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Adult dyslexic readers do not demonstrate regularity effects in sentence processing: evidence from eye-movements

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Abstract We report an eye-movement study that demonstrates differences in regularity effects between adult developmental dyslexic and control non-impaired readers, in contrast to findings from a large number of word recognition studies (see G. Brown, 1997). For low frequency words, controls showed an advantage for Regular items, in which grapheme-to-phoneme strategies could be employed, compared with Irregular Consistent and Inconsistent items, in which rime comparisons or whole word recognition strategies would be advantageous. We propose that in sentential contexts, dyslexic readers do not generate sufficient phonological cues in the parafovea in order to demonstrate the regularity effects typical of unimpaired readers (e.g., S. Sereno & K. Rayner, 2000). These findings suggest that phonological strategies are sensitive to task demands, and underline the impact of methodology on the conclusions that are drawn about dyslexic reading ability.

Keywords Eye-tracking · Dyslexia · Regularity

It is well established that an important characteristic of developmental dyslexia is impaired phonological decoding, whereby segmenting the speech sounds of written words is problematic (Snowling, 2000). However, a number of studies using lexical decision and naming paradigms have demonstrated regularity effects, suggesting that dyslexic readers are surprisingly sensitive to the intrinsic phonological structure of words (e.g., Brown, 1997; Seidenberg, Bruck, Fornalarolo, & Backman, 1985; Stanovich & Siegel, 1994). Here, we investigate whether a phonological influence on word recognition can be found in naturalistic reading: Are dyslexic readers generally sensitive to word regularity, or are existing findings influenced by the demands of lexically based tasks?

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Regularity refers to the availability of a direct grapheme-to-phoneme mapping from the orthographic to the phonological representation of a word. For the competent reader, sounding out regular words is relatively straightforward using such a mapping. For irregular words, however, generating a phonological response via one-to-one correspondence between graphemes and phonemes is not possible and whole word recognition or phonological chunking strategies are employed (Brown, 1997). A regularity effect emerges during the acquisition of literacy skills such that competent readers soon show facilitated reading for regularly spelled words compared to irregularly spelled words (Masterson, Laxon, & Stuart, 1992). This effect tends to manifest itself as a frequency-by-regularity interaction: a processing advantage for regularity is only observed for low frequency words, when phonological processing is most necessary (e.g., Baron & Strawson, 1976; Hino & Lupker, 2000; Inhoff & Topolski, 1994).

A robust regularity effect has been found for skilled readers in isolated word recognition tasks such as naming and lexical decision and in tasks that involve on-line silent reading in which target items are embedded in a sentential context. Using an eye-tracking paradigm, Sereno and Rayner (2000) demonstrated that readers spent less time fixating targets that had regular grapheme-to-phoneme correspondence. When parafoveal preview of the target word was obscured, however, the regularity effects disappeared. This finding suggests that parafoveal vision in fluent reading allows preliminary phonological processing of the upcoming word such that a decision on its processing requirements can be made. Other studies have provided converging evidence (e.g., Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995; Pollatsek, Lesch, Morris, & Rayner, 1992).

Demonstrations of regularity effects in dyslexic readers, however, are currently restricted to word recognition tasks, which have yielded variable findings. Despite early failures to find an effect (e.g., Snowling, Stackhouse, & Rack, 1986), the majority of naming and lexical decision tasks have demonstrated that dyslexic readers are faster to respond to regular than irregular words (e.g., Brown, 1997; Seidenberg et al., 1985; Stanovich & Siegel, 1994). In view of the fundamental dyslexic impairment in grapheme-to-phoneme correspondence, this sensitivity to phonological structure is somewhat surprising. To explain the emergence of the regularity effect in dyslexic readers, Brown (1997) suggested that although detailed knowledge of grapheme-to-phoneme correspondence is impaired, dyslexics can phonologically analyse words into larger chunks. These chunks are inadequate for producing novel or non-words accurately because such words require grapheme-to-phoneme analysis, but are useful in predicting phonological rimes through analogy, which in turn predict word pronunciation.

