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PAPER

PHONOLOGY AND PHONETICS — LINKED, BUT DISTINCT: EVIDENCE FROM DYSLEXIA

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A large phonological literature debates whether the phonological grammar is distinct from the phonetic system. Here, we address this question using evidence from developmental dyslexia.

Individuals with dyslexia are known to exhibit subtle auditory and phonetic impairments, but their linguistic phonological competence is spared (e.g., Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2012). This result is puzzling, as phonetics provides the building blocks of phonology (e.g., features). If the phonetic system is impaired, then how can phonological structure stand intact?

We suggest that people with dyslexia compensate for their phonetic difficulties by over-relying on the phonological grammar. Our experiments gauge such top-down effects from phonology to phonetics. Participants—adult native Hebrew speakers—performed phonetic discrimination of a voicing contrast (e.g., *pa-ba* vs. *pa-pa*), embedded in novel tri-syllabic sequences (e.g., *ta**papa*** vs. ***pata**ta*). Our manipulation exploited the fact that ABB Hebrew stems favor identical over similar consonants (*ta**papa***>*ta**paba***), whereas BBA stems ban both forms (e.g., _**papa**ta_=_**paba**ta_). Of interest is whether this phonological principle biases phonetic discrimination.

Results from the dyslexia group showed that phonetic discrimination was strongly influenced by phonology. In particular, phonetic sensitivity (d') was reduced when the ambiguous targets (BB) were embedded in well-formed ABB phonological sequences (e.g., _ta**papa**_) relative to ill-formed BBA ones (e.g., _**papa**ta_). Typical readers exhibited no such effect. A follow up experiment established that the context effect is not simply due to sequential ordering, as the cost for ABB sequences was eliminated once the context syllable (A) was replaced by its sine wave analog.

These results show for the first time that adult individuals with dyslexia mitigate their auditory/phonetic difficulties by over-relying on their grammatical phonological knowledge. The resilience of phonology to perinatal sensory perturbations is in line with its view as a system of core knowledge. These results also contribute to the large body of evidence suggesting that phonology and phonetics are linked, but distinct.

Dyslexia, Phonology, Phonetics, Hebrew, OCP.

1 INTRODUCTION

The link between phonology and phonetics has been the topic of a heated controversy (e.g., Archangeli & Pulleyblank, 2015; Blevins, 2004; Bybee, 2002; Flemming, 2001, 2004; Hale & Reiss, 2008; Hayes, 1999; Hayes, Kirchner, & Steriade, 2004; Jun, 2004; Ohala & Kawasaki-Fukumori, 1990; Ohala, 1975; Pierrehumbert, 2012; Samuels, 2011; Steriade, 1997; Steriade, 2007; Volence & Reiss, 2020; Wright, 2004).

In her extensive contribution to linguistics, Outi Bat-El has argued that phonology is governed by abstract phonological constraints, and that these constraints cannot be attributed to experience alone (e.g., Bat-El, 1989, 1994, 2003a, 2003b, 2005, 2006, 2009; 2012). For example, she has shown that the phonological structures that children attempt at producing mirror not the speech of their parents, but rather the cross-linguistic preference which they have not directly experienced (Bat-El, 2012)

Bat-El has further shown how language disorders can speak to these theoretical debates. For example, her work on consonant harmony has demonstrated that the phonological grammar of children with speech dyspraxia differs from that of typical (Hebrew) children (Bat-El, 2009). Both groups exhibit errors in their speech production, and in both groups, the errors are systematic—they involve repetition. Critically, the types of errors differ. Typically developing Hebrew speakers align the repetition with the left edge of prosodic words (e.g., *klemantina* (tangerine) → *tatina*, not *manina*), whereas children with dyspraxia show right-alignment (e.g., e.g., *kofecet→kotetet*, for 'jumping').

In honor of her many contributions, here, we follow her lead, and consider how evidence from a disordered system—that of individuals with dyslexia— can shed light on the organization of the phonological grammar and its relation to the phonetic system.

We begin by describing the case of dyslexia, generally, and how it speaks to the separation between the phonological grammar and phonetics, in particular. We show that individuals with dyslexia exhibit subtle phonetic deficits, yet their phonological grammar is demonstrably intact. This dissociation between the (intact) phonological system and (disordered) phonetic system suggests that the two cannot be one and the same.

Having demonstrated that the phonological and phonetic systems are distinct, we next move to consider how the two distinct systems interact. The two studies reported here examine this question. Altogether, the case of dyslexia shows that, although the phonological and phonetic systems are demonstrably linked, they are nonetheless distinct.

1.1 THE PHONOLOGY-PHONETIC DIVIDE: WHAT IS THE DEBATE ABOUT?

Before we consider the case from dyslexia and its implications to the phonology-phonetics debate, let us briefly comment on what the debate is about. The debate, as we see it, is *not* about whether phonological processes are *grounded* in phonetic pressures. A large literature suggests that many phonological processes are “sensible” inasmuch as phonological processes seem to “conspire” to improve speech perception and production (Hayes, 1999; Hayes & Steriade, 2004; Steriade, 2001). Clearly, many phonological processes are “motivated” by phonetic pressures. The real debate, then, is *how*.

One possibility is that phonology and phonetics are indistinguishable. In this view, phonological representations and principles are not different in kind from phonetic ones. For example, analog phonetic values, such as acoustic duration, or “voice onset time” can directly inform phonological computations (e.g. Flemming, 2001; Kirchner, Moore, & Chen, 2010; Pierrehumbert, 2006; Zhang, 2004). Phonology and phonetics, then, are one and the same.

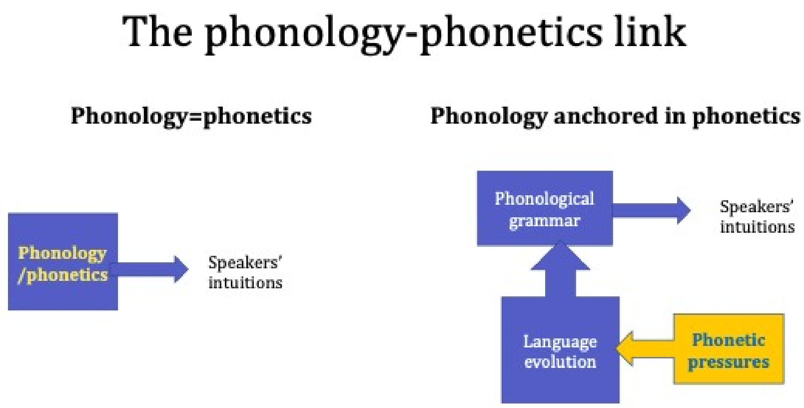

Figure 1. Two accounts of the phonology-phonetics link.

