The role of word knowledge in error detection: A challenge to the broken-error-monitor account of dyslexia

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The role of word knowledge in error detection: a challenge to the broken error monitor account of dyslexia

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Abstract

Dyslexic children often fail to correct errors while reading aloud, and dyslexic adolescents and adults exhibit lower amplitudes of the error-related negativity (ERN)—the neural response to errors—than typical readers during silent reading. Past researchers therefore suggested that dyslexia may arise from a faulty error detection mechanism that interferes with orthographic learning and text comprehension. An alternative possibility is that comprehension difficulty in dyslexics is primarily a downstream effect of low-quality lexical representations—that is, poor word knowledge. On this view, the attenuated ERN in dyslexics is a byproduct, rather than a source, of underdeveloped orthographic knowledge.

Because the second view implies a direct association of the error response with comprehension skill in populations of all ability levels, the present study evaluates these alternatives through a reanalysis of behavioral and neural data from 31 typical adult readers. If it is true that faulty error processing can manifest as dyslexia, a model in which error detection contributes directly to comprehension should outperform a model in which it does not. ERNs recorded during spelling judgments were used as a measure of error detection aptitude in path analyses of reading comprehension. The data were better fit by a model in which error detection aptitude was a consequence of word knowledge than a model in which it contributed directly to comprehension. The findings challenge the notion that comprehension difficulty in dyslexics is attributable to error processing deficits and are consistent with the hypothesis that comprehension difficulty in dyslexics is partially attributable to low-quality word knowledge.

Keywords Dyslexia · Error monitoring · Lexical quality · Reading comprehension · Spelling judgments

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The error-related negativity, or ERN, is an event-related brain potential that appears within 100 ms of an error commission. It is generated in anterior cingulate cortex (Debener et al., 2005; Herrmann et al., 2004), a prefrontal brain region associated with performance monitoring (Carter et al., 1998). ERN amplitudes and effect sizes have been shown to be smaller for individuals with dyslexia—that is, individuals who struggle with word reading accuracy and fluency—than for typically developing readers. This ERN difference between dyslexics and non-dyslexics has been observed in both children (Horowitz-Kraus, 2011; Horowitz-Kraus & Breznitz, 2013, 2014; Van De Voorde et al., 2010) and adults (Horowitz-Kraus & Breznitz, 2008, 2009, 2011; Horowitz-Kraus, 2011, 2016a).

This association between strength of the error signal and reading difficulties led to the hypothesis that the suite of cognitive deficits implicated in dyslexia could include impaired error monitoring capabilities (Horowitz-Kraus & Breznitz, 2008). Orthographic learning occurs as a reader successfully decodes a word over repeated encounters with it (Share, 1995). Children with dyslexia, however, often fail to correct errors when reading aloud (Breznitz, 1987) and make different errors across encounters with a word (Bar-Kochva et al., 2016). This behavior suggests that they may not monitor their reading performance to the same degree typically reading children do and that orthographic learning is impeded as a result (Horowitz-Kraus, 2016b). The weak error signal observed in individuals with dyslexia is consistent with a theory of dyslexia that has impaired error monitoring as a cause—i.e., a “broken-monitor” leads to poor word knowledge and, possibly, underspecified or inaccurate mental models of texts.

However, there is an alternative perspective on error signals: If learning written word forms has been impeded, as it has in dyslexia, then a weak error signal during word reading is the expected result. Low-quality lexical representations—that is, poor word knowledge—will leave readers unsure as to whether they have committed errors when reading or responding to words, and the ERN will be attenuated as a result (Harris et al., 2014). The ERN, in other words, is a “mirror-of-knowledge,” with weak word knowledge resulting in correspondingly weak ERNs. As Horowitz-Kraus (2012, pp. 126–127) acknowledges, the finding that error monitoring is impaired in poor readers presents a chicken-and-egg dilemma: Do poor readers fail to detect word reading errors because of poor knowledge of word forms (orthography, phonology) and word meanings? Or does poor knowledge of words develop in individuals who have difficulty monitoring errors? And is the cause of the relation between word reading problems (dyslexia) and comprehension problems a direct one or one in which both are caused by faulty error monitoring?

Error-related negativities, word knowledge, and reading comprehension

The ERN effect is the difference in ERN amplitudes for correct responses compared with incorrect responses (Gehring et al., 2000; Luu et al., 2000). Although some studies report only ERN amplitudes on incorrect (error) trials rather than an ERN effect, an ERN is observable following any response, with the magnitude of the deflection reflecting the participant’s level of certainty that he or she has made an error (Pailing & Segalowitz, 2004).¹

¹ An ERN on correct trials is sometimes termed a correct-related negativity, or CRN, but we refer to all response-locked negative deflections in the EEG as ERNs for simplicity.
In basic perceptual tasks there is typically no ERN on correct trials, because a participant is very certain of the correctness or incorrectness of the response. Studies using linguistic tasks, however, often report ERNs on correct trials, reflecting some level of uncertainty in most responses.