It is not clear, however, that these findings generalise to tasks beyond those which require a pre-planned decision response to a single lexical item, or for naming, an explicit phonological response to each target. Reading in its natural environment is generally silent, and the lexical status of words is not at issue: readers are seeking to make sense of the text presented as a whole rather than in artificially segmented chunks. The purpose of this study was to establish whether orthographic regularity would influence dyslexic readers in naturalistic reading. We used eye-tracking to measure the on-line processing of frequent and infrequent target words in sentential contexts. As well as comparing regularly with irregularly spelled words, we categorised words according to consistency, defined by the number of other words in the language that share the same rime pronunciation as the target word (see Treiman, Mullennix, Bijelijac-Babic, & Richmond-Welty, 1995). The additional consistency categorisation in this experiment yielded three lexical conditions: *regular* words (with grapheme-to-phoneme correspondence), *irregular inconsistent* words (with irregular, inconsistent spellings), and *irregular consistent* words. The latter group contains rimes such as *ike*, which has an irregular grapheme-phoneme mapping (the letter *i* is infrequently pronounced /aI/) but a consistent rime pronunciation (e.g., *like*, *mike*, *bike*, *hike*). Irregular Consistent words are therefore similar to Regular words, but instead of a grapheme-to-phoneme processing strategy, phonology may be accessed by analogy with other members of the group in a manner similar to that suggested by Brown (1997, but see Katzir et al., 2006, for an alternative view).

For the control participants, we predicted that Regular words would be processed faster than Irregular Consistent as well as Irregular Inconsistent low frequency words, on the assumption that regularity effects in skilled reading of words in sentential contexts are driven by grapheme-to-phoneme processing. For dyslexics, previous research provides evidence of impairment in grapheme-to-phoneme processes but not in accessing phonology through analogy with other sub-lexical units. If the Regularity effect observed in single-word studies is driven by dyslexic participants' ability to use an analogy strategy, we might expect Regular and Irregular Consistent low-frequency words to be read faster than Irregular Inconsistent words. On the other hand, if a grapheme-to-phoneme impairment results in a general insensitivity to regularity, we should observe a lack of regularity effects (i.e., no regularity-by-frequency interaction) in the dyslexic group.

Method

Participants

Forty-eight native English speaking University of Edinburgh students (24 unimpaired readers; 24 formally diagnosed with dyslexia; age 18–25 years) with normal vision or vision corrected to normal with soft contact lenses, were recruited.[1]

[1] Unfortunately, the control participants were not tested for literacy, since their data was originally collected for a different study. However, no control participant reported any difficulty with reading, writing, or spelling.

Materials and design

Pre-test apparatus and materials

British Dyslexia Association Adult Checklist scores demonstrated that all the dyslexic readers in the group were on or below the 40th percentile level; 20 were below the 10th percentile. Reading and cognitive profiles were established using tests of exception and non-word reading, verbal memory, writing speed (reflecting general speed of processing) and spelling (Hatcher, Snowling, & Griffiths, 2002; See Appendix 1 for details of scores). Participants in the control group reported no problems in reading, writing or spelling.

Eye-tracking materials

A 2 (Frequency: low vs. high) × 3 (Regularity: Regular, Irregular consistent, Irregular inconsistent) × 2 (Reader: non-impaired vs. dyslexic) mixed design was used. The target words therefore comprised 6 experimental conditions, giving rise to 72 targets in total (see Appendix 2). Mean (type) consistency scores, calculated from CUVOALD (Mitton, 1986) according to the procedure set forth by Treiman et al. (1995) are given in the appendix for the six types of target. The consistency of Regular and of Irregular Consistent targets did not differ by the three types of word used or by frequency (*F*s < 1.84). However, we established that Irregular Inconsistent targets were significantly less consistent than their Irregular Consistent counterparts (.53 vs. 1, $F(1, 44) = 60.86$, $P < .001$). There was a marginal trend for more frequent Inconsistent items to be more consistent ($F(1, 44) = 3.71$, $P = .06$).

