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Do Dyslexics Misread a ROWS for a ROSE?

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Abstract

Insufficient knowledge of the subtle relations between words' spellings and their phonology is widely held to be the primary limitation in developmental dyslexia. In the present study the influence of phonology on a semantic-based reading task was compared for groups of readers with and without dyslexia. As many studies have shown, skilled readers make phonology-based false-positive errors to homophones and pseudohomophones in the semantic categorization task. The basic finding was extended to children, teens, and adults with dyslexia from familial and clinically-referred samples. Dyslexics showed the same overall pattern of phonology errors and the results were consistent across dyslexia samples, across age groups, and across experimental conditions using word and nonword homophone foils. The dyslexic groups differed from chronological-age matched controls by having elevated false-positive homophone error rates overall, and weaker effects of baseword frequency. Children with dyslexia also made more false-positive errors to spelling control foils. These findings suggest that individuals with dyslexia make use of phonology when making semantic decisions both to word homophone and non-word pseudohomophone foils and that dyslexics lack adequate knowledge of actual word spellings, compared to chronological-age and reading-level matched control participants.

Keywords

developmental dyslexia; homophone; pseudohomophone; semantic judgments; word frequency

The goal of the present study was to test whether individuals with dyslexia are constrained by phonology in making semantic judgments when reading. It is well documented that individuals with dyslexia have a phonological coding deficit in reading printed words and nonwords (Rack, Snowling, & Olson, 1992) and this phonological coding deficit is also found in silent reading (Olson, Kliegl, Davidson, & Foltz, 1985). The phonological coding deficit in written language is preceded and predicted by earlier phonological problems in spoken language, most notably in phonological awareness (Bradley & Bryant, 1978, 1983; Lundberg, Olofsson, & Wall, 1980; Scarborough, 1990; Elbro, Borstrom, & Peterson, 1998).

These two robust empirical results form the basis of the widely accepted phonological theory of dyslexia. Yet, these phonological deficits in oral and written language are hardly absolute. Dyslexics' phonological problems in spoken language are subtle and many dyslexics learn to use "phonics" to pronounce unfamiliar words. So, dyslexics use phonological coding in reading, but they just do it less well.

Because much of the research on dyslexia has focused on single word reading, much less is known about how dyslexics use phonological coding in reading for meaning, which of course is the purpose of reading as a cultural invention. The current study uses a well-established experimental paradigm for evaluating the role of phonology in making semantic judgments about printed text, the semantic categorization task. Using this task, Van Orden (1987) and Van Orden, Johnston, & Hale (1988) showed that typical readers are affected by the phonology of printed text when making semantic judgments. That is, when responding Yes-or-No to category judgments for target words (A FLOWER, followed by ROWS), typical readers make more false positive errors to homophone foils (responding yes to ROWS) than when responding to orthographically-similar spelling control words (ROBS). A similar pattern of performance is found with pseudohomophone foils (e.g., ROZE) compared to spelling control nonwords (e.g., RONE).

Several competing theories exist for how dyslexics might use phonology in reading for meaning, and these competing theories make different predictions for how dyslexics will perform on the semantic categorization task. First, according to a dual process theory account of developmental dyslexia (e.g., Castles & Coltheart, 1993), they could bypass phonology and rely on direct access. That is, when performing the categorization task, dyslexic readers should not have access to a phonological code for ROWS, and therefore would not make a false positive response to the category prompt A FLOWER. Thus, dyslexic readers should make the same number of false positive errors for spelling control words as homophone foils (e.g., ROBS and ROWS for the baseword ROSE) in a meaning-based task, due to their core deficits. And a similar pattern of performance would be predicted for pseudohomophones and their spelling controls.

Second, dyslexic readers could use real word phonology (addressed phonology) to activate semantics, but be unable to phonologically decode pseudowords (assembled phonology). This account fits with previous work that showed poor readers compensate for their weak decoding by relying more on contextual (i.e., meaning-based) cues to identify words (Stanovich, West, & Freeman, 1981). In this sense, the categorization task may act to prime words related to the category and their whole-word phonology. Following the compensation hypothesis of Nation and Snowling (1998), dyslexics should rely on whole-word reading based exclusively on lexical knowledge to compensate for deficient phonology. This leads to the prediction that dyslexics will make more false positive errors to word homophone foils, compared to yoked word spelling controls, but not to pseudohomophone stimuli, which, being non-words, would not be present the lexicon..

Third, dyslexics could use both addressed and assembled phonology, but do so less well than typical readers. In this case, they would make significantly more false positive errors to both homophones and pseudohomophones relative to spelling controls, but the magnitude of

this phonology effect would be less than that seen in controls. From a connectionist perspective, (e.g., Plaut, 1997) skilled reading involves a system with robust mappings between orthographic, phonological and semantic codes, such that input from any single code will cause rapid activation of covariant codes. In contrast, dyslexia is viewed as weaker and less stable links in semantic-phonological-orthographic mappings, resulting from compromised phonological input that affects reading but that is not severe enough to affect speech perception (Harm & Seidenberg, 1999). Therefore, the semantic demands of the categorization task would result in weaker activation of covariant phonological and orthographic codes which will less frequently reach threshold for a false positive response.

Finally, a fourth possibility is that dyslexic performance would be identical to controls, indicating a similar use of phonology in semantic access, despite a phonological coding deficit.