Another possibility, however, is that phonology and phonetics are distinct, and they each rely on different kind of representations. While phonological representations are abstract, inasmuch as they are discrete and algebraic, phonetic representations are analog and continuous. So, to the extent that phonological processes are phonetically motivated, this "motivation" applies only distantly. Phonetics, in this view, shapes the evolution of the phonological grammar: it "conspires" to favor the evolution of "sensible" phonological processes—ones that improve speech perception and production (Blevins, 2004). These phonetic forces, then, shape phonology *indirectly,* by constraining which phonological processes will likely "make it" into the grammars of individual speakers. But once the grammar is in place, it is now these phonological principles that are the direct cause of speakers' intuitions. In this way, then, phonology could be phonetically motivated, but still distinct from phonetics. Our following case from dyslexia tests this hypothesis.

As we next show, dyslexia compromises not only reading but also speech perception. Of interest, then, is what, precisely, is the nature of the deficit. We reason that, if phonology and phonetics are one and the same, then a deficit to one system (e.g., to phonetics) would necessarily entail a deficit to the other (e.g., to phonology). But if the two systems are distinct, then phonology and phonetics can *dissociate*: dyslexia could impair phonetic processes while leaving the phonological grammar intact. The former view (phonology=phonetics) predicts an association between the state of the two systems in dyslexia; the latter predicts a *dissociation* (see Figure 2). By offering evidence that such dissociation exists, we seek to bolster the case that phonology and phonetics are indeed distinct.

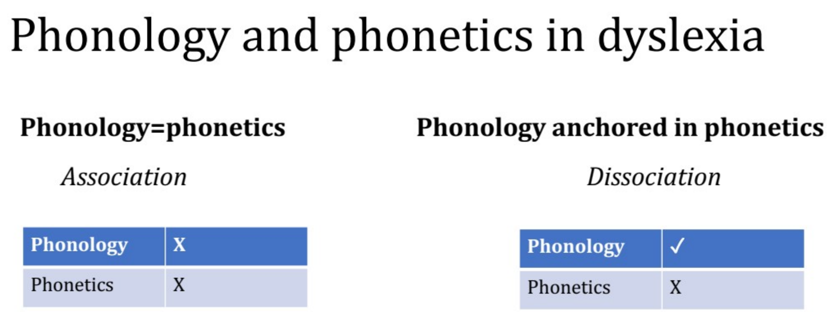

Figure 2. Two accounts of the preservation of phonology and phonetics in dyslexia. X marks impairment; √ marks intact functioning.

1.2 THE PHONOLOGICAL GRAMMAR IN DYSLEXIA AND ITS DISSOCIATION FROM THE PHONETIC SYSTEM

While dyslexia is primarily a reading disability, these difficulties with reading are often speech-based. A large literature shows that people with dyslexia exhibit subtle difficulties **in *speech perception*** (e.g., in phonetic categorization: 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), in gaining ***phonemic awareness*** (e.g., in detecting rhymes; Bradley & Bryant, 1978; Ramus et al., 2003) and in the ***mapping of graphemes to phonemes*** (e.g., in noticing that the letters *c* maps to /k/; 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).

Accordingly, many researchers attribute dyslexia to a "phonological deficit" (e.g., Bradley & Bryant, 1978; Mody et al., 1997; Olson, 2002; Paulesu et al., 2001; Perrachione, Del Tufo, & Gabrieli, 2011; Pugh et al., 2000; Savill & Thierry, 2011; Shankweiler, 2012; Shaywitz, 1998; Tanaka et al., 2011). But the precise significance of this claim is unclear. Indeed, "phonology" in the reading literature acquires quite a different meaning than in linguistics.

In the reading literature, "phonology" is defined quite broadly, to refer to any psychological process that is generally linked to "speech processing". This includes processes such as phonetic categorization, phonemic awareness and phonological decoding. Given that these processes are all demonstrably impaired in dyslexia, researchers have concluded that dyslexia arises from a "phonological" deficit.

Linguists, however, typically define phonology far more narrowly—as the grammatical system that generates the sound structure of language (Chomsky & Halle, 1968; Prince & Smolensky, 1993/2004). And as noted, many linguists further contrast phonology with the phonetic system—the interface that extracts discrete features from the continuous speech input (e.g., Anderson, 1981; de Lacy, 2004, 2008; Keating, 1988; Prince & Smolensky, 1993/2004). Phonology, then, is only one of the many systems mediating speech perception. Similarly, the phonological grammar is distinct from the system that maps graphemes to phonemes in reading. Consequently, deficit to speech perception and phonological decoding (as seen in dyslexia) does not necessary indicate a grammatical phonological impairment.

When the dyslexia literature is reexamined in light of this definition, the evidence for a "phonological deficit" all but vanishes. While the phonetic and auditory difficulties of individuals with dyslexia are well documented (for review, see Ramus & Ahissar, 2012), far fewer studies have examined the linguistic phonological system itself, and the ones who did typically found no evidence of a deficit (e.g., Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2013b; Berent et al., 2012; Blomert et al., 2004; Maïonchi-Pino, de Cara, Écalle, & Magnan, 2012a, 2012b; Maïonchi-Pino et al., 2013; Marshall, Ramus, & van der Lely, 2010; Szenkovits & Ramus, 2005; for review, see Berent et al., 2013b).

To directly contrast the phonological and phonetic systems in dyslexia, our past research has compared the sensitivity of the same group of participants on various aspects of phonological structure with their performance on standard phonetic categorization tasks (identification and discrimination).

Results from the ***phonetic*** tasks revealed the typical pattern of phonetic impairment. Remarkably, however, the dyslexia group was as sensitive as controls to ***phonological*** structure (Berent et al., 2013b, 2012; Berent, Zhao, Balaban, & Galaburda, 2016b). Moreover, these conclusions converged across two different languages—English and Hebrew, and two different aspects of phonological knowledge.