The targets were 4 letters long and were derived from Sereno and Rayner (2000), with the addition of Irregular Consistent words. Word frequencies were obtained from the CELEX database (Baayen, Piepenbrock, & Guilkers, 1995), and a 2 way ANOVA established that High Frequency items were more frequent than their Low Frequency counterparts (4,395.03 vs. 189.75; $F(1, 22) = 19.5$, $P < .001$), but frequency did not differ by word class ($F = .14$).

Each target was embedded within a sentence frame (e.g., *It seems that the ______ ones were rarely recognised*). These frames allowed one word from each condition to be inserted (e.g., *meek; lame; foul; dark; fine; good;* see Appendix 1). Participants saw all target words, and all sentence frames, but each target in only one sentence frame. Target words were rotated across experimental treatments such that each word appeared in one of six appropriate sentence frames.

Stimuli were presented on a 15″ VGA monitor in a monospaced font, as light cyan characters on a black background. Participants were seated 75 cm from the monitor, at which distance one character subtended approximately 16 min of visual angle (i.e., 3.75 characters per degree). A Fourward Technologies Generation 6.3 Dual Purkinje Image eye tracker, with a resolution of less than 10 min of arc, was used to record eye movements from the right eye. In order to minimise participants' head movements, a bite-bar and forehead rest were employed.

Procedure

Eye position was calibrated by asking participants to fixate on squares distributed throughout the display area. Three practice sentences were subsequently presented, identical to experimental trials. Each trial was immediately preceded by the presentation of a square in the same screen location as the initial letter of the sentence in order to ensure that the participant was fixating at the beginning of the sentence when it was presented. When the experimenter judged that the participant was fixating the square, she pressed a button to begin the trial. Participants were instructed to read each sentence normally and to press a button to indicate that they had finished reading and had understood the sentence. Pressing the button cleared the screen and triggered the display of the fixation point for the subsequent trial.

In a third of the trials, a yes-no comprehension question was randomly presented after a third of all trials. It occurred after the stimulus sentence and prior to the subsequent fixation point to ensure that participants were reading for meaning. Participants responded to the question using one of two buttons. The message "ERROR" was displayed if the question was answered incorrectly. If necessary, a recalibration took place after the end of a stimulus presentation or question, as appropriate. Eye-movements were recorded by sampling eye positions every millisecond.

Results

There was no significant difference between groups in question-answering accuracy (dyslexic: 90.5%; control: 94.3% correct; t (46) = 1.55). Dyslexic participants took longer overall to read the target sentences than controls (3,811 vs. 2,732 ms: t_1 (46) = 4.59, $P < .001$; t_2 (71) = 13.19, $P < .001$), making more fixations per sentence on average than controls (12.5 vs. 9.4: t_1 (46) = 3.83, $P < .001$; t_2 (71) = 15.71, $P < .001$). However, across the whole sentence, the average duration of fixations did not vary between groups (261 vs. 247 ms: t_1 (46) = .97; t_2 (71) = .84). Instead, readers with dyslexia were significantly more likely to make regressive eye movements (31% vs. 25%: t_1 (46) = 3.40, $P < .001$; t_2 (70) = 6.22, $P < .001$).

To examine the effects of word frequency and regularity, we used three measures of reading time for the critical region of each sentence, comprising the 4-letter target word and the space which preceded it: *first fixation duration* (initial fixation duration on the target region), *gaze duration* (the sum of all fixations on the target region occurring before the eye reached either edge of the target region) and *total reading time* (every fixation on the target region, including those after the eye had initially left the region). Table 1 summarises the mean reading times for each measure by experimental condition. A separate 2 (participant group) × 2 (frequency) × 3 (regularity) mixed ANOVA was first conducted for each of these dependent variables.

