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REGULAR ARTICLE

Phonology and phonetics dissociate in dyslexia: evidence from adult English speakers

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ABSTRACT
Individuals with dyslexia exhibit subtle impairments in speech processing. Informed by these findings, a large literature has attributed dyslexia to a phonological deficit. Phonology, however, is only one of many systems engaged in speech processing. Accordingly, the speech perception deficit is consistent with any of multiple loci, including both the phonological grammar and lower level systems – auditory and phonetic. Our present research seeks to dissociate these possibilities. To gauge phonological competence, we examined the sensitivity of adults with dyslexia, native speakers of English, to putatively universal grammatical restrictions on syllable structure. Phonetic processing was examined using standard phonetic identification and discrimination tasks. Across all experiments, participants with dyslexia exhibited multiple phonetic difficulties, while their sensitivity to grammatical phonological structure was intact. These results demonstrate a dissociation between the functioning of the phonetic and phonological systems in dyslexia. Contrary to the phonological hypothesis, the phonological grammar appears to be spared.

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Dyslexia; phonology; phonetics; onset clusters; sonority

Although dyslexia is defined as a reading disability, its effects on speech perception are well documented. Individuals with dyslexia exhibit subtle impairment to the categorisation of speech sounds (e.g. discriminating *ba* from *pa*, e.g. Blomert, Mitterer, & Paffen, 2004; Brandt & Rosen, 1980; Chiappe, Chiappe, & Siegel, 2001; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Mody, Studdert-Kennedy, & Brady, 1997; Paul, Bott, Heim, Wienbruch, & Elbert, 2006; Rosen & Manganari, 2001; Serniclaes, Sprenger-Charolles, Carré, & Demonet, 2001; Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004; Werker & Tees, 1987; Ziegler, Pech-Georgel, George, & Lorenzi, 2009), the discrimination of speech from non-speech (e.g. Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2012), and the identification of human voices (e.g. Perrachione, Del, Tufo, & Gabrieli, 2011). These impairments echo the pervasive difficulties of individuals with dyslexia in mapping graphemes to phonemes (e.g. Araújo, Faísca, Bramão, Petersson, & Reis, 2014; Bruno, Lu, & Manis, 2013; Olson, Wise, Conners, & Rack, 1990; Rack, Snowling, & Olson, 1992; Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014; Shaywitz, 1998; Wang, Nickels, & Castles, 2015) and in gaining awareness of phonological structure (Bradley & Bryant, 1978; Ramus et al., 2003). While dyslexia is undoubtedly a complex disorder, the effects of which also extend to visual and motor skills (e.g. Bosse, Tainturier, & Valdois, 2007; Gori, Seitz, Ronconi, Franceschini, & Facoetti, 2015; Ramus et al., 2003; Stein & Walsh, 1997), "sound-related" difficulties are quite common (for review, see Ramus & Ahissar, 2012). This constellation of "sound related" difficulties has led many researchers to attribute dyslexia to a phonological impairment (e.g. Bradley & Bryant, 1978; Mody et al., 1997; Olson, 2002; Paulesu et al., 2001; Perrachione et al., 2011; Pugh et al., 2000; Savill & Thierry, 2011; Shankweiler, 2012; Shaywitz, 1998; Tanaka et al., 2011).

Phonology, however, is not synonymous with sound perception. This is because the processing of auditory linguistic stimuli recruits multiple mechanisms (see Figure 1). When presented with an auditory stimulus (e.g. *blog*), listeners must first run an initial auditory analysis. The phonetic system next extracts discrete phonemes (e.g. *b,l*) from the continuous speech stream. Finally, the phonological grammar combines those discrete phonological elements to form linguistic structure (e.g. syllables). While phonology and the phonetic systems are clearly linked, there is much evidence to suggest that the two systems are distinct (Abler, 1989; Hayes, 1999; Hyman, 2001; Pierrehumbert, 1975; Zsiga, 2000) and dissociable (e.g. de Lacy & Kingston, 2013). Phonological structure is projected to both speech and manual gestures (in sign languages), and, despite the contrast in

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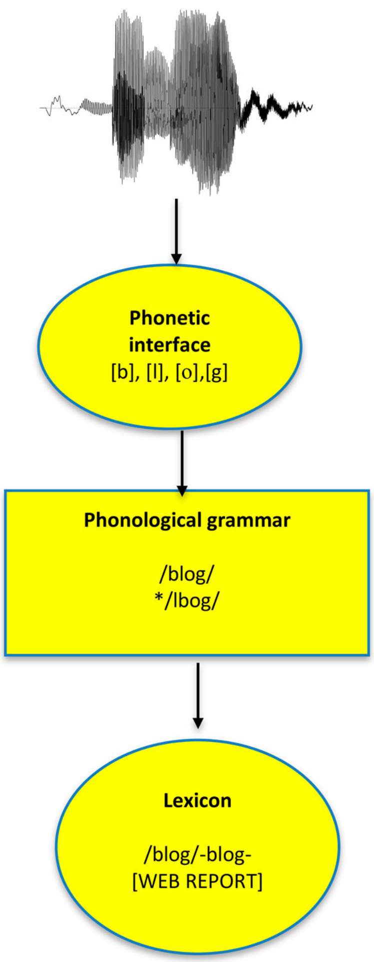

Figure 1. Components of the speech processing system.

sensory channels, some aspects of phonology appear to be shared across modalities (e.g. Berent, Dupuis, & Brentari, 2013; Sandler & Lillo-Martin, 2006). Accordingly, a deficit in "sound processing" can result from impairment to either the linguistic phonological system or to the phonetic and auditory systems. And of course, additional difficulties could stem from lexical storage and retrieval (Ramus & Szenkovits, 2008), the formation of perceptual anchors (Ahissar, Lubin, Putter-Katz, & Banai, 2006) and working memory (Wolf, Bally, & Morris, 1986). Our interest here concerns the distinction between phonology and the levels of sound processing upon which it is dependent. Clearly, phonology and sound processing are not one and the same.

Whether dyslexia specifically compromises the phonological system is far from certain. Compared to the large literature on phonetic processing, only a handful of studies has probed the phonological system in dyslexia, and their results, for the most part, yielded no evidence for a phonological deficit (e.g. Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2012; 2013; Blomert et al., 2004; Maïonchi-Pino, de Cara, Écalle, & Magnan, 2012a, 2012b; Maïonchi-Pino et al., 2013; Marshall, Ramus, & van der Lely, 2010; Szenkovits, Darma, Darcy, & Ramus, 2016; for a recent review of these findings, see Berent, Vaknin-Nusbaum, Balaban, & Galaburda 2013). In past research, we sought to directly contrast the phonetic and (grammatical) phonological systems in adult Hebrew speakers (Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2012, 2013). Our results showed that participants with dyslexia were impaired in various aspects of phonetic categorisation – an outcome that agrees with many previous findings in the literature. Remarkably, these same individuals were fully sensitive to linguistic phonological structure, and their performance indicated full command of regularities that are both specific to Semitic stems (Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2012) and ones that are putatively universal (Berent, Vakinin-Nusbaum, Balaban, & Galaburda, 2013).

To evaluate the generality of these findings, we have extended our inquiry to English speaking participants. As a test of the linguistic phonological system, we compared the sensitivity of adult individuals with dyslexia and typical readers to the restrictions on syllable structure. Their auditory and phonetic sensitivity was further examined using standard phonetic identification and discrimination tasks. Our findings reveal a dissociation between the two systems. While we identify multiple aspects of phonetic/auditory difficulty (and these difficulties are evident across all tasks), the phonological grammar appears to be spared.