In one case, we examined the restrictions on syllable structure—the preference for syllables like *bnif* over *bdif*, which, in turn, are preferred to *lbif;* this preference has been documented across languages (e.g., Berent, Lennertz, Jun, Moreno, & Smolensky, 2008; Berent, Steriade, Lennertz, & Vaknin, 2007; Zhao & Berent, 2016), in children (e.g., Berent, Harder, & Lennertz, 2011; Ohala, 1999), and even newborn infants (Gómez et al., 2014), and there are reasons to believe this preference arises from the phonological grammar (Berent, 2013a). If dyslexia impairs the phonological grammar, then unlike typical readers, in people with dyslexia, the preference for better-formed syllables (e.g., *bnif>bdif>lbif*) should be attenuated. Results, however, offered no support for this hypothesis. Participants with dyslexia were just as sensitive to syllable structure as typical readers, and this was the case for both English and Hebrew speakers (Berent et al., 2013b; Berent et al., 2016b).

Another study examined the sensitivity of Hebrew speakers to the phonological structure of the stem morpheme in their language (a case with further explore below). Like other Semitic languages, in Hebrew, ABB stems (e.g., *ka__l__a__l__*, he included) are frequent, but AAB stems (e.g., *__k__a__k__al*) are banned. If dyslexia compromises the phonological grammar, then once again, one would expect Hebrew speakers with dyslexia to be less sensitive to the ABB vs. AAB asymmetry. This, however, was not found: individuals with dyslexia were just as sensitive to stem structure as typical readers (Berent et al., 2012).

Together, these results suggest that dyslexia impairs phonetic processing, a result that is in line with past research (e.g., Serniclaes & Seck, 2018). Contrary to widespread claims, however, our findings indicate that the phonological grammar in dyslexia is spared.

1.3 CAN INTACT PHONOLOGY COMPENSATE FOR A FAULTY PHONETIC SYSTEM?

The *dissociation* we have documented between the phonological and phonetic systems in dyslexia presents evidence that the two systems are in fact distinct. If they weren't, then deficit to the phonetic system ought to have compromised phonological computations, but the existing results suggest that this is not the case (at least for adult participants).

This possibility, however, also raises a conundrum. To assemble the phonological structure of a spoken word, hearers must first extract its phonetic form. This is not to say that phonology, or its building blocks (e.g., syllables, features) *are* phonetic. Rather, phonetic processing is the “gateway” to the phonology of spoken words. For example, to compute the phonological form of the spoken word *blog* (e.g., that *blog* has a complex onset) speakers must first correctly extract its phonetic form (e.g., as [blɔg], not [lɔg]); there is no other “direct” route from speech to phonology. But if the phonetic system is faulty, how can the phonological edifice stand intact?

In what follows, we test a novel explanation for this puzzle. We propose that adults with dyslexia ***compensate*** for their deficient auditory/phonetic processing by over-relying on top-down feedback from their phonological grammar. We reason that, if the phonological grammar in dyslexia is intact, then adults with dyslexia might be able to exploit the phonological context in order to resolve phonetic ambiguities in speech sounds. We thus predict that people with dyslexia will show atypical phonetic processing, but that these anomalies would be governed by intact phonological knowledge.

1.4 THE PRESENT STUDIES

In the following experiments, we gauge phonetic processing using a standard AX discrimination task. In each trial, people heard two target syllables, sampled from continuum that gradually changed from a voiced to a voiceless consonant (e.g., *ba→pa*) in ten equal sets. These targets were either identical (e.g. pa_1-pa_1; the subscripts denote two targets from set 1), or ones separated by two steps (e.g., pa_1-pa_3). Participants were asked to determine whether or not the targets were identical. Of interest is whether individuals with dyslexia perform the phonetic discrimination task by over-relying on phonological knowledge of their native language—Hebrew.

Our study exploits the fact that Hebrew constrains the co-occurrence of consonants in the stem morpheme. Identical consonants are allowed at the end of the stem (e.g., *ratat*,) but not at its beginning (e.g., *rarat*, Greenberg, 1950). In contrast, adjacent similar (nonidentical) consonants (those with the same place of articulation) are banned irrespective of position (Berent, Vaknin, & Shimron, 2004). Thus, at the beginning of the stem, identical and similar consonants are both banned (e.g., ***tat**ar*=***tad**ar*). In contrast, at the stem's end, identical consonants are abundant (e.g., *ra**tat***, 'vibrated'), whereas similar consonants are avoided (e.g., *ra**tad***). Previous research has shown that individuals with dyslexia are fully sensitive to the phonological constraint on stem structure (Berent et al., 2012). Our question here is whether this phonological knowledge informs the phonetic discrimination of identical and similar consonants (e.g., between *t* and *d*).

To address this question, the discrimination targets (e.g., pa_1-pa_2) were presented in a tri-syllabic sequence, either followed or preceded by a context syllable (e.g., *ta* ***pa₁pa*** vs. ***pa₁pa₂**ta*). The resulting sequences thus exhibited either an ABB or BBA structure, and they were invariably novel Hebrew words. Our experiments examined whether the phonological structure of these sequences constrains the resolution of their phonetic ambiguity.

Recall that in the ABB context, identical consonants are better formed than similar consonants (e.g., ta**papa**>ta**paba**). Accordingly, the ABB context favors the interpretation of the ambiguous phonetic targets as identical (i.e., as *ta**papa***, not *ta**paba***). By contrast, BBA sequences are ill-formed regardless of whether the consonants are identical or similar (e.g., ***papa**ta* =***bapa**ta*), so no bias is expected there.

If phonological knowledge constrains the resolution of phonetic ambiguity, then phonetic discrimination (e.g., is pa_1=pa_3) should be impaired in the well-formed ABB relative to the ill-formed BBA context. Of interest is whether this effect of phonological context can be found in individuals with dyslexia.

If the phonological grammar in dyslexia is impaired, then for people with dyslexia, the effect of phonological context should be attenuated. But if, as we argue, the phonological grammar in dyslexia is intact, and furthermore, if people with dyslexia over-rely on their phonological grammar to compensate for their faulty phonetic system, then they should show a *stronger* effect of phonological context. Consequently, people with dyslexia should show stronger tendency to perceive distinct phonetic tokens (e.g., *pa_1 vs.* pa_3) as identical in the ABB context (where ta**papa**>ta**paba**) compared to the BBA context (where ***papa****ta* =***bapa****ta*), and this context effect (the ABB vs. BBA contrast) should be *stronger* in people with dyslexia compared to typical readers.