ERNs for correct responses are attenuated (less negative) relative to ERNs for incorrect responses (Gehring et al., 2000; Luu et al., 2000). This pattern of results reflects a functioning error monitoring system and is the pattern associated with high levels of knowledge and skill for a given task. When stimuli are nonlinguistic visual symbols (such as arrows) and the task is to discriminate congruent symbols from incongruent ones (as in a flanker task), “high knowledge and skill” describe most individuals with typical vision and motor capabilities. When the stimuli are written words and the task is to discriminate correct from incorrect spellings, the knowledge tapped by the ERN is knowledge of orthographic forms, which varies considerably even among skilled readers. The ERN effect results from the “noticing” of mistaken judgments. For low levels of word knowledge, the ERN effect is diminished, because the reader has lower knowledge of correct spellings, reducing the discrimination between correctly and incorrectly spelled words (Harris et al., 2014). Thus, someone with reading or spelling difficulties can show a diminished ERN effect because of low knowledge.

A reader knowledgeable about a given word understands the full range of its meaning dimensions and has precise orthographic and phonological representations of the word stored in memory. In the framing of the Lexical Quality Hypothesis (Perfetti, 2007, 2017; Perfetti & Hart, 2002), the quality of mental representations of each of the lexical constituents (orthography, phonology, semantics/morphology) of a word’s form and meaning is variable. The aggregate of the constituent quality is the lexical quality. A skilled reader has many words of high lexical quality and many words of low lexical quality. A less-skilled reader has fewer words of high lexical quality than the skilled reader. A downstream consequence of low-quality lexical representations, according to the Lexical Quality Hypothesis and the Reading Systems Framework (Perfetti & Stafura, 2014), is poor reading comprehension. This is because high-quality word knowledge (including phonological specificity and orthographic precision as well as word meaning) supports the fluent identification and meaning retrieval of most words during text reading. This fluency at the word level allows, among other things, the rapid integration of words into the mental model of a text as they are encountered. That lexical quality contributes to comprehension has been supported in a number of recent studies with children (e.g., Richter, Isberner, Maumann, & Neeb, 2013; Segers & Verhoeven, 2016; Swart et al., 2017; Verhoeven et al., 2019).

The orthographic constituent of lexical knowledge has arguably been underappreciated in the discussion of dyslexia. Although the hallmark of dyslexia is a deficit in phonological processing ability, the direct consequence of this deficit, and the ultimate impediment to fluent reading, is underdeveloped orthographic knowledge. Both orthographic and phonological representations of words tend to be of low quality in individuals with dyslexia (e.g., Cao et al., 2006; Georgiou et al., 2021; Swan & Goswami, 1997), resulting in generally weak word knowledge and attendant word identification difficulties. Given the centrality of word knowledge to reading comprehension, underdeveloped word knowledge alone could account for reading comprehension difficulties in many dyslexics. Positing a prominent role for additional cognitive deficits, such as a broken error monitor, is a less parsimonious explanation of the frequent coexistence of word reading and comprehension deficits in individuals with dyslexia than is the “mirror-of-lexical-knowledge” hypothesis. The latter assumes that the ERN mirrors knowledge, not merely error monitoring. If the mirror-of-knowledge account is correct (i.e., poor readers fail to detect word reading errors because
of poor word knowledge), then word knowledge, but not error monitoring itself, directly affects comprehension. If, conversely, the broken-monitor account is correct (i.e., poor word knowledge develops in individuals who have difficulty monitoring errors), then error monitoring and word knowledge each affect comprehension independently.

The ERN: poor error monitoring or low word knowledge?

Although the ERN effect can be diminished in tasks with word stimuli as a result of low word knowledge (Harris et al., 2014), a diminished ERN following a response to a written word can be interpreted either as a problem in error monitoring or as arising from low-quality word form knowledge. Two studies that did not use word stimuli—one used a Sternberg working memory task that employed digit stimuli (Horowitz-Kraus & Breznitz, 2009) and one used a go/no-go attention-control task that employed triangle stimuli (Van De Voorde et al., 2010)—reported reduced ERNs in readers with dyslexia compared to typical readers. A third study that did not use word stimuli—the task required participants to discriminate the letters X and O—found no difference in ERN amplitude to incorrect responses between dyslexic and non-dyslexic participants, but found that participants without a learning disability had a marginally less negative ERN to correct responses than participants with both a reading and math disability (Burgio-Murphy et al., 2007). Although these studies appear to offer some support for the conclusion that individuals with dyslexia suffer from a general impairment in error monitoring, it is possible to question the assumption that these nonlinguistic tasks do not engage language resources or the processes in reading that rely on these resources (including memory and attention). The Sternberg task employed by Horowitz-Kraus and Breznitz (2009), for example, requires participants to determine whether a number probe appeared in a series of previously presented digits. Such a memory depends on the retention and retrieval of language-like symbols as well as rehearsal, which relies on implicit speech processes.

Finally, if dyslexia has multiple causes, as is increasingly recognized, problems in visual attention, visual memory, and rapid memory retrieval could also underlie performance on nonlinguistic tasks among a sample of dyslexics (McGrath et al., 2020; Perfetti & Harris, 2019). Diminished ERNs in the Sternberg task, for instance, are as likely to reflect memory limitations as they are error monitoring limitations. Nevertheless, we acknowledge that executive function deficits may be part of the dyslexic profile. However, we question generally whether they are a core deficit or part of a cognitive profile that emerges from other causes. More specifically, we question whether ERN evidence is support for error monitoring as the causal link between word reading problems (dyslexia) and reading comprehension problems.

