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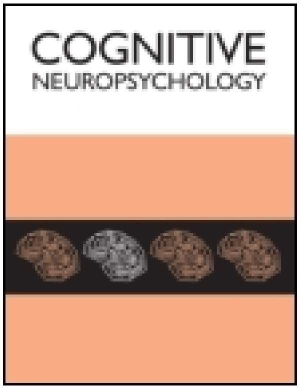

Cognitive Neuropsychology
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/pcgn20

Phonological generalizations in dyslexia: The phonological grammar may not be impaired

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Published online: 17 Dec 2013.

To cite this article: Iris Berent, Vered Vaknin-Nusbaum, Evan Balaban & Albert M. Galaburda (2013) Phonological generalizations in dyslexia: The phonological grammar may not be impaired, Cognitive Neuropsychology, 30:5, 285-310, DOI: 10.1080/02643294.2013.863182

To link to this article: http://dx.doi.org/10.1080/02643294.2013.863182

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Cognitive Neuropsychology, 2013
Vol. 30, No. 5, 285–310, http://dx.doi.org/10.1080/02643294.2013.863182

Phonological generalizations in dyslexia: The phonological grammar may not be impaired

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Dyslexia is commonly attributed to a phonological deficit, but whether it effectively compromises the phonological grammar or lower level systems is rarely explored. To address this question, we gauge the sensitivity of dyslexics to grammatical phonological restrictions on spoken onset clusters (e.g., *bl* in *block*). Across languages, certain onsets are preferred to others (e.g., *blif* ≻ *bnif*≻ *bdif*, where≻ indicates a preference). Here, we show that dyslexic participants (adult native speakers of Hebrew) are fully sensitive to these phonological restrictions, and they extend them irrespective of whether the onsets are attested in their language (e.g., *bnif* vs. *bdif*) or unattested (e.g., *mlif* vs. *mdif*). Dyslexics, however, showed reduced sensitivity to phonetic contrasts (e.g., *blif* vs. *belif; ba* vs. *pa*). Together, these results suggest that the known difficulties of dyslexics in speech processing could emanate not from the phonological grammar, but rather from lower level impairments to acoustic/phonetic encoding, lexical storage, and retrieval.

Keywords: Dyslexia; Phonology; Phonetics; Hebrew; Onset clusters; Sonority.

Dyslexia is defined by a failure to acquire reading skill in the face of adequate opportunities to learn and in the absence of intellectual or emotional barriers to do so (Shaywitz, 1998). Nonetheless, the difficulties of dyslexic individuals are not confined to reading. A large body of research demonstrates that dyslexia is associated with a host of deficits to the processing of spoken language, including abnormalities in the identification and categorization of speech sounds (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), and deficits in talker identification (Perrachione, Del Tufo, & Gabrieli, 2011) and in discriminating

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speech from nonspeech (Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2012). Moreover, many of these deficits are already evident in early development, well before reading is acquired (van Herten et al., 2008; Leppänen et al., 2002). However, a comprehensive explanation of all of these difficulties remains elusive.

Although dyslexia has been frequently attributed to a "phonological" deficit (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 claim is not directly supported by the available evidence. This is by no means the result of a shortage of papers that test the "phonological" processing of dyslexics. Rather, the problem arises because the dyslexia literature rarely defines "phonology" in the first place. When definitions are offered, they often equate "phonology" with "speech processing" (Ramus & Ahissar, 2012)—a practice that is inconsistent with many linguistic proposals.

The conflation of phonology with speech processing obscures the precise characteristics of dyslexia and its origins. We suggest that a linguistically informed account of phonology can help identify the sources of the speech perception deficit in dyslexia; the experiments presented here support this contention.

We begin our investigation by outlining a linguistically motivated account of the phonological system and proceed to evaluate the "phonological" deficit hypothesis in light of this analysis. These conclusions lead to our experimental investigation, discussed next.

PHONOLOGY, PHONETICS, SPEECH

All human languages possess two levels of patterning (Hockett, 1960). One level combines words (meaningful elements) to form sentences (e.g., *the* + *dog* + *barks*); another level forms words (e.g., *dog*) by patterning smaller meaningless elements (e.g., those corresponding to the speech sounds *d,o,g*). That such patterns exist is evident from the fact that a given set of meaningless elements can combine in multiple ways (e.g., *dog* vs. *god*) and give rise to novel combinations (e.g., *blog*), yet such patterns are constrained—English, for instance, allows *dog*, not *dgo*. People's productive knowledge concerning the patterning of meaningless linguistic elements is called *phonology*.

In most human communities, linguistic communication proceeds via speech, so it is tempting to equate phonology with speech patterns. But a closer inspection suggests that this is not the case. First, phonological patterns are not confined to speech. Sign languages rely on manual gestures, but just like their spoken counterparts, signed words are composed of productive phonological patterns that combine meaningless elements (Stokoe, 1960). In fact, some aspects of phonological design are amodal. Like spoken languages, signed phonological systems encode syllables (units distinct from morphemes) defined by principles comparable to those constraining syllables in spoken language (Berent, Dupuis, & Brentari, 2013; Brentari, 1998; Sandler & Lillo-Martin, 2006).

A second reason for the distinction between phonology and speech processing is presented by the distinct computational properties of these two systems (Abler, 1989). The phonological system is discrete and combinatorial (Chomsky & Halle, 1968; Hayes, 1999; Hyman, 2001; Keating, 1988; Pierrehumbert, 1975, 1990; Zsiga, 2000). It consists of discrete features (e.g., voicing, a feature that contrasts /b/ and /p/) that are preserved under combinations. For example, adding the voicing feature to /t/ has a predictable effect, equivalent to its addition to /k/—in both cases, the segment changes to its voiced counterpart (i.e., to /d/ and /g/, respectively). Accordingly, features define classes (e.g., "voiced segments", e.g., /b/, /d/, /g/) that are subject to productive phonological rules—algebraic operations that apply to all members of a class alike. These rules constitute the *phonological grammar*.

In contrast to the discrete combinatorial system of phonology, the speech signal is analogue (Abler, 1989; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967)—it carries multiple cues that vary continuously (e.g., voice onset time, Lisker & Abramson, 1964). Moreover, once combined, phonetic cues blend, such that their contribution varies depending on neighbouring cues, the talker's identity, and the speaking rate (e.g., Liberman et al., 1967; Miller & Grosjean, 1981).

These dissociations between phonology and low levels of the speech processing system suggest that the two mechanisms are distinct. The *phonetic* system is the interface that bridges between them by extracting the discrete elements of phonology from the analogue sensory input—either acoustic or visual (for speech and signs, respectively). To use a metaphor, the combinatorial phonological grammar is akin to a Lego system; the phonetic interface is likened to the process that extracts discrete Lego blocks from the continuous mass of plastic material the blocks are made out of.

Summarizing then, speech processing deploys a host of mechanisms (see Figure 1), ranging from low-level auditory analysis of the acoustic input to its phonetic categorization into discrete features, the extraction of phonological representations, the evaluation of their well-formedness using grammatical phonological rules, and the storage of these representations in memory. The phonological grammar is one such component, distinct from the phonetic system.

THE "PHONOLOGICAL DEFICIT" IN DYSLEXIA

Armed with the above-mentioned distinction between phonology, specifically, and speech processing, broadly, we can now turn back to the dyslexia literature and ask what findings single out the phonological grammar as the source of the speech processing difficulty. Viewed in this way, the evidence for the "phonological deficit" hypothesis is rather limited.

Most of the empirical support for a "phonological deficit" is based on three observations: (a) Dyslexics exhibit well-documented deficiencies in the phonological decoding of *printed* language

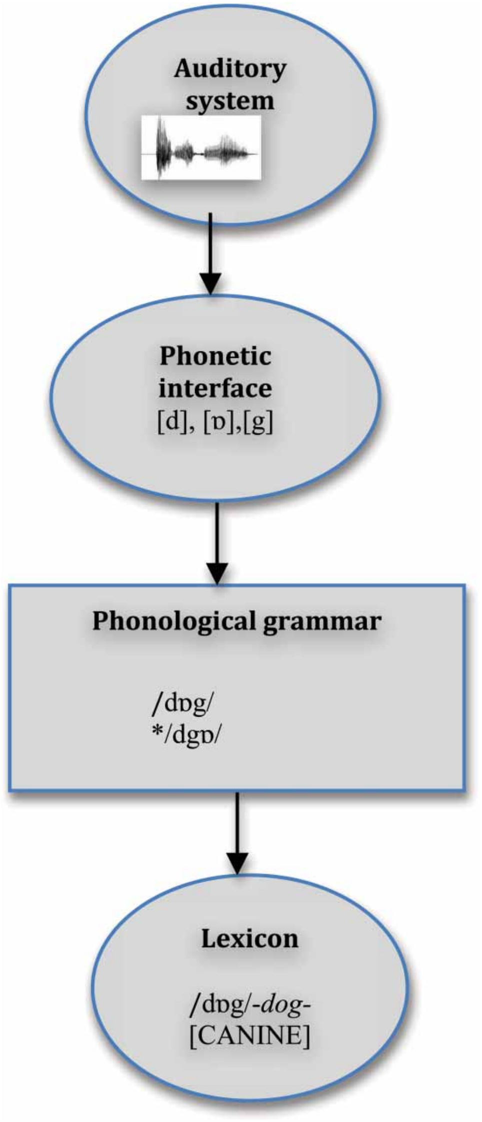

Figure 1. *Components of the speech processing system. Upon an encounter with a spoken word (e.g.,* dog*), the auditory input undergoes acoustic processing, followed by the extraction of its segments (by the phonetic interface) and the computation of its phonological representation by the phonological grammar—a set of algebraic constraints that evaluate the relative well-formedness of phonological representations. Such constraints, for instance, render syllables like* dog *better formed than* dgo *(ill-formedness is indicated by the asterisk). The resulting phonological form is stored in the mental lexicon, along with the corresponding meaning and orthographic form.*

(e.g., Olson, Wise, Conners, & Rack, 1990; Rack, Snowling, & Olson, 1992; Shaywitz, 1998); (b) they exhibit difficulties in gaining *conscious awareness* of the structure of language (e.g., Bradley & Bryant, 1978; Ramus et al., 2003); and (c) many dyslexic individuals exhibit coarse deficits in *speech processing*—mostly in the identification and discrimination of phonetic categories (e.g., *b* vs. *p*; Blomert et al., 2004; Brandt & Rosen, 1980; Chiappe et al., 2001; Godfrey et al., 1981; Mody et al., 1997; Paul et al., 2006; Rosen & Manganari, 2001; Serniclaes et al., 2001; Serniclaes et al., 2004; Werker & Tees, 1987; Ziegler et al., 2009), and the discrimination of speech from nonspeech (Berent, Vaknin-Nusbaum, et al., 2012) and of talkers' voices (Perrachione et al., 2011) The initial two lines of evidence (a–b) do not specifically concern linguistic competence, whereas the third—global deficits in speech processing—is too broad to specifically implicate a phonological disorder.