Part 1: the phonological grammar in dyslexia

Across languages, syllables like *blog* are preferred to *lbog* (Greenberg, 1978). Our research examines whether the sensitivity to this putative phonological universal is preserved in dyslexia. We reasoned that, if dyslexia results from an intrinsic disruption to the function of the phonological system, then this impairment will likely undermine core aspects of phonological computation. The restriction on syllable structure is a good candidate for a core phonological constraint: this restriction is well documented across languages, and it has been amply studied in typical individuals (adults, children and neonates) across numerous languages. Accordingly, if dyslexia were to impair the phonological grammar, then knowledge of syllable structure would likely be compromised.

The specific constraint in question concerns the structure of the onset – the string of consonants occurring at the beginning of the syllable (e.g. *bl* in *blog* and *blif*). Onset structure, in turn, is constrained by sonority (denoted *s*) – a scalar phonological property that correlates with the salience of segments (Clements, 1990;

Hooper, 1976; Smolensky, 2006). Most sonorous among consonants (loudest) are liquids and glides (e.g. *l,y*, $s = 3$), followed by nasals (e.g. *m,n;* $s = 2$) and finally, obstruents (e.g. *b,d*; $s = 1$). Using these sonority levels, we can next compute the sonority cline of the onset by subtracting the sonority level of the first consonant from the second. Syllables like *blog* and *blif* exhibit a large rise in sonority (from *b*, $s = 1$ to *l*, $s = 3$, $\Delta s = 2$), *bnif* exhibits a smaller rise ($\Delta = 1$), *bdif* manifests a sonority plateau ($\Delta s = 0$), whereas *lbif* falls in sonority ($\Delta = -2$). Together, these sonority preferences form a syllable hierarchy (e.g. *blif*≻*bnif*≻*bdif*≻*lbif*; where ≻ indicates preference).

There is considerable evidence to suggest that the syllable hierarchy is broadly represented in many grammars, perhaps universally. First, across languages, syllables with small sonority clines are systematically underrepresented (Berent, Steriade, Lennertz, & Vaknin, 2007; Greenberg, 1978). Moreover, a large body of experimental evidence has shown that speakers of various languages are sensitive to this hierarchy (English: Berent et al., 2007; Spanish: Berent, Lennertz, & Rosselli, 2012; French: Maïonchi-Pino et al., 2013; Korean: Berent, Lennertz, Jun, Moreno, & Smolensky, 2008 and Mandarin: Zhao & Berent, 2016). Sensitivity, in turn, is inferred from a phenomenon of grammatical repair.

It is well known that ill-formed syllables are systematically misidentified. For example, English speakers misidentify the syllable *bna* (as in *bnei-Israel*, “sons of Israel” from Hebrew) as *bena* (e.g. Massaro & Cohen, 1983). While misidentification could, of course, originate from various sources (an issue we will consider shortly), there is much evidence to suggest that misidentification is (inter alia) a grammatical phonological reflex (Berent et al., 2007). Because *bna* (for instance) violates the syllable structure of English (English requires onsets to exhibit large sonority rises, as in *bla*), inputs such as *bna* do not yield a faithful output (i.e. outputs identical to the input, *bna*→*bna*); instead, the grammar systematically recodes (i.e. repairs) the *bna* by separating the onset consonants by a vowel (*bna*→*bena*).

In modern phonology (e.g. Prince & Smolensky, 1993/2004), however, ill-formedness is not an “all or none” notion, but rather a matter of degree: some structures are worse-formed than others. Moreover, well-formedness constraints are universal: they include restrictions on structures that speakers have never encountered before, including the syllable hierarchy (e.g. *blif*≻*bnif*≻*bdif*≻*lbif*). Combining these two ideas with the proposal that ill-formed structures are repaired, we can expect the scalar restrictions on ill-formedness to result in scalar repair – as ill-formedness increases, so will the likelihood of repair (e.g. Davidson, Jusczyk, & Smolensky, 2006). Those conclusions allow us to make specific predictions that link well-formedness (as defined by the syllable hierarchy) and behaviour. If people represent the syllable hierarchy, then the identification accuracy of any given syllable should be monotonically related to its position on the syllable hierarchy – the worse-formed the syllable, the more likely its repair, hence, its misidentification. For example, the worst-formed onsets of falling sonority (e.g. *lbif*) should be more likely to be misidentified (as *lebif*) than better-formed onsets (e.g. *bdif*).

This prediction is borne out by a large body of research from typical speakers of different languages (Berent et al., 2007, 2008; Berent, Lennertz, & Rosselli, 2012; Maïonchi-Pino et al., 2013; Zhao & Berent, 2016). It is unlikely that the repair results from lexical analogy (e.g. English speakers prefer *bnif* because they analogise it to *sniff*) because similar preferences obtain even in languages whose lexicons have no onset clusters (e.g. Korean: Berent et al., 2008; Mandarin: Zhao & Berent, 2016) and even in the absence of any lexicon at all – among neonates (Gómez et al., 2014). It is also unlikely that misidentification results solely from failure to extract the auditory or phonetic properties of *lbif*, as similar findings obtain with printed materials – in the absence of auditory demands (Berent & Lennertz, 2010; Berent, Lennertz, Smolensky, & Vaknin-Nusbaum, 2009; Tamasi & Berent, 2015). Similarly, misidentification is unlikely to result solely from a process of articulatory motor simulation (in line with the hypothesis of embodied cognition), as the results replicate even when the motor system is disrupted using Transcranial Magnetic Stimulation (Berent et al., 2015). By elimination, then, these results imply an abstract phonological source that appears to be active very broadly, perhaps universally. Our question here is whether this phonological function is spared in dyslexia.

Our past research has examined this question using individuals with dyslexia who are Hebrew speakers (Berent, Vakinin-Nusbaum, Balaban, & Galaburda, 2013). Results suggested that their sensitivity to the syllable hierarchy is intact, irrespective of reading ability, for both adults with dyslexia and typical readers. Critically, these same adults with dyslexia exhibited a variety of subtle difficulties in phonetic processing. Together, these results suggested that the phonological and phonetic systems might dissociate in dyslexia.

The findings from Hebrew, however, are limited, inasmuch as this language exhibits a relatively large inventory of onset clusters (e.g. it allows syllables like *ktiv*, “spelling”, *knas*, “fine, penalty” and *klal* “rule”). Accordingly, despite the above-mentioned evidence against the lexical account in typical individuals, we cannot rule out the possibility that our participants with dyslexia could have compensated for their putative phonological deficit by relying on lexical mechanisms. While this possibility is countered by the observation of similar findings in French speakers (Maïonchi-Pino et al., 2013), that study did not probe for phonetic processing, so it is unclear whether these participants had the typical difficulties with speech processing. Moreover, the syllable structure of French is only slightly more restrictive than Hebrew (French bans most stop-stop onsets, which Hebrew freely allows), so the possibility of compensatory lexical mechanisms remains a concern.

English syllable structure is far more restrictive than either Hebrew or French (e.g. English bans stop-fricatives, and sonorant-sonorant sequences that are possible in French and Hebrew; Fery, 2003), so this language presents a stronger test for the phonological hypothesis. Experiment 1 first tests the sensitivity of speakers to the structure of obstruent-initial clusters; in Experiment 2, we move to inspect nasal-initial syllables. Phonetic sensitivity is directly examined in Experiment 3.