Moreover, these patterns of results could vary by age group or by control group (chronological age, CA, controls vs. reading age, RA, controls.). Phonological deficits in dyslexia are pervasive across development (Goldstein & Kennemer, 2005; Scarborough, 1990), so we investigated whether the relation of phonological coding for meaning is also universal across developmental stages. The present study tested these possibilities in cross-sectional samples of child, teen, and adult dyslexics compared to both CA and RA control groups. Further, there is an evidence base for a genetic source of dyslexia (Brkanac et al., 2008; Castles, Datta, Gayan & Olson, 1999; Raskind et al., 2005); thus, we included samples with known familial cases of dyslexia, and with clinic-referred cases to compare performance on the present categorization task across forms of dyslexia. Effects of reading exposure were also observed by comparing relatively familiar word foils with less familiar word and non-word foils.

Contrast Comparing Word Homophones and Nonword Pseudohomophones

METHOD

The method was modeled on that of Van Orden et al. (1988), Experiment 1, with the addition of dyslexic participants.

Participants—The three groups of dyslexic participants were children ranging in age from 7.0 to 11.9 ($N = 32$), teens ranging in age from 12.0 to 18.0 ($N = 33$), and adults ($N = 30$) recruited from familial- and clinic-based samples. The source for the familial sample was from extended families with three-generation histories of dyslexia who were part of a genetic linkage analysis of dyslexia (Cardon et al., 1994; Smith, Kimberling, Pennington & Lubs, 1983; Smith, Pennington, Kimberling, & Ing, 1990). The clinic-based samples consisted of (a) newly-diagnosed dyslexic youngsters from the Child Neuropsychology Clinic at the University of Denver, (b) students attending Denver Academy, a school that serves children with various learning disabilities, and (c) students enrolled in a reading disability treatment program at a local community college. There were approximately equal numbers of dyslexics ascertained from families or clinical settings at each age level, exhausting the slightly larger samples described by Pennington, Van Orden, Smith, Green, and Haith (1990), and Pennington, Cardoso-Martins, Green, and Lefly, (2001)—that is, 32 of

35 children, 33 of 36 teens, and all 30 adults—while maintaining equivalent descriptive and control criteria among the familial and clinic-based samples and their respective controls.

The criteria used for establishing a diagnosis of dyslexia were as follows: all dyslexic participants (children, teens, and adults) had a history of reading and spelling difficulty, plus objective evidence of a significant discrepancy between oral reading and/or spelling and other cognitive skills. This discrepancy was measured by either the reading quotient (RQ) or specific dyslexic algorithm (SDA). Details of the RQ and SDA are described in previous publications (Pennington, Lefly, Van Orden, Bookman, & Smith, 1987; Pennington et al. 1986, 1990, 2001). The RQ combines age and IQ-discrepancy definitions of dyslexia because it compares observed reading fluency and written spelling (numerator) to what would be predicted based on the average of IQ, age, and grade level (denominator), whereas the SDA is an IQ-discrepancy definition. Mean values for RQ are given in Tables 1 and 2. As can be seen, the dyslexic groups achieved RQ scores of less than 0.80, which indicates a significant discrepancy between their actual and expected reading/spelling ability. The majority of participants also met an age discrepancy definition of dyslexia. In contrast, both CA and RA control groups for each age sample had RQ scores around 1.0, indicating no discrepancy between their actual and expected reading and spelling abilities. Exclusionary criteria for each dyslexic participant included: absence of (a) an IQ less than 85, (b) severe perinatal complications, (c) uncorrected visual or hearing problems, (d) epilepsy or other documented neurological disorders, or (e) socio-cultural deprivation.

Each of the dyslexic groups was matched to two control groups, a chronological age (CA) control group matched on age and sex, and a reading age (RA) control group matched on a measure of single-word reading accuracy (Peabody Individual Achievement Test, PIAT, Reading Recognition subtest; Dunn & Markwardt, 1970). As Table 1 shows, the dyslexic and CA control groups were similar in age and education in each sample, whereas the RA control group was inevitably younger and less educated than the other two groups in each sample. In addition, on the PIAT Reading Recognition subtest each RA control group scored similarly to its matched dyslexic group and its own grade level. In contrast, each CA control group scored well above their grade level, whereas each dyslexic group scored below its grade level on this measure.

As Table 2 shows, both the dyslexics and CA controls were young adults with mean education beyond high school, whereas the RA controls were adolescents with about an eighth-grade education. Each dyslexic group had significantly less education ($p < .05$) than its CA control group, a result found in several follow-up studies of dyslexic adults (Finucci, 1986; Schonhaut & Satz, 1983). The CA controls performed close to ceiling on the PIAT RRec, the RA controls were close to their education level, and the dyslexics performed well below their education level on this measure.

Three measures of IQ are reported in Tables 1 and 2, a verbal IQ score (VIQ) and a performance IQ score (PIQ) based on the Wechsler Intelligence Scales (Wechsler, 1974), and a measure of fluid intelligence from Raven's Matrices (Raven's IQ; Raven, Court, & Raven, 1988). Both child and teen CA control groups scored in the above average range on VIQ, and were significantly higher than their respective dyslexic comparison group, with the

child CA group also being higher on the Raven's IQ. In addition, the teen RA controls scored significantly higher than their dyslexic comparison group, on both VIQ and Raven's IQ. Neither control group differed significantly from their respective dyslexic comparison group on PIQ at either age level. For adults, both dyslexic groups had average verbal IQs and above-average scores on the two nonverbal IQ measures, on which they were generally similar to controls. Each dyslexic group was significantly lower in verbal IQ than their respective RA control groups, but neither dyslexic group was lower than CA controls in verbal IQ, once education was covaried out.