A main effect of group was found in the majority of analyses: dyslexic participants tended towards longer first fixations (278 ms) than controls (266 ms: F_2 (1, 71) = 11.52, $P < .001$), although the effect did not reach significance in the by-

Table 1 Mean reading times: first fixations, gaze durations, total reading times (ms) and percentage fixations for target regions as a function of word frequency and word regularity, for control and dyslexic groups

			Word regularity					
			Control readers			Dyslexic readers		
			Regular consistent	Irregular consistent	Irregular inconsistent	Regular consistent	Irregular consistent	Irregular inconsistent
First-fixation duration	High frequency	Mean	262	265	257	267	266	281
		Std. Err.	6.2	7.1	6.2	6.1	7	7.6
	Low frequency	Mean	263	277	274	280	295	282
		Std. Err.	7.1	8.1	7.6	8.5	9.6	10.6
Gaze duration	High frequency	Mean	277	274	265	287	285	296
		Std. Err.	7.7	7	5.6	7.1	9.1	8.6
	Low frequency	Mean	274	292	297	312	322	306
		Std. Err.	7	9.7	9.8	15.3	12.2	14.9
Total reading time	High frequency	Mean	324	321	298	381	371	407
		Std. Err.	13.6	11.6	9.3	17.4	17.6	19.9
	Low frequency	Mean	344	336	334	450	460	434
		Std. Err.	18.5	11.2	13.3	34.5	27.9	27.4
Percentage fixations	Low frequency	%	76	71.2	74.7	71.2	72.2	67
	High frequency	%	72.6	73.3	71.2	72.6	68.4	65.6

participants analysis (F_1 (1, 46) = 2.1, $P > .05$). Dyslexic readers also had longer gaze durations (301 ms) than controls (280 ms: F_1 (1, 46) = 4.46, $P < .05$, F_2 (1, 71) = 20.71, $P < .05$) as well as longer total reading times (dyslexic 417 ms vs. control 326 ms: F_1 (1, 46) = 16.03, $P < .001$, F_2 (1, 71 = 117.3, $P < .001$). Overall, there was a robust frequency effect. This was demonstrated in the first fixation analysis (frequent 266 ms vs. rare 279 ms: F_1 (1, 46) = 16.06, $P < .001$, F_2 (1, 71) = 10.54, $P < .01$), gaze duration (281 vs. 301 ms: F_1 (1, 46) = 17.16, $P < .001$, F_2 (1, 71) = 16.37, $P < .001$) and total reading time measures (350 vs. 393 ms: F_1 (1, 46) = 19.44, $P < .001$, F_2 (1, 71) = 19.80, $P < .001$). Total reading times also showed a group-by-frequency interaction (F_1 (1, 46) = 3.99, $P = .052$, F_2 (1, 71) = 4.79, $P < .05$), such that dyslexic readers demonstrated a significantly larger effect of frequency than controls. No analysis showed a main effect of regularity.

A 3-way Group-by-Regularity-by-Frequency interaction approached significance for first fixation times (F_1 (1, 23) = 2.53, $P = .08$; F_2 (2, 142) = 2.37, $P = .09$) and was significant for gaze duration (F_1 (2, 92) = 3.14, $P < .05$; F_2 (2, 142) = 4.34, $P < .05$). This finding held for total reading times by participants (F_1 (1, 23) = 3.38, $P < .05$) but not by items (F_2 (2, 142) = 2.27, $P < .11$). Focusing on gaze durations, non-impaired readers showed a frequency-by-regularity interaction (F_1 (1, 23) = 4.75, $P < .05$; F_2 (2, 142) = 4.49, $P < .05$). There was no such interaction for dyslexic participants (Fs < 1.17). Post hoc tests on the control group gaze-duration measures revealed that in the low-frequency condition, Regular words elicited significantly lower gaze durations (275 ms) than Irregular Consistent (292 ms: F_1 (1, 23) = 4.20, $P < .05$; F_2 (1, 72) = 4.14, $P < .05$) or Irregular Inconsistent (298 ms: F_1 (1, 23) = 6.21, $P < .05$; F_2 (1, 72) = 5.51) word types, but there was no difference between Irregular Consistent and Irregular Inconsistent words (Fs < 1). No significant differences were found for the control group high-frequency condition. In sum, the control group analysis replicates the frequency-by-regularity interaction found in previous studies.