Experiment 1

Experiment 1 examines the sensitivity of adults with dyslexia to the structure of obstruent clusters. In this experiment, participants are presented with one stimulus at a time – either a monosyllable (e.g. *blif*) or its disyllabic counterpart (e.g. *belif*), and participants are asked to perform a syllable count (e.g. does *blif* include one syllable or two?). Our main interest is in the structure of the monosyllables, as those are composed of four types, arrayed on the syllable hierarchy (e.g. *blif≻bnif≻bdif≻lbif*). If people are sensitive to the syllable hierarchy, then, as the syllable becomes worse-formed, the likelihood of its phonological repair should increase, and consequently misidentification should ensue. The systematic misidentification of ill-formed syllables presents a litmus test of phonological knowledge (e.g. Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Massaro & Cohen, 1983). Our question here is whether this knowledge is intact in adults with dyslexia. If the difficulty with syllables like *lbif* results from their phonological ill-formendess, then deficit to the phonological grammar should paradoxically improve performance in the dyslexia group relative to controls. In contrast, if the phonological grammar in dyslexia is intact, then ill-formedness should exert similar costs in both groups, irrespective of reading ability.

Although the primary goal of this experiment is to probe for phonological knowledge, the processing of auditory stimuli could also provide some insights into the phonetic system. The discrimination of monosyllables from disyllables requires one to accurately encode the phonetic properties of consonants and vowels. The most critical property examined here is the encoding of the schwa – the short vowel that distinguishes disyllables (e.g. *bəlif*) from monosyllables (e.g. *blif*). If the phonetic system in dyslexia is impaired, then we expect individuals with dyslexia to show an attenuated discrimination (irrespective of syllable structure). The comparison of the encoding of the schwa and the computation of syllable structure thus allows us to contrast phonetic and phonological processing, respectively. We hypothesise that the two processes dissociate in adults with dyslexia.

Methods

Participants: Two groups of participants took part in Experiments 1–3. Both groups consisted of young adult, native English speakers. The control group consisted of 20 Northeastern University students (7 males) who reported having no reading difficulties. Individuals with dyslexia comprised the experimental group ($n = 20$, 10 males), all of whom had an established diagnosis of reading disability (19 of those individuals were given a specific diagnosis of dyslexia, and one was listed as having decoding deficits). Most of these individuals (17/20) were university students (16 Northeastern University students and one student at Wentworth Institute of Technology). A subset of the dyslexia group was subsequently assessed for sight word and phonetic decoding efficiency using the Test of Word Reading Efficiency test (Torgesen, Wagner, & Rashotte, 1999), and their mean percentile on these two tests were 9.71 (SD = 6.05) and 9.14 (SD = 7.71), respectively.

Within each group, half of the participants ($n = 10$) took part in all experiments. Of the remaining 10 participants, 8 participants within each group only participated in the phonological tasks (Experiments 1–2) and the remaining 2 only took part in the phonetic tasks (Experiment 3). Thus, Experiments 1–2 each included 18 participants per group, whereas Experiment 3 included 11 and 12 participants for the identification and discrimination tasks, respectively. The order of the four experiments was varied across participants, and it was strictly matched across participants with dyslexia and control participants. The entire experimental session lasted approximately 50 minutes.

Materials: The experimental materials consisted of 90 monosyllabic non-words and their disyllabic counterparts, used in previous research with English (Berent et al., 2007) and Korean (Berent et al., 2008) speakers. The monosyllabic items were $C_1C_2VC_3$ non-words arranged in 30 quartets (see Appendix, for a list of experimental stimuli). Quartet members mostly shared their rhyme and differed on the sonority structure of their onset – either a large rise in sonority (mostly stop-liquid combinations, e.g. *blif*), a small rise in sonority (mostly stop-nasal combinations, e.g. *bnif*) a sonority plateau (stop-stop sequences, e.g. *bdif*) or a fall in sonority (sonorant-stop sequences, e.g. *lbif*). Disyllabic items differed from their monosyllabic counterparts only on the presence of an epenthetic schwa between the onset consonants (e.g. *b***e***lif, b***e***nif, b***e***dif, l***e***bif*). The materials were presented aurally. They were recorded by a native Russian speaker who produced all items naturally (Russian allows all four types of onset clusters, for more information, see Berent et al., 2007).

Procedure: Participants wearing headphones were seated in front of a computer. The trial began with a fixation point (*) and a message indicating the trial number. Participants initiated the trial by pressing the space-bar key, triggering the presentation of a single auditory item. They were instructed to indicate as quickly and accurately as possible whether the item included one syllable or two by pressing one of two keys (1 = one syllable, 2 = two syllables). Response time was measured from the onset of the auditory stimulus. Prior to the experiment, participants were familiarised to the procedure and the talker's voice with a brief practice session including real English words (e.g. *blow* – *below*). The order of trials was randomised.

Results and discussion

Sensitivity analysis: Figure 2 plots the sensitivity (d') of the dyslexia and control groups to syllable structure. An inspection of the means indicates that the overall d' scores of participants with dyslexia were lower than controls, indicating difficulties in the discrimination between monosyllables and disyllables. Participants were also sensitive to the internal structure of the syllable: as the syllable became worse-formed, sensitivity declined monotonically. Crucially, the effect of syllable structure was evident in both groups.

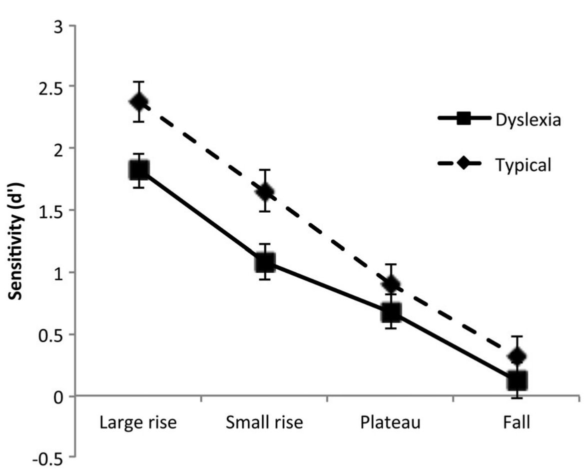

Figure 2. The sensitivity of participants with dyslexia and typical controls to the syllable hierarchy in Experiment 1. Error bars are 95% confidence intervals for the difference between the means.

These conclusions were supported by 2 Group (Dyslexia/Control) × 4 Syllable type ANOVAs of the discrimination scores (d'), conducted using both participants (*F1*) and items (*F2*) as random effects. The ANOVAS yielded a marginally significant effect of group ($F1(1, 34) = 3.48$, $p < .08$, $\eta^2 = .036$; $F2(1, 58) = 18.15$, $p < .0001$, $\eta^2 = .054$), as participants with dyslexia were overall less sensitive to the distinction between monosyllables and disyllables. The ANOVA also yielded a significant effect of syllable type ($F1(3, 102) = 110.11$, $p < .0001$, $\eta^2 = .465$; $F2(3, 174) = 61.23$, $p < .0001$, $\eta^2 = .392$), and no evidence for an interaction ($F1(3, 102) = 1.81$, $p < .16$, $\eta^2 = .008$; $F2(3, 174) = 1.18$, $p < .33$, $\eta^2 = .008$).

Planned comparisons demonstrated that the best-formed syllables with large sonority rises (e.g. *blif*) yielded significantly better sensitivity than small rises (e.g. *bnif*, $t1(102) = 6.75$, $p < .0001$; $t2(174) = 7.65$, $p < .0001$), which, in turn, elicited better sensitivity than sonority plateaus (e.g. *bdif*, $t1(102) = 5.35$, $p < .00012$; $t2(174) = 7.37$, $p < .0001$). Sonority plateaus elicited better sensitivity than sonority falls (e.g. *lbif*, $t1(102) = 5.23$, $p < .0001$; $t2(174) = 5.04$, $p < .0001$) – the worst on the sonority hierarchy.