Experiment 1 addresses this question using adult Hebrew speakers with dyslexia and typical readers (controls). To determine whether the context effect is due to phonological structure or the position of the targets in the sequence (first vs. last), Experiment 2 replaced the context syllable A by its sine wave analog; subjectively, the A sound was now perceived a musical tone. If the effect of context concerns phonological structure, then top-down effects should only obtain in the speech context (in Experiment 1), but not in the nonlinguistic (temporally matched) nonspeech condition (in Experiment 2).

2 EXPERIMENT 1: AMBIGUOUS SPEECH SOUNDS IN PHONOLOGICAL CONTEXT

Experiment 1 evaluated the phonetic discrimination between two spoken syllables, that are ambiguous with respect to their voicing (between *papa* and *paba*; hereafter, BB). Of interest is whether the resolution of this phonetic ambiguity is influenced by the phonological context.

To this end, we presented these ambiguous syllables in in two contexts—one (ABB)—in which identical syllables would be preferred to nonidentical syllables (e.g., *tapapa>tapaba*); another context (BBA) elicited no such bias, as here, both syllables are (equally) ill-formed (*papata=pabata*).

If people with dyslexia suffer difficulties in *phonetic* processing, then they should show greater difficulty in the identification of ambiguous speech sounds than controls. Critically, if their phonological grammar is intact, then it is conceivable that individuals with dyslexia would over-rely on phonological context in order to compensate for their phonetic difficulties. Accordingly, we expect the phonological context to exert stronger effect on the resolution of the phonetic ambiguity in the dyslexia group relative to the control group.

2.1 METHODS

2.1.1 Participants

Experiments 1-2 each employed two groups of participants (N=12 per group). One group consisted of individuals with an existing diagnosis of dyslexia; the control group included typical readers. Those two groups were drawn from a sample of 17 individuals with dyslexia and 20 typical readers (16 females per sample), students at the Western Galilee College, Israel.

2.1.2 Reading assessment

Prior to the experiments, each group took part in three reading tests. One test (from Shany, Lachman, Shalem, Bahat, & Zeiger, 2005) elicited naming of 37 nonwords; the two other tests (developed by M. Shani, A Biemiller & I. Ben-Dror) required the reading aloud of two passages (100 words each), either with vowel diacritic[1] or without them. The dyslexia group was slower on all three tests. Its error rate was likewise higher, and significantly so in the nonword reading test (see Table 1).

1 The Hebrew orthography is a consonantal system; most vowels are omitted in typical texts. However, children's books, religious texts and poetry typically indicate vowels using a system of diacritic marks. Hebrew readers are typically adept at reading diacritics.

Table 1. The performance of the dyslexia and control group on reading tests.

		Mean		***SD***		***t(35)***	***p value***
		Dyslexia	*Typical*	*Dyslexia*	*Typical*		
Nonword reading	Time (S's)	95.36	73.46	39.10	25.59	2.04	.05
	Number of errors	10.00	5.00	6.87	3.87	2.78	.009
Text reading (no diacritics)	Time (S's)	65.06	51.93	14.24	10.89	3.18	.003
	Number of errors	4.82	1.55	7.88	1.23	1.84	.07
Text reading (with diacritics)	Time (S's)	59.20	46.99	16.01	10.64	2.77	.009
	Number of errors	3.24	1.10	5.06	1.25	1.83	.08

2.1.3 Stimuli

The experimental materials consisted of tri-syllabic sequences, generated from recordings of a native Hebrew speaker. Each such sequence paired two target syllables (BB) with a context syllable (A), resulting in either an ABB sequence or a BBA sequence.

The target syllables were sampled from the two continua used in Berent et al., 2012 and described therein. Each continuum progressively varied from a voiced consonant to its voiceless counterparts in ten steps; either /ba/-/pa/ or /ta/-/da/. Half of the stimuli featured two identical targets (e.g., pa_1-pa_1), the other half of the stimuli featured two non-identical targets, separated by 2 continua steps (e.g., pa_1-pa_3). To match the identical and non-identical conditions for the frequency of the different steps in the experiment, we divided the materials into sets. Each such set featured two steps, balanced for the frequency of occurrence in the set, their position in the pair (first/last) and their identity (e.g., pa_1-pa_1, pa_3-pa_3, pa_1-pa_3, pa_3-pa_1). In what follows, we refer to these sets as "***step-sets***", and we number them from 1-8 according to the lowest step-set (e.g., pa_1-pa_3 forms part of step-set 1).

Each of the target syllables was next paired with a context syllable A, corresponding to the voiceless endpoint of the opposite continuum, either /ta/ (for the *pa-ba* continuum) or /pa/ (for the *ta-da* continuum). Half of the stimuli featured the context syllable prior to the targets (ABB); in the other half, the context followed the targets (BBA). Thus, ABB and BBA sequences were comprised of precisely the same phonetic tokens; the only difference concerned the order of their presentation.

The context syllable and targets were inspected using Praat (Boersma & Weenink, 2018) and they were matched for their pitch contours. To render the resulting trisyllabic stimuli natural sounding, we further separated the three syllables by two equal silence intervals whose length was set to 25% of the preceding target (M=111ms, SD=10ms). The average duration of the trisyllabic stimuli was 1475 ms (range: 1426 in step-set 7 to 1588 ms in step-set 1). Each participant was presented with a total of 256 trials, balanced for context type (ABB/BBA), place (labial/alveolar), target identity (identical/different) and step-set (1-8). The two voicing continua (labial vs. alveolar) and two contexts (ABB/BBA) were presented in four separate blocks, counterbalanced for order. Within block, trial order was randomized. The materials and data for this and the subsequent experiment is posted on the OSF (DOI 10.17605/OSF.IO/7A2G9).