Additional academic achievement measures were taken for each of the groups and are reported in Pennington et al. (1990, 2001). Overall, these measures indicated specific impairment in the dyslexic groups on spelling recognition and nonword reading compared with their scores on general information, math, and reading comprehension. In particular, despite being matched with the RA groups on real-word naming accuracy, the dyslexic groups performed worse on the spelling and nonword reading measures, which can be considered more sensitive measures of the dyslexics' phonological deficit.

In sum, the IQ discrepant groups in this study are well matched to their comparison groups on the variables used in matching. These dyslexic groups are also similar to those in the literature in having a nonword reading deficit (Rack et al., 1992) and in being predominantly a mixed subtype exhibiting difficulties with both spelling recognition and reading nonwords aloud.

Stimuli—Each participant was presented with a total of 240 targets for categorization, with 20 categories presented. Category names that appeared in the 40 practice trials did not appear in experimental trials. Each experimental category name (i.e., any category name that is followed in some trial by a homophonic foil) appeared in 6 “yes” trials and 6 “no” trials. Each target appeared once. The targets of interest were 10 nonword homophones (SHEAP), 10 word homophones (STARE), and 20 respective nonword and word, yoked, spelling controls (SHELP and START; a complete list of these targets appears in Appendix A). All the pseudohomophone targets had been tested multiple times in naming tasks to insure they produced the expected homophonic pronunciations. The target stimuli also satisfy other criteria listed in Van Orden et al. (1988), including careful matching of yoked nonword and word homophone foils in their respective orthographic similarity to corresponding base-word exemplars (sheep and stair) and the word frequency counts of the corresponding base-words.

Procedure—Each participant was seated in a quiet room before a computer monitor on which the stimuli were presented. Each trial began with the presentation of the word READY. Participants signaled that they were ready to begin by pressing a “ready” key. When the “ready” key was pressed, a category name appeared (e.g., A FOUR-FOOTED ANIMAL). The category name was followed immediately by a plus sign (this fixation stimulus appeared in the center of the forthcoming target letter-string). Participants were instructed to read the category name and then look directly at the plus sign. A target letter string (e.g., SUTE) followed the plus sign, and upon presentation of the target the participant

responded by pressing a “yes” key if the target was an exemplar of the preceding category and a “no” key otherwise.

Each session began with 20 “yes” and 20 “no” practice trials; all of the practice targets were words and none were homophone foils. Participants were instructed to use these trials to practice responding quickly while being accurate. The practice trials were followed by 200 experimental trials. Half of the trials included targets that were exemplars of their preceding categories. The practice trials were presented in the same order to all participants. However, each participant was presented with a different random ordering of the experimental trials. The only condition on this ordering was that equal numbers of word and nonword homophones, and their respective spelling controls, appeared in the first and second halves of the experimental session. An entire experimental session lasted about 45 minutes.

Viewing conditions—Stimuli were presented as dark letters on a white screen. The timing of the stimulus presentation was as follows: The category name remained visible for 2 seconds, the plus sign for 500 milliseconds, and the target until the subject responded.

RESULTS

False-positive error rates were first entered into separate MANOVAs with subjects or items as the random variable. For the item analysis, yoked quartets of word homophone, word spelling control and non-word homophone, non-word spelling control were treated as the random factor. For the subjects analysis, participant triplets of a dyslexic with each reading-age matched control (RA), and chronological-age matched control (CA) were the random factor. Each analysis also included between-group factors of age—child, teen, and adult, defined by the age of the dyslexics—and sample—familial versus clinic-based—and repeated measures factors of target type—homophone foils versus spelling-control foils—and lexical status—words versus non-word foils.

The effect of familial versus clinic sample was not found to be statistically reliable, neither as a main effect nor in interactions with other factors. Also, the effect of words vs. nonwords was not statistically reliable as a main effect, replicating the previous findings of Van Orden, et al. (1988). The interaction among CA vs. dyslexics vs. RA reading group, homophone versus spelling control, and age was statistically reliable in both item, $F(4, 106) = 12.99, p < .001$, and subject, $F(4, 170) = 12.23, p < .001$, analyses. The clinical and familial samples follow the same pattern in this regard and the outcomes for word and non-word foils overlap in the data plotted in Figure 1.

Subsequent univariate analyses were performed to explore the reliable three-way interaction, and to test planned contrasts of interest. The main question asked was whether the dyslexic group differed from the control groups in their pattern of false-positive errors to homophone foils (foils like ROWS) versus spelling-controls (foils like ROBS). Four separate ANOVAs tested for the interaction effect of reading group (dyslexic versus control) and target type (homophone versus spelling control): (1) the first ANOVA compared dyslexics with CA controls on word foils, (2) the second ANOVA compared dyslexics with CA controls on non-word foils, (3) the third ANOVA compared dyslexics with RA controls on word foils, and (4) the fourth ANOVA compared dyslexics with RA controls on non-word foils.

Because the clinical versus familial contrast was not a statistically reliable factor, the data from familial and clinical samples were combined and age (child, teen, and adult) was entered into each analysis as a between group factor. Thus, each univariate ANOVA was a 2 (dyslexic vs. control) X 3 (child, teen, adult) X 2 (homophone foils vs. spelling controls) mixed-design analysis.