The ERN: evidence for the “mirror-of-knowledge” view of error monitoring in low reading ability

The hypothesis that low lexical quality rather than impaired error monitoring explains the reduced ERNs among low-ability readers has support in other event-related potential (ERP) studies. For instance, the ERN effect was found to correlate with experimental performance on a spelling judgment task, as well as offline measures of spelling, vocabulary and (in Experiment 1) reading comprehension within a sample of adult typical readers.
(Harris et al., 2014). Important in this study is the range of reading skill in the sample. The between-subjects design of dyslexia studies does not allow the discovery that the strength of the ERN tracks word knowledge. The correlation of the ERN with offline individual differences in spelling and vocabulary is consistent with the Lexical Quality Hypothesis, which assumes that, although readers of all skill levels have both high- and low-quality lexical representations for words in their lexicon, a less-skilled reader has fewer high-quality representations than a more-skilled reader. The Lexical Quality Hypothesis also predicts that the average quality of lexical representations, and the number of high-quality representations, increases as reading experience accumulates, which is consistent with cross-sectional developmental research that has found stronger ERNs in older participants (Heldmann et al., 2017; Horowitz-Kraus, 2011).

The ERN effect itself, reported in Harris et al. (2014) and some ERP studies of error monitoring during reading (e.g., Horowitz-Kraus & Breznitz, 2008; Van De Voorde et al., 2010), could be viewed as evidence that the error signal during reading tasks reflects word knowledge. The ERN effect observed in Harris et al. (2014) is consistent with the existence of a continuum of error monitoring system functionality within the population of typical adult readers; but it is also consistent with the continuum of word knowledge predicted by the Lexical Quality Hypothesis and supported in a number of other studies (e.g., Hersch & Andrews, 2012; O’Connor et al., 2019; Rossi, Martin-Chang, & Ouellette, 2018). That an ERN effect was found and correlated with reading ability in typical adult readers makes plausible the mirror-of-knowledge account of the ERN—that it reflects word knowledge and that word knowledge, not error monitoring, is the main link to comprehension.2

Finally, we emphasize the congruence of the mirror-of-knowledge hypothesis with leading theories of the ERN, which depict the process of error monitoring as an emergent property of knowledge. On the “mismatch hypothesis,” the ERN reflects a comparison between the incorrect, executed response and the correct, not-executed response (Gehring et al., 1993). On the “conflict-monitoring hypothesis,” the ERN reflects the degree of conflict between alternative responses (Yeung et al., 2004). Both hypotheses implicate word knowledge for provoking an ERN in decisions about words. For an ERN to indicate conflict between competing answers requires knowledge of plausible responses (i.e., broad lexical knowledge); for an ERN to indicate a mismatch between the correct and executed response requires knowledge of what was the correct response to execute (i.e., knowledge of the specific word form presented). Neither hypothesis appears to allow that the error signal itself can be faulty.

The present study

One way of adjudicating between the broken-monitor and mirror-of-knowledge accounts is to test which of two models better captures ERN results: (1) a model in which word knowledge, but not error monitoring itself, directly affects comprehension or (2) a model in which error monitoring and word knowledge each affect comprehension independently. We can compare these models for typical adult skilled readers using the results of Harris et al. (2014), which showed that reading ability was associated with ERN magnitude within the population of

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2 One study that uses a linguistic task to elicit the ERN is difficult to situate in this review of the literature. Balass, Halderman, Benau, and Perfetti (2016) recorded ERNs during semantic categorization rather than word reading per se. Moreover, although they discovered some associations of the ERN with reading-related individual differences, these were not consistent across the board.
skilled adult readers. These results are evidence against a strong version of the broken-monitor view, in which the error signal is present in typically developing readers and absent in dyslexics. Still tenable, however, is a weak version of the broken-monitor view, in which dyslexia represents the lower end of a distribution of error monitoring system functionality. Although error monitoring and comprehension in children with dyslexia needs to be studied directly, our data from typically developing college-age participants can contribute valuable information to this debate. These data can address the question of whether the ERN contributes to comprehension beyond what is contributed by word knowledge to an equal extent across all populations, beginning with a sample of typical adults of varying skill. If a model that includes error monitoring (in addition to word knowledge) predicts comprehension better than a model that has only word knowledge, that would suggest a specific role for monitoring differences in explaining comprehension skill. To test this, we use path analysis to model the broken-monitor and mirror-of-knowledge accounts of dyslexia, using ERNs recorded during spelling judgments in skilled adult readers as an indicator of error monitoring. The data, originally collected for other purposes (Harris et al., 2014), are repurposed here to examine the relationship between error monitoring and reading comprehension.

Method

The Harris et al. (2014) study comprised two experiments in which ERNs were recorded, the first of which included 15 participants and the second of which included 24 participants. Although individual stimuli differed between the two experiments, both required participants to judge the spellings of approximately 830 English words, half of which were correctly spelled and half of which were misspelled. Data from the two experiments were thus combined for the present analyses. We used a path analysis rather than a mediation analysis approach because our question was not whether the relation between error monitoring and reading comprehension is mediated by word knowledge (or whether the relation between word knowledge and reading comprehension is mediated by error monitoring). Rather, we were interested in whether our data were better fit by a model in which (1) error monitoring and word knowledge affect comprehension or (2) word knowledge alone affects comprehension.