Only few studies have explicitly examined the sensitivity of dyslexics to phonological patterns (evidence we review next), and their outcomes, for the most part, do not point to a phonological impairment (Blomert et al., 2004; Maïonchi-Pino et al., 2013; Marshall, Ramus, & van der Lely, 2010; Szenkovits, Darma, Darcy, & Ramus, 2011). This state of affairs thus raises two questions. First, do dyslexics exhibit an attenuated sensitivity to the phonological regularities of their spoken language.[1] To the extent that their sensitivity to phonological patterns is reduced, one can ask whether the impairment originates from problems with the phonological grammar (the system of algebraic rules that support phonological generalizations), or from nonphonological sources including basic auditory processing (Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006; Pasquini, Corriveau, & Goswami, 2007; Tallal & Piercy, 1973), phonetic analysis (Mody et al., 1997), and lexical storage and retrieval (Ramus & Szenkovits, 2006).

We begin by reviewing existing evidence concerning the phonological competence of dyslexics (i.e., their tacit knowledge of grammatical phonological rules). We next introduce a new case study, explain why it potentially presents a significant challenge to dyslexic individuals, and finally describe the experiments and their results.

THE PHONOLOGICAL COMPETENCE OF DYSLEXIC INDIVIDUALS

Existing evidence concerning the phonological competence of dyslexics mostly comes from three cases. The first concerns phonological processes that "compel" adjacent speech segments to agree on their features. For example, English enforces an agreement in the voicing of the plural suffix and preceding consonant—stems ending with a voiced consonant (e.g., *dog*) take a voiced suffix (e.g., *dogs*, where the *s* is realized as a /z/) whereas those ending with a voiceless consonant (e.g., *cat*) take a voiceless suffix /s/ (e.g., in *cats*). A related process enforces feature agreement in the place of articulation—this process explains the tendency of English speakers to produce *green beans* as *greem beans*, where the coronal place (of *n*) assimilates to the following labial *b* to yield a labial nasal, *m*. These processes have been explored in dyslexic speakers of multiple languages (English, French, Dutch). Although some behavioural studies using auditorally presented words report normal sensitivity to feature agreement (Blomert et al., 2004; Marshall et al., 2010; Szenkovits et al., 2011), some impairment was detected in brain responses (Bonte, Poelmans, & Blomert, 2007), and abnormalities were also detected as in a behavioural study using printed words (Bedoin, 2003).

A second case concerns the restriction on fully identical consonants in Hebrew. Like other Semitic languages, Hebrew allows identical

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[1] We use the term "regularities" and "patterns" interchangeably, to refer to the co-occurrence of phonological elements in the linguistic input. Whether such patterns are in fact encoded by individual speakers, and whether they do so by relying on the phonological grammar, is a separate empirical question.

consonants to occur at the end of the stem (e.g., *simem*) but bans them at its beginning (e.g., **sisem*; Greenberg, 1950). Adult Hebrew dyslexics were fully sensitive to the restriction on identical consonants, and they freely extended it to novel stems (Berent, Vaknin-Nusbaum, et al., 2012). Remarkably, however, these same individuals showed various phonetic impairments in the identification and discrimination of phonemes.

Intact phonological rules are also evident in a third case, examining the sensitivity of dyslexics to sonority restrictions on syllable structure. Those restrictions are detailed next, but for now, suffice it to note that certain syllable shapes and combinations are systematically preferred to others. Across languages, syllable combinations like *al.ba* (where the initial syllable ends with a sonorant, and the following syllable begins with a stop) are preferred to the reverse sequences (e.g., *ab.la*). Previous studies compared the sensitivity of French dyslexic participants (French dyslexic children) with controls to this restriction. Results showed either intact sensitivity to sonority restrictions (i.e., the effects of sonority were not reliably modulated by reading ability; Maïonchi-Pino, de Cara, Écalle, & Magnan, 2012), or even enhanced sensitivity in the dyslexic sample (Fabre & Bedoin, 2003).

How is one to reconcile this apparently intact competence of dyslexics to various phonological rules with their widely documented difficulties in processing other aspects of spoken language? We propose that dyslexics may possess a fully intact grammatical phonological system, but exhibit subtle deficits in phonetic processing. If this is true, then dyslexic impairments would presumably reside in lower level systems of auditory and phonetic processing, perhaps coupled with impairments to lexical storage and access. A large literature shows that dyslexics exhibit abnormalities in acoustic and phonetic processing (for review, see Ramus & Ahissar, 2012) and that these difficulties appear to be exacerbated when the acoustic input is presented either rapidly (Galaburda et al., 2006; Merzenich et al., 1996; Tallal, 2004; Tallal & Piercy, 1973) or in a degraded form (Ziegler et al., 2009). Because the extraction and application of phonological regularities hinges on an intact encoding of the input, it is conceivable that dyslexics could exhibit difficulties in the application of phonological rules concerning events that are phonetically challenging—those that are rapidly occurring and/or vulnerable to masking from neighbouring segments.

Onset clusters present a case with significant phonetic challenges. It is well known that onset clusters (e.g., *pla*) are generally harder to identify and produce than simple onsets (e.g., *pa*). Simple onsets allow for the consonant and vowel to be coarticulated (Mattingly, 1981). Coarticulation not only optimizes the production of the two sounds, but also facilitates their perception, as critical phonetic cues for the consonant are carried by the neighbouring vowels (Wright, 2004). Consonant clusters offer no additional benefit for coarticulation (relative to simple onsets), and they typically raise the potential for acoustic masking. Consonant sequences that occur at the onset of a word (e.g., *bla*) are particularly vulnerable, as unlike the intervocalic consonants studied in previous research (e.g., *abla*), onset consonants (e.g., *bla*) cannot benefit from coarticulation with a preceding vowel. In addition, syllables with complex onsets are also confusable with similar disyllables (e.g., *plight* vs. *polite, sport* vs. *support*, Pitt, 1998; see also Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999), as the brief vowels in such forms are difficult to extract. Accordingly, it is conceivable that even if dyslexics have a relatively normal sensitivity to the structure of intervocalic clusters (e.g., *abla* vs. *alba*), it still would be difficult for them to encode the phonological properties of onset clusters (e.g., *blif* vs. *lbif*). Only one previous study has systematically examined this question with French dyslexic children, and the results show that the performance of dyslexic children was comparable to that of typical controls (Maïonchi-Pino et al., 2013). But because this research did not assess the phonetic capacities of these individuals, it is unclear whether they exhibit the speech disorder deficit typical of dyslexic individuals. The research reported below probes for such impairments among adult Hebrew-speaking dyslexics.

SONORITY RESTRICTIONS ON ONSET CLUSTERS

Many languages allow syllables to begin with onset clusters, and the range of clusters that are allowed varies greatly across languages. English systematically allows only clusters like *blog*, Hebrew allows *bl* (e.g., *bli*, "without") and *bd* (e.g., *bdil*, "tin"), but not *lb* (Bat-El, 2012), whereas all three types of clusters are attested in Russian (Halle, 1971). Nonetheless, not all clusters are equally preferred across languages. While clusters like *bl* are frequent, clusters like *bd* are less prevalent, and clusters like *lb* are quite rare (Berent, Steriade, Lennertz, & Vaknin, 2007). These regularities have been captured by sonority restrictions on syllable structure.

Sonority (indicated by s) is a scalar phonological property that correlates with the acoustic loudness of segments—loud segments (e.g., vowels, $s = 5$) tend to be more sonorous than quieter segments (e.g., consonants). Among consonants, most sonorous (i.e., loudest) are glides (e.g., *w*, *y*), with a sonority level of 4 ($s = 4$), followed by liquids (e.g., *l*, *r*, $s = 3$), nasals (e.g., *m*, *n*, $s = 2$), and obstruents (e.g., *p*, *t*, *k*, *b*, *d*, *g*, *v*, *f*, *s*, *z*, $s = 1$). Thus, onsets such as *bl* manifest a large rise in sonority (a sonority distance of 2, $\Delta s = 2$), *bn* onsets manifest a smaller rise ($\Delta s = 1$), *bd* onsets exhibit a sonority plateau ($\Delta s = 0$), whereas in *lba*, the onset falls in sonority ($\Delta s = -2$).