To ensure that individuals with dyslexia were indeed sensitive to the syllable hierarchy, we further tested their performance separately, using a one-way ANOVA. The main effect of syllable type was highly significant ($F1(3, 51) = 51.45$, $p < .0001$, $\eta^2 = .416$; $F2(3, 87) = 31.39$, $p < .0001$, $\eta^2 = .429$), and planned comparisons confirmed that sensitivity declined monotonically along the syllable hierarchy (*blif-bnif*: ($t1(51) = 5.25$, $p < .0001$; $t2(87) = 2.57$, $p < .02$); *bnif-bdif*: ($t1(51) = 2.85$, $p < .007$; $t(87) = 2.86$, $p < .006$; *bdif-lbif*: ($t1(51) = 3.96$, $p < .0003$; $t2(87) = 2.08$, $p < .05$). These results confirm that, despite their reading disability, participants with dyslexia were fully sensitive to the phonological structure of the syllable.

Response bias: To assess the possibility that reading disability was associated with a response bias, we also examined the effect of syllable type on response bias (operationalised as the natural log of beta, Stanislaw & Todorov, 1999). Response bias estimates the tendency of the two groups to select a given response, irrespective of the stimulus presented to them. In our analyses, negative values reflect a bias towards a monosyllabic response; positive values indicate a disyllabic bias. The results are plotted in Figure 3.

To gauge the effect of response bias, we submitted the beta scores to 2 Group (Dyslexia/Control) × 4 Syllable

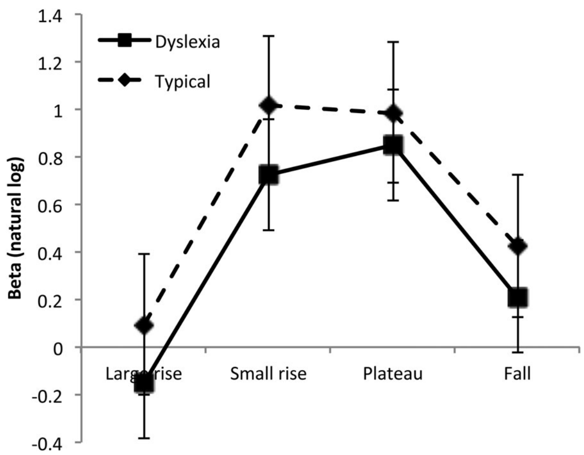

Figure 3. The effect of bias on participants with dyslexia and typical controls in Experiment 1. Bias is captured by the natural log of the beta parameter (low values indicate a monosyllabic bias). Error bars are 95% confidence intervals for the difference between the means.

type ANOVAs. Results only yielded a reliable effect of syllable type ($F1(3,\ 102) = 11.51$, $p < .0001$, $\eta^2 = .160$; $F2(3,\ 174) = 7.38$, $p < .0009$, $\eta^2 = .080$). The effect of group was not significant across participants ($F1(1,\ 34) = 1.21$, $p < .27$, $\eta^2 = .013$; $F2(1,\ 58) = 12.47$, $p < .0009$, $\eta^2 = .050$), nor did group interact with syllable type (both F's < 1, $\eta^2 = .001$, $\eta^2 = .004$).

Planned contrasts showed that participants were reliably more likely to give monosyllabic responses to *blif*-type stimuli (as well as their disyllabic counterparts) relative to *bnif*-type items ($t1(102) = 4.73$, $p < .00002$; $t2(174) = 2.98$, $p < .004$), which, in turn, did not differ from *bdif*-type stimuli ($t1(102) < 1$; $t2(174) = 1.66$, $p < .10$). The increase monosyllabic bias to *blif*-type stimuli suggests that the familiarity (or well-formedness) of these monosyllabic stimuli biased participants to opt for a monosyllabic response. Remarkably, the worst-formed syllables like *lbif* resulted in a marginally significant i*ncrease* in the monosyllabic bias ($t1(102) = 3.16$, $p < .0001$; $t2(174) = 1.91$, $p < .06$). This result converges with the outcome of sensitivity analysis, where ill-formed syllables resulted in a decrease in sensitivity. Together, these findings indicate that the misidentification of *lbif*-type items as disyllables cannot be attributed to a bias in response selection per se.

These conclusions were further confirmed in a separate analysis of the dyslexia group. Specifically, a one-way ANOVA on response bias yielded a reliable effect of syllable type ($F1(3,\ 51) = 7.85$, $p < .0003$, $\eta^2 = .185$; $F2(3,\ 87) = 5.22$, $p < .003$, $\eta^2 = .113$). Syllables like *blif* produced a monosyllabic bias relative to *bnif* ($t1(51) = 3.74$, $p < .00005$; $t2(87) = 2.67$, $p < .01$), which did not differ from *bdif*-type syllables ($t1(51) < 1$; $t2(87) = 1.06$, $p < .30$). As in the omnibus analysis, however, *lbif* type syllables tended to elicit a monosyllabic bias, a result that was significant across participants ($t1(51) = 2.72$, $p < .001$; $t2(87) < 1$). Accordingly, the tendency of the dyslexia group to misidentify *lbif*-type stimuli as disyllables (i.e. the decrease in sensitivity to *lbif*, reported in the previous section) cannot be possibly due to a response bias.

Taken as a whole, these results confirm that individuals with dyslexia are impaired in the processing of spoken syllables. They were less sensitive to the contrast between monosyllables and disyllables, possibly because they experience difficulty in the phonetic processing of the brief schwa that contrasts monosyllables and disyllables. But despite those phonetic difficulties, individuals with dyslexia were fully sensitive to the internal phonological structure of the syllable.

Experiment 2

Experiment 2 seeks to further evaluate the putative dissociation between phonological computation and phonetic processing using nasal syllables, such as *mlif* and *mdif*. Across languages, *mlif* (with a sonority rise) is better-formed than *mdif*, and our past research has shown that speakers of various languages are sensitive to this contrast. Here, we ask whether individuals with dyslexia are likewise sensitive to this distinction.

To address this question, we presented participants (individuals with dyslexia and controls) with speech continua that gradually shifted from a monosyllable (e.g. *mlif*) to a disyllable (e.g. *melif*) by extending the duration of the pretonic schwa in six equal steps. Our experiment contrasted two such continua. In one continuum, the monosyllabic endpoint consisted of an onset of rising sonority (e.g. *mlif*), whereas in the other, the monosyllabic endpoint exhibited a sonority fall (e.g. *mdif*). In each trial, participants were presented with one auditory stimulus, sampled from the two continua, and they were asked to indicate whether the stimulus includes one syllable or two. This manipulation allowed us to test participants' sensitivity to both the phonetic length of the vowel and the phonological structure of the syllable.

If people are sensitive to the phonetic length of the vowel, then as vowel duration increases, the proportion of disyllabic responses should increase. Sensitivity to phonological structure, in contrast, should be evident in the responses to the monosyllabic endpoint. If *mdif*-type syllables are ill-formed, then these syllables should be more likely to undergo repair (e.g. *medif*). Accordingly, when presented with the monosyllabic endpoint (at step 1), onsets of falling sonority should yield larger proportion of disyllabic responses compared to sonority rises. Of interest is whether these phonological and phonetic computations dissociate in dyslexia.

Methods

Materials: The materials were three pairs of nasal $C_1C_2VC_3$-$C_1əC_2VC_3$ continua (ə stands for schwa) used in our past research (Berent, Balaban, Lennertz, & Vaknin-Nusbaum, 2010; Berent, Lennertz, & Balaban, 2012; Berent et al., 2009). Members of the pair were matched for their rhyme and the initial consonant (always an *m*), and contrasted on the second consonant – either *l* or *d* (/mlɪf/-/mdɪf/, /mlɛf/-/mdɛf/, /mlɛb/-/mdɛb/). To generate those continua, we first had an English talker naturally produce the disyllabic counterparts of each pair member (e.g. /məlɪf/, /mədɪf/) and selected disyllables that were matched for length, intensity and the duration of the pretonic schwa. We next continuously extracted the pretonic vowel at zero crossings in five steady increments, moving from its centre outwards. This procedure yielded a continuum of six steps, ranging from the original disyllabic form (e.g. /məlɪf/) to an onset cluster, in which the pretonic vowel was fully removed (e.g. /mlɪf/). The number of pitch periods in Stimuli 1–5 was 0, 2, 4, 6 and 8, respectively; Stimulus 6 (the original disyllable) ranged from 12 to 15 pitch periods.