2.1.4 Procedure

Participant initiated each trial by pressing the space bar. Their response triggered the presentation of a trisyllabic auditory sequence, either ABB or BBA. Participants were asked to indicate whether the target syllables (BB) were identical by pressing the appropriate key (1=identical; 2=nonidentical). Participants were advised to listen carefully, as the differences between the stimuli were very subtle. They were also asked to listen to the entire sequence before making your choice. Slow (RT>2500 ms) triggered a warning message. Prior to the experimental session, participants received 12 practice trials, similar in kind to the experimental trials. During the practice, participants received feedback on both speed and accuracy.

2.2 RESULTS AND DISCUSSION

Figure 4 plots the sensitivity (d') of the dyslexia and control groups in the phonetic discrimination task. Unlike accuracy, sensitivity (d') is affected not only by correct responses (hits) but also by false alarms—the higher the difference between hits and false alarms, the stronger the sensitivity. In this experiment, "hits" are defined as correct responses to identical trials. All data figures were generated in JASP (Goss-Sampson, 2020), where error bars are normalized standard errors (Morey, 2008).

An inspection of the means suggests typical readers were largely indifferent to the phonological context (ABB vs. BBA) . In contrast, for individuals with dyslexia, the identification of phonetically ambiguous syllables was heavily influenced by the phonological context, so in the ABB context, phonetic sensitivity (d') decreased.

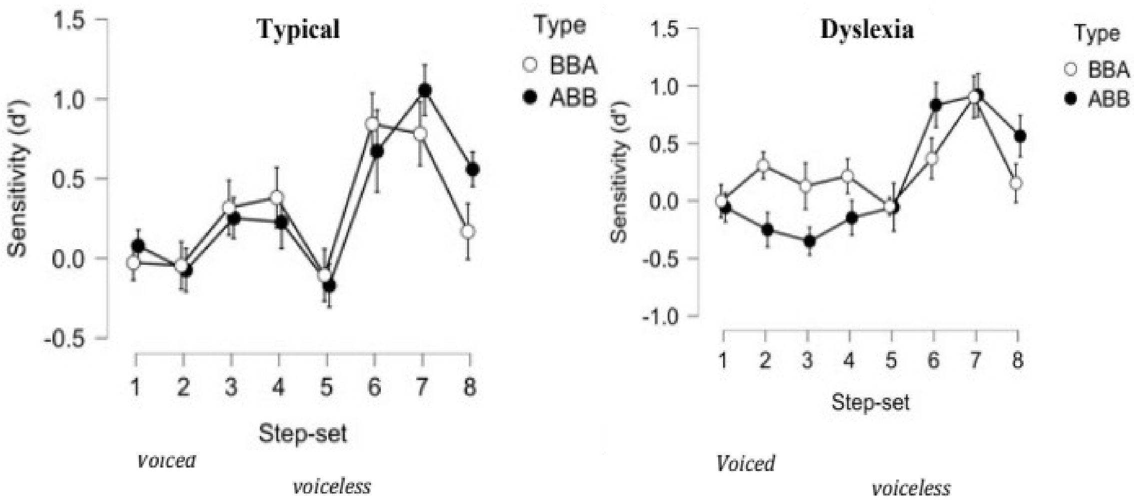

Figure 4. Sensitivity (d') of the dyslexia group and typical readers in the phonetic discrimination task using speech context.

Recall that the critical syllables were ambiguous with respect to their voicing (e.g., in between *papa* vs. *paba*), and they were presented in two phonological contexts—one (ABB) that favors identical consonants (e.g., *tapapa*>*tapaba*) and one that does not (*papata*=*pabata*). Results showed that people with dyslexia were more likely to identify the two syllables as identical when the context favored identity—in the ABB relative to the BBA context.

Thus, for people with dyslexia, the resolution of the voicing ambiguity at the ***phonetic*** level (*papa* vs. *paba*) was apparently affected by ***phonological*** well-formedness. In contrast, typical readers appeared to have resolved the phonetic ambiguity “on its own terms”, without “assistance" from the phonological level.

To evaluate the reliability of these observations, we next submitted the results of each group to a 2 context (BBA/ABB) x 8 step-set ANOVA . As we next demonstrate, the statistical analyses indeed bear these conclusions out.

2.2.1 Typical readers

The analysis of typical readers yielded only a significant main effect of step-set ($F(7,77)=8.26$, $p<.0001$; $\eta^2_{partial}=.43$). Typical participants exhibited higher sensitivity to voiceless (e.g., *tapapa*) relative to voiced (e.g., *tababa*) sequences, possibly because these sequences were acoustically shorter (see Methods), hence, easier to maintain in working memory.

Tukey HSD tests showed that step-set 7 yielded reliably better discrimination than step-sets 1-5; similarly, step-set 6 yielded better sensitivity than step-sets 1,2 and 5 (all $p<.05$). Critically, the main effect of context (BBA vs. ABB) and its interaction with step-set were not significant (both $Fs<1.20$, n.s.). These results demonstrate that the ability of typical readers to identify speech sounds that were phonetically ambiguous with respect to their voicing was unaffected by the phonological context.

2.2.2 People with dyslexia

Unlike typical readers, the dyslexia group showed strong effects of phonological context on phonetic discrimination. The 2 context x 8 step-set ANOVA yielded a reliable step-set x context interaction ($F(7,77)=3.20$, $p<.005$; $\eta^2_{partial}=.22$).

The simple main effect of context was significant at step-set 2 ($F(1,11)=7.38$, $p<.03$; $\eta^2_{partial}=.40$), and marginally so at step-set 3 ($F(1,11)=4.00$, $p<.08$; $\eta^2_{partial}=.27$). Thus, the dyslexia group was less sensitive to the voicing contrast when targets were embedded in the phonologically well-formed ABB context (e.g., *ta**ba_1ba_3***) compared to the ill-formed BBA context (e.g., ***ba_1ba_3**ta*).

Like typical participants, however, individuals with dyslexia showed a significant effect of step-set ($F(7,77)=9.80$, $p<.0001$; $\eta^2_{partial}=.47$). Tukey HSD tests revealed that, like typical readers, for the dyslexia group, step-set 7 yielded higher sensitivity than step-sets 1-5; similarly, discrimination at step-set 6 was higher than step-sets 1,2 and 5 ($p<.05$). Unlike the typical group, however, the dyslexia group additionally showed better sensitivity at step-set 7 relative to step-set 8; similarly, step-set 6 yielded higher sensitivity than step-sets 3-4 ($p<.05$).