The preference (denoted $\succ$) for $bl \succ bn \succ bd \succ lb$ favours onsets with large sonority distances (i.e., large rises $\succ$ small rises $\succ$ plateaus $\succ$ falls)—the larger the sonority distance, the more preferred the onset (Clements, 1990; Hooper, 1976; Smolensky, 2006). Typological research has indeed shown that the frequency of a cluster across languages is predicted by its sonority distance—small sonority distances are systematically underrepresented (Berent et al., 2007). Moreover, languages that allow small sonority distances tend to also allow larger distances, whereas the reverse does not follow. For example, Russian allows sonority falls (e.g., *lb*), along with plateaus and rises (both small and large), whereas English allows large rises, but it does not systematically tolerate smaller sonority distances (i.e., small rises, plateaus, and falls in sonority). The generality of sonority restrictions across spoken languages suggests that they might form a universal phonological restriction on syllable structure.[2] In this view, all phonological grammars share universal phonological rules that render onsets with large sonority distances better formed—the larger the distance the better formed the onset. Crucially, such restrictions are expected to operate universally in all grammars, regardless of whether the particular cluster is present or absent in the language (Prince & Smolensky, 1993/2004; Smolensky, 2006).

Consistent with this prediction, we have previously found that speakers of various languages (English: Berent, Balaban, Lennertz, & Vaknin-Nusbaum, 2010; Berent, Lennertz, & Balaban, 2012; Berent, Lennertz, Jun, Moreno, & Smolensky, 2008; Berent, Lennertz, Smolensky, & Vaknin-Nusbaum, 2009; Berent et al., 2007; Spanish: Berent, Lennertz, & Rosselli, 2012; Korean: Berent et al., 2008; Mandarin: Zhao & Berent, 2013) favour onsets with large sonority distances over clusters with small sonority distances, and such preferences are evident even when these structures are unattested in the participants' language. For example, English speakers favour onsets like *bn* ($\Delta s = 1$) over onsets like *bd* ($\Delta s = 0$), which, in turn, are preferred to *lb* (e.g., $\Delta s = -2$), despite no familiarity with either sonority profile.

In these experiments, participants were presented with matched monosyllables whose onset structure was systematically varied (e.g., *blif, bnif, bdif, lbif*) along with disyllables that minimally differed from their monosyllabic counterparts inasmuch as the onset cluster was separated by a schwa (e.g., *belif, benif, bedif, lebif*). In one set of tasks, participants were simply asked to identify the input as either

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[2] Sonority restrictions also account for the occurrence of clusters across syllables. Here, clusters that fall in sonority (e.g., *al.ba*) are preferred to sonority rises (e.g., *ab.la*), as high-sonority elements are preferred at the syllable's end (i.e., coda; Clements, 1990).

monosyllabic or disyllabic; in other experiments, people were presented with a pair of items—either identical (e.g., *blif–blif; belif–belif*) or nonidentical pairing of monosyllables with their disyllabic counterparts (e.g., *blif–belif*), and they were asked to determine whether the pair members are identical (AX discrimination). Results consistently showed that performance was systematically modulated by the sonority profile of the onset. As the sonority distance of the onset decreased, participants were more likely to misidentify the monosyllable with its disyllabic counterparts. Thus, illicit monosyllables (e.g., *lbif*) were often misidentified as disyllables (in the syllable count), and they were frequently misperceived as identical to their disyllable counterparts (in the AX discrimination)—the worse formed the onset, the more likely its misidentification (Berent et al., 2007, 2008).

This systematic misidentification of ill-formed onsets is unlikely to be the result of "innocent misperception" (Blevins, 2007). That is, listeners' difficulties with *lbif* do not occur because people simply fail to encode the auditory or phonetic form of such items (Davidson, 2011; Davidson & Shaw, 2012; Dupoux, Parlato, Frota, Hirose, & Peperkamp, 2011). Likewise, these sonority effects are not the result of the similarity of such items to onsets that are attested in participants' languages (Daland et al., 2011), as the findings were replicated even in languages that lack onset clusters altogether (e.g., in Korean and Mandarin Chinese, Berent et al., 2008; Zhao & Berent, 2013), and their precursors are evident in the brain of neonate infants (Gomez et al., 2013).

By elimination, then, these results suggest that the effects of onset structure stem from a grammatical phonological source. In this view, all grammars ban onsets with small sonority distances. Accordingly, when presented with such onsets, the input (e.g., *lbif*) is actively *repaired* (i.e., recoded) by the phonological grammar (e.g., as *lebif*) in order to abide by universal grammatical phonological constraints. While these conclusions are not free of controversy (issues we revisit in the General Discussion), these findings, along with the findings from linguistic analyses, open up the possibility that sonority restrictions are universal grammatical constraints (Berent, 2013). The experiments below examine whether the sensitivity to these sonority restrictions is intact among dyslexic individuals.

THE PRESENT EXPERIMENTS

The present experiments examined the sensitivity of dyslexic individuals and controls to the sonority profile of onset clusters. Our participants were all adult college students who were native speakers of Hebrew—a language that exhibits a rich variety of onset clusters. Not only does Hebrew allow obstruent-initial onsets with large sonority rises (e.g., *blamim*, "brakes") but it even tolerates small rises (e.g., *bnei-Israel*, "sons of Israel") and plateaus (e.g., *ptil,* "wick"). However, Hebrew bans falls in sonority (Bat-El, 2012), and it also disallows onset clusters that begin with a sonorant—either sonority rises (e.g., *mla*) or falls (e.g., *lba, mda*).

Our previous investigation indicated that these dyslexic participants exhibited an intact sensitivity to another grammatical phonological constraint (the restriction on identical consonants across vowels), but their phonetic processing was impaired (Berent, Vaknin-Nusbaum, et al., 2012). In light of these findings, the present research asks whether these same individuals extract phonological regularities present in onset clusters—phonological structures whose phonetic properties are far more challenging. Two experiments address this question; in both, participants were asked to discriminate auditory monosyllables from disyllables. The materials and tasks are identical to those employed in our previous published experiments, demonstrating systematic phonological effects of sonority. In Experiment 1, the sonority manipulation concerned onsets that are attested in Hebrew (e.g., *blif, bnif, bdif*), whereas Experiment 2 probed participants' sensitivity to the structure profile of nasal-initial onsets (e.g., *mlif* vs. *mdif*) that are unattested in their language.

In view of the documented low-level phonetic/auditory processing deficits of these dyslexic participants, we expect them to be impaired in the *overall* discrimination of monosyllables and disyllables (i.e., across the various sonority types). Of interest is whether these individuals are nonetheless sensitive to the sonority of monosyllables (e.g., In Experiment 1, the contrast between *blif, bnif, bdif;* in Experiment 2, the contrast between *mlif* and *mdif*).

If the phonological grammar is impaired in dyslexia, then the effect of sonority should be attenuated in dyslexic participants. Likewise, if, contrary to our phonological account, the misidentification of onset clusters reflects phonetic (Davidson, 2011; Davidson & Shaw, 2012; Dupoux et al., 2011) or lexical factors (i.e., the similarity of these novel stimuli to attested Hebrew words), then these dyslexic individuals should exhibit a diminished sonority effect, as our past results with the same participants have shown that their phonetic processing is impaired, and other studies have argued that dyslexics exhibit a lexical deficit (Ramus & Szenkovits, 2006; for some support with these individuals, see Berent, Vaknin-Nusbaum, et al., 2012, Experiment 1). While a phonetic deficit would attenuate the effect of sonority of dyslexics across the two experiments, a lexical deficit would produce stronger attenuation with attested onsets (e.g., *blif* vs. *bnif,* in Experiment 1) than with unattested ones (e.g., *mlif* vs. *mdif;* in Experiment 2).

In contrast, if sonority restrictions are indeed phonological, and if this knowledge is intact in dyslexia, then, despite their demonstrable phonetic deficits, dyslexic individuals will exhibit full sensitivity to sonority, irrespective of familiarity (for both Experiments 1 and 2). As sonority distance decreases, the onset should become worse formed, and, consequently, it should be more likely to undergo grammatical repair that will recode the monosyllabic input as a disyllable (e.g., *mdif*→ *medif*)—the worse formed the onset, the more likely the repair. Since our task requires participants to count the number of syllables, the phonological repair of monosyllables will impair their discrimination from disyllables, resulting in slower and less accurate responses to monosyllables with small sonority distances than to those with larger distances.

EXPERIMENT 1

Experiment 1 presented participants with monosyllabic nonwords of four types (see Table 1). Three of those types had onsets that are attested in Hebrew, and they all began with a stop (large rises, small rises, and plateaus), whereas the fourth type (sonority falls—e.g., *lbif*) started with a sonorant and was unattested. These items were presented to participants along with their disyllabic counterparts (e.g., *belif, benif, bedif, lebif*), and participants were asked to determine whether the input had one syllable or two.

This experiment examined two questions: (a) Are participants sensitive to whether or not a monosyllable is attested in Hebrew, and (b) is the identification of attested monosyllables further modulated by their sonority distance? Because attested onsets are stored in the Hebrew lexicon, their identification should be typically superior to that for unattested onsets. To the extent that dyslexic individuals exhibit a lexical impairment, then they should exhibit an attenuated advantage of attested onsets (collapsed over the various sonority types) over unattested onsets.

Our main question concerns the sensitivity of dyslexics to the internal structure of the onset. To this end, we next turn to compare the identification of the various attested onsets to each other. Because monosyllables with small sonority distances (e.g., *bdif*) are ill formed, they are more likely to undergo repair (e.g., as *bedif*); since the

Table 1. *An illustration of the materials used in Experiment 1*

Attestation	*Onset type*	*Monosyllables*	*Disyllables*
Attested clusters	Large rise	blif	belif
	Small rise	bnif	benif
	Plateau	bdif	bedif
Unattested clusters	Fall	lbif	lebif

repair recodes monosyllables as disyllables (e.g., *bdif→bedif*), it should impair their discrimination—the smaller the sonority distance, the greater the difficulty. Our previous research has documented such misidentification using the same materials and task (Berent et al., 2007, 2008), and subsequent studies confirmed the phonological locus of these effects (e.g., by using printed materials, Berent & Lennertz, 2010). Of interest is whether dyslexics will show full sensitivity to this phonological restriction—comparable to that of typical readers.

