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Language-universal Sensory Deficits in Developmental Dyslexia: English, Spanish, and Chinese

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Abstract

■ Studies in sensory neuroscience reveal the critical importance of accurate sensory perception for cognitive development. There is considerable debate concerning the possible sensory correlates of *phonological processing*, the primary cognitive risk factor for developmental dyslexia. Across languages, children with dyslexia have a specific difficulty with the neural representation of the phonological structure of speech. The identification of a robust sensory marker of phonological difficulties would enable early identification of risk for developmental dyslexia and early targeted intervention. Here, we explore whether phonological processing difficulties are associated with difficulties in processing acoustic cues to speech rhythm. Speech rhythm is used across languages by infants to segment the speech stream into words and syllables. Early difficulties in perceiving auditory sensory cues to speech rhythm and prosody could lead developmentally to impairments in phonology. We compared matched samples of children with and without dyslexia, learning three very different spoken and written languages, English, Spanish, and Chinese. The key sensory cue measured was rate of onset of the amplitude envelope (rise time), known to be critical for the rhythmic timing of speech. Despite phonological and orthographic differences, for each language, rise time sensitivity was a significant predictor of phonological awareness, and rise time was the only consistent predictor of reading acquisition. The data support a language-universal theory of the neural basis of developmental dyslexia on the basis of rhythmic perception and syllable segmentation. They also suggest that novel remediation strategies on the basis of rhythm and music may offer benefits for phonological and linguistic development. ■

INTRODUCTION

Developmental dyslexia affects around 7% of children and has been found in all writing systems so far studied (e.g., Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Korne, 2003). The hallmark of developmental dyslexia across languages is a specific difficulty in the ability to identify or manipulate the component sounds in speech (called "phonological awareness"; Ziegler & Goswami, 2005). Similar neural structures support phonological processing across different languages. Given its high heritability, sensory difficulties in developmental dyslexia may thus be linked to universal features of phonological processing, for example, those important for perceiving syllable structure. Syllabic segmentation of the speech stream is linked to rhythmic and prosodic features, and rhythmic processing appears to be the first speech segmentation strategy used by infants (Juscyzk et al., 1992; Mehler et al., 1988). Nevertheless, the specific characteristics of phonological systems can differ between languages.

One important cross-language phonological variable is syllable structure. Syllables can be simple, comprising an onset consonant (C) and a vowel (V), or complex, comprising both onset and coda consonants (CCVCC, as in the English word "stamp"). Whereas Spanish and Chinese have simple syllables, English has a complex syllable structure. The types of sound elements that constitute syllables can also vary across languages. Vowels are the most sonorant sounds that we can make, and obstruents or plosive sounds are the least sonorant (e.g., /p/, /d/, /t/). Whereas Spanish syllables have many sonorant sounds (e.g., /l/, /n/), English syllables have many plosive sounds. Aspects of auditory structure, such as the pitch and duration of sounds, can also change the meaning of syllables in some languages. For example, Chinese is a tonal language, where identical syllables can be spoken in one of four pitches, conveying distinct meanings. In English and Spanish, pitch does not change the semantic meaning of syllables.

If sensory difficulties in developmental dyslexia are linked to universal features of phonological processing important for perceiving syllable structure, acoustic cues like pitch and duration would be expected to have different weightings across languages. In contrast, the deliberate rhythmic timing of speech appears to depend on the same sensory cue across languages, the rate of change of the amplitude envelope at the onset of the syllable, or rise time (Hoequist, 1983; Morton, Marcus, & Frankish, 1976). Rise time is correlated with vowel onset (Scott, 1998). Adults hear alternating syllables like "ba" and "la" as nonrhythmic in timing when syllable onset–onset times are isochronous.

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This is because, across languages, listeners attend to syllable-internal events called "perceptual centers" or "stress beats" to determine speech rhythm rather than to the physical onsets of the syllables. Even babies are sensitive to the perceptual centers of syllables (Fowler, Smith, & Tassinary, 1986). Stress beats are principally determined by the acoustic structure of amplitude modulation at relatively low rates in the signal (Scott, 1998).

All languages contain consonant–vowel (CV) syllables, and prereading children learning all languages so far tested appear to be aware of syllables and further are able to divide syllables at the vowel, making two phonological units that linguists call *onsets* (onsets are any sounds before the vowel, such as the "tr" sound in "trip" and the "str" sound in "strip") and *rimes* (the "ip" sound in "trip" and "strip"; see Ziegler & Goswami, 2005). In languages with CV syllable structure, onsets and rimes are equivalent to *phonemes*, units used by linguists to refer to the smallest sound elements in words. Phonemes describe a category of sounds and do not have an exact acoustic correspondence. Instead, there are assumed to be language-general acoustic or physical features that make up these sound elements, with particular languages grouping sets of acoustic features into the phonemes used by that language. Nevertheless, the development of phonological awareness appears to follow a very similar sequence across languages. Children first gain awareness of syllables, then of onset–rime units, and then—if taught an orthographic representation at this grain size—of phonemes (Ziegler & Goswami, 2006). For example, both syllable-level and onset–rime tasks are performed well by young children in English (Bradley & Bryant, 1983; Treiman & Baron, 1981), Chinese (McBride-Chang & Ho, 2005), and Spanish (Goikeotxea, 2005; Cisero & Royer, 1995). Both onset–rime and syllable measures have been shown to be significant predictors of reading acquisition in English, Spanish, and Chinese (e.g., Siok & Fletcher, 2001; Jimenez Gonzalez & Del Rosario, 2000; Bradley & Bryant, 1983).

Languages are also typically ordered into one of three rhythm classes. Classically, languages have been classified as having either stress-timed rhythms (where the intervals between stressed syllables are roughly equal, e.g., English), syllable-timed rhythms (where successive syllables are of nearly equal length, e.g., Spanish), or moraic timing, where the vowel and any preceding consonants in syllables (the moraic unit, e.g., Japanese) are rhythmically equally spaced. Modern linguistics