For the dyslexic readers, there were no differences for any measure in the reading times for the words of each regularity type in the high (Fs < 1) or low (Fs < 1.03) frequency conditions. As the patterns of gaze durations for frequent items were qualitatively different between groups, we conducted a final 3 (regularity) × 2 (participant group) analysis for high frequency items only. There was no significant interaction (F_1 (2, 92) = 2.10, P = .13; F_2 (2, 142) = 1.71, P = .19), although the effect of group was marginal by participants and significant by items (F_1 (1, 46) = 3.10, P = .05; F_2 (1, 71) = 8.35, P < .01).

The lack of effect for dyslexic readers in the low frequency condition cannot be attributed to dyslexics being less likely to fixate target regions: target words were fixated 74% of the time by control participants and 69% of the time by dyslexic readers (also see Table 1). A between-participants t-test revealed that this difference was not significant (t (46) = .16, P > .05). Additional analysis investigated individual effects in both groups for Regular word fixation time measures. The number of individuals in each group falling 1 standard deviation from the control mean on each dependent measure is as follows: first fixation: dyslexic 12, control 5; gaze duration: dyslexic 13, control 7; total time: dyslexic 14, control 7).

Discussion

When reading sentences, dyslexic readers tended to take significantly longer on first fixations, gaze durations and total reading time of a word, and made more regressions, than did control participants. There were, however, some similarities in the pattern of behaviour of the dyslexic and control readers. For both groups of readers, frequent words elicited significantly shorter initial fixations than infrequent words, suggesting that dyslexic readers can process intrinsic orthographic or phonological word properties to facilitate reading when items are familiar.

In the low frequency condition, control performance demonstrated a benefit for processing Regular words compared with Irregular Consistent or Irregular Inconsistent words, strongly suggesting that regularity effects in sentential reading are driven by grapheme-to-phoneme processing. It should be noted, however, that the Consistent and Inconsistent items only differed in rime consistency, and it may be that sequences such as word-final *...mb* could be considered consistent. In this context it is important to point out that there is no evidence in the by-items analyses that the Inconsistent targets give rise to more variable responses than the Consistent ones. Whatever the role of consistency, dyslexic participants, importantly, showed no advantage for any word type, demonstrating relative insensitivity to the intrinsic phonological structure of words. This finding stands in striking contrast to the considerable body of evidence from other paradigms such as naming and lexical-decision studies that demonstrate comparable regularity effect between dyslexic groups and controls (e.g., Brown, 1997; Seidenberg et al., 1985; Stanovich & Siegel, 1994).

Dyslexia is however notoriously heterogeneous (see Snowling, 2000); the analysis investigating the number of individuals deviating from the control mean demonstrates this. It is possible that this might have resulted in an overall lack of power in the dyslexic group's results, which might account for the marginal Group-by-Regularity-by-Frequency interaction. However, the data argue against this possibility: dyslexic readers were demonstrably affected by lexical frequency (in fact, to a greater extent than controls for total reading times). In other words, as a group our dyslexic participants were sensitive to differences in the target materials.

We therefore turn to possible explanations of why reading groups demonstrated dissociable regularity effects depending on the frequency of the lexical items used. A crucial process in fluent reading is the parafoveal uptake of orthographic, and some preliminary phonological, information (Starr & Rayner, 2001). In Sereno and Rayner's (2000) study, when parafoveal information was obscured, skilled readers did not demonstrate a regularity effect, suggesting that early phonological activation is critical in this process. Evidence for parafoveal processing anomalies in poor readers has been demonstrated in a number of studies (see Rayner, 1998 for a review). Chace, Rayner and Well (2005), for example, demonstrated that less skilled readers do not demonstrate normal preview benefit effects in sentence processing.

