token in nonword contexts, showed no such learning effect. Therefore, Norris et al. (2006) concluded that perceptual learning is a domain general learning mechanism that allows lexical information to mediate sublexical processes for not only speech perception, but also letter perception.

There is a growing body of literature indicating that reading ability is influenced to a large degree by lexical recruitment. An early model of reading ability, termed the *simple view of reading* (Gough & Tunmer, 1986), proposes that reading comprehension is a product of two independent components: decoding and listening comprehension. More recent work highlights the complex relations involved in skilled reading, notably the impact of lexical/semantic information (Perfetti & Hart, 2002; Perfetti, 2007) and vocabulary knowledge (Braze et al., 2007). The LQH (Perfetti & Hart, 2002; Perfetti, 2007) posits that skilled reading depends on high quality lexical representations, indexed by integrated components of word knowledge such as phonology, orthography, and semantic information. Based on this model, repeated exposure to words facilitates secure, well-specified lexical representations. Thus, a skilled reader is believed to have higher quality lexical representations given the inherent positive relationship between reading exposure and reading ability (Perfetti, 2007). Braze and colleagues (2007) extend this claim, asserting that robust word knowledge facilitates printed word recognition when the print signal is weak. Another way this disparity manifests is that skilled readers show faster lexical decisions compared to poor readers (Katz et al., 2012).

In the current study, the paradigm of Norris and colleagues (2006) was adapted to analyze the effects of reading ability on perceptual learning of letters. Our results are consistent with previous findings, such that seeing an ambiguous token in the context of words influenced participants to shift their perception of an H-N letter continuum based on prior exposure. For example, seeing the ambiguous token "?" in "WEIG?" during the training phase lead the reader to categorize more of the continuum as H at test, whereas participants who saw the ambiguous token in N-context words such as "REIG?" were more apt to categorize the continuum as N. Strikingly, this learning effect was more robust for the skilled readers as compared to the average readers. When viewed through the lens of the LQH, these results suggest that lexical quality exerts a gradient influence on lexically-informed perceptual learning of letters. In terms of orthographic transparency, no significant difference was observed when critical stimuli had a one-to-one letter to phoneme correspondence compared to when this was not present.

In accord with previous research conducted by Katz and colleagues (2012), advanced readers made lexical decisions, for words and nonwords, faster than the average readers. Moreover, latencies for words were faster for both groups. However, both reading groups were equally accurate at the lexical decision, suggesting that lexical decision performance of the two groups only varied by speed. A possible explanation for this disparity may be that average readers rely partly on decoding to process words in a lexical decision task, whereas advanced readers use primarily top-down sight word recognition during these tasks. Similarly, average readers may process nonwords by means of decoding to a greater degree than advanced readers, resulting in a slower, more laborious latencies. Another noteworthy finding is that the learning effect was larger in the N-bias condition compared to the H-bias condition. This may be due to the notion that “H” is inherently less flexible based on its visual characteristics; readers may be less willing to retune their perception of “H” because of its horizontal line that forms a right angle. Conversely, “N” exemplars are more flexible and thus readers may be more accepting of variable “N” graphemes.

The current work provides striking findings that open an array of avenues for future research. Here we attribute the observed difference in the reading groups to an underlying difference in lexical quality that presents as differences in performance on the standardized assessments of reading. That is, skilled reading depends on high quality lexical representations, indexed by integrated components of word knowledge such as phonology, orthography, and semantic information (Perfetti & Hart, 2002; Perfetti, 2007). In other words, could attention or selective recruitment to specific aspects during the training task cause one group of participants to perform like average readers and a different group of participants to perform like advanced readers? It would be interesting to analyze individual contributions of these three components as they relate to perceptual learning, as well as individual differences along a continuum from very poor to very skilled readers. With this information, we can gain a comprehensive understanding of the effects of reading ability on perceptual learning.