Participants

Participants in this study represent 31 of the 39 participants across the two experiments in the Harris et al. (2014) study. Three of the original 39 had fewer than 80% of their ERP segments remaining after artifact detection; one had too few trials remaining after artifact detection; and four had fewer than 16 miss trials (incorrect responses to correctly spelled words). All were right-handed, native speakers of English who had never received a diagnosis of a reading disorder. Participants received financial compensation.

Measures

Offline measures

Five measurements from the battery of reading-related assessments completed prior to the experiments contributed to constructs in our models. These included an orthographically
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Based test of phonological analysis (PhAT); an orthographically based pseudohomophone recognition test (real word test [RWT]), which included items from Olson et al. (1989); the Nelson-Denny comprehension test (Nelson & Denny, 1973), Form E (Brown et al., 1981) with a 15-min time limit; the vocabulary portion of the Nelson-Denny reading test (Brown et al., 1981) with a 7.5-min time limit; and a recognition spelling test, with items adapted from Olson et al. (1989) and with the addition of more difficult items, some of which were obtained from the Baroff Spelling Test (Perfetti & Hart, 2002). One participant did not complete the PhAT, so n = 30 for models that use the PhAT as the proxy for phonological knowledge. We provide the PhAT, RWT, and spelling test in the supplementary materials.

Online measures

Two online electrophysiological measures were used as proxies for the error response. These were ERN amplitude (ErrorTrials, the adaptive mean ERN amplitude on incorrect trials) and ERN effect (CorminusErrorTrials, the adaptive mean ERN amplitude on incorrect trials less the adaptive mean ERN amplitude on correct trials). We also used experimental d’ (Exptdprime) as a measure of signal sensitivity; in this case, indicating the ability to discriminate correctly spelled versus misspelled words.

Procedure

Each participant viewed approximately 830 English words of five to ten letters, half of which were misspelled and half of which were correctly spelled. Items were counterbalanced so that the misspelled version of each item was seen by approximately half of participants. A 20-trial practice block familiarized participants with the procedure. Items were presented at the center of a computer screen in a random order, using E-Prime (Psychology Software Tools, Pittsburgh, PA) software. Subjects were instructed to hit one key if the word they saw was spelled correctly and another key if it was spelled incorrectly. Each trial began with a white fixation cross appearing in the center of a black screen, which was replaced after 500 ms by the stimulus, also in white. The stimulus remained on screen for 350 ms and was followed by an empty black screen for 1150 ms. Participants could respond any time during this 1500-ms interval, after which point a randomized (150–400 ms) interstimulus interval was initiated. If subjects failed to hit a key within 1500 ms, a “Too late!” message appeared in red.

ERP data acquisition and preprocessing

Participants were fitted with a Geodesic Sensor Net with a 128 Ag/AgCl electrode array, and data were recorded and preprocessed using associated NetStation acquisition software (Electrical Geodesics, Inc., Eugene, OR). Scalp potentials were recorded with a sampling rate of 250 Hz and a hardware bandpass filter of 0.1–200 Hz, with impedances below a threshold of 40 kΩ, a conservative value for dense-array high-impedance electrode arrays (Junghofer, Elbert, Tucker, & Rockstroh, 2000).

Offline, trials were segmented into 700-ms epochs, starting 200 ms before response onset. Segmented data were digitally filtered with a 30-Hz lowpass filter. Bad channels were removed from the recordings and replaced via interpolation of data from surrounding channels, with data re-referenced to the average of the recording sites. (A channel was considered bad if it was contaminated by artifacts in more than 15% of trials; the number of
bad channels for the 31 participants included in analyses ranged from zero to 12, and averaged 3.8.) Finally, the ERP segments were corrected relative to a 125-ms baseline ending 75 ms before the response. Electrodes used in statistical analyses correspond to the international 10–20 system electrode FCz (electrode 6) and a cluster of six electrodes surrounding FCz. Data from this cluster, which is the main site of an ERN, was averaged for analyses. An adaptive mean amplitude for each participant, defined as the average amplitude for the ERN cluster from ±50 ms around the peak negativity that occurred between 25 ms pre-response and 75 ms post-response, was used for the ERN measures in the present analyses.

Data analytic approach

The *sem* command built into Stata/SE (15.1) (StataCorp, 2017) was used for path analysis to fit the two theoretical models (described below) to the data and compare the non-nested
models. Figure 1 represents the two general models, with panel A representing the broken-monitor model and panel B representing the mirror-of-knowledge model. The latent constructs are in bold, and the available proxies are in italics below.

Ideally, we would have used the multiple measures of orthographic knowledge, phonological knowledge, and error monitoring to first conduct confirmatory factor analyses and then include latent constructs in our models. However, the confirmatory factor analysis and models including latent constructs did not converge. We therefore leveraged our variables by running eight different models for each path diagram (Figs. 1a and b) representing all combinations of the three constructs for which we had multiple measures.