Overall, the dyslexic groups had higher error rates on all foils than CA controls (p 's < .001), and higher error rates to word foils than RA controls (p = .01). ANOVA's 1 and 2 also showed statistically reliable differences in error rates to homophone versus spelling control foils for the dyslexic readers and CA controls that varied across the three age groups in a three-way interaction effect, F 's (2, 89) = 16.39, 3.93, p 's < .05. The interaction effect appeared as a relatively consistent difference between homophone foil and spelling control foil error rates across all ages of dyslexics, whereas the corresponding error rates to homophone foils by CA controls appeared to converge toward the error rates to the spelling control foils from children to teen to adult CA controls. Comparing dyslexic readers to RA controls (ANOVA's 3 and 4) we found similar performance at the same comparable reading level for both homophone and spelling control foils.

DISCUSSION

The dyslexic readers performed differently than age-matched non-dyslexic readers on the categorization task, but not in the expected direction. It was anticipated that dyslexic readers would make fewer false positive responses when judging non-word pseudohomophone foils of category exemplars (the foil ROZE for the base word ROSE), because they should lack access or exhibit diminished access to the phonology of pseudohomophones. The dyslexic readers' performance was in the opposite direction, however. Dyslexic readers made more false positive responses to both pseudohomophone and word homophone foils, indicating that the problem on this task is not the availability of phonology, in either case. In fact, they also showed exaggerated false positive error rates to non-word homophone foils compared with age-matched controls. This is in contrast to much previous evidence that deficient non-word decoding is a hallmark of individuals with dyslexia (Elbro et al., 1998; Snowling, 1981). Nonetheless, the dyslexic readers were strongly affected by phonology in making the categorization judgments, as indicated by the contrast between error rates to homophone foils versus spelling-control foils. The dyslexics' error rates were statistically equivalent to those of the reading-age matched controls, indicating that the effect on dyslexics' category judgments of the misleading phonology of foils is in line with their reading level.

Contrast Comparing Word Homophones that Differ in Baseword Frequency

From the previous study, dyslexic readers made substantially more false positive errors to homophone foils when making categorization judgments, including pseudohomophone foils that are nonwords. In the next study, all the foils were words and the frequency of the base-word was manipulated. That is, for any given homophone foil, such as FEAT, the baseword category exemplar, such as FEET (e.g., PART OF THE HUMAN BODY), was either a high frequency or a low frequency word. Van Orden (1987) found that participants' error rates were affected by baseword frequency, in spite of not having seen any of the actual basewords during the experiment. Word homophone targets with high frequency basewords

produced fewer false positive responses than did targets with low frequency basewords. Ordinary readers can be expected to have better knowledge of high frequency basewords, including knowledge of their correct spellings, and thus are less likely to accept the misspelled homophone foil as the category exemplar.

Skilled readers are commonly thought to develop well-integrated knowledge of frequently encountered words, incorporating the word's sound, spelling and meaning (Ehri, 2005; Perfetti, 1992). Less skilled readers, on the other hand, do not appear to develop well-integrated knowledge to the same extent (Perfetti & Hart, 2002), and spelling knowledge in general is found to be deficient in dyslexic readers of all ages (Berninger et al., 2006; Bruck, 1993; Connolly or Connelly, Campbell, MacLean, & Barnes, 2006; Ehri, 1992; Miles, 1983; Scarborough, 1984). Lacking well-integrated or readily available word knowledge, dyslexic readers would not be expected to show the baseword frequency effect in the categorization task, and therefore they would produce equivalent false positive error rates to homophone foils for high and low frequency basewords. However, if they are only affected by a relative lack of exposure to high frequency words, they would produce a baseword frequency effect comparable to the reading-age matched controls.

METHOD

The method was identical with that of the previous study except that new stimuli were constructed to manipulate baseword frequency. The participants were those from the first study and participated on a different day subsequent to that of the first categorization experiment.

Stimuli—The key targets were 20 word homophone foils and their 20 yoked spelling control foils (see Appendix B). The word homophone foils were chosen to manipulate baseword frequency, such that each pair of yoked word-homophone foils included a foil that was homophonic to a higher frequency baseword with the corresponding yoked foil homophonic to a lower frequency baseword ten of each. High frequency basewords ranged from an estimated frequency per million tokens (Zeno, Ivens, Millard, & Duvvuri, 1995) of 6 to 329 ($M = 113.9$, $SD = 91.9$) and low frequency basewords ranged from 2 to 32 ($M = 10.4$, $SD = 12.7$). Word homophone foils were also controlled for orthographic similarity to basewords between the two groups of homophone foils, and yoked spelling control foils were matched to respective basewords to control for the typically similar spellings of homophone foils and basewords.

RESULTS

False-positive error rates were first entered into separate MANOVAs with subject or item as random variables. For the item analysis, yoked quartets of the word homophone and word spelling control foils of the higher-frequency baseword versus the word homophone and word spelling control foils of the lower-frequency baseword were treated as the repeated measure. For the subject analysis, yoked participant triplets of CA versus dyslexics vs. RA readers were the repeated measure. Each analysis also included the between-group factors of age (child, teen, and adult) and familial versus clinic-based sample, and the repeated-

measure factors of homophone foils versus spelling-control foils versus low and high baseword frequency.