An alternate explanation is that there may be an underlying cognitive or neural basis that give rise to differential performance on reading and perceptual learning measures. Perhaps memory differences interact with perceptual learning. In terms of a neural basis, recent research investigated the neural regions involved in perception of non-standard speech tokens (Myers and Mesite, 2014). Myers and Mesite (2014) reported specific regions involved in perceptual learning of ambiguous speech sounds, notably an initial activation of the right frontal and middle temporal regions, followed by sensitivity in left temporal regions over time. Future research is needed to address the neural mechanisms underlying perceptual learning of *letters* and whether this mechanism varies depending on reading ability. Moreover, based on the finding that lexically guided perceptual learning is domain general (Norris et al., 2006), future research may examine whether or not this differential learning effect remains for an auditory paradigm. If this learning effect persists across auditory and visual modalities, this would be strong evidence that the same learning mechanism is utilized in both modalities. Future research should examine if the generalization, persistence over time, and maintenance of this learning effect are the same for letter perception as they are for sound perception.

Clinically, future research may utilize similar paradigms to understand the locus of impairment in individuals with reading disabilities. Perhaps, those with reading disabilities will not show this type of learning mechanism, which given its role in accommodating variability may put them at a disadvantage with visual (e.g., font) and speech sound variation due to less stable mapping to prelexical representations. Alternately, perhaps lexical information in this population may be recruited stronger as a way to compensate for deficits in the early mapping process. In other words, perceptual learning of letters may not follow a linear trend. These are all interesting avenues to address in future research.

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Table 1

Mean, standard deviation (in parentheses), *t*, *p*, and Cohen's *d* for the average and advanced readers for each component of the standardized assessment battery and the composite reading score. The *t* and *p* values reflect those derived from independent t-tests (*df* = 70) for each assessment measure. See the main text for a description of each assessment.

Assessment		**Average Readers**	**Advanced Readers**	***t***	***p***	***d***
TONI–4		33 (24)	45 (22)	-2.199	0.031	-0.521
CTOPP	Elision	51 (20)	62 (13)	-2.825	0.006	-0.652
	Blending	60 (27)	77 (15)	-3.281	0.002	-0.778
	Nonword Repetition	49 (25)	66 (20)	-3.251	0.002	-0.751
RAN/RAS	RAN Numbers	72 (10)	80 (7)	-4.376	0.000	-0.927
	RAN Letters	65 (12)	76 (11)	-4.151	0.000	-0.956
	RAS 2-Set	74 (12)	84 (8)	-4.125	0.000	-0.981
TOWRE	Sight Word	57 (20)	78 (17)	-4.714	0.000	-1.131
	Phonemic Decoding	62 (16)	84 (13)	-6.329	0.000	-1.509
WRMT–III	Word Identification	57 (22)	85 (14)	-6.477	0.000	-1.519
	Word Attack	55 (26)	81 (14)	-5.385	0.000	-1.245
	Passage Comprehension	67 (18)	81 (10)	-4.090	0.000	-0.962
Composite Reading Score		61 (9)	78 (5)	-10.26	0.000	-2.335

Figure 1

Mean percent H responses for the pre-test continuum. Error bars indicate standard error of the mean. The five tokens shown in the red box indicate those selected for use as test stimuli in the primary experiment.