Method

Participants

The experiment included groups of dyslexic participants and controls ($N = 21$ per group). Participants were all native Hebrew speakers, students at the University of Haifa. Dyslexic individuals are the same group of participants as that who also took part in our past published research (Berent, Vaknin-Nusbaum, et al., 2012). All dyslexic participants presented a documented diagnosis of dyslexia, issued by a certified clinician. Given that students at the University of Haifa must achieve a minimum score of 450 points on a standardized psychometric test (the Israeli SAT, $M = 540$, $SD = 70$, range: 200−800), and that SAT scores are known to correlate with IQ (Beaujean et al., 2006; Frey & Detterman, 2004), our participants probably fell within the normal IQ range. To assure that control participants were skilled readers, we first administered a battery of reading tests to a group of 30 participants and next selected the 21 top-performing individuals (matched in number to the dyslexic participants).

Reading tests

Reading ability was assessed by means of three tests. In the nonword naming task (from Shany, Lachman, Shalem, Bahat, & Zeiger, 2005), participants read aloud a list of 37 nonwords (printed with orthographic diacritics, to indicate all vowels). In the homophone detection task (from Breznitz, Nevo, & Shatil, 2004), participants were presented with a list of 104 pseudohomophones (printed with vowel diacritics), and they were asked to mark the ones that spell out words of a given conceptual category. To use an English illustration, people were asked to detect food items from a list including *kat, bred*, and *roze*. Finally, in the text reading task (Shany & Ben-Dror, 2011) people were presented with two short passages consisting of 100 words each (one printed with vowel diacritics and one without them) and were asked to read them aloud. Results (see Table 2) showed that typical readers outperformed dyslexic participants in all tests.

Materials

The experimental materials consisted of 48 monosyllabic nonwords 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 $C_1C_2VC_3$ (C = consonant, V = vowel) nonwords

Table 2. *Reading scores of dyslexic and control participants in Experiments 1−2*

Task	*Performance measure*	*Typical*	*Dyslexic*	t-*value*	df	p
Pseudohomophone reading	Response time (minutes)	1.15	1.46	−2.23	40	<.03
	Errors	1.24	7.19	−9.86	40	<.0001
Homophone reading	Response time (minutes)	2.39	2.91	−1.93	40	<.07
	Errors	0.48	2.76	−4.06	40	<.0003
Text 1 (without diacritics)	Response time (minutes)	0.50	0.79	−4.02	40	<.0003
	Errors	0.67	1.57	−2.53	40	<.02
Text 2 (with diacritics	Response time (minutes)	0.49	0.67	−2.46	40	<.02
	Errors	0.24	1.52	−5.49	40	<.00001

arranged in 12 quartets (see Appendix A, for a list of experimental stimuli). Quartet members mostly shared their rhyme and differed on the sonority structure of their onset. Three of the four quartet members had an onset structure that is attested in Hebrew—a large rise in sonority (mostly stop–liquid combinations, e.g., *blif*), a small rise in sonority (mostly stop–nasal combinations, e.g., *bnif*), or a sonority plateau (stop–stop sequences, e.g., *bdif*). The fourth quartet member had a fall in sonority (sonorant–stop sequences, e.g., *lbif*)—a sonority profile that is unattested in Hebrew. Disyllabic items differed from their monosyllabic counterparts only on the presence of an epenthetic schwa between the onset consonants (e.g., *belif, benif, bedif, lebif*).

The experiment also featured another group of 18 monosyllabic quartets of similar onset structure (large rises, small rises, plateaus, and falls) along with their disyllabic counterparts. Those items were originally included in the experiment because the sonority profile of the obstruent-initial members is attested Hebrew onsets (e.g., the large rise in *twag*). However, each such quartet included at least one item whose onset was not effectively native to Hebrew. Half of these quartets featured the non-native consonant *w*, and an inspection of the results showed that participants (typical Hebrew readers) had great difficulty in discriminating these items from their disyllabic counterparts. The remaining quartets included onsets that violate Hebrew phonotactics, mostly because they exhibit a labial stop at the second onset position (e.g., *tpif*; Hebrew only allows labial stops in the initial onset position, e.g., *ptakim*, "notes"). Not only did these quartets include unattested onsets, but unattested and attested onsets were not matched for their conformity to Hebrew phonotactics. For example, the quartet *twag, tmak*, *tpak,* and *mtak* pits a large sonority rise with a non-native phoneme *w* against a sonority plateau with native phonemes, but illicit phonotactics (*tpak*); the small rise (*tmak*) is perfectly native to Hebrew. Since it is impossible to equate those items for the degree of their illegality (e.g., the illicitness of *twag* is not comparable to that of *tpak*), these stimuli do not allow one to test the effect of sonority. For this reason, these items were excluded from all analyses and were treated as fillers. These filler items are provided in Appendix B.

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 further information, see Berent et al., 2007).

Procedure

Participants were seated in front of a computer wearing headphones. 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 familiarized to the procedure and the talker's voice with a brief practice session including real English words (e.g., *blow–below*). Because the talker who produced these materials was not a Hebrew speaker, it was impossible to conduct the practice in Hebrew, but given that most Hebrew speakers are familiar with English, the English practice presents an acceptable compromise. As the results (below) demonstrate, the responses of Hebrew participants differ substantially from our previous results from English speakers, so it is unlikely that the findings are due to the induction of a generic "English" processing mode. The order of trials was randomized. In this and all subsequent experiments, the instructions to the participants were presented in Hebrew. Participants were tested in groups of up to three participants at a time.

Results

As an initial coarse assessment of the phonological knowledge of dyslexics, their overall sensitivity (d') to the status of onset clusters was examined as a function of whether they are unattested in

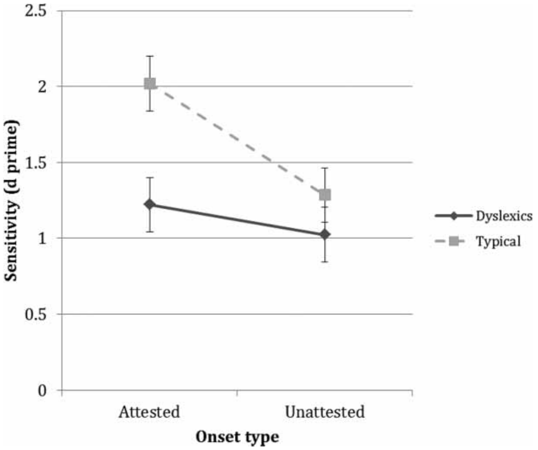

Figure 2. *The effect of reading ability and attestation on the discrimination of monosyllables from disyllables in Experiment 1. Note: Error bars are 95% confidence intervals for the difference between the means.*

Hebrew, or attested (collapsed over the three types of onset structures). The sensitivity of dyslexic and typical readers was then compared on the internal structure of attested onsets.

The effect of attestation

The sensitivity (d') of dyslexic and controls to attestation (attested. vs. unattested onsets) is presented in Figure 2. The 2 group (dyslexics vs. controls) × 2 attestation (attested vs. unattested onsets) analyses of variance (ANOVAs), conducted using both participants (F_1) and items (F_2) as random variables, yielded reliable main effects of group [$F_1(1, 40) = 5.82$, $MSE = 1.01$, $p < .03$; $F_2(1, 22) = 12.39$, $MSE = 0.21$, $p < .002$] and attestation [$F_1(1, 40) = 13.68$, $MSE = 0.33$, $p < .0007$; $F_2(1, 22) = 57.64$, $MSE = 0.07$, $p < .002$]. These main effects indicate that dyslexics were overall less sensitive than controls to the distinction between monosyllables and disyllables, and attested onsets yielded higher sensitivity than unattested onsets. Crucially, reading skill modulated the sensitivity to onset structure [$F_1(1, 40) = 4.55$, $MSE = 0.33$, $p < .04$; $F_2(1, 22) = 12.45$, $MSE = 0.07$, $p < .002$]. Tukey honestly significant difference (HSD) tests showed that control participants exhibited greater sensitivity to attested than to unattested items ($p < .002$, by participants and items), whereas this effect was not fully reliable for dyslexic readers (by participants: $p > .69$, *ns*, by items: $p < .05$).

Additional 2 (group) × 2 (attestation) × 2 (syllable) ANOVAs, comparing the response time[3] of the two groups to attested and unattested structures (see Table 3), found that dyslexics were slower than controls [$F_1(1, 39) = 6.07$, $MSE = 165{,}188$, $p < .02$; $F_2(1, 22) = 52.25$, $MSE = 7748$, $p < .0001$]. The ANOVA also yielded reliable effects of attestation [$F_1(1, 39) = 18.43$, $MSE = 8216$, $p < .0002$; $F_2(1, 22) = 5.06$, $MSE = 14{,}051$, $p < .04$], as well as a reliable Attestation × Syllable interaction [$F_1(1, 39) = 37.69$, $MSE = 6383$, $p < .0001$; $F_2(1, 22) = 8.43$, $MSE = 6135$, $p < .0009$]. Tukey HSD tests showed that monosyllables with attested onsets elicited slower responses than unattested onsets ($p < .006$ by participants and items), whereas attestation did not affect responses to their disyllabic counterparts ($p > .89$, by participants and items). These effects, however, were not further modulated by reading ability (for the interactions, all $p > .25$).

Together, these results suggest that dyslexics exhibit difficulties in the discrimination of monosyllables from disyllables, and they are also less sensitive to the distinction between monosyllables that are attested in their language and those that are not. Because attested and unattested onsets differ on both their lexical familiarity and grammatical structure, this contrast could reflect either a grammatical or a nongrammatical (e.g., lexical) impairment. To adjudicate between these two explanations, we next turn to examine the sensitivity of dyslexic participants to the sonority of attested onsets. Unlike the attestation contrast, this effect of sonority concerns onsets that are all

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[3] Outliers (defined as correct response times falling either 2.5 standard deviations above the mean or faster than 200 ms) were removed from the analyses of response time. This procedure resulted in the exclusion of less than 3.7% of the responses of each group (dyslexic and control participants).