2.2.3 Group comparison

We next examined whether the two groups differed with respect to their reliance on phonological context in resolving phonetic ambiguity. To this end, we compared responses to the phonetically ambiguous step-sets (step-sets 2-7; steps 1& 8 corresponded to the unambiguous endpoints of the continuous) via a 2 Group (Typica/Dyslexia) x 2 Context (BBA vs. ABB) x 6 Step-set. The hypothesized three way interaction was significant ($F(5,110)=2.27$, $p=.05$, $\eta^2_{partial}=.017$)[2].

2 An analysis of response times further showed that individuals with dyslexia were slower to respond to identical stimuli relative to typical readers ($\Delta=130$ ms, $t(22)=2.42$, $p<.03$; for non-identical stimuli: $\Delta=29$, $t(22)<1$).

Summarizing, the results of Experiment 1 show that people with dyslexia differed from typical readers with respect to their reliance on phonological context. When typical readers were presented with syllables that were ambiguous with respect to their voicing (in between *papa* and *paba*), they resolved the ambiguity by exploiting phonetic cues, ignoring the phonological context.

In contrast, for people with dyslexia, the resolution of this phonetic ambiguity was heavily dependent on the phonological context. When the phonological context favored identical consonants (i.e., in the ABB context), these participants were more likely to identify the ambiguous phonetic inputs as identical (e.g., *tapapa*>*tapaba*) compared to when the context did not favor identity (i.e., for the BBA context, where *papata* and *pabata* are both ill-formed). Consequently, in the ABB context, their phonetic sensitivity (d') decreased.

3 EXPERIMENT 2: AMBIGUOUS SPEECH SOUNDS EMBEDDED IN NON-SPEECH CONTEXT

Experiment 1 showed that, in the dyslexia group, phonetic sensitivity was attenuated when the phonological context (ABB) favored the interpretation of the phonetic inputs as identical (e.g., as *ta**papa***, relative to *ta**paba***). This finding is in line with the possibility that these participants compensate for their faulty phonetic system by over-relying on phonological knowledge. However, it is possible that the difficulties with ABB sequences could arise not from phonological structure, but rather from sequential position: the fact that ABB sequences feature the BB target last (whereas in BBA sequences, these targets appear first).

To address this possibility, in Experiment 2 we replaced the critical context syllable (A) with its sine wave analog (hereafter*). The resulting sequences sounded like a hybrid of two speech syllables (BB) and a musical tone (*). This manipulation thus faithfully maintained all temporal aspects of the original speech sequences, but eliminated the differences in their phonological structure.

If the disadvantage of ABB sequences is due to their sequential ordering, then similar results should obtain with their sine wave analogs (BB*). In contrast, if the context effect in Experiment 1 is due to phonological knowledge, then the context effect should now be eliminated.

3.1 METHODS

Two groups of participants took part in Experiment 2 (N=12 per group). One group consisted of typical readers; the other included participants with dyslexia. Participants with dyslexia also took part in Experiment 1 (for their characteristics, see Table 1); four of the typical readers likewise took part in Experiment 1.

The materials and procedures were identical to Experiment 1, except that the context syllable A was replaced with its sine wave analog, preserving the pitch and intensity of the original sound (hereafter: *). These analogs were prepared by using the synthesize command in Boersma & Weenink, 2018). Instructions were as in Experiment 1, except that participants were informed that each trial presents them with three sounds, two of the sounds are either identical (e.g., *papa*) or very similar (e.g., *bapa*); whereas the third sound consists of a musical tone.

3.2 RESULTS AND DISCUSSION

Figure 5 plots the sensitivity (d') of the dyslexia and control groups for the BB and BB sequences in the context of the nonspeech (tone) context, *. As in Experiment 1, both groups showed superior performance at step-set 7. But unlike the speech context, when the ambiguous syllables were embedded in the context of nonspeech, now, participants with dyslexia no longer relied on the context in resolving the phonetic ambiguity. Thus, participants with dyslexia responded similarly in the *BB and BB* context. As expected, this was also the case for typical readers. These conclusions are borne out by the analyses of the two groups.

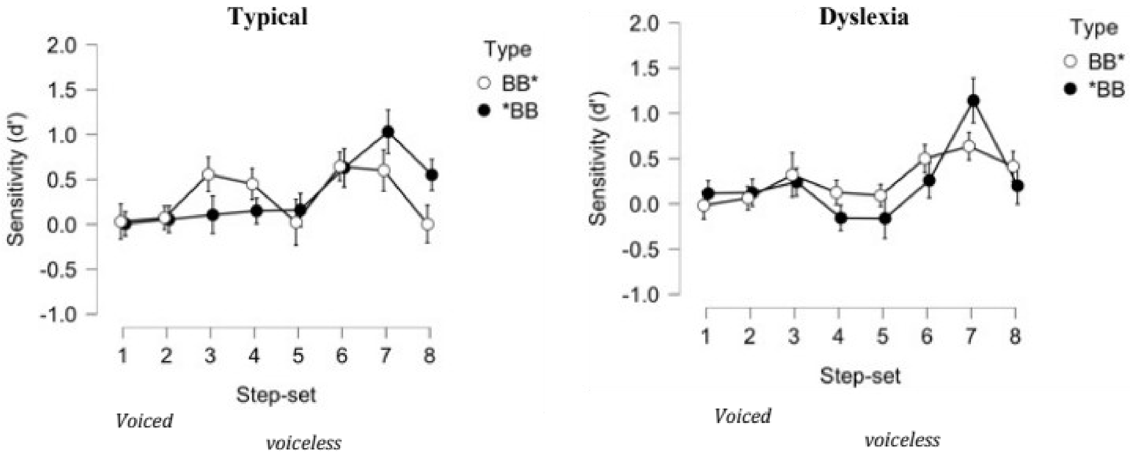

Figure 5. Sensitivity (d’) of the dyslexia group and typical readers in the phonetic discrimination task in the ***nonspeech*** context (* indicates a tone)

The 2 context x 8 step-set ANOVA yielded only a main effect of step-set, significant for both the dyslexia ($F(7,77)=5.65$, $p<.0001$; $\eta^2_{partial}=.34$) and control ($F(7,77)=4.76$, $p<.0002$; $\eta^2_{partial}=.30$) groups.