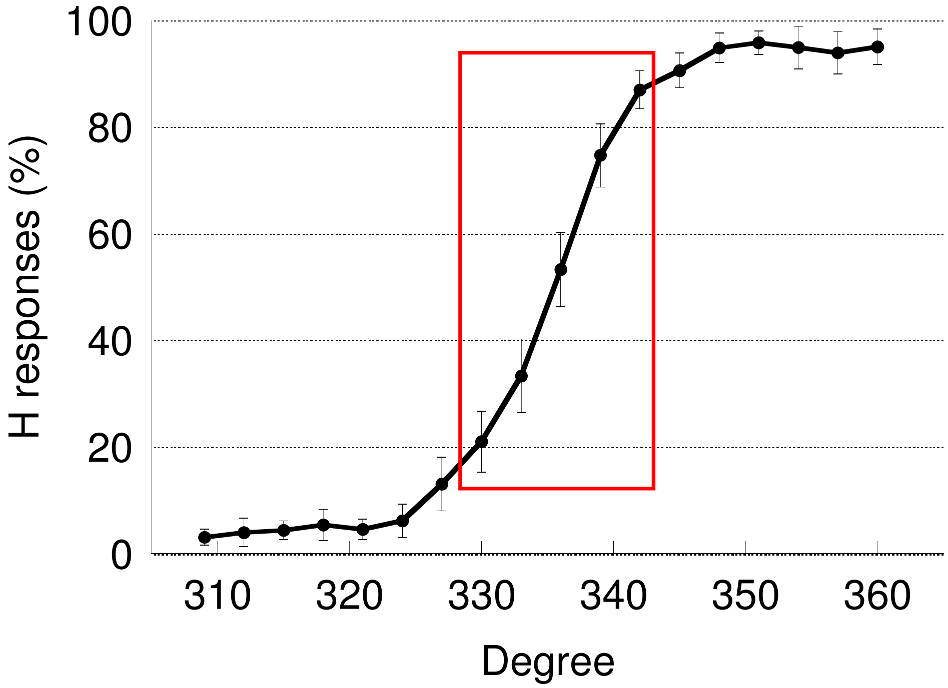


Figure 2

The five graphemes selected for use as test stimuli in the primary experiment. The intermediate grapheme, degree 336, was also used as the ambiguous grapheme in the training stimuli.

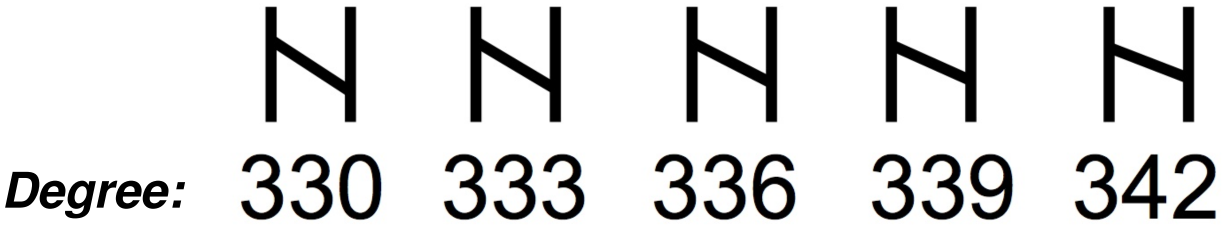


Figure 3

Example of critical items for the H-bias and N-bias training conditions.

H-biasing condition **N-biasing condition**

Figure 4

Mean percent correct lexical decisions to words and nonwords for the two groups of readers.