Table 3. *The effect of attestation and reading skill in Experiment 1*

			Dyslexics		*Controls*	
Performance measure	*Syllables*		*Attested*	*Unattested*	*Attested*	*Unattested*
Response accuracy	Monosyllables	Mean	.77	.50	.89	.52
		SD	.18	.23	.10	.24
	Disyllables	Mean	.62	.81	.74	.87
		SD	.22	.23	.15	.19
Response time (ms)	Monosyllables	Mean	1259	1332	1110	1230
		SD	244	408	188	253
	Disyllables	Mean	1324	1304	1158	1154
		SD	252	257	190	177

highly familiar. Of interest is whether the two groups differ with respect to their sensitivity to the fine-grained phonological structure of such familiar onsets.

Sensitivity to the structure of attested onsets

Analyses of d′. We first examined the sensitivity (d') of dyslexic and typical readers to the structure of onsets that are attested in Hebrew—those with large rises in sonority (e.g., *blif*), small rises (e.g., *bnif*), or plateaus (e.g., *bdif*, for the means, see Table 4). The 2 (group) × 3 (onset type) ANOVA only yielded a reliable main effect of group [$F_1(1, 40) = 10.36$, $MSE = 1.94$, $p < .003$; $F_2(1, 11) = 60.37$, $MSE = 0.224$, $p < .0001$]. This effect showed that dyslexics were overall less sensitive to the distinction between monosyllables and disyllables than were typical readers. No other effects were significant (all $F <$ 1.1).

Response time. Figure 3 plots the effect of onset structure on response time to monosyllables with attested onsets. An inspection of the means suggests that, as the onset became more ill-formed (sonority distance decreased), response time increased. Crucially, this trend was evident in both groups.

These conclusions are borne out by the results of the 3 (onset type) × 2 (group) ANOVAs on responses to monosyllables. These analyses yielded reliable main effects of group [$F_1(1, 40)$

Table 4. *The effect of reading skill and onset structure on the sensitivity accuracy and response time to monosyllables and their disyllabic counterparts*

			Dyslexics			*Controls*		
Performance measure	*Syllables*		*Large rise*	*Small rise*	*Plateau*	*Large rise*	*Small rise*	*Plateau*
Sensitivity (*d* prime)		Mean	1.22	1.20	1.24	1.96	1.88	2.22
		SD	0.96	0.92	1.08	0.93	0.78	0.97
Response accuracy (proportion correct)	Monosyllables	Mean	.76	.78	.77	.90	.90	.87
		SD	.21	.19	.19	.11	.12	.15
	Disyllables	Mean	.63	.61	.62	.71	.70	.81
		SD	.25	.23	.27	.21	.15	.19
Response time (ms)	Monosyllables	Mean	1198	1251	1328	1097	1100	1133
		SD	263	214	321	179	211	204
	Disyllables	Mean	1368	1288	1299	1168	1141	1166
		SD	318	291	250	215	212	192

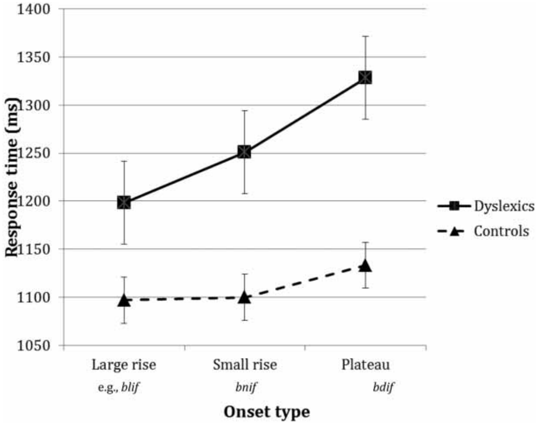

Figure 3. *The effect of onset structure and reading ability on response time in Experiment 1. Note: Error bars are 95% confidence intervals for the difference between the means.*

$= 4.93$, $MSE = 142{,}183$, $p < .04$; $F_1(1,\ 11) = 144.36$, $MSE = 2266$, $p < .0001$] and onset type [$F_1(2,\ 78) = 5.89$, $MSE = 12{,}789$, $p < .005$; $F_1(2,\ 22) = 6.44$, $MSE = 7088$, $p < .007$]. The interaction was not fully reliable [$F_1(2,\ 80) = 1.81$, $MSE = 12{,}789$, $p < .17$; $F_1(2,\ 22) = 4.75$, $MSE = 4446$, $p < .02$]. Planned comparisons indicated that the more ill-formed onsets of level sonority (e.g., *bdif*) yielded significantly slower responses than better formed onsets of rising sonority—either small rises [e.g., *bnif*; $t_1(80) = 2.24$, $p < .03$; $t_2(22) = 2.47$, $p < .03$] or large rises [e.g., *blif*; $t_1(80) = 3.38$, $p < .002$; $t_2(22) = 3.49$, $p < .003$], which in turn, did not differ from each other [$t_1(80) = 1.13$, $p < .26$; $t_2(22) = 1.02$, $p < .32$].

To ensure that dyslexics were indeed sensitive to onset structure, we further tested their responses to monosyllables using a one-way ANOVA. The main effect of onset type was highly significant [$F_1(2,\ 40) = 4.63$, $MSE = 19{,}438$, $p < .02$; $F_1(2,\ 22) = 7.09$, $MSE = 8391$, $p < .005$]. Planned comparisons confirmed that ill-formed onsets of level sonority produced reliably slower responses than large rises [$t_1(40) = 3.02$, $p < .005$; $t_2(22) = 3.73$, $p < .002$] and marginally so relative to small rises [$t_1(40) = 1.80$, $p < .08$; $t_2(22) = 2.27$, $p < .03$], which, in turn, did not differ reliably from each other [$t_1(40) = 1.23$, $p < .23$; $t_2(22) = 1.46$, $p < .16$].

To ascertain that this effect of onset type is not simply due to differences in the inherent durations of the auditory stimuli, we next submitted the response times of dyslexic individuals to a stepwise linear regression analysis in which item duration was forced into the model in the initial step. Results showed that onset type, entered last, accounted for a reliable unique variance [$R^2_{\text{change}} = .146$, $F(1,\ 33) = 7.09$, $p < .02$], even after statistically controlling for stimulus duration (in the initial step).

Finally, to demonstrate that the effect of onset type is specifically due to the structure of onset clusters in monosyllables, we also conducted similar 3 (onset type) × 2 (group) ANOVAs on the responses to disyllables (for the means, see Table 4). These analyses only yielded a reliable effect of group [$F_1(2,\ 78) = 4.72$, $MSE = 144{,}976$, $p < .04$; $F_1(2,\ 22) = 24.45$, $MSE = 12{,}877$, $p < .0005$]. Thus, onset structure selectively modulated responses to monosyllables, but not to their disyllabic counterparts.

Discussion

The results of Experiment 1 suggest that adult dyslexics are less sensitive than controls to the phonological structure of auditory words. Not only were dyslexics slower and less accurate in discriminating monosyllables from disyllables, but they also showed an attenuated sensitivity to the distinction between onsets that are attested in their language and unattested onsets. These results converge with a large body of research suggesting that dyslexics show subtle impairments in speech perception. Such deficits, however, might well originate from sources that are external to the phonological grammar. Because monosyllables and disyllables differ only by a brief schwa, the attenuated discrimination could reflect phonetic/auditory difficulty to encode these rapid acoustic events (Galaburda et al., 2006; Merzenich et al., 1996; Tallal, 2004; Tallal & Piercy, 1973). Likewise, the attenuated sensitivity to attestation (i.e. a distinction between familiar and unfamiliar structures) could originate from a deficit in lexical storage and retrieval (Ramus & Szenkovits, 2006). Because attested onsets (e.g., *blif*) can be stored in the lexicon, a deficit to lexical retrieval is expected to selectively attenuate their identification while sparing unattested onsets. Our question here is whether those difficulties extend to the phonological grammar itself.

To address this question, we next gauged the sensitivity of dyslexics to the putatively universal restriction on the structure of onset clusters. Across languages, syllables such as *bla* are preferred to *bna*, which, in turn, are favoured relative to *bda.* All three types of onsets are further attested in Hebrew, so they are grossly matched for lexical familiarity. Results suggest that dyslexics in our experiments were highly tuned to the phonological constraint on onset structure. As the onset became more ill formed, participants exhibited greater difficulty in discriminating monosyllables from their disyllabic counterparts. Our analyses further established that this difficulty is specific to monosyllables (no such effect was found with their disyllabic counterparts), and it is found even when the duration of the stimulus is statistically controlled.

This difficulty, also found in past research in English, Spanish, Korean, and Mandarin (Berent, Balaban, et al., 2010; Berent, Harder, & Lennertz, 2010; Berent & Lennertz, 2010; Berent, Lennertz, & Balaban, 2012; Berent et al., 2008; Berent, Lennertz, & Rosselli, 2012; Berent et al., 2009; Berent et al., 2007; Zhao & Berent, 2013) might result from a process of grammatical repair. Because ill-formed onsets (e.g., *bdif*) violate higher ranked grammatical constraints, they are more likely to undergo repair (e.g., *bedif*), and, for this reason, they are harder to discriminate from their matched disyllables. Crucially, these effects of onset structure were evident irrespective of reading ability.

The full sensitivity of dyslexics to the structure of attested onset suggests that their phonological grammar might be intact and include productive restrictions on sonority. If this interpretation is correct, then dyslexics might be able to generalize their knowledge across the board, even to onsets that are unattested in their language. Experiment 2 evaluates this possibility.