Each of the three item pairs (sonority rise vs. fall) was presented in all six-vowel durations, resulting in a block of 36 trials. Each such block was repeated four times, yielding a total of 144 trials. The order of trials within each block was randomised.

Results

Figure 4 plots the proportion of disyllabic responses as a function of the duration of the pretonic vowel (e.g. in m**e**lif) and continuum type (*ml* vs. *md*). An inspection of the means suggests that, as vowel duration increased, people were more likely to identify the input as disyllabic. Participants with dyslexia, however, were less likely to identify disyllabic endpoints (at step 6) as such, whereas at the monosyllabic endpoint (at step 1), the two groups responded similarly. Remarkably, the identification of monosyllables was modulated by their internal syllable structure: people were far more likely to give disyllabic responses to sonority falls (e.g. *mdif*) compared to rises (e.g. *mlif*). Critically, this phonological effect of syllable structure was evident irrespective of reading ability.

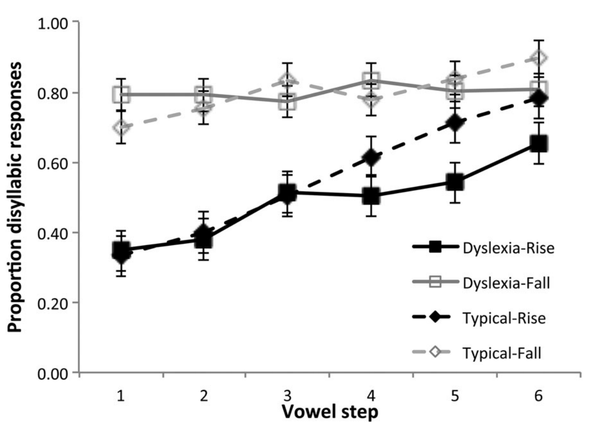

Figure 4. The proportion of disyllabic responses as a function of vowel duration and syllable type of participants with dyslexia and typical controls in Experiment 2 Error bars are 95% confidence intervals for the difference between the means.

These conclusions were borne out by the results of a 2 Group (dyslexia/control) × 6 Vowel step × Continuum type (sonority rise/fall) ANOVA on the proportion of disyllabic responses (arcsine transformed).[1] The ANOVA yielded a significant effect of vowel step ($F(1, 34) = 23.45$, $p < .0001$, $\eta^2 = .079$), and Tukey HSD tests confirmed that people were reliably more likely to identify the input as disyllabic given a disyllable (at step 6) relative to each of the previous five steps (all $p < .05$). However, the effect of vowel step was modulated by group ($F(5, 70) = 2.98$, $p < .02$, $\eta^2 = .010$). The simple main effect of group was marginally significant at step 6 ($F(1, 34) = 4.12$, $p < .06$), indicating that participants with dyslexia were less likely to identify the disyllabic endpoint as such. No other differences were found in the other steps (all $p > .21$).

The ANOVA also yielded a reliable effect of continuum type ($F(1, 34) = 55.5$, $p < .0001$, $\eta^2 = .248$), as well as an onset type × vowel step interaction ($F(5, 170) = 8.32$, $p < .0001$, $\eta^2 = .020$). Planned comparisons showed that, when presented with monosyllabic inputs (at step 1), people were reliably more likely to give disyllabic responses to the *mdif*-type continuum compared to the *mlif*-type counterpart ($t(170) = 8.34$, $p < .0001$). Although these effects were also found in the other steps (all $p < .05$), their magnitude was weaker. Specifically, the *mdif-mlif* contrast was over three times larger for monosyllables (at step 1, $\Delta = .41$) relative to disyllabic inputs (at step 6 $\Delta = .13$). Accordingly, a separate comparison of the two endpoints (at step 1 and step 6) yielded a reliable interaction ($F(1, 34) = 16.58$, $p < .0003$, $\eta^2 = .029$). Critically, this effect of syllable structure was found irrespective of reading ability in either the analysis of the endpoints ($F < 1$) or the omnibus analysis ($p > .14$).

To ensure that participants with dyslexia were in fact sensitive to syllable, we analysed the performance of this group separately. The 2 Continuum-type × 6 Vowel step interaction was highly significant ($F(5, 85) = 4.48$, $p < .002$, $\eta^2 = .021$). Planned contrasts at step 1 confirmed that *mdif*-type monosyllables were reliably more likely to elicit disyllabic responses relative to *mlif* ($\Delta = .44$, $t(85) = 9.20$, $p < .0001$). A significant, but far smaller effect obtained for disyllabic inputs at step 6 ($\Delta = .15$, $t(85) = 3.82$, $p < .0003$).

Discussion

Experiment 2 compared the sensitivity of individuals with dyslexia to the phonological and phonetic properties of nasal-initial stimuli. To test for phonological knowledge, we contrasted responses to better-formed monosyllables (e.g. *mlif*) and worse-formed ones (e.g. *mdif*). We reasoned that, if people are sensitive to phonological structure, then onsets of falling sonority should be ill formed, and consequently, they should be repaired as disyllabic. These predictions were borne out by our findings. Remarkably, this effect was found irrespective of reading ability, and the results held even when the dyslexia group was inspected separately.

While participants with dyslexia were highly sensitive to phonological structure, their phonetic processing was impaired. Both groups were sensitive to the phonetic duration of the vowel, as disyllabic responses increased along the step continuum. This effect, however, was attenuated for participants with dyslexia. Specifically, when these individuals were presented with fully disyllabic inputs (at step 6), they were reliably less likely to identify them as such relative to typical subjects.

The reduced sensitivity of individuals with dyslexia to the phonetic properties of vowels mirrors their attenuated discrimination of monosyllables and disyllables (in Experiment 1), and contrasts with their full sensitivity to phonological structure across the two experiments. The dissociation between phonological and phonetic processing is in line with our hypothesis that the speech processing deficits in dyslexia selectively impair phonetic and or/auditory processing. Experiments 3–4 directly compare the performance of the two groups in phonetic processing.

Part 2: the phonetic system in dyslexia

Experiment 3

Experiment 3 gauges the phonetic processing of individuals with dyslexia using standard phonetic identification and discrimination tasks. Participants in these experiments are presented with phonetic continua that gradually shift between two phonemes in 10 steps (e.g. between *ba* and *pa*). Our experiments included four such continua – two consonants (/t/-/d/; /b/-p/) and two vowels (/ɔ/-/ʊ/ and /æ/-/e/, e.g. *bought-foot*, and *bad-bed*). The phonetic sensitivity of poor and typical readers to these continua was gauged using phonetic identification and ABX discrimination tasks (Experiments 3a–b, respectively).

In the identification task, participants were presented with one stimulus at a time, and they were asked to make a forced choice (e.g. did you hear *ba* or *pa*?); in the ABX discrimination task, participants were presented with two stimuli (A and B) followed by a third stimulus X; their task was to determine whether X is identical to A or B. Of interest is whether individuals with dyslexia differ from controls in the shape of identification and discrimination functions, as well as overall discrimination accuracy (in the ABX task).