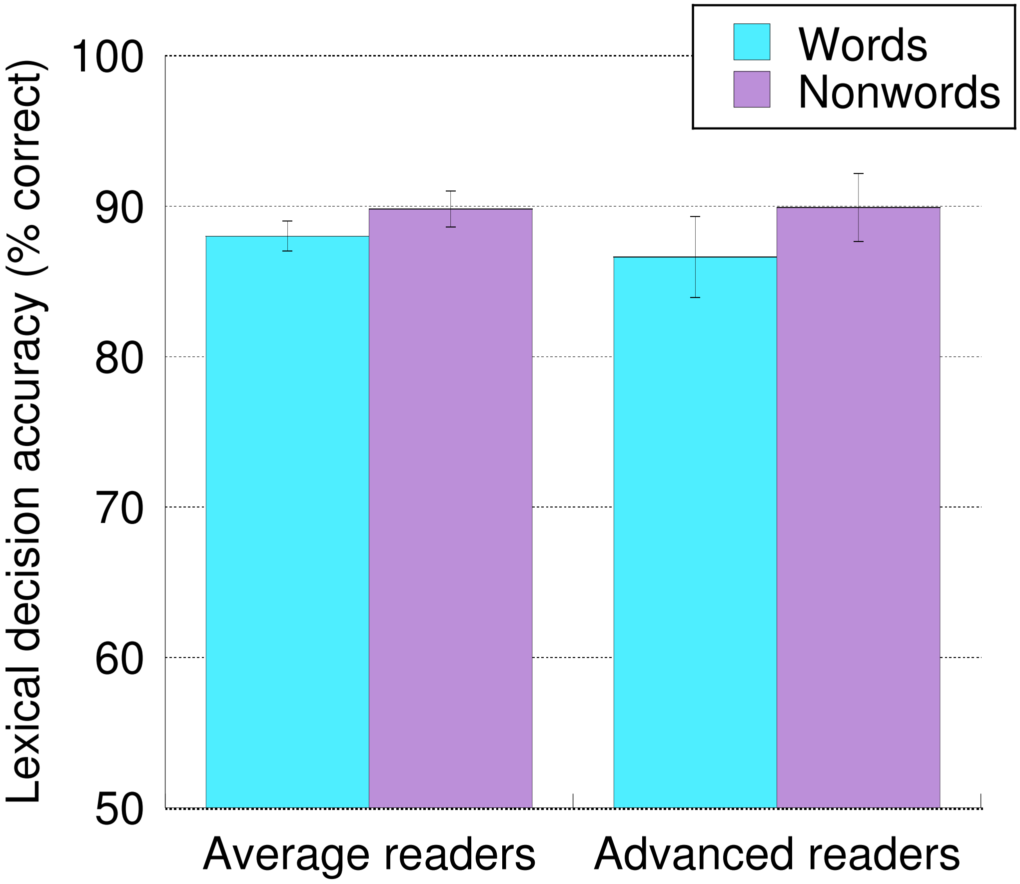


Figure 5

Mean response time (in milliseconds) for lexical decisions to words and nonwords for the two groups of readers.

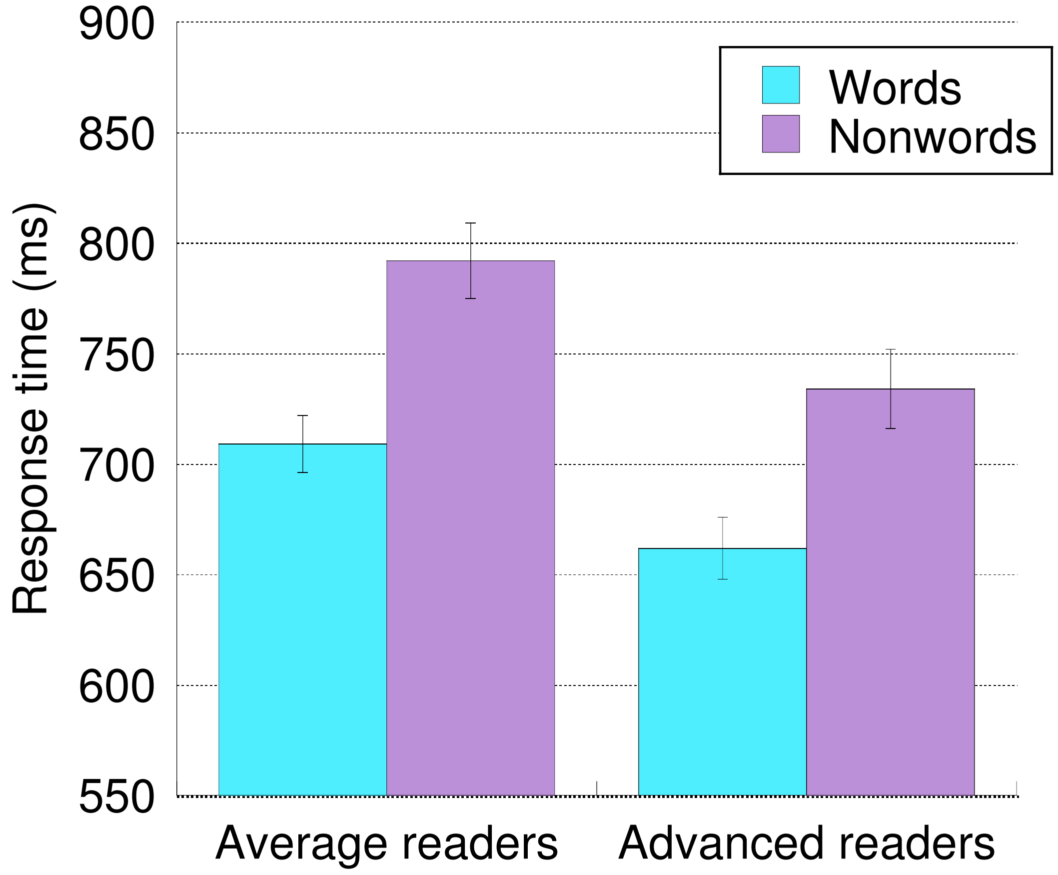


Figure 6

Mean percent H responses for the average and advanced readers in each training condition across the five degrees of the test continuum. Error bars indicate standard error of the mean.