Tukey HSD contrasts showed that the voiceless endpoint yielded better sensitivity. For the control group, step-set 7 yielded higher sensitivity than step-sets 1,2, and 5, and step-set 6 yielded superior performance relative to step-sets 1-2. The dyslexia group showed a hyper-sensitivity to the step set, with an advantage of step-set 7 over both step-sets 1-5 and step-set 8-- a pattern mirroring the findings of Experiment 1. Critically, the effect of step-set did interact with context in either group (for the dyslexia group: $F(7,77)=1.47$, $p>.20$; $\eta^2_{partial}=.12$; for the control: $F(7,77)=1.72$, $p>.12$; $\eta^2_{partial}=.14$).

To confirm the lack of a context effect, we further probed the simple main effect of context at steps 2-3—neither comparison approached significance (both F<1). The main effect of context was likewise not significant in the omnibus ANOVAs (F<1 for both groups).

To further secure the differences between the speech (in Experiment 1) and non-speech context (in Experiment 2) , we next compared the performance of each group in Experiments 1-2 by means of a 2 Experiment x 2 Context x 8 Step-set ANOVA.

This analysis yielded a reliable three-way interaction for the dyslexia ($F(7,154)=2.65$, $p<.02$; $\eta^2_{partial}=.11$), but not for the control group (F<1). These results demonstrate that the advantage of the dyslexia group with BBA sequences (in Experiment 1) is specifically due to their phonological structure, rather than their sequential order.

4 GENERAL DISCUSSION

In this research, we sought to revisit the contentious links between the phonological and phonetic systems using evidence from dyslexia. Individuals with dyslexia are known to exhibit subtle difficulties in phonetic processing (for review, see Ramus & Ahissar, 2012). Surprisingly, their sensitivity to linguistic phonological structure appears intact (e.g., Berent et al., 2013b, 2012; Blomert et al., 2004; Maïonchi-Pino et al., 2012a, 2012b; Maïonchi-Pino et al., 2013; Marshall et al., 2010; Szenkovits & Ramus, 2005).

These results would seem to suggest that the phonological and phonetic systems are distinct, inasmuch as developmental neurological disorder can impact one system (phonetics) while sparing the other (phonology). Yet this proposal immediately encounters a problem: How can a faulty auditory/phonetic system give rise to intact phonological structure in on-line language processing?

The present research sought to address this conundrum, and in so doing, shed light on the interaction between phonology and phonetics, generally. We suggest that adult individuals with dyslexia compensate for their faulty phonetic system by over-relying on their phonological knowledge. The results of our two experiments are in line with this proposal.

Experiment 1 showed that, unlike typical readers, in the dyslexia group, phonetic discrimination was strongly modulated by phonological context. The dyslexia group was more likely to perceive ambiguous phonetic inputs as identical when this percept yielded a better-formed phonological sequence (*e.g., tapapa>tapaba*) compared to when it didn't (e.g., *papata=pabata*). No such effect was found with typical readers.

Experiment 2 demonstrated that this context effect is not simply due to the temporal orderings in two sequences—the fact that the ABB context presents the critical BB pair last, whereas in BBA, it is presented first. Indeed, when the context syllable (A) was replaced by its sine wave analog (*), the difficulties of the dyslexia group with target-final sequences were eliminated. These results suggest that the context effect observed with the speech context (in Experiment 1) is specifically due to phonological structure of these sequences, not merely temporal order.

Our present results are limited inasmuch as they obtain from a single case study (the restrictions on identical consonants in Semitic stems), and a single study with a rather small group of participants. Whether these results generalize to other cases remains to be seen. Another limitation of the study arises from the fact that participants are adults, and thus, their phonological system is fully in place. Whether similar results would obtain in children and infants at-risk for dyslexia remains to be seen.

Notwithstanding these limitations, these results support several conclusions. First, the differences we had unveiled between typical readers and ones with dyslexia in phonetic discrimination (in Experiment 1) show that phonetic processing in dyslexia is impaired. Second, our results also show, for the first time, that individuals with dyslexia compensate for this phonetic challenge by over-relying on phonological knowledge. Third, the fact that people with dyslexia can exploit such grammatical phonological principles further demonstrates that, unlike their atypical phonetic system, their phonological grammar is intact.

This conclusion speaks to two broad literatures—one concerning phonological theory; another concerning dyslexia. The finding that the phonological and phonetic systems *dissociate* in dyslexia offers evidence that these systems cannot be one and the same. As such, these results are in line with the hypothesis that the phonological grammar is distinct from the phonetic system.

Our conclusions also speak to the literature on dyslexia. Our findings challenge the widely held belief that dyslexia originates from a phonological deficit. To be sure, we do not question the empirical findings that are routinely cited in support of the "phonological deficit" hypothesis, including the difficulties of individuals with dyslexia in phonological decoding, phonemic awareness and speech perception cited in the Introduction. Those difficulties are firmly established, and we do not doubt these conclusions. Rather, we suggest that, for adult individuals, these difficulties originate not from impairment to the phonological grammar, but rather in the phonetic interface.

We hypothesize that the phonological grammar is resilient to such deficits because phonology is rooted in core knowledge. Core knowledge systems are innate, domain-specific systems of knowledge that set the foundation for the acquisition or knowledge later in life (Spelke, 1994; Spelke & Kinzler, 2007). For example, newborn infants demonstrably possess rudimentary understanding of numerosity (Izard, Sann, Spelke, & Streri, 2009) and of the physical world (Mascalzoni, Regolin, Vallortigara, & Simion, 2013), and these innate principles offer the scaffolding for the emergence of mathematical and physical understanding, later in life.

Phonology exhibits similar characteristics, as its design seems to be innately constrained, and these constraints set the foundations for both mature phonological systems as well as for the acquisition of the related system of reading (Berent, 2013a, 2013b). These innate phonological constraints might also allow individuals with dyslexia to converge on a functionally intact grammar despite impairment to low level phonetic and auditory processing. The possibility that phonology is a system of core knowledge is supported by previous findings, showing that people exhibit knowledge of phonological principles that are unattested in their language (e.g., Berent et al., 2008; Berent et al., 2007), and precursors of this knowledge are evident at birth (Gómez et al., 2014). Other results show that phonological principles are abstract, as speakers with no knowledge of a sign language spontaneously extend phonological principles from their native phonology to signs (Berent, Bat-El, Brentari, Dupuis, & Vaknin-Nusbaum, 2016a; Berent, Dupuis, & Brentari, 2013a). We suggest that a more precise characterization of the linguistic phonological system can bring important insights into the study of dyslexia, and language, generally.