Experiment 3a: identification

Methods

Materials:The materials were four 10-step continua generated from recordings made by a native English speaking female. Each such continuum varied progressively between two syllables that contrasted by a single phoneme – /ta/-/da/; /ba/-/pa/) and two vowels (/ɔ/-/ʊ/ and /æ/-/e/. In each trial, participants were presented a single continuum step and they were asked to quickly indicate their percept (e.g. *ba* or *pa*?).

The four continua were presented in separate blocks. Each block was preceded by a display, announcing the following continuum and the appropriate response keys. Each such block repeated the 10 continuum-steps four times (a total of 40 trials), and each such block was repeated four times (a total of 160 experimental trials). Prior to each block, participants were presented with 8 practice trials, and provided feedback on their accuracy. The order of the four blocks was counterbalanced across participants; within each block, trials were randomised.

The preparation of the continua:Stimulus manipulations were performed using SIGNAL software (Engineering Design, Berkeley, CA) and Matlab (Mathworks, Natick, MA). All continua were made from recordings of isolated syllables produced by native speakers (16 bits, 44.1 kHz sampling rate). The “pa-ba” continuum was produced by removing the DC component from both endpoint syllables, setting non-vocalisation portions of the recording to zero, and truncating the recording lengths to the shorter of the two stimuli. The “ba” syllable was then rotated to align its vowel periodicity with the “pa” syllable, and a “hybrid pa” syllable was created using the first 159.19 ms of the “pa” and the rest of the “ba” from 159.19 ms to the recording end, joined at a zero crossing. The noisy initial part of this “hybrid pa” syllable was then progressively shortened at successive zero crossings occurring every 114–131 ms to make the eight steps of the continuum. At its shortest value, the original “ba” syllable was reproduced.

The “ta-da” continuum was produced by removing the DC component from both endpoint syllables, setting non-vocalisation portions of the recording to zero, and truncating the recording lengths to the

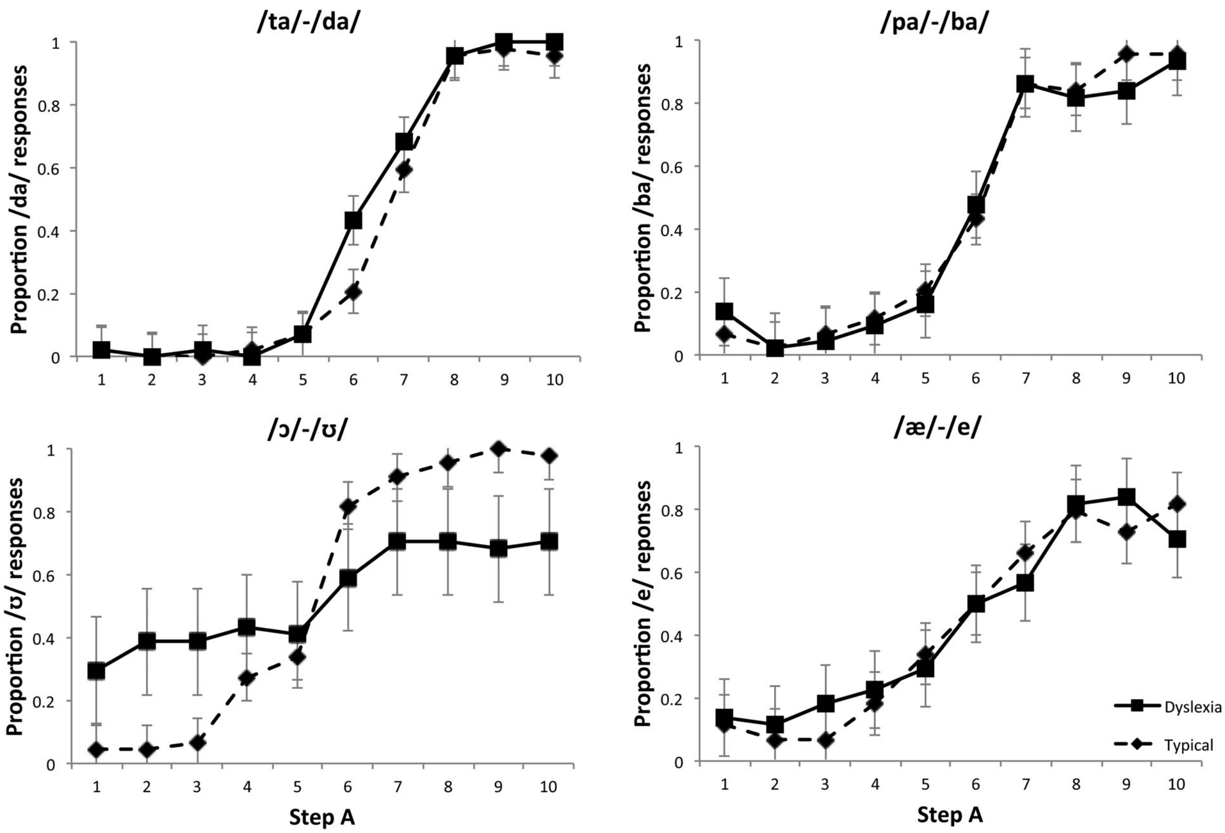

Figure 5. Phonetic identification by participants with dyslexia and typical controls in Experiment 3. Error bars are 95% confidence intervals for the difference between the means.

shorter of the two stimuli. The "da" syllable was then rotated to align its vowel periodicity with the "ta" syllable, and a "hybrid ta" syllable was created using the first 183.38 ms of the "ta" and the rest of the "da" from 183.38 ms to the recording end. The first six stimuli in the continuum were made by progressively shortening the noisy part of the "hybrid ta" syllable starting from the zero crossing that was proximal to the start of the voicing for the vowel, and proceeding backwards at successive zero crossings occurring every 7–10 ms. The rest of the stimuli in the continuum were made by successively replacing the remaining portion of the noisy signal before the start of the voicing by successive voiced vowel periods present in the original "da" syllable at these same positions in time (splicing done at zero crossings), ending up with a perfect reproduction of the original "da" syllable at the end of the continuum.

The vowel continua were created via custom-written MATLAB scripts utilising the analysis, morphing and synthesis functions provided by the TandemSTRAIGHT vocoder Matlab package (Kawahara & Morise, 2011). Recorded examples of the endpoint syllables were turned into parameterised representations used for high-fidelity resynthesis via the functions provided by the TandemSTRAIGHT Morphing Menu. Parameter value sets for the intermediate syllables between the two endpoints were generated by linear interpolation, and the parameter value sets for the two endpoints and all intermediates were used to re-synthesise the syllables. This procedure produced a series of syllables with controlled, natural-sounding transitions of all acoustic parameters. All stimuli in each continuum were equalised for their average root-mean-square (RMS) value.

Procedure: Participants wore headphones, and sat in front of a computer. Each trial began with a message indicating the trial number and a fixation point (*), which remained visible throughout the trial. Participants initiated each trial by pressing the spacebar. They were asked to quickly categorise their percept using two computer keys (*ba* = 1, *pa* = 2; *da* = 1, *ta* = 2; o = 1, u = 2, a = 1, e = 2), and their response triggered the presentation of an auditory stimulus. Slow responses (RT > 2500 ms) triggered a computer warning (there was no accuracy feedback in the experimental trails).

Results

Figure 5 presents the identification curves for the four continua. An inspection of the means suggests that, in most continua, participants with dyslexia and controls exhibited similar patterns of responses. However, the

Table 1. The parameters of the sigmoid models, fitted for the identification functions of participants with dyslexia and typical readers in Experiment 3. Values indicate estimates for the maximum, minimum, midpoint and slope of the identification function. N represents the number of individuals whose performance fitted a sigmoid function.