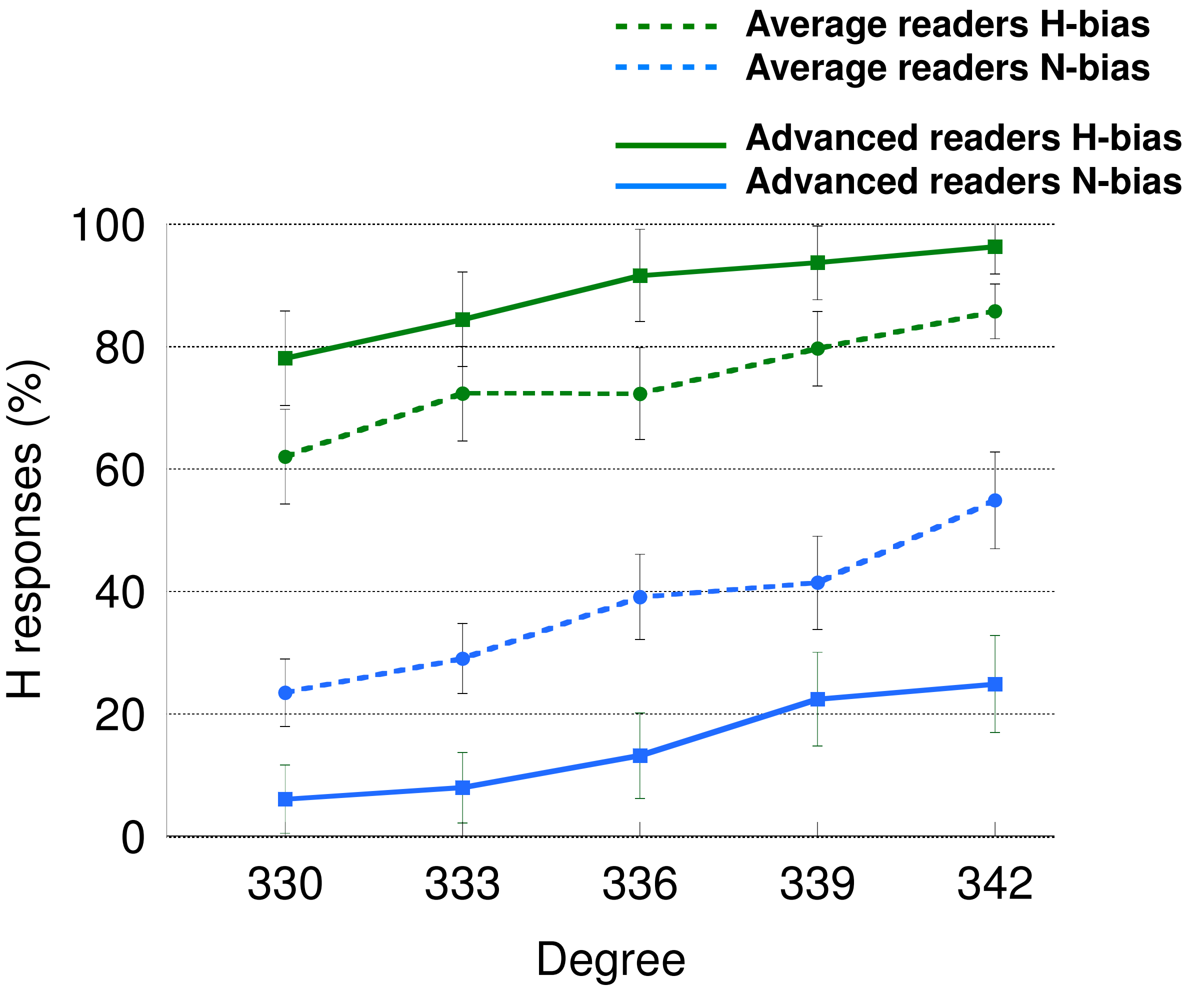


Figure 7

Mean percent H responses for the average and advanced reading groups in the H-bias training condition and the N-bias training condition. Error bars indicate standard error of the mean.