EXPERIMENT 2

Experiment 2 further compares the sensitivity of dyslexics and controls to sonority restrictions on onset structure. The procedure, once again, elicits a syllable count. Unlike Experiment 1, however, here, we focus on nasal-initial onsets (e.g., *ml* vs. *md*)—structures that are unattested in the participants' language.

Participants in this experiment were presented with stimuli that gradually changed from a monosyllable (e.g., *mlif*) to a disyllable (e.g., *melif*). To this end, we first obtained a recording of the disyllabic endpoint (e.g., *melif*), and we next gradually excised the schwa *e* in five incremental steps, such that one endpoint of the continuum (Step 6) presented the original disyllable (e.g., *melif*), whereas the other end (Step 1) featured a monosyllabic item (e.g., *mlif*). Our experiments included two types of continua. In one continuum type, the monosyllabic endpoint exhibited a sonority rise (*ml*, $\Delta s = 1$) whereas another continuum type had a fall in sonority (e.g., *md*, $\Delta s = -1$). Since Hebrew bans onset clusters that begin with a nasal, both onset types are unattested in this language.

Past research with English participants has shown that the identification of these continua is modulated by their sonority distance (Berent et al., 2010; Berent, Lennertz, & Smolensky, 2011). As vowel duration increased, participants were more likely to identify the stimulus as disyllabic. But remarkably, when presented with the monosyllabic endpoint at Step 1 (e.g., *mlif* vs. *mdif*), "one syllable" responses were less likely to be sonority falls (e.g., *mdif*) than were rises (e.g., *mlif*).

The misidentification of sonority falls is not simply due to an inability to encode the phonetic form of such onsets. Subsequent research (Berent, Lennertz, & Balaban, 2012) has shown that, once participants' attention is directed to phonetic detail (e.g., by asking them to detect the presence of the *e* in *medif* and *melif*—a task that shifts attention from the syllabic to the segmental level), performance on sonority falls (e.g., *mdif*) did not differ from rises (e.g., *mlif*), given the very same acoustic stimuli. Moreover, the segmental task was also associated with an increased sensitivity to phonetic coarticulatory cues (e.g., the contrast between natural and spliced stimuli; the phonetic salience of consonants and their coarticulation with the preceding schwa)—confirming that participants did, in fact, shift their attention from the phonological level (in the syllable count) to the phonetic level (in the vowel detection task). Crucially, once engaged in the phonetic mode, the phonetic form of *mdif* was no more confusable than *mlif*. Together, these results imply that the systematic misidentification of *mdif* originates from repair occurring at the phonological level. And indeed, these findings replicate even when monosyllabic and disyllabic items are presented in print (Berent et al., 2009).

In view of these past results demonstrating the propensity of this manipulation to tap into the phonological restrictions on sonority, we next asked whether this phonological knowledge is intact in dyslexia. To this end, Experiment 2 examines whether dyslexic individuals might be sensitive to the phonological structure of those unattested onsets. The critical test comes from responses to monosyllables (i.e., at Step 1). If dyslexics are sensitive to the phonological restrictions on sonority, then, like typical readers, they should be more likely to repair sonority falls. This, in turn, should result in an increase in disyllabic responses at Step 1 to sonority falls (e.g., *mdif*) relative to rises (e.g., *mlif*).

Method

Participants

Participants were the same dyslexic and control individuals as those who took part in Experiment 1—the two experiments were administered in counterbalanced order.

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, et al., 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 12−15 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 randomized.

Procedure

The procedure was the same as that in Experiment 1.

Results and discussion

Figure 4 plots the proportion of disyllabic responses to the rise and fall continua as a function of vowel duration. An inspection of the means suggests that, as vowel duration decreased, people were more likely to identify the input as monosyllabic. However, “two syllable” responses were less likely given monosyllables (i.e., Step 1 items) of falling than of rising sonority. Moreover, this effect of sonority was evident for both typical readers and dyslexics.

To evaluate the reliability of these observations, we compared the effect of vowel duration and continuum type on the two groups by means of a 2

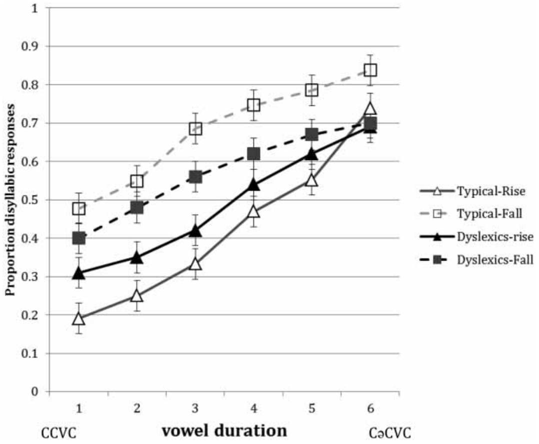

Figure 4. *The effect of onset structure and reading ability on the identification of the nasal continua in Experiment 2. Note: Error bars are 95% confidence intervals for the difference between the means. CCVC indicates monosyllables; CəCVC indicates disyllables (C = consonant, V = vowel).*

(group) × 2 (continuum type) × 6 (vowel duration) ANOVA using participants as random variables (because our experiments included only three item pairs, it was impossible to evaluate the reliability of these effects by items).

The ANOVA yielded reliable effects of continuum type, $F(1,\ 40) = 29.34$, $MSE = .1251$, $p < .009$, and vowel duration, $F(5,\ 200) = 90.61$, $MSE = .0213$, $p < .0001$. Tukey HSD tests showed that as vowel duration increased, so did the rate of disyllabic responses ($p < .05$)—the only exception was found at the initial step, where the contrast (between Step 1 and Step 2) was marginally significant ($p < .06$). Disyllabic responses, however, were overall more likely for the fall than for the rise continuum. Furthermore, this effect of continuum type was stronger for typical readers than for dyslexics, resulting in a Continuum Type × Group interaction, $F(1,\ 40) = 7.66$, $MSE = .1251$, $p < .009$. While dyslexic individuals were less sensitive to the contrast between the two continua, this effect does not specifically concern monosyllables (i.e., inputs with onset clusters), and, consequently, it is not directly relevant to the sonority hypothesis. If people are sensitive to sonority, then the difference between the two continua should emerge selectively for monosyllabic (or ambiguous) inputs. The ANOVA indeed yielded a reliable interaction of continuum type by vowel duration, $F(5,\ 200) = 5.29$, $MSE = .018$, $p < .0002$. However, this interaction was not further modulated by the group factor ($F < 1$).[4] No other effects were significant (all $p > .17$).

Planned comparisons demonstrated that disyllabic responses were significantly more likely for the fall than for the rise continuum at Step 1 [$t_1(200) = 2.53$, $p < .0001$], Step 2 [$t_1(200) = 2.71$, $p < .0001$], Step 3 [$t_1(200) = 2.89$, $p < .000$]), Step 4 [$t_1(200) = 2.44$, $p < .0001$], and Step 5 [$t_1(200) = 2.18$, $p < .0001$]. In contrast, these two continua did not reliably differ given disyllabic items [Step 6; $t_1(200) = 1.34$, $p < .08$]. These results suggest that participants were reliably more likely to interpret monosyllabic or ambiguous items as disyllabic when their sonority profile was ill formed—a finding that replicates past results with English speakers (Berent, Harder, & Lennertz, 2011; Berent, Lennertz, & Balaban, 2012; Berent et al., 2009; Berent et al., 2007). These observations are consistent with the hypothesis that small sonority distances are more likely to undergo grammatical repair (as disyllables).

Finding that this effect of sonority was not further modulated by reading ability (i.e., the absence of a three-way interaction) suggests that the sensitivity of dyslexics to this grammatical constraint was intact. To ascertain that dyslexics were indeed sensitive to the structure of unattested Hebrew, we further submitted their responses to a separate 2 (continuum type) × 6

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[4] To ensure that these results were not due to artifacts associated with binary data (Jaeger, 2008), we also submitted response accuracy data to a mixed-effects logit model using group, onset type, and vowel duration as fixed effects, and subjects and item pair as random effect. The model yielded reliable interactions of group with both type ($\beta = -.2656$, $SE = .06784$, $Z = -3.94$, $p < .0001$) and vowel duration ($\beta = .06$, $SE = .0177$, $Z = 3.57$, $p < .0001$). However, the three-way interaction was not significant ($Z < 1$).

(vowel duration) ANOVA. This analysis yielded a marginally significant effect of continuum type, $F(1, 20) = 3.44$, $MSE = .128$, $p < .08$, and a significant effect of vowel duration, $F(5, 100) = 31.16$, $MSE = .024$, $p < .0001$. Although the interaction was not significant in the ANOVA, $F(5, 100) = 1.45$, $MSE = .019$, $p < .22$, it was reliable in the logit analysis—a method that is better suited for the analysis of binary data (Jaeger, 2008).[5] Planned comparisons further indicated that disyllabic responses were reliably more likely for the fall than for the rise continuum at Step 1 [$t(100) = 2.29$, $p < .03$], Step 2 [$t(100) = 3.15$, $p < .003$], and Step 3 [$t(100) = 3.32$, $p < .002$], but not at Step 4 [$t(100) = 1.73$, $p < .09$], Step 5 [$t(100) = 1.10$, $p < .27$], and Step 6 [$t(100) < 1$]. These results converge with the findings of Experiment 1 to suggest that the dyslexics are fully sensitive to grammatical sonority restrictions.