Continuum	Comparison	Dyslexia	Typical	df	*t* Value
ta-da	Maximum	98.30	99.04	11	<1
	Minimum	1.90	1.54	11	<1
	Midpoint	6.14	6.63	11	−1.5
	Slope	3.02	4.69	11	<1
	N	6.00	7.00		
pa-ba	Maximum	98.73	97.97		
	Minimum	3.44	−1.60	10	<1
	Midpoint	5.89	6.07	10	<1
	Slope	2.14	3.23	10	<1
	N	5.00	7.00		
o-u	Maximum	57.83	103.56	10	2.26*
	Minimum	31.37	1.90	10	1.83$
	Midpoint	4.15	4.62	10	<1
	Slope	2.12	0.73	10	1.36
	N	6.00	6.00		
ae	Maximum	91.68	97.17	15	<1
	Minimum	17.40	13.19	15	<1
	Midpoint	5.38	5.52	15	<1
	Slope	2.28	1.67	15	<1
	N	10.00	7.00		

*<.05, two-tailed.
$<.05, one-tailed.

two groups differed in the perception of the /ɔ/-/ʊ/ vowel continuum.

To test the reliability of this conclusion, we fit the responses of each individual participant with a sigmoid curve and calculated the maximum, minimum, midpoint and slope of the sigmoid identification function for each individual participant. Participants whose responses could not be reliably fitted with a sigmoid curve (those where the identification percentages did not rise or fall nearly-monotonically from one end of the continuum to the other) were excluded from subsequent analyses (the number of the remaining participants, see Table 1). *T*-tests were used to compare the two groups on these four parameters. Results from the /ɔ/-/ʊ/ continuum suggested that the individuals with dyslexia exhibited a lower maximum and a higher minimum (for statistical results, see Table 1). No other differences were significant.

Experiment 3b: discrimination

Methods

Materials and procedure: The materials corresponded to the same four continua used in Experiment 3a. In each trial, participants were presented with two step-members (A and B) followed by a third stimulus X, the probe, which was identical to either A or B. Stimulus A corresponded to steps 1–7, whereas stimulus B was always three steps higher than A (i.e. 1–4, 2–5, 3–6, etc.), a total of 7 combinations. Each of these 7 combinations was repeated twice – in half the trials, the probe X corresponded to A, in the other half, it corresponded to B, and the entire 14-trial sequence was repeated 4 times. Thus, each continuum (*da-ta, pa-ba, o-u, a-e*) gave rise to a block of 56 trials. Prior to each such block, participants were presented with 8 practice trials, comprising the naturally produced endpoints of the relevant continuum. Likewise, the identification and discrimination tasks were administered in a counter-balanced order. The order of the four continua was counter-balanced; within each block, trials were randomised.

Each trial began with a message indicating the trial number and a fixation point (*), which remained visible throughout the trial. Participants initiated each trial by pressing the spacebar, and their response triggered the presentation of three auditory stimuli. Stimulus A was presented for 700 ms, followed (Inter Stimulus Interval (ISI) of 500 ms) by stimulus B (displayed for 700 ms), and followed (ISI = 800 ms) by the probe X. Participants were asked to quickly indicate whether X was identical to A or B. Slow responses (RT > 2500 ms) triggered a warning message (there was no accuracy feedback in the experimental trials).

Results

Figure 6 plots participants' accuracy in the ABX discrimination tasks. Response accuracy of the two groups was compared by means of four logistic regression analyses, conducted separately for each of the four continua. Group and continuum step were entered as fixed effects (using treatment coding), whereas participants were considered as a random effect. Given that the group × step interaction did not improve the model's overall fit, we only considered an additive model. The main effect of group was significant for the *ta-da* continuum ($\beta = .39$, SE = .18, $Z = 2.16$, $p < .04$); participants with dyslexia were impaired in the identification of *da* and *ta*. No other group differences were significant (all $p > .7$).

Discussion

Experiment 3 gauged the phonetic performance of individuals with dyslexia and typical readers using identification and ABX discrimination tasks. The overall pattern of results from the two groups was quite similar, as the effect of group was not significant for most continua. While null group differences in phonetic tasks have been reported elsewhere in the dyslexia literature (e.g. Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009; Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreëls, 2001; Ramus et al., 2003; Robertson, Joanisse, Desroches, & Ng, 2009), in the present case, these null effects may have a methodological origin. First, the

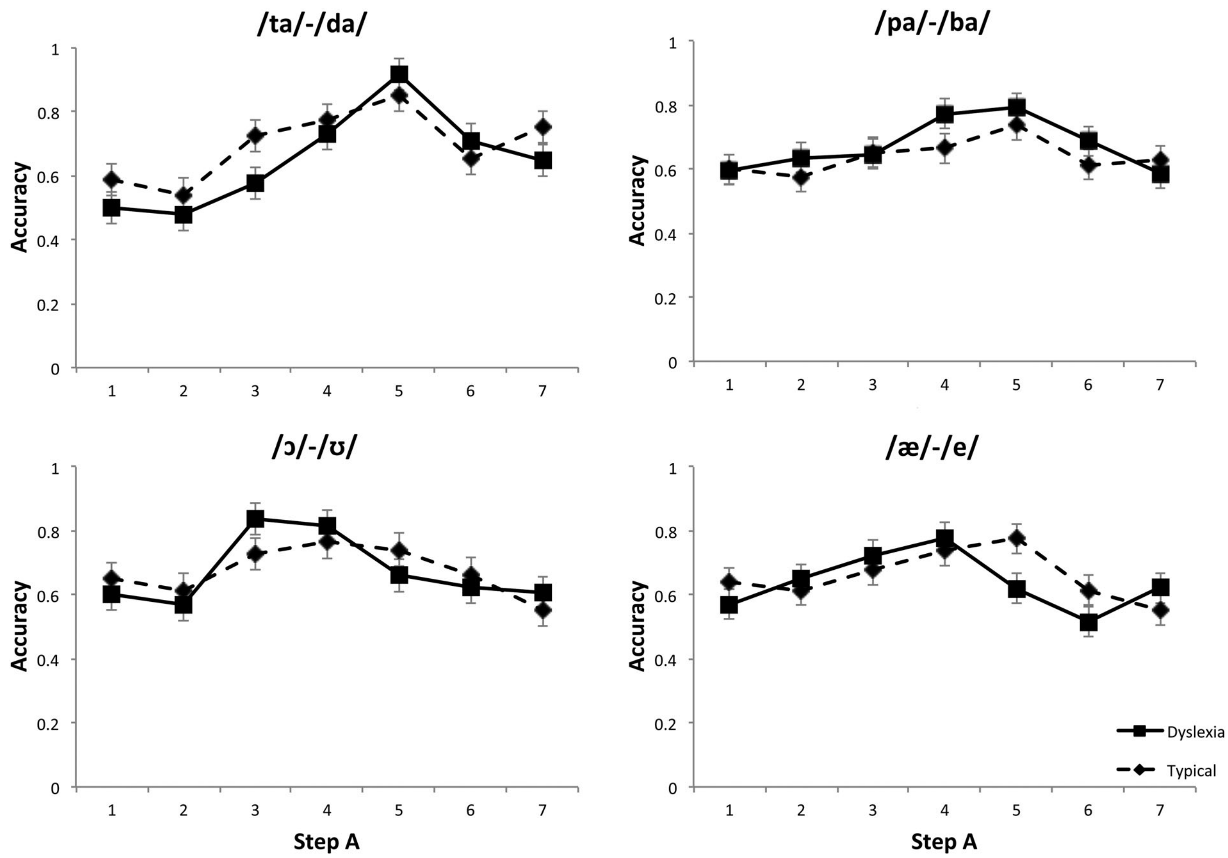

Figure 6. Response accuracy of participants with dyslexia and typical controls in the ABX task in Experiment 3. Error bars are 95% confidence intervals for the difference between the means.

sample size in Experiment 3 ($n = 11–12$) was smaller than in previous experiments ($n = 18$ in Experiments 1–2), and the power of the identification analysis was further diminished by the exclusion of participants whose percepts exhibited a poor sigmoid fit. Despite these methodological limitations, we still observed reliable group differences in each of the two procedures. In the identification of the /ɔ/-/ʊ/ continuum, individuals with dyslexia exhibited a lower maximum and a higher minimum compared to typical subjects, suggesting that their sensitivity to vowel quality was attenuated. Individuals with dyslexia likewise exhibited lower accuracy in the discrimination of the /t/-/d/ continuum. These phonetic difficulties mirror the impairment of individuals with dyslexia in the discrimination of monosyllables from disyllables in Experiments 1–2. Together these results indicate some subtle impairment to the phonetic system in these individuals.