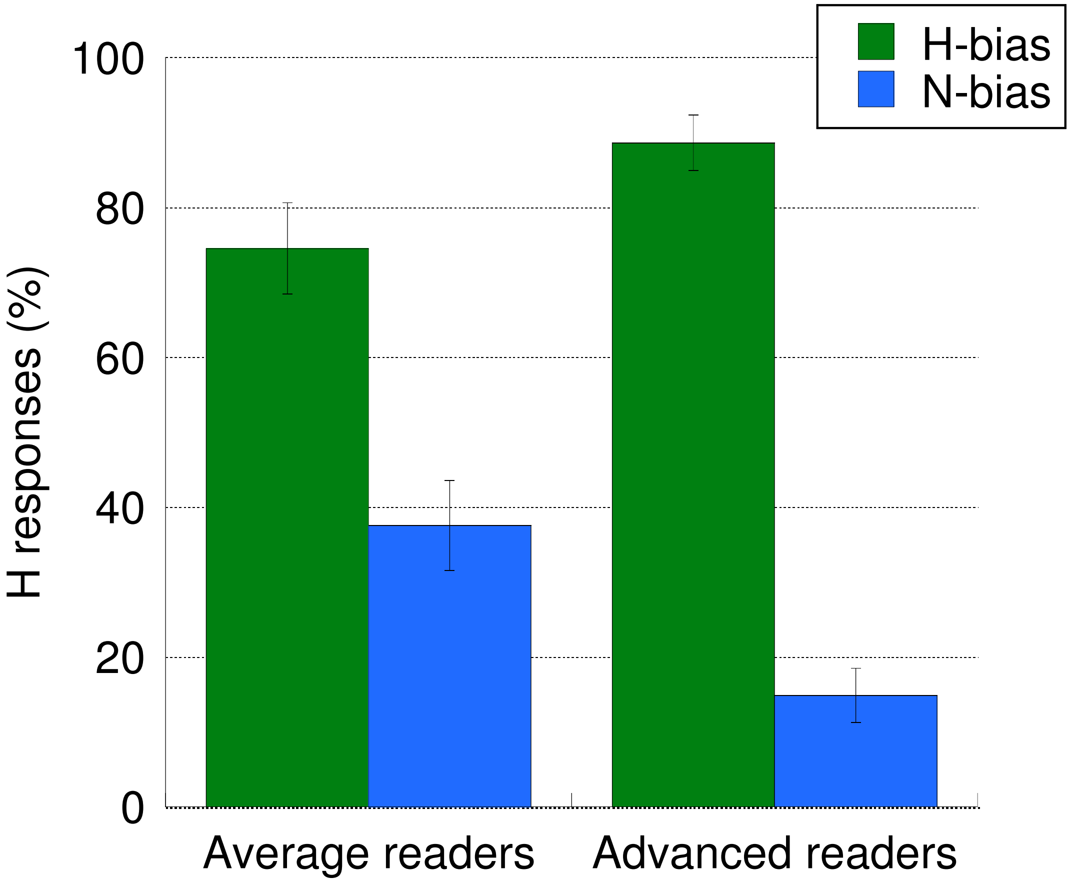
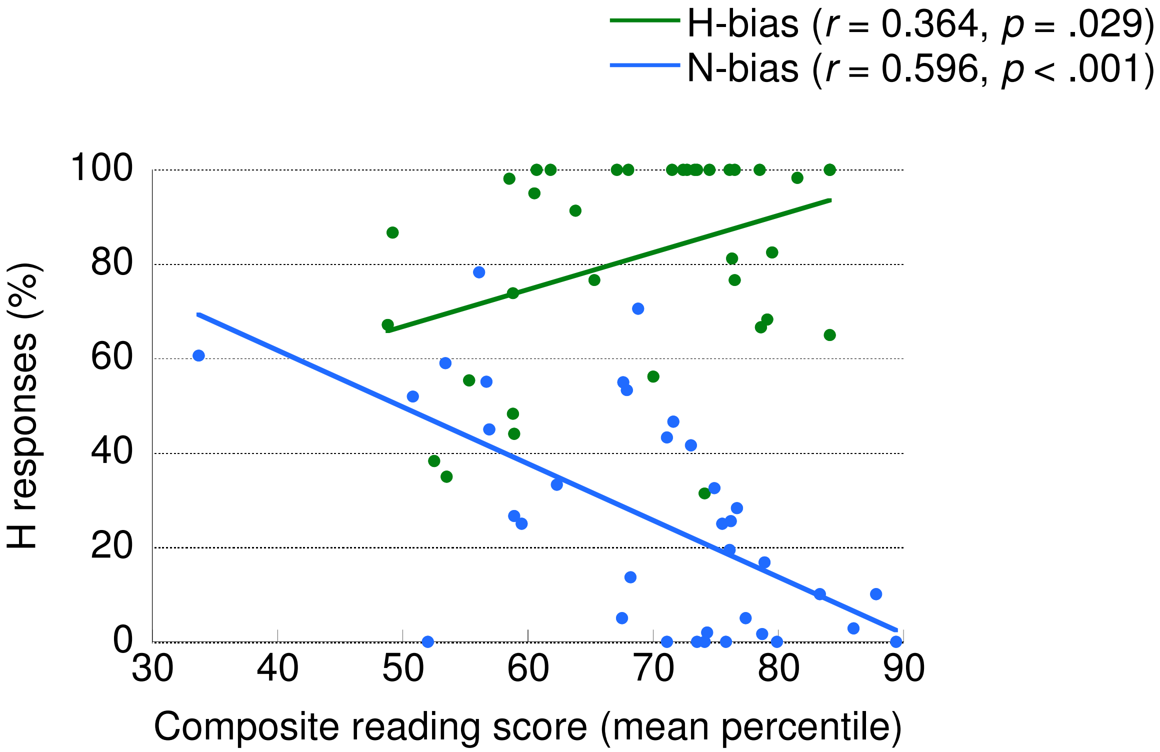