GENERAL DISCUSSION

A growing body of research shows that dyslexics exhibit subtle deficits in the encoding of spoken language (reviewed by Ramus & Ahissar, 2012). Previous findings, however, focused on the identification of phonetic categories, so it remained unclear whether those problems might also impair the phonological grammar. This lacuna is particularly important given the widely held assumption that dyslexia is associated with a phonological deficit—an assumption that is rarely specified and not expressly supported by evidence. The present experiments directly tested this hypothesis by investigating the sensitivity of adult, native Hebrew-speaking dyslexic participants and controls to grammatical restrictions on onset clusters.

In what follows, we first summarize our results and bring them to bear on the status of the phonological grammar in dyslexia. We next move to consider the implications of our findings to ongoing debates concerning the sonority hierarchy.

The phonological grammar in dyslexia

Past research has repeatedly shown that individuals with dyslexia exhibit abnormalities in processing spoken stimuli. Our present results replicate this finding. Specifically, when compared to controls, dyslexic participants in Experiment 1 were impaired in the discrimination of monosyllables from disyllables (e.g., *blif* vs. *belif*) and the contrast between onsets that were attested in their language (e.g., *blif*) and unattested onsets (e.g., *lbif*). These participants were also less sensitive to the distinction between the two speech continua studied in Experiment 2 (*mlif* vs. *mdif*). The attenuated sensitivity of dyslexics to the internal properties of these spoken inputs and their attestation in the Hebrew language could well result from difficulties in extracting the phonetic form of these acoustic inputs (Galaburda et al., 2006; Merzenich et al., 1996; Tallal, 2004; Tallal & Piercy, 1973) and comparing them against stored lexical items (Ramus & Szenkovits, 2006). Our past research with the same individuals has documented such phonetic and lexical impairments (in the identification and discrimination of phonetic categories, and in word/nonword and speech/nonspeech discrimination, Berent, Vaknin-Nusbaum, et al., 2012).

While these individuals exhibited deficits in nongrammatical aspects of speech processing, they showed no impairment in the extraction of grammatical phonological regularities. Across languages, onsets with small sonority distances are dispreferred, and past research has documented a similar pattern of preferences among speakers of various languages, even when the relevant structures are absent in their language (Berent, Harder, et al., 2011; Berent, Lennertz, & Balaban, 2012; Berent et al., 2008; Berent, Lennertz, & Rosselli, 2012; Berent et al., 2009;

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[5] Unlike the ANOVA, the logit analyses of dyslexic participants did yield a reliable interaction ($\beta = .05$, $SE = .0241$, $Z = 2.10$, $p < .04$). The main effects of onset type ($\beta = -.3787$, $SE = .0926$, $Z = -4.09$, $p < .0001$) and vowel duration ($\beta = .3428$, $SE = .0244$, $Z = 14.02$, $p < .0001$) were likewise significant.

Berent et al., 2007; Zhao & Berent, 2013). To gauge the sensitivity of dyslexic individuals to this constraint, Experiment 1 manipulated the sonority profiles of onsets that were attested in Hebrew (e.g., *blif, bnif, bdif*); Experiment 2 extended this investigation to unattested onsets (e.g., *mlif* vs. *mdif*). Dyslexic participants showed a normal pattern of sensitivity to onset structure in each of these experiments.

Specifically, Experiment 1 showed that, as the sonority distance of attested onsets decreased, dyslexics took longer to discriminate these monosyllables from their disyllabic counterparts. Such difficulties are expected by the hypothesis that monosyllables with small sonority distances are worse formed; hence, they are subject to repair as disyllables (e.g., *bdif*→*bedif*). Experiment 2 further showed that large sonority distances were identified more accurately than small ones even when both onset types were unattested in the participants' language (e.g., *mlif* vs. *mdif*). An inspection of the sensitivity of our individual participants (dyslexic and controls) to the effect of sonority in the two experiments (see Figure 5) further indicates that the sensitivity to sonority is widely spread across participants.

These findings suggest that, once attestation is held constant, dyslexics may be fully sensitive to the effect of sonority. The contrast between dyslexics' full sensitivity to sonority and their attenuated sensitivity to attestation (e.g., *blif* vs. *lbif*) further bolsters our claim that the effect of attestation originates from a lexical deficit, rather than a phonological impairment. We should note that our results are limited inasmuch as they obtain from a single sample of college students, and, as such, they may not speak to the state of the grammar in all dyslexic individuals. Nonetheless, our present results demonstrate that at least some dyslexics (like control participants) can productively extend sonority restrictions to both onsets that are attested in their language as well as to unattested onsets. These findings are consistent with the possibility that the phonological grammar of dyslexic individuals is intact.

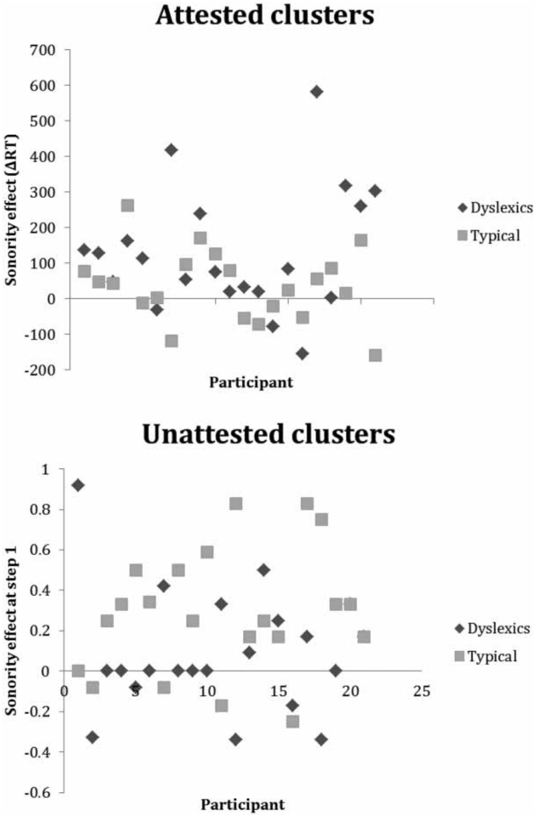

Figure 5. *Individual differences in the sensitivity of dyslexic and typical readers to the structure of attested onsets (in Experiment 1) and unattested onsets (in Experiment 2). RT = response time. Note: The sonority effect in Experiment 1 is defined as the difference in response time to onsets of level sonority relative to large rises in sonority; in Experiment 2, this effect is defined as the difference in the rate of "disyllabic response" to sonority falls relative to rises at Step 1. Thus, in both cases, positive values indicate larger sonority effects.*

The sonority controversy

Beyond their immediate implications to dyslexia research, our findings are also relevant to an ongoing controversy in the linguistic literature concerning the origins of sonority restrictions. The controversy, as we see it, concerns two key questions: (a) Is syllable structure constrained by universal phonological restrictions? and (b) does the notion of sonority offer the proper phonological account of such restrictions?

The answer to (b) evidently rests on the conclusion concerning (a) and bears little relevance to our present investigation. While our description of the onset hierarchy (e.g., *bla* ≻ *bna* ≻ *bda* ≻ *lba*) is couched in terms of sonority, our interest is in the origin of the hierarchy itself, not in its detailed formal analysis (cf., Clements, 1990 vs. Smolensky, 2006), and, for this reason, we do not consider this issue further (for recent discussions, see Berent, 2013; Parker, 2012). Rather, we ask whether the onset hierarchy is phonological, and possibly universal. Our interest, then, squarely concerns Question (a). It is this question that is challenged by some recent experimental findings.

The challenge rests on two arguments. The first states that the effects we attribute to the onset hierarchy stem not from the phonological structure of the onset, but rather from its phonetic correlates. A second challenge is presented by evidence that links the onset hierarchy to the statistical structure of the lexicon. In what follows, we briefly review the main findings supporting these two challenges and contrast them with empirical evidence for the phonological alternative.

A phonetic explanation

According to the phonological account of sonority defended thus far, onsets with small sonority distances are misidentified because they severely violate phonological restrictions on the syllable. These violations, in turn, trigger a grammatical process that repairs (i.e., recodes) ill-formed syllables (e.g., by inserting an intermediate schwa between the onset consonants), and, consequently, such onsets are misidentified. Misidentification, then, is the direct consequence of the grammatical ill-formedness of such onsets. But on an alternative phonetic view, people misidentify these onsets because they simply fail to accurately register their auditory or phonetic form—grammatical structure is irrelevant. Forms like *lbif*, for instance, are not repaired—they are never encoded faithfully in the first place (see Figure 6).

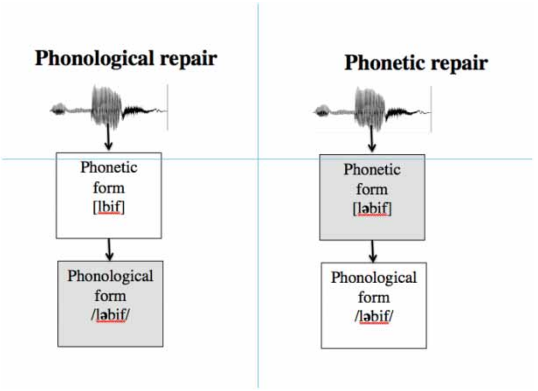

Figure 6. *Phonological versus phonetic accounts of repair. This figure provides a schematic account for the encoding of the auditory input* lbif *(identified as such by speakers whose languages allow such clusters). Both accounts show that the representation of the input is ultimately recoded as lebif, but on the phonological account, this repair occurs at a later phonological stage—note that the phonetic form of this input is accurate,* [lbif]. *On the phonetic account, by contrast, the distortion of the input occurs during its initial phonetic encoding.*

The phonetic alternative has been recently advanced by Davidson and colleagues based on experimental findings of two types. One line of evidence is presented by the failure to observe reliable effects of sonority in a series of production (Davidson, 2006, 2010; Davidson, Jusczyk, & Smolensky, 2006; Wilson & Davidson, in press) and perception (Davidson, 2011; Davidson & Shaw, 2012) experiments using unattested onset clusters. In the authors' view, these outcomes favour a phonetic over a phonological account of sonority. A second challenge to our conclusions is presented by positive findings suggesting that the perception and production of unattested clusters is modulated by phonetic factors. For example, Davidson and Shaw (2012) have shown that the identification of stop−nasal combinations (e.g., *pna*) correlates with the intensity of the burst release in the initial stop (e.g., *p*). Likewise, Davidson (2006) demonstrated that the phonetic properties of intended (lexical) schwas (e.g., *potato*) differ from those of (unintended) repairs (e.g., *petato*—an unintended mispronunciation of *ptato*). Such differences are taken to favour the phonetic view of repair (a similar argument is presented by Dupoux et al., 2011).