The between-group familial versus clinical sample factor was not statistically reliable either as a main effect or in interactions with other factors. The interaction of homophone versus spelling control foils with age was statistically reliable in both item, $F(4, 106) = 12.99, p < .001$, and subject, $F(4, 170) = 12.23, p < .001$, analyses. And base-word frequency produced a reliable main effect, and a four-way interaction effect with target type, reading group, and age in both subject and item analyses (p 's = .000 and .002). As in our first study, both the clinical and familial samples follow the same overall pattern in each reading group and across age (see Figure 2). The data variation for higher and lower frequency yoked spelling control foils also overlaps in each plot. However, the false-positive error rates to homophone foils were affected by baseword frequency—homophones with lower-frequency basewords elicited higher error rates for all, with the exceptions of dyslexic children and their RA control group.

Subsequent univariate analyses were performed to explore the previous interaction, and to test the main question of interest: whether the dyslexic groups differed from the control groups in terms of their error response rates to homophone versus spelling control targets (the phonology effect) or with respect to basewords that were either higher or lower in frequency. Two separate ANOVAs were run to test for this interaction effect of dyslexics versus controls, homophones versus spelling controls, and higher versus lower baseword frequency: (1) the first ANOVA compared dyslexics with CA controls, (2) the second ANOVA compared dyslexics with RA controls. The familial and clinical samples were combined, because sample was not a predictive factor, but age (child, teen, and adult) was entered into each analysis as a between group factor. Thus, each univariate ANOVA was a 2 (dyslexic versus control) X 3 (child, teen, adult) X 2 (homophone foils versus spelling controls) X 2 (higher versus lower base-word frequency) mixed-design analysis.

Results from ANOVA 1 showed that dyslexic readers overall committed more false-positive errors than CA controls, $F(1,90) = 82.82, p < .001$. The four-way interaction of dyslexic vs. CA controls, age, homophones vs. spelling controls, and base-word frequency was also statistically reliable, $F(2,90) = 8.20, p = .001$. All age groups showed an interaction of reading group by target type (p 's < .001) in which dyslexic readers made proportionally more errors to homophone foils than spelling controls, compared with CA controls. The only interaction effect that included the factor base-word frequency was due to the error pattern of the children: a three-way interaction of reading group by target type by base-word frequency conditions, $F(1,30) = 16.47, p < .001$. Dyslexic children and CA controls had similar false-positive error rates to homophone foils of lower-frequency basewords (each c. 70%), but dyslexics made more false-positive errors to the spelling-control foils associated with lower-frequency basewords (c. 40%), again compared to CA controls (c. 20%).

Results from ANOVA 2 indicated a three-way interaction in which the dyslexic group differed from the RA controls in error rates to homophone vs. spelling control and in the base-word frequency conditions, $F(1,90) = 6.43, p = .013$, across all three age groups. Here, the RA controls showed a slightly larger effect of baseword frequency in their relative error

rates to homophone foil. Interestingly, the dyslexic children also showed elevated error rates to the spelling-control foils compared with the RA group for both lower- and higher-frequency basewords (Means $D = 38$ vs. $RA = 24$, and $D = 35$ vs. $RA = 24$ for low and high frequency spelling-control foils, respectively).

DISCUSSION

As in the first study, dyslexic readers made reliably more false positive errors to homophones compared with the CA controls. The results from this second study also showed that dyslexic readers as a group produced a reliable but weaker effect of baseword frequency compared with nondyslexic controls. On the one hand, the adult and teen dyslexics showed the same pattern of base-word frequency as their control groups, with higher error rates to low frequency homophones, but on the other hand, the dyslexic children did not produce a reliable baseword frequency effect to homophone foils similar to their RA controls. The dyslexic children also made more errors to spelling control foils compared with RA and CA controls. However, all the dyslexic readers produced marked effects of homophone phonology, clearly modulated by baseword frequency in teen and adult performance, and by adulthood the baseword frequency effect produced by dyslexics appears to be at least as large in magnitude as the comparable effects produced by nondyslexic controls.

CONCLUSION

Skilled readers must derive a word's meaning to make a meaning-based judgment of the printed word in the categorization task. The fact that skilled readers commit false-positive errors to homophones demonstrates that semantic category judgments are in some sense constrained by word and nonword phonology (Van Orden, 1987; Van Orden et al., 1988). The present study tested whether reading for meaning is affected by phonology when the readers are individuals with dyslexia. Several hypothetical outcomes were plausible, based on competing theories of dyslexia.

The first hypothesis, that dyslexic readers bypass phonology and directly access meaning of text, predicted that dyslexics would make no more errors when judging homophones than to spelling control foils. To the contrary, results from both studies showed that dyslexics' false-positive error rates are reliably higher to homophone foils compared with spelling control foils. In this respect, the dyslexics' pattern of performance was similar to the nondyslexics' performance of age- and reading-matched controls, and to the performance of skilled readers in prior studies (Van Orden, 1987; Van Orden et al., 1988). Thus, individuals with dyslexia are affected by word and non-word phonology when making semantic categorization judgments. These results were systematically similar to the results produced by control participants across samples and age groups of dyslexics.

The second hypothesis, that dyslexic readers could be affected by the addressed phonology of familiar words but not by the phonology of nonwords, predicted that dyslexics' performance would resemble nondyslexics' performance to word homophone foils but not so when foils were non-word pseudohomophones. This prediction also was disconfirmed. Dyslexics produced the same pattern of errors as nondyslexics to both word homophone

foils and non-word pseudohomophone foils. That is, all groups made more errors to homophone foils relative to yoked spelling controls. This finding indicates that dyslexic readers do derive word-like phonology from non-word pseudohomophones, which misleads the performance of the semantic category judgments.