**Broken-monitor model construction**

The view first proposed by Horowitz-Kraus and Breznitz (2008) that deficits in error monitoring and orthographic knowledge are reciprocally related is presented in Fig. 1A—poor error monitoring disrupts the formation of high-quality orthographic representations, which in turn allows word identification errors to pass “under the radar” of the error monitoring system. Horowitz-Kraus and Breznitz (2008) do not comment on whether phonological representations should be similarly affected by poor error monitoring. However, because the mirror-of-knowledge model assumes a relationship between the error signal and phonological knowledge, a reciprocal path between those measures is included so the two models differ only in the pathways of primary interest.

Error monitoring also contributes directly to comprehension in this model because the same deficient monitor that prevented orthographic learning also disrupts comprehension monitoring. The broken-monitor view is consistent with the assumption that orthographic, phonological, and vocabulary knowledge independently contribute to reading comprehension (e.g., Leppänen et al., 2008; Muter et al., 2004; Richter et al., 2013; Ricketts et al., 2007), and these pathways are therefore incorporated into the model.

**Mirror-of-knowledge model construction**

This model (Fig. 1B) includes the same measures as the broken-monitor model, but with three of its pathways removed. First, reciprocity between the error signal and lexical knowledge is not assumed, so the paths from the error signal to orthographic and phonological knowledge are not included. This is because the monitor itself is not assumed to be broken, so it does not have an active role in the formation of lexical representations.

Additionally, the error signal does not influence comprehension in this model. If the error signal is merely a reflection of knowledge, then there is no “broken-monitor” to interfere with comprehension monitoring. Thus, any association between strength of the error signal while reading the words in a particular text and comprehension of that text arises from the status of lexical knowledge as a common source of both error signal strength and comprehension skill, consistent with the Reading Systems Framework (Perfetti & Stafura, 2014).
Results

Electrophysiological results

Figure 2 displays the grand average ERN to correct and incorrect responses during the spelling judgment task. A clear deflection in the waveforms of both correct and incorrect responses begins approximately 100 ms before the response (recorded at 0 ms) and peaks approximately 25 ms following the response. The ERN effect was significant, with the mean amplitude of correct trials more positive than that of incorrect trials, $F(1, 14) = 5.65, p < 0.05$.

Path analysis results

Descriptive statistics and associations among the variables are given in Tables 1 and 2. We included all combinations of the three constructs with multiple measures (orthographic knowledge, phonological knowledge, and error monitoring) as well as one model in which all variables were included. Tables 3 and 4 present the various combinations for the broken-monitor model and the mirror-of-knowledge model, respectively. Given our small sample sizes ($n = 30$ or 31), the results should be considered exploratory and interpreted as such.

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3 Deflection begins prior to the moment the response is recorded because uncertainty can arise as soon as a motor sequence is initiated. In addition, use of a keyboard rather than a serial response box delays recording of the response by approximately 25 ms.

4 The models with all variables included are not presented as they fit the data worse than the other eight models.
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The results for the path analysis for the broken-monitor hypothesis are presented in Table 3. Each column in Table 3 represents a different specification of the path analysis model predicting reading comprehension using various combinations of the variables measuring lexical knowledge (orthographic, phonological, and vocabulary) and the error monitoring system. The coefficient estimates and their associated \( p \) values are presented in the top panel; model fit indices are presented in the bottom panel. The broken-monitor model hypothesizes that a weak error monitoring system would negatively impact reading comprehension directly as well as indirectly through orthographic

### Table 1 Descriptive statistics for online and offline measures of reading-related skills

<table>
<thead>
<tr>
<th>Measure</th>
<th>N</th>
<th>Mean</th>
<th>Std. Dev</th>
<th>Min</th>
<th>Max</th>
</tr>
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<tbody>
<tr>
<td>Nelson-Denny comprehension composite score</td>
<td>31</td>
<td>21.019</td>
<td>7.226</td>
<td>0</td>
<td>33.6</td>
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<tr>
<td>Accuracy on the PhAT</td>
<td>30</td>
<td>0.776</td>
<td>0.186</td>
<td>0.272</td>
<td>1</td>
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<tr>
<td>(d') for the RWT</td>
<td>31</td>
<td>2.226</td>
<td>0.891</td>
<td>0.53</td>
<td>4.57</td>
</tr>
<tr>
<td>Experimental (d')</td>
<td>31</td>
<td>1.936</td>
<td>0.496</td>
<td>1.064</td>
<td>2.927</td>
</tr>
<tr>
<td>(d') on the offline spelling assessment</td>
<td>31</td>
<td>2.309</td>
<td>0.387</td>
<td>1.724</td>
<td>3.264</td>
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<tr>
<td>ERN Effect</td>
<td>31</td>
<td>442.774</td>
<td>136.982</td>
<td>158</td>
<td>678</td>
</tr>
<tr>
<td>ERN amplitude</td>
<td>31</td>
<td>118.452</td>
<td>47.567</td>
<td>37</td>
<td>204</td>
</tr>
<tr>
<td>Nelson-Denny vocabulary composite score</td>
<td>31</td>
<td>49.523</td>
<td>18.844</td>
<td>6.4</td>
<td>95.2</td>
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</table>