Neither argument, in our view, disproves the phonological alternative. Null sonority effects do not support the phonetic account because they fail to establish any systematic distinction between different onset types—phonetic or otherwise. And indeed, other results demonstrate that the sonority effect is reliable and replicable. It has been documented with stop−sonorant onsets (e.g., *bl* ≻ *bn* ≻ *bd;* Berent, Harder, et al., 2011; Berent et al., 2008; Berent, Lennertz, & Rosselli, 2012; Berent et al., 2007), nasal-initial combinations (*ml* ≻*md*; Berent, Lennertz, & Balaban, 2012; Berent, Lennertz, et al., 2011; Berent et al., 2009), and, recently, even the minute sonority clines consisting of stop−fricative onsets (*ps* ≻ *pt*; see also Lennertz & Berent, 2011; Maïonchi-Pino et al., 2013; Tamasi & Berent, 2013). We thus suspect that the null results reported by Davidson and colleagues result not from the fragility of the onset hierarchy, but rather from various methodological factors (e.g., failures to equate the sonority conditions on the initial consonant, different task characteristics, and the evaluation of sonority effects by a post hoc analysis of an imbalanced design and a small number of unmatched items). In any case, these null sonority effects do not demonstrate that the effects attributed to sonority can be subsumed by phonetic factors.

The positive phonetic effects do not do so either (Davidson, 2006; Davidson & Shaw, 2012). To show that phonetic factors subsume the effect of sonority (e.g., the *bna* ≻ *bda* ≻ *lba* preference), one must demonstrate that *lba* type clusters, for instance, exhibit systematic phonetic challenges (relative to *bda*, for instance) that can capture performance above and beyond the contribution of (phonological) sonority factors. The available findings do not provide such evidence. Rather, they show that misidentification (and misproduction) is modulated by phonetic factors. Such findings support the uncontroversial claim that speech perception and production are sensitive to phonetic factors—they do not address the debate between phonetic/phonological accounts of sonority. Likewise, the contrast between lexical and inserted schwas in speech production (Davidson, 2006) convincingly demonstrates that these processes stem from distinct origins. However, this does not establish that the origin of repair is specifically phonetic, and, more crucially, it does not prove that its triggers (i.e., onset structure) are purely phonetic.

While the support for the purely phonetic account is weak, other studies directly challenge it. Central to the phonetic explanation is the assumption that onsets with small sonority distance are misidentified because their auditory/phonetic form is difficult to encode—more difficult, presumably than the form of onsets with large distances. Contrary to this assumption, our findings show that participants show no greater difficulty in the processing of ill-formed onsets (relative to better formed ones) once the experimental conditions call attention to the phonetic level (Berent, Lennertz, & Balaban, 2012; Berent et al., 2007). These conclusions are inconsistent with the possibility that the misidentification of ill-formed onsets is solely due to a failure to extract their phonetic form. Moreover, other findings show that the effects of sonority replicate with printed materials (Berent & Lennertz, 2010; Berent et al., 2009)—in the absence of any auditory phonetic demands altogether. While we do not question the possibility that misidentification has multiple origins, the available findings are entirely consistent with the possibility that the phonological grammar is a key factor.

A lexical explanation

A second challenge to our proposal concedes that the people are sensitive to the phonological structure of the onset. But in this account, this phonological effect reflects lexical analogy induced from the statistical properties of the lexicon, rather than universal grammatical restrictions (e.g., analogizing *bnif* to *sniff*). The critical finding is presented by a computational simulation that captures the responses of English participants to various onset structures in the absence of any innate universal grammatical biases (Daland et al., 2011).

We do not dispute the possibility that some aspects of performance could be induced from experience—this is particularly plausible in the case of English, a language whose onset inventory is rather rich. Such evidence, however, does not show that all speakers do so, nor does it explain why distinct languages converge on similar lexical systems. And contrary to the view of the inductive lexical account, sonority effects have been documented even in Korean (Berent et al., 2008)—a language that arguably lacks onset clusters altogether, and Mandarin Chinese (Zhao & Berent, 2013)—a language with an impoverished cluster inventory of any kind. Computational simulations suggest that such effects are unlearnable in the absence of a priori sonority-related biases (Hayes, 2011). Moreover, precursors of the sonority hierarchy are evident even in the absence of a lexicon—in the brain of neonate infants (Gomez et al., 2013).

Our present results from dyslexic individuals offer another piece of evidence relevant to the sonority controversy. If sonority effects were phonetic or lexical in origin, then one would expect these effects to be diminished in our dyslexic participants, as past research has established that these individuals are impaired in both phonetic and lexical processing. Our present results offer no support for this account. While a resolution of the sonority controversy requires further inquiry, the present evidence suggests that universal phonological sonority restrictions remain a viable hypothesis.

Conclusions and conundrums

Despite demonstrable phonetic and lexical deficits, the sample of dyslexic participants in our experiments exhibited full sensitivity to the phonological structure of the onset, irrespective of whether the relevant onsets are attested or unattested in their language. Dyslexics' full sensitivity to the structure of onset clusters agrees with past studies of heterosyllabic clusters (e.g., *alba* vs. *abla*; Fabre & Bedoin, 2003; Maïonchi-Pino et al., 2012), onset clusters (Maïonchi-Pino et al., 2013) and other phonological restrictions on assimilation (Blomert et al., 2004; Szenkovits et al., 2011), and identical consonants (Berent, Vaknin-Nusbaum, et al., 2012). In all cases, dyslexics exhibited intact sensitivity to grammatical phonological constraints.

While these results help clarify the nature of the speech processing deficits in dyslexia, the findings also raise a puzzle: How can a deficient phonetic/auditory system supply the necessary conditions for an intact phonological grammar to develop?

We consider several possible answers to this question. One possibility is that phonological deficits to the grammar might exist transiently earlier in development (Galaburda et al., 2006; Temple et al., 2003; White et al., 2006). Alternatively, the phonetic/auditory deficits of dyslexics could compromise some other areas of the adult phonological grammar, which are yet to be determined. Dyslexia is also a heterogeneous condition, so it is conceivable that distinct dyslexic individuals could vary with respect to their sensitivity to grammatical constraints. Finally, there remains the possibility that the phonological system in dyslexia might be relatively impervious to subtle phonetic perturbations because its development may rely more strongly on the function of very different (less affected) parts of the brain, or its development could be more strongly shaped by innate restrictions. Such resilience of the phonological mind, its putative universal design, and its role in scaffolding reading are all predicted by its view as a system of core knowledge (Berent, 2013).

The status of the phonological grammar in other dyslexic samples—adults and children—remains to be determined. Our present results, however, strongly challenge the widely held assumption that dyslexia results from a (linguistic) phonological deficit. More generally, these findings underscore the contribution of a detailed account of linguistic phonological competence to the study of reading ability and disability (Berent, Vaknin-Nusbaum, et al., 2012; Blomert et al., 2004; Maïonchi-Pino et al., 2013; Marshall et al., 2010; Ramus & Szenkovits, 2006; Szenkovits & Ramus, 2005).

Manuscript received 1 April 2013
Revised manuscript received 27 October 2013
Revised manuscript accepted 29 October 2013
First published online 18 December 2013

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APPENDIX A

The experimental materials employed in Experiment 1

Attested clusters		*Unattested clusters*	
Large rise	*Small rise*	*Plateau*	*Fall*
brɑp	bnɑp	bdɑp	rgɑp
krɛk	knɛk	ktɛg	rtɛk
drɑf	dlɑf	dgɑf	rdɑf
glɛp	gmɛp	gdɛp	lgɛp
klɛf	kmɛf	ktɛf	lkɛf
krik	knik	ktik	rkik
klɑp	kmʊp	ktɑp	ltɑp
krɛp	kmɛp	ktɛp	rkɛp
plik	pnik	pkik	ltik
præf	pnæf	ptæf	rpæf
trʊf	tlʊf	tkʊf	rtʊf
trɑk	tnɑk	tkɑk	rtɑk

APPENDIX B

The filler items employed in Experiment 1

Attested clusters		*Unattested clusters*	
Large rise	*Small rise*	*Plateau*	*Fall*
blif	*bwif	bdif	lbif
klim	knim	*kpim	lpim
drif	dlif	*dbif	rdif
*dwip	dmip	dgip	mdip
*dwʊp	dmʊp	dgʊp	mdʊp
*drʊp	dnʊp	*dbʊp	rdʊp
driʃ	*dniʃ	dgiʃ	rbiʃ
glɑn	gmɑn	*gbɑn	lfɑn
grɛf	gmɛf	*gbɛf	rgɛf
*gwit	gmit	*gbit	mgit
kræf	kmæf	*kpæf	rgæf
*kwʊg	knʊk	*kpɑk	mkʊk
*twɛp	tlɛp	tkɛp	mtɛp
*twæf	tmæf	*tpæf	mtæf
trɛf	tnɛf	*tpif	rtɛf
*twʊk	tnʊk	tgʊk	mgʊk
træp	tmæp	*tpæp	rpæp
*twɑg	tmɑk	*tpɑk	mtɑk

Note: Unattested clusters are indicated by asterisks.