A third hypothesis that we considered was that while dyslexics may use both addressed and assembled phonology, they would do so less effectively than nondyslexic readers. This led to the prediction that dyslexics could produce more false-positive errors to homophone and pseudohomophone foils (relative to spelling controls), but that the magnitude of the effect would be smaller compared to yoked control participants. All participants produced phonology effects, and the dyslexic readers, overall, produced statistically equivalent or greater phonology effects than controls. Looking at homophone errors by themselves, the adult age-matched controls made far fewer errors to homophone foils.

The fourth hypothesis, that dyslexic and nondyslexic groups would not differ appreciably in performance of the categorization task was, thus, also disconfirmed. Dyslexics did differ from age-matched controls - they committed more false positive errors overall - as well as from reading-matched controls - they showed a weaker baseword frequency effect.

The details of this set of results, taken all together, contradict many of the predictions from models of dyslexia: Dyslexics do not bypass phonology to directly access a lexicon of meaning-based words, nor do they over-rely on lexical knowledge to compensate for deficient phonology. Overreliance on lexical knowledge would have resulted in fewer rather than more false positive errors to pseudohomophones. Yet the dyslexic groups paralleled their age-matched and reading-age-matched controls, with statistically equivalent error-rates to word homophones and non-word pseudohomophones. The findings indicate that the dyslexic groups were processing these stimuli phonologically, in seeming contrast to phonological-deficit models of dyslexia.

Although the present results may not coincide with all the predictions of any theory of dyslexia, none of these models are entirely incorrect. It may yet be true that dyslexics derive insufficiently precise phonology to perform a task requiring explicit phonology. Overt reading aloud of nonwords or a covert silent judgment that a non-word sounds exactly like an actual word, for example, may both require precisely and correctly formulated phonology, which may better reveal deficient phonology. An overt phonology was not required to complete the categorization task, though the false-positive errors to homophone foils are conclusive that this source of constraint was present, imperfect or not. It should be noted that this account may reconcile the apparent disparity shown by this dyslexic sample with poor nonword reading performance (see Study 1 Methods) who, nevertheless, showed strong phonological mediation on the categorization task. That is, for non-words read in isolation (as on the nonword reading pretest), dyslexic readers have no semantic context to support their decoding of the nonwords. In contrast, for the categorization task the preceding category name effectively primes exemplars of the category. Then the target (whether a misspelled homophone or pseudohomophone) can be matched to the primed exemplar's phonology, whereas the spelling controls do not match that phonology. Thus, a meaning-

based context serves to compensate for a decoding deficit, following the findings of Stanovich et al. (1981).

While phonological decoding appears compensated on this task, the intra-lexical verification process appears to reflect a weakness rather than a strength of the dyslexic readers. Adult age-matched controls made far fewer errors to homophone foils possibly through more effective verification of baseword spelling. Models of word recognition have proposed that the stage of verification is characterized by an inhibitory process, which would require extra time to inhibit false positive error responses (Davis et al., 2009, however see Hollis, 2010). In this sense, verification involves a comparison of spellings linked to a common phonology to inhibit the tendency to respond to the activated exemplar meaning. All the dyslexic readers, across a wide age range and from both familial and clinically drawn samples, appeared to make less effective use of verification, suggesting that dyslexia has consequences for the verification process. Similar findings are reported in more transparent languages, for instance, Italian dyslexics also show deficit performance in rejecting phonologically plausible errors (Marinelli, Angelelli, Notarnicola, & Luzzatti, 2009). A problem with this process can also account for their higher error rates to pseudohomophones, which effectively are misspelled words that a dyslexic reader may not detect as a misspelling.

The apparent difficulties for the dyslexics in the present reading task lie with the rejection of homophonic foils in the comparison and/or inhibition of alternative spellings of words' phonology. That is, the apparent problem for correctly rejecting homophonic foils in the categorization task resides with the co-determining links between phonology and the semantics of the exemplar category context versus between phonology and the appropriate spelling for that context. Another study has reported the similar lack of deficit phonology when poor readers perform a priming task, which relies on priming from the phonology of one word to the next (e.g., goat-boat; Betjemann & Keenan, 2008; Keenan & Betjemann, 2008). Ten-year-olds with reading disability produced similar phonological priming effects, compared to age-matched controls, but reduced priming effects by semantic primes (e.g., ship-boat) or semantic/phonological (float-boat) primes in visual and auditory lexical decision tasks.

Previous reports of dyslexics' performance choosing correct spellings in a two-alternative forced choice task also agree with the present finding of weaker spelling verification. In one report, the two alternatives to choose from were two word homophones (e.g., EIGHT, ATE), and the choice was framed as a choice based on meaning (e.g., "which is a number?"; Barker, Torgesen, & Wagner, 1992; Cunningham & Stanovich, 1990; Stanovich & West, 1989). In the other report, a word homophone was paired with a non-word pseudohomophone (e.g., RAIN, RANE; Olson, Kliegl, Davidson, & Folz, 1985). Individuals with dyslexia perform poorly on both these tasks compared to nondyslexics (Curtin, Manis, & Seidenberg, 2001; Gayan & Olson, 2003; Geva & Willows, 1994; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Olson, Wise, Conners, Rack, & Fulker, 1989).