General discussion

A large literature asserts that dyslexia originates from a phonological deficit (e.g. Bradley & Bryant, 1978; Mody et al., 1997; Olson, 2002; Paulesu et al., 2001; Perrachione et al., 2011; Pugh et al., 2000; Savill & Thierry, 2011; Shankweiler, 2012; Shaywitz, 1998; Tanaka et al., 2011). This assertion, however, has rarely been submitted to a direct empirical test. The few previous studies that have attempted to assess the linguistic phonological grammar in individuals with dyslexia have all obtained results that do not indicate a phonological impairment (Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2012, 2013; Blomert et al., 2004; Maïonchi-Pino et al., 2012a, 2012b; Maïonchi-Pino et al., 2013; Marshall et al., 2010; Szenkovits et al., 2016). The present study addressed this gap by directly contrasting phonological computation with auditory/phonetic processing.

To test the phonological grammar, we examined the sensitivity of individuals with dyslexia to a putatively universal constraint on syllable structure. Building on past research, we predicted that syllables with small sonority clines should be ill-formed, hence, they should be repaired (i.e. recoded) by the grammar as better-formed structures (e.g. lbif→*lbif*). The systematic repair of ill-formed syllables provides evidence for phonological computation. Our question here was whether these phonological computations are impaired in adults with dyslexia.

The results yielded no evidence for the phonological deficit hypothesis. Adults with dyslexia were fully sensitive to phonological structure in each of our two experiments, and their performance was indistinguishable from typical controls. This finding is remarkable given that most of the test syllables are unattested in the participants' language. The fact that individuals with dyslexia are able to freely generalise their phonological knowledge to novel forms is in line with the possibility that their phonological grammar is intact.

Unlike the phonological system, however, our three experiments yielded various indications of phonetic processing difficulties. These difficulties were evident even in our phonological tasks (Experiments 1–2), as participants with dyslexia were impaired in the discrimination of monosyllables from disyllables (in Experiment 1) and they were likewise impaired in the identification of disyllables as such (in Experiment 2). Because these effects were independent of syllable structure, these results must indicate difficulties not in phonological computation, but rather in the auditory/phonetic processing of brief vowels that differentiates monosyllables from disyllables. Our third experiment sought to explicitly compare the performance of individuals with dyslexia and typical control readers in standard phonetic identification and discrimination tasks. Although the performance of the two groups did not differ reliably for most continua – an outcome that is undoubtedly affected in part by the small sample size employed in the experiment, our dyslexia group did exhibit reliable impairments in each of the two phonetic tasks. While it is conceivable that some of the difficulties we observed in Experiment 3 result from the memory and metalinguistic demands of the ABX task (Ramus & Ahissar, 2012; Ramus, Marshall, Rosen, & van der Lely, 2013), we note that similar difficulties were also observed in both our phonetic identification task (Experiment 3a) and our forced-choice phonological tasks (Experiments 1–2), and they mirror similar findings in speech/nonspeech discrimination in our previous research (Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2012). Accordingly, the contrast between the difficulties in phonetic categorisation and the intact sensitivity to phonological structure cannot be explained by task demands alone.

Taken as a whole, our present results replicate and underscore the dissociation between the phonological and phonetic systems previously found in studies with Hebrew readers (skilled and disabled). While grammatical phonological generalisations appear to be intact, we observe various (albeit subtle) signs of phonetic impairments. Likewise, these results are in line with previous reports of intact phonological generalisations in adults with dyslexia, on the one hand, and numerous demonstrations of auditory/phonetic difficulties demonstrated in these individuals (e.g. Ahissar et al., 2006; Ramus & Szenkovits, 2008) as well as in animal models of dyslexia (Szalkowski et al., 2011, 2013; Threlkeld, Hill, Rosen, & Fitch, 2009; Threlkeld et al., 2007).

These results are nonetheless limited in several important respects. First, while our findings suggest some kind of deficit in auditory/phonetic processing, these results are insufficient to pinpoint the precise locus of this impairment (auditory or phonetic). Second, finding impairment in auditory/phonetic processing does not rule out the possible contribution of deficiencies in other realms that impact speech and language processing, including difficulties in lexical storage and retrieval, attention and working memory (e.g. Bosse et al., 2007; Ramus & Szenkovits, 2008; Wolf et al., 1986). Third, the intact sensitivity of adult participants with dyslexia to syllable structure does not rule out other potential impairments in the adult phonological grammar in features not examined here, nor does it preclude the possibility that such deficits might be present at birth, but may be ameliorated later in development (e.g. Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006; Temple et al., 2003; White et al., 2006). Finally, none of this work addresses underlying biological causes that could be altering the functions of other perceptual-cognitive systems, such as vision. While these outstanding questions await further research, our present results make it clear that the phonological deficit hypothesis cannot be taken for granted. The bulk of the existing evident suggests that the impairment in dyslexia originates from a phonetic rather than phonological source.

Note

1. Because each continuum type in this experiment was represented by only three items, we did not assess the reliability of the results across items.

Disclosure statement

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Appendix. The monosyllables used in Experiment 1

	Large rise	Small rise	Plateau	Fall
1	blif	bwif	bdif	lbif
2	brɑp	bnɑp	bdɑp	rgɑp
3	klim	knim	kpim	lpim
4	krɛk	knɛk	ktɛg	rtɛk
5	drif	dlif	dbif	rdif
6	drɑf	dlɑf	dgɑf	rdɑf
7	dwip	dmip	dgip	mdip
8	dwʊp	dmʊp	dgʊp	mdʊp
9	drʊp	dnʊp	dbʊp	rdʊp
10	driʃ	dniʃ	dgiʃ	rbiʃ
11	glɛp	gmɛp	gdɛp	lgɛp
12	glɑn	gmɑn	gbɑn	lfɑn
13	grɛf	gmɛf	gbɛf	rgɛf
14	gwit	gmit	gbit	mgit
15	klɛf	kmɛf	ktɛf	lkɛf
16	kræf	kmæf	kpæf	rgæf
17	krik	knik	ktig	rkik
18	kwʊg	knʊk	kpɑk	mkʊk
19	klɑp	kmʊp	ktɑp	ltɑp
20	krɛp	kmɛp	ktɛp	rkɛp
21	plik	pnik	pkik	ltik
22	præf	pnæf	ptæf	rpæf
23	trʊf	tlʊf	tkʊf	rtʊf
24	twɛp	tlɛp	tkɛp	mtɛp
25	trɑk	tnɑk	tkɑk	rtɑk
26	twæf	tmæf	tpæf	mtæf
27	trɛf	tnɛf	tpif	rtɛf
28	twʊk	tnʊk	tgʊk	mgʊk
29	træp	tmæp	tpæp	rpæp
30	twɑg	tmɑk	tpɑk	mtɑk