### Table 2 Pearson correlations between measures of reading-related skills

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<tr>
<th>NDcompscore</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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</thead>
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<tr>
<td>PhATaccuracy</td>
<td>0.0561</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>RWT-dprime</td>
<td>-0.0989</td>
<td>0.4478**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Expt-dprime</td>
<td>0.2354</td>
<td>0.5228***</td>
<td>0.4464**</td>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>speldprime</td>
<td>0.1314</td>
<td>0.5577***</td>
<td>0.4987***</td>
<td>0.5977***</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CorminusErrorTrials</td>
<td>0.2061</td>
<td>0.5418***</td>
<td>0.3948**</td>
<td>0.7738***</td>
<td>0.4945***</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ErrorTrials</td>
<td>-0.2343</td>
<td>-0.4314***</td>
<td>-0.3247</td>
<td>-0.8671***</td>
<td>-0.4609***</td>
<td>-0.4300**</td>
<td>1</td>
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<tr>
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<td>0.2383</td>
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<td>0.4618***</td>
<td>0.3415*</td>
<td>0.4332**</td>
<td>-0.3859**</td>
<td>1</td>
</tr>
</tbody>
</table>

*p < .10; **p < .05; ***p < .01

NDcompscore Nelson-Denny comprehension composite score, PhATaccuracy accuracy on the PhAT, RWT-dprime \(d'\) for the RWT, Expt-dprime experimental \(d'\), speldprime \(d'\) on the offline spelling assessment, CorminusErrorTrials ERN effect, ErrorTrials ERN amplitude, voccompscore Nelson-Denny vocabulary composite score

**Broken-monitor model fit estimates**

The results for the path analysis for the broken-monitor hypothesis are presented in Table 3. Each column in Table 3 represents a different specification of the path analysis model predicting reading comprehension using various combinations of the variables measuring lexical knowledge (orthographic, phonological, and vocabulary) and the error monitoring system. The coefficient estimates and their associated \( p \) values are presented in the top panel; model fit indices are presented in the bottom panel. The broken-monitor model hypothesizes that a weak error monitoring system would negatively impact reading comprehension directly as well as indirectly through orthographic
Table 3  SEM estimates and model fit statistics for the broken-monitor hypothesis

<table>
<thead>
<tr>
<th>Reading comprehension</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
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<th>(6)</th>
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<tbody>
<tr>
<td><strong>Phonological knowledge proxy</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Phonological awareness test</td>
<td>-2.343</td>
<td>-3.154</td>
<td>-2.064</td>
<td>-3.859</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<td>(PhATaccuracy)</td>
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<td>(5.837)</td>
<td>(5.676)</td>
<td>-</td>
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<tr>
<td>d’ for the real world test</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-2.558**</td>
<td>-2.526*</td>
<td>-2.588*</td>
<td>-2.659**</td>
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<td>(RWTdprime)</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>(9.87)</td>
<td>(9.92)</td>
<td>(1.035)</td>
<td>(1.026)</td>
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<tr>
<td>Experimental d’</td>
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<td>-3.565</td>
<td>-</td>
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<td>0.566</td>
<td>-1.241</td>
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<td>(3.688)</td>
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<td>d’ on offline spelling assessment</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>(Speldprime)</td>
<td>-</td>
<td>-</td>
<td>(2.762)</td>
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<td>(2.531)</td>
<td>(2.530)</td>
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<td>Nelson-Denny vocabulary score</td>
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<td>0.325***</td>
<td>0.330***</td>
<td>0.314***</td>
<td>0.317***</td>
<td>0.316***</td>
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<td>0.002</td>
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<td>(ErrorTrials)</td>
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<td>(.035)</td>
<td>-</td>
<td>(.021)</td>
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<td>(.033)</td>
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<td>(.019)</td>
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<tr>
<td>n</td>
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<td>30</td>
<td>31</td>
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<td><strong>Fit indices</strong></td>
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<td>0.000</td>
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<td>0.000</td>
<td>0.000</td>
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<tr>
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<td>AIC</td>
<td>834.583</td>
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<td>BIC</td>
<td>862.607</td>
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<td>987.451</td>
<td>907.068</td>
<td>989.595</td>
<td>926.984</td>
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</table>

Each column represents a unique path analysis model testing the broken-monitor hypothesis by using the available proxies for lexical knowledge and the error monitoring system. All combinations of variables are included using one measure for each construct (variable names are in parentheses). The top panel presents the estimates for the relationship of reading comprehension (measured by the Nelson-Denny vocabulary composite score) with phonological, orthographic, and vocabulary knowledge as well as the error monitoring system (the path diagram in Fig. 1a). Robust standard errors for all estimates are in parentheses. The bottom panel presents goodness of fit indices for each path analysis model. *p < .05; **p < .01; ***p < .001
knowledge. Generally, the modeling results suggest that the data from this sample do not support the broken-monitor hypothesis model. No statistically significant relationship exists between either measure of the error monitor ($CorminusErrorTrials; ErrorTrials$) and reading comprehension. The offline measure of vocabulary ($voccompscore$) consistently reached statistical significance for a positive relationship with reading comprehension across all 8 models suggesting a relatively robust relationship between higher vocabulary knowledge and higher reading comprehension scores. The only other measure reaching statistical significance was the phonological knowledge variable $RWTdprime$. Neither measure of orthographic knowledge ($Exptdprime; speldprime$) reached statistical significance. The reported chi-square tests all indicate poor model fit but should be interpreted cautiously given the small sample size (e.g., Kline, 1998).