Figure 8

Correlations between mean percent H responses and composite reading score for the H-bias and N-bias training conditions.



Appendix

Words used for the low orthographic transparency stimulus items.

H-critical		N-critical		Filler		
hilt	shadow	nice	snazzy	bask	veil	afford
harp	shovel	navy	snorkel	scold	yell	discard
hoop	plough	norm	design	bump	zeal	mallard
helm	sleigh	newt	assign	bored	tool	fester
shop	trough	snob	malign	deal	twill	football
shut	approach	snub	arraign	deck	bottom	defame
haste	holiday	nasal	nostril	dog	blazer	before
hedge	humdrum	nerve	nullify	sail	buried	effect
husky	haircut	nudge	naively	void	bitter	defect
hoist	heretic	noise	neutral	field	rumble	corral
ghost	ghastly	gnome	gnarled	owl	scramble	battery
shirt	shuttle	sniff	snuggle	crawl	defeat	bewilder
khaki	shopper	knack	snoozer	mild	delay	boulevard
shirk	shimmer	snipe	snigger	dream	radar	butterfly
sheaf	shelter	sneak	sneaker	weird	spider	syllable
shard	borough	snarl	foreign	posed	ready	terrible
shoal	messiah	snoop	utopian	fact	glider	resemble
weigh	heritage	reign	negative	far	abide	gullible
bough	humility	align	numeracy	game	crowded	flexible
tough	hardback	deign	narcotic	vague	decode	portable
cough	horribly	feign	novelist	cross	embed	devastate
pariah	shoelace	pagan	snowball	male	exceed	diagram
hammer	shoulder	native	snobbery	pail	reside	limited
hockey	outweigh	novice	campaign	reel	salad	accepted
hectic	hostility	nectar	nostalgia	rule	saddle	orderly
humor	hamburger	nutmeg	narrative	stole	tidal	fallacy
shell	horoscope	sneeze	normative	spill	border	sarfari
shiver	harvester	sniper	narcissus	file	ordeal	qualify
shifty	shoemaker	snivel	snowflake	eel	wardrobe	deficit
shelve	shortfall	sneaky	snowboard	style	dial	buffalo

Words used for the high orthographic transparency stimulus items.