The poorer performance by dyslexics in these published experiments may also indicate a lack of sufficient spelling knowledge of known words on which to base the forced choice, at

the same time that they are misled by the phonology of the word and non-word homophones. Less skilled readers are known to require more exposures to learn a new word's spelling (Ehri & Saltmarsh, 1995; Reitsma, 1983; Share & Shalev, 2004). Taken as a whole, these published results show that dyslexic readers have difficulty identifying correct spellings in a choice between word and non-word homophones without semantic context, and identifying the correctly spelled of a pair of word homophones within a semantic context. The present results with pseudohomophones on the categorization task further indicate that judging non-word homophones within a semantic context is also problematic for individuals with dyslexia. From a developmental perspective, the dyslexic readers did not show the steep decline in the proportion of homophone errors with reading development, as did the age-matched peers in this cross-section of development, which also estimates the dyslexics' capacity for identifying correct spellings. Adult age-matched controls made relatively few errors to homophones and pseudohomophones. Dyslexics, on the other hand, performed more like their reading-level control participants, although dyslexic adults made slightly fewer errors to homophones and pseudohomophones than their reading-level peers.

Models of learning to read assume either self-teaching of orthographic images (Share, 1995; 2008), the fine-tuning of lexical knowledge between similar orthographic images that comes with an increase in the number of known-words (Castles, Datta, Gayan, & Olson, 1999; Castles, Davis, Cavalot, & Forster, 2007), or a consolidation phase in which children increase their sight-word vocabularies because sub-word units of orthography become unitized as lexical knowledge (Ehri, 1995, 2005). Self-taught and stage-based sight word vocabularies both emphasize a buildup of orthographic images through repeated exposure to words. In the contrast of baseword frequency, however, between word-homophone error rates to homophones with higher or lower frequency basewords, dyslexics at all ages produced smaller baseword frequency effects when compared with younger, reading-matched controls. If the dyslexic readers are assumed to have comparable print exposure as their reading-matched controls, this effect suggests a deficit in acquiring the spelling knowledge specific to particular words.

Connectionist models assume that repeated exposure to print strengthens connections between word phonology and word spellings early in reading acquisition, and that word use in context strengthens semantic connections with spelling later in development (e.g., Plaut, 1997). The so-called triangle model, depicted in Fig. 3, illustrates the consequences of this developmental sequence. Phonology and semantic pairings are learned prior to reading in oral language, and the reading network inherits these strong connections (the darker arrow), while structural co-variation across words between word and sub-word phonology and orthography, also grow strong connections in learning to read. Connections between semantic and spelling pairings accumulate more slowly with repeated exposure because morphological and spelling structure, though correlated, are more weakly and inconsistently correlated than spelling and phonology (as depicted by the lightest arrow, e.g., Berninger & Abbott, 1994; Bosman & Van Orden, 1997; Bosman et al., 2006; Van Orden & Goldinger, 1994; Van Orden et al., 1990).

Dyslexics honor this rank order of connection strength in their pattern of false-positive categorization judgments. Stronger connections between spelling and phonology and

between phonology and semantics are effectively forces that favor false-positive errors to homophone foils, and dyslexics' performance suggests that these forces are sufficiently strong to misread ROWS as ROSE, so to speak. The weaker connections between semantics and spelling are implicated in the weaker, and perhaps more vulnerable efficacy of spelling verification by dyslexics.

Likewise, the phonology of a printed word is more transparently derived from its spelling than from its meaning, which implies a more reliable source of priming effects in word phonology than semantics in a lexical decision task (Keenan & Betjeman, 2008). Thus, task requirements may create a view of dyslexic readers' performance that will appear more compensated (or less compensated), due to the less precise constraints that exist on a given side of the triangle model, because the task better (or more poorly) recruits constraints from other sides of the triangle model (compare Farrar, Van Orden, Hamouz, 2001; Gottlob, Goldinger, Stone, & Van Orden, 1999; Van Orden & Kloos, 2005). The present categorization task allows the category judgment to be constrained by knowledge of the relation between spelling and phonology, without requiring perfect knowledge, while at the same time recruiting constraints that come from knowledge of relations between word phonology and semantics—and many dyslexics show a relative strength in listening comprehension compared with reading comprehension. Thus, their strong connections between the phonology and semantics (oral language skills) allowed the dyslexic readers to compensate for weaker phonology to orthography connections, but not for the weakest link of semantic to orthography pairings. Therefore, while exhibiting both nonword decoding and spelling deficiencies, phonological but not orthographic processing may be compensated with semantic context for dyslexic readers.

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Figure 1.
Categorization task errors to word homophones and nonwords pseudohomophones.

Figure 2.

Categorization task errors to word homophone foils for high frequency and low frequency base words.

Figure 3.

Developmental perspective of the triangle model of reading (from Bosman & Van Orden, 1997). Reproduced with permission of Taylor & Francis Group LLC.

TABLE 1

Demographic data, and group means and standard deviations for cognitive and reading measures by children and teens in the dyslexic, reading-age (RA) control, and chronological-age (CA) control groups.

	Children			Teens		
	Dyslexic (<i>n</i> = 35)	RA controls (<i>n</i> = 26)	CA controls (<i>n</i> = 21)	Dyslexic (<i>n</i> = 36)	RA controls (<i>n</i> = 31)	CA controls (<i>n</i> = 20)
Gender (M/F)	32/4	22/3	17/4	27/9	24/7	16/4
Age (years)	9.91 (1.29)	9.04* (1.27)	9.86 (1.15)	14.92 (1.73)	11.32*** (2.66)	14.65 (1.73)
Education (years)	4.43 (1.12)	3.48** (1.16)	4.33 (1.24)	9.31 (1.74)	5.68*** (2.61)	9.00 (1.56)
Verbal IQ	107.29 (13.18)	112.72 (12.72)	121.4*** (8.82)	104.61 (9.55)	113.9*** (9.53)	114.6** (10.79)
Performance IQ	108 (14)	106.2 (11.62)	113 (13.61)	107.64 (9.96)	108.39 (13.44)	112.75 (11.97)
Raven's IQ	112.91 (11.38)	113.8 (8.14)	119.95* (9.52)	105.25 (12.35)	114.94** (9.41)	110.9 (11.42)
Reading Quotient (RQ)	0.79 (0.06)	0.92*** (0.06)	1.10*** (0.12)	0.71 (0.12)	1.01*** (0.13)	1.04*** (0.12)
PIAT Reading Recognition (grade equiv)	3.66 (1.26)	4.06 (1.02)	7.69*** (1.62)	7.69 (2.99)	7.25 (3.01)	11.38*** (1.62)

Note

* $p < .05$,

** $p < .01$,

*** $p < .001$ difference from dyslexic group

Demographic data, and group means and standard deviations for cognitive and reading measures by adults in the familial and clinic samples for dyslexic, reading-age (RA) control, and chronological-age (CA) control groups.

TABLE 2

	Adults					
	Familial Sample			Clinical Sample		
	Dyslexic (<i>n</i> = 15)	RA controls (<i>n</i> = 15)	CA controls (<i>n</i> = 15)	Dyslexic (<i>n</i> = 15)	RA controls (<i>n</i> = 15)	CA controls (<i>n</i> = 15)
Gender (M/F)	9/6	9/6	9/6	11/4	11/4	11/4
Age (years)	25.6 (6.2)	13.2* (2.8)	26.5 (6.2)	30.9 (7.8)	14.3* (2.8)	30.8 (7.6)
Education (years)	13.5 (2.1)	7.8* (3.0)	15.1 (1.6)	15.1 (1.4)	8.9* (3.1)	16.0 (1.0)
Verbal IQ	96.4 (12.4)	113.7* (13)	104.7 (12.5)	89.9 (8.1)	112.1* (10.4)	111.3 (15.7)
Performance IQ	108 (11.5)	118.3 (6.5)	113.3 (9)	112 (10)	116.7 (11.5)	115.3 (6.5)
Raven's IQ	106.6 (12.5)	113.6 (8.5)	116.7* (7.8)	115.7 (7.8)	120.1 (7.1)	116.7 (8.1)
Reading Quotient(RQ)	.67 (.15)	1.01* (.08)	1.04* (.09)	.69 (.15)	1.02* (.10)	1.01* (.07)
PIAT Reading						
Recognition (grade equiv)	8.5 (3.3)	8.6 (3.3)	12.8* (.10)	10.5 (2.5)	9.8 (3.3)	12.7* (0.5)

Note

* *p* < .05 difference from dyslexic group

Appendix A

Category	Homophone Foil	Spelling Control
Words		
A PART OF A BUILDING	SELLER	TELLER
A PART OF A BUILDING	STARE	START
A NON-ALCOHOLIC BEVERAGE	TEE	TEN
A CARPENTER'S TOOL	PLAIN	PLACE
A METAL	STEAL	STEEP
A PART OF A LION'S BODY	TALE	TALK
A FOUR-FOOTED ANIMAL	DEAR	DYER
A BODY OF WATER	SEE	SET
A VEGETABLE	BEATS	BELTS
A FLOWER	ROWS	ROBS
Nonwords		
A VEGETABLE	KARRET	SARRET
A FOUR-FOOTED ANIMAL	SHEAP	SHELP
A TREE	OKE	ONK
A PART OF THE HUMAN BODY	BRANE	BRAFE
AN ARTICLE OF CLOTHING	SHURT	SHART
A PLACE OF CONFINEMENT	JALE	JALK
A VEHICLE	JEAP	JELP
THINGS IN A WOMAN'S PURSE	KEE	KET
A WEATHER PHENOMENON	SLEAT	SLERT
A KITCHEN UTENSIL	BOLE	BOLF

Appendix B

Category	Homophone Foil	Spelling Control
Low Frequency		
A PLACE TO SHOP	MAUL	MULL
A FOUR-FOOTED ANIMAL	DEAR	DYER
PART OF A SHIP	SALE	SOIL
A PART OF A BIKE	BREAK	BRAVE
AN INSECT	FLEE	FLED
A VEGETABLE	BEATS	BELTS
A PART OF A HORSE'S BODY	MAIN	MANY
A WILD ANIMAL	BORE	BORN
A PART OF A DRESS	SEEM	SLAM
A SMALL STREAM	CREAK	CHEEK
High Frequency		
PART OF A HOUSE	HAUL	HAIL
PART OF THE HUMAN BODY	FEAT	FELT
A COLOR	BLEW	BLED
A CARPENTER'S TOOL	PLAIN	PLACE
A FOUR-FOOTED ANIMAL	BARE	BEER
A METAL	STEAL	STEEP
A SERVANT	MADE	MAIL
A PART OF THE HUMAN BODY	HARE	HARP
TYPE OF FOOD	MEET	MELT
A FEATURE OF AN OCEAN SHORE	BEECH	BELCH