**Mirror-of-knowledge model fit estimates**

The results of the path analysis of the mirror-of-knowledge model are presented in Table 4; once again, each column represents a different specification of the underlying mirror-of-knowledge model. The top panel presents the results for how phonological and orthographic knowledge relate to the measures of the error monitor system. The middle panel of Table 4 shows the relationship between our three measures of lexical knowledge (orthographic, phonological, and vocabulary) and reading comprehension. The bottom panel presents the fit indices—measures of how well the models fit the underlying data.

The top panel of Table 4 displays the relationship between the error monitoring system and both orthographic and phonological knowledge. On the one hand, the results suggest that neither measure of phonological knowledge was consistently related to either ERN effect or the ERN amplitude. On the other hand, the online measure of orthographic knowledge ($Exptdprime$) was consistently and statistically significantly associated with the ERN effect and amplitude in the predicted directions. Additionally, the offline measure of orthographic knowledge ($speldprime$) was marginally significant in Models 7 and 8. Taken together, there is some evidence the error response may reflect orthographic knowledge. To examine the second prediction of this hypothesis, the bottom panel of Table 4 shows that both the phonological knowledge variable $RWTdprime$ and the measure of vocabulary knowledge were consistently related to reading comprehension, consistent with the mirror-of-knowledge hypothesis. The reported chi-square tests all indicate good model fit, except Model 3. Again, these should be interpreted cautiously given the small sample size.

**Discussion**

The aim of this study was to operationalize, through path analysis of data collected during a spelling decision task, alternative interpretations of ERN effects elicited during word reading tasks in skilled adult readers. In what we have termed the “mirror-of-knowledge” model, word knowledge, but not error monitoring itself, directly affects comprehension. In what we have termed the “broken-monitor” model, error monitoring and word knowledge each affect comprehension independently. Vocabulary and one measure of phonological knowledge ($RWTdprime$) emerged as key predictors of reading comprehension in the broken-monitor model, but orthographic knowledge and the ERN proxies did not. This pattern is inconsistent with the notion that a weak error monitoring system leads to reading comprehension difficulty both directly and indirectly, through orthographic knowledge—the
Table 4  SEM estimates and model fit statistics for the mirror-of-knowledge hypothesis

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
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<td>Phonological awareness test</td>
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<td>273.788*</td>
<td>-64.168</td>
<td>-</td>
<td>-</td>
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<tr>
<td>(PhAT accuracy)</td>
<td>(97.114)</td>
<td>(27.678)</td>
<td>(131.028)</td>
<td>(49.107)</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.479</td>
<td>4.156</td>
<td>30.325</td>
<td>-6.744</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(19.478)</td>
<td>(5.289)</td>
<td>(27.156)</td>
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<tr>
<td>Experimental $d'$</td>
<td>187.224***</td>
<td>-84.734***</td>
<td>-</td>
<td>-</td>
<td>206.273***</td>
<td>-86.550***</td>
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<tr>
<td>(Exptdprime)</td>
<td>(35.881)</td>
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<td>-</td>
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<td>(35.01)</td>
<td>(9.506)</td>
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<tr>
<td>$d'$ on offline spelling assessment</td>
<td>-</td>
<td>-</td>
<td>111.523</td>
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<td>-</td>
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<td>-48.857*</td>
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<tr>
<td>ERN effect</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>(CorminusErrorTrials)</td>
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<tr>
<td>ERN amplitude</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>Phonological awareness test</td>
<td>-3.336</td>
<td>-3.336</td>
<td>-3.997</td>
<td>-3.997</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>(PhAT accuracy)</td>
<td>(5.345)</td>
<td>(5.345)</td>
<td>(5.538)</td>
<td>(5.538)</td>
<td>-</td>
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<tr>
<td>$d'$ for the real world test</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-2.583**</td>
<td>-2.583***</td>
<td>-2.641**</td>
<td>-2.641**</td>
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<td>(1.022)</td>
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<td>Experimental $d'$</td>
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<td>-1.592</td>
<td>-</td>
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<td>(Exptdprime)</td>
<td>(2.172)</td>
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<td>-</td>
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<td>(2.719)</td>
<td>-</td>
<td>-</td>
<td>(2.408)</td>
<td>(2.408)</td>
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</table>
Each column represents a unique path analysis model testing the mirror-of-knowledge hypothesis using the available proxies for lexical knowledge the error monitoring system, and reading comprehension. The paths leading to the error monitoring system and reading comprehension in Fig. 1b are presented in the top and middle panels. The top panel presents the estimates for the relationship between phonological and orthographic knowledge with the error response system (the top path in Fig. 1b). The outcome for the error response system used in each path analysis model is indicated with an “X” at the bottom of the top panel. The middle panel presents the estimates for the relationship of phonological, orthographic, and vocabulary knowledge with reading comprehension (the bottom path in Fig. 1b). Robust standard errors for all estimates are in parentheses. All combinations of variables are included using one measure for each construct (variable names are in parentheses) in Models (1) through (8). The bottom panel presents goodness of fit indices for each path analysis model. *p < .05; **p < .01; ***p < .001
central tenet of the broken-monitor hypothesis. In the mirror-of-knowledge model, as in the
broken-monitor model, RWTdprime and vocabulary, but not orthographic knowledge, were
significant predictors of reading comprehension. Orthographic knowledge was, however, a
significant predictor of the ERN proxies in the mirror-of-knowledge model. This relation-
ship between orthographic knowledge and the ERN suggests that the ERN reflects reader
knowledge of orthographic forms, a key assertion of the mirror-of-knowledge hypothesis.