Reduced parafoveal processing can be explained in terms of dyslexic processing speed deficits. Processing speed is considered to be a precursor of fluency in reading, and is underpinned by the rate at which alphanumeric stimuli can be automatically retrieved (Wolf & Bowers, 1999). A failure to automatise retrieval of such stimuli would require increased attention allocation to the foveal stimulus, leaving fewer resources to begin processing parafoveal items. Preview would enable skilled readers to allocate minimal foveal processing time to words with a readily accessible (grapheme-to-phoneme) phonological structure. Degraded phonological representations in the dyslexic readers, however, implies little or no preview benefit, leading to increased foveal processing time. Dyslexic readers would not, therefore, demonstrate a processing advantage for words with transparent grapheme-to-phoneme correspondence (Regular), which might otherwise have required only *brief* viewing, a pattern reflected in the results of this study. The concomitant effects of inefficient parafoveal preview on fluency are also evident in dyslexics' increased latencies for sentence processing relative to controls.

In view of the novel methodology employed to address this research question, conclusions concerning the exact processes underlying the absence of a regularity effect in the dyslexic group are necessarily tentative. The findings of this study, however, stand in contrast with those from a number of studies based on single-word tasks. If the current findings are shown to be robust, then clearly extrapolating findings from word recognition tasks concerning phonological processing ability in dyslexia to general reading is misleading. We propose that reading in sentential contexts is a more ecologically valid measure of phonological processing and a more fruitful avenue of research for investigating a phonological deficit.

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Appendix 1 Dyslexic readers' literacy profiles

Participant	BDA (*N* checked /20)	Non-word decoding (% errors /45)	Exception words (% errors/45)	Spelling (% errors/20)	Digits backwards *N* errors/6	Writing speed (*N* wds. per 2 min)
1	12	6	9	20	0	66
2*	11	13	15	40	2	58
3	7	6	0	20	0	74
4	15	30	10	60	4	65
5*	7	29	10	50	4	71
6	11	6	2	15	0	66
7*	6	0	40	45	0	53
8*	15	6	5	20	4	58
9	13	0	3	10	2	41
10*	12	6	28	65	4	52
11*	19	9	35	35	2	56
12*	13	6	3	20	0	48
13	18	0	3	5	2	57
14*	10	6	25	65	0	54
15*	8	16	8	35	0	52
16	8	5	5	15	0	69
17	13	0	15	30	0	62
18	12	3	2	5	0	53
19*	15	12	19	25	1	52
20*	13	0	11	30	1	45
21*	13	28	11	25	6	52
22*	7	0	5	15	1	53
23	9	11	10	35	6	52
24*	17	11	7	20	2	61

Note: * Participants scoring 1 SD below the control mean on total time target eye-fixation latencies

Appendix 2 Target items by experimental condition. Mean consistency scores (*C*) and frequencies (*F*) are given for each condition

Low frequency			High frequency		
Regular consistent	Irregular consistent	Irregular inconsistent	Regular consistent	Irregular consistent	Irregular inconsistent
Limp	Numb	Sour	Flat	Calm	Full
Meek	Lame	Foul	Dark	Fine	Good
Rump	Mane	Teat	Back	Tail	Foot
Crab	Mask	Doll	Fish	Face	Bear
Dock	Pail	Tomb	Pack	Hole	Door
Dell	Hike	Isle	Hill	Race	Tour
Cult	Ruse	Feud	Test	Task	Pose
Rack	Cane	Sash	Rock	Line	Club
Sock	Tile	Comb	Dish	File	Shoe
Fern	Bike	Pear	Pump	Wine	Wood
Sack	Cask	Cart	Week	Game	Hour
Pest	Mole	Lamb	Seal	Life	Soul
C = .99	C = 1.0	C = .41	C = 1.0	C = 1.0	C = .65
F = 200.58	F = 140.33	F = 228.33	F = 4,064.67	F = 3,948.67	F = 5,054.75

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