H-critical		N-critical		Filler		
hilt	mishap	nice	snazzy	bask	veil	afford
harp	pothole	navy	snorkel	scold	yell	discard
hoop	alcohol	norm	design	bump	zeal	mallard
helm	keyhole	newt	assign	bored	tool	fester
birdhouse	backhoe	snob	malign	deal	twill	football
reheat	diehard	snub	arraign	deck	bottom	defame
haste	holiday	nasal	nostril	dog	blazer	before
hedge	humdrum	nerve	nullify	sail	buried	effect
husky	haircut	nudge	naively	void	bitter	defect
hoist	heretic	noise	neutral	field	rumble	corral
grasshopper	cohort	gnome	gnarled	owl	scramble	battery
Ohio	uphold	sniff	snuggle	crawl	defeat	bewilder
perhaps	adhere	knack	snoozer	mild	delay	boulevard
uphill	outhit	snipe	snigger	dream	radar	butterfly
forehead	redhead	sneak	sneaker	weird	spider	syllable
behave	behoove	snarl	foreign	posed	ready	terrible
playhouse	overheat	snoop	utopian	fact	glider	resemble
ahoy	heritage	reign	negative	far	abide	gullible
superhero	humility	align	numeracy	game	crowded	flexible
foothill	hardback	deign	narcotic	vague	decode	portable
cahoots	horribly	feign	novelist	cross	embed	devastate
rehab	exhale	pagan	snowball	male	exceed	diagram
hammer	behold	native	snobbery	pail	reside	limited
hockey	outhouse	novice	outnumber	reel	salad	accepted
hectic	hostility	nectar	nostalgia	rule	saddle	orderly
humor	hamburger	nutmeg	narrative	stole	tidal	fallacy
ahead	horoscope	sneeze	normative	spill	border	sarfari
seahorse	harvester	sniper	narcissus	file	ordeal	qualify
beehive	behavior	snivel	snowflake	eel	wardrobe	deficit
rehearsal	dollhouse	sneaky	snowboard	style	dial	buffalo

Nonwords used for stimulus items.

Nonwords						
blart	splork	driced	seggs	bulder	glifer	baldrimer
greem	prite	jied	mieb	steldy	smorite	spolamers
bluzz	raists	zerm	wroaked	slidis	spigal	skovatter
ploard	pouse	malp	yalse	spilip	criddle	darmesote
dreeb	stuldge	sculfed	sembed	smelky	drickle	disadled
glabed	crype	spraumed	pruized	stabic	vardice	fiberate
stup	breib	cleeped	gilque	spolly	resteem	adoller
stof	druck	plodge	giel	saligy	glofted	commitate
burl	palse	steaste	clawp	curpal	paldest	cleamary
brald	pormes	griles	fick	comidry	repote	emteral
blaiste	stelts	ooke	clolbed	grofted	jurby	comaprid
skecked	wregged	sweam	daive	stuskled	cladle	reberate
deave	tief	dreized	smugged	slesterm	bratick	goraside
leam	spoard	deaste	jerbs	slember	grism	curpat
korged	grot	clufs	yeam	sloffle	vosis	purdrid
sikes	stift	bliped	meaf	froodle	dartor	spolter
glorp	smull	joom	lup	stible	glermize	stember
warpul	crulds	plike	gadum	skilted	godal	torepate
gluke	tolm	fobe	galag	paddit	waper	covatter
sleals	sworck	josks	peder	bilted	frady	gurmera
dag	wreaze	gapt	dillart	imparf	wooty	tology
blelf	drell	kiled	garmur	parsty	fratied	krispit
smalp	troped	flelbed	dasmar	exulp	gabber	cubital
lurrs	aves	meabes	wertile	polter	quolmy	jugaloo
yaves	cagged	trulfed	gusik	sumtry	varet	futory
clatt	torst	scorve	smaics	streger	scorvel	sutiped
spourge	sprimmed	prive	podal	kirby	ploral	froltier
vurps	eald	bloved	jaster	quipter	fesolate	wabbery
squeid	varm	warsed	crupult	wezlat	dudilimy	paltriest
glards	zair	gorm	bectil	plerty	dorepate	brillarty