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DISCUSSION WITH CHLOË MARSHALL

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COMMENTS

There is much to admire in the article by Berent, Vaknin-Nusbaum and Galaburda (henceforth BVG). The premise and design of their study are neat. On the whole, I am convinced by their interpretation that the findings reveal a distinction between impaired phonetics and intact phonology, a situation that would not be possible if phonetics and phonology were one and the same, but that *is* possible for a phonological system anchored in phonetics yet distinct from it. One of things I find particularly helpful is their clarification of how the term ‘phonology’ is used in the dyslexia literature. There, it is most usually used very broadly to encompass any aspect of speech processing, but this characterisation is arguably too broad to pinpoint where phonology breaks down in dyslexia. Some researchers have instead attempted to draw a distinction between, for example, the ability to access phonological representations and the quality of those phonological representations (Ramus & Szenkovits 2008, Ramus, Marshall, Rosen & van der Lely 2013), and have located the phonological deficit in the former. Related work has discovered that assimilation for place in English and voicing in French – an aspect of phonological grammar – does not appear to be impaired in dyslexia (for English: Marshall, Ramus & van der Lely 2010, for French: Szenkovits, Darma, Darcy & Ramus 2016). Thus, wherever the phonological deficit lies in dyslexia, it arguably lies neither in phonological representations nor in phonological grammar.

BVG’s argument develops this line of work and centres on being able to show a dissociation between phonology and phonetics, with dyslexic individuals’ phonological grammar being unaffected despite a phonetic (speech perception) impairment. In the developmental cognitive science literature, there has long been an effort to use developmental disorders to discover dissociations between language and non-language abilities, and between different components of language, in order to reveal the modular structure of the mind.

However, despite the appeal of developmental dissociations where it comes to theory, empirically they are rarely clean-cut. At the end of the last century there was considerable excitement that specific language impairment (SLI; now more commonly referred to as developmental language disorder, and characterised by grammatical deficits) and Williams Syndrome (WS, a rare genetic condition leading to developmental delays and learning challenges) might provide evidence of a double dissociation between grammar and non-verbal intelligence. Pinker summed up this excitement by writing "...the genetic double dissociation is striking, suggesting that language is both a specialization of the brain and that it depends on generative rules that are visible in the ability to compute regular forms. The genes of one group of children [i.e., SLI] impair their grammar while sparing their intelligence; the genes of another group of children [i.e., WS] impair their intelligence while sparing their grammar." (Pinker 1999: 262). But this characterisation has been challenged numerous times by, amongst others, Karmiloff-Smith, who writes "Empirical data show that absolute statements about "sparing" of intelligence or grammar should actually be relative statements. True, people with WS are better at language than at nonverbal tasks, but their language is far from «intact». Many studies reveal that WS language follows an atypical developmental trajectory... Similar arguments can be made with respect to SLI where intelligence is claimed to be «spared». Many studies now point to subtle impairments in the intelligence of children with SLI that cannot be explained away by the linguistic component of tasks." (Karmiloff-Smith, Scerif & Ansari 2003: 161).

Further dissociations have been posited between different subgroups of individuals with SLI, such as grammatical-SLI (van der Lely, Rosen & McClelland 1998) and syntactic, phonological, lexical and pragmatic subtypes of SLI (Friedmann & Novogrodsky 2008), all named after the locus of impairment within a putative modular language system. However, these subgroups are not widely accepted (e.g., Joanisse & Seidenberg 2003, Tomblin & Pandich 1999) and are not recognised clinically.

None of this implies that a dissociation between phonology and phonetics does *not* exist and can*not* be revealed in a developmental disorder such as dyslexia, but we need to be aware that the data might turn out to be too messy to show it clearly. A hallmark of dyslexia is that it frequently co-occurs with other learning conditions (e.g., SLI, attention deficit and hyperactivity disorder), and trying to distinguish which phonological behaviour is characteristic of which condition is challenging (Messaoud-Galusi & Marshall 2010). There is also considerable individual variability in how dyslexia manifests, which raises questions of just how characteristic of dyslexia particular experimental findings are. And like any small-scale experimental work, BVG's study needs replication in order to determine the robustness of its findings. In particular, we would want to see studies involving different individual participants using the same experimental materials that BVG used (to counter the objection that there might have been something particular about the 12 dyslexic participants who took part in BVG's studies), but also experimental materials involving comparable phenomena across different languages (to counter the objection that there might be something particular to Hebrew).

Even assuming that BVG's findings are replicable under the conditions set out above, and that we can therefore have confidence in phonetics and phonology being distinct, there remains a very intriguing puzzle. That puzzle concerns how a seemingly normally-functioning phonological grammar can be built out of a phonetic system that is *not* functioning normally. BVG claim that "the phonological grammar is resilient to such deficits because phonology is rooted in core knowledge", in line with Berent's previous proposal of "a unique design that is relatively invariant across all individuals and forms the scaffold for the acquisition of all subsequent knowledge" (Berent 2013: 36). But what does such a core system look like at birth, and what is gained through language exposure? Berent further writes "While some aspects of core phonology could manifest themselves in infancy, this system might nonetheless be triggered by phonetic experience" (Berent 2013: 48). But the language-specific knowledge of dyslexic individuals (be it Hebrew's ban on AAB syllables, or French's assimilation for voicing in contrast to English's assimilation for place) comes via phonetic experience that – due to their impaired speech perception – is not typical. Is it, however, good enough to support the development of phonological grammar? And does orthography play a role? Although learning to spell and read is challenging for dyslexic individuals, does experience with categorical visual symbols (i.e., letters) support Hebrew dyslexics' learning that ABB words like *tapapa* occur but AAB words like **papata* do not?

Like the very best studies, BVG's raises many questions and provides the motivation for further exciting experimental work which, as they write, "can bring important insights into the study of dyslexia, and language, generally."

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