As for the fit of the models, only the mirror-of-knowledge model fit the data signifi-
cantly better than a baseline model, as indicated by the $p > \chi^2$ value ranging from 0.203
to 0.910 for 7 out of 8 of the mirror-of-knowledge models (Model 5 had a value of 0.081),
versus a $p > \chi^2$ value consistently of 0 for the broken-monitor model. Additionally, the
lower Akaike information criterion (AIC) and Bayesian information criterion (BIC) val-
ues for the mirror-of-knowledge model indicate that it is preferred over the broken-monitor
model. Simply put, the data were better fit by a model in which error detection aptitude is
a consequence of word knowledge than a model in which it contributes directly to compre-
hension. Given the small and relatively homogenous sample of the original experiment,
however, further research is needed to verify that the pattern of results is robust.

The relative success of the mirror-of-knowledge model converges with other lines of
evidence suggesting that the attenuated ERN in dyslexics is a byproduct, rather than a
source, of underdeveloped orthographic knowledge, e.g., the correlation of the ERN effect
with spelling measures in skilled adult readers and increases in ERN strength with increas-
ing age in developmental research (Harris et al., 2014; Heldmann et al., 2017; Horowitz-
Kraus, 2011). It is also consistent with the Lexical Quality Hypothesis and the mismatch
and conflict-monitoring hypotheses of the ERN. These considerations suggest that the
executive function problems observed in individuals with dyslexia—including the few
studies that found an attenuated ERN in dyslexics during nonlinguistic tasks—may be a
result of dyslexia rather than a cause.

**Implications for understanding developing readers and dyslexia**

The relatively poor fit of the broken-monitor model compared to the mirror-of-knowledge
model in predicting comprehension skill in adult readers without dyslexia presents a chal-
lenge to the notion that a faulty error signal in children with dyslexia is a source of compre-
hension difficulties in a subset of that population. The assumption behind this challenge is
that the error monitoring system contributes directly to comprehension, above and beyond
word knowledge; i.e., this contribution is a property of the reading systems and thus applies
to all populations. On this assumption, broken error monitors lead to poor comprehension,
and intact error monitors lead to skilled comprehension. The broken-monitor model can be
saved by rejecting that assumption, instead assuming that the relationship between error
monitoring and comprehension is direct only for dyslexic readers. This assumption seems
implausible, given the fundamental problem dyslexics have with word reading, which pro-
vides a direct link to downstream problems in comprehension.

However, the more specific issue about drawing conclusions from ERN data needs
more research with larger samples of individuals with dyslexia using a variety of cognitive
tasks, as is longitudinal research that tracks the development of error monitoring and read-
ing ability over time. If such studies reveal that atypical cognitive processing patterns in
individuals with reading difficulties are indeed a result rather than a cause of the difficulty
(as the current findings suggest), it would follow that interventions for dyslexic children
should be knowledge rather than process-focused. That is, building strong orthographic,
phonological, and semantic representations should lead to increases in reading speed, fluency, and error detection, rather than the other way around. An intervention that supports lexical quality development might, in fact, incorporate error detection—not because it fixes something that is malfunctioning, but because it provides on-time word knowledge feedback. We suspect that a focus on knowledge development will lead to improved word reading and mitigate comprehension difficulties in all children and in children with dyslexia in particular.

Conclusion

The primary shortcomings with our dataset include its relatively small size, which left our analyses underpowered, and the fact that the individual differences measures collected during the study were not selected with the present research question in mind. Additionally, although orthographic learning is ongoing and lexical representations continue to be refined throughout adulthood, a large amount of orthographic learning had taken place prior to this study for our sample of college-age participants. Research with younger participants would allow models to be compared during a period when lexical representations are more actively being developed. Despite these limitations, our findings contribute valuable information to the discussion of the role of executive functions broadly, and error monitoring specifically, in reading. Although our findings do not directly address the comprehension difficulties of children with dyslexia, they establish a challenge to the idea that deficiencies in the error monitoring system are a cause of these difficulties and draw attention to the importance of word knowledge both in the error detection task and in comprehension. The inability of a model in which error monitoring contributes directly to comprehension to perform as well as a model in which it does not suggests the error monitoring system is only as effective as the knowledge available to it.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11881-021-00248-8.

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Declarations

Conflict of interest The authors declare no competing interests.

References

attention-deficit hyperactivity disorder, oppositional defiant disorder, reading disorder, and math disorder. *Biological Psychology, 75*(1), 75–86.


The role of word knowledge in error detection: a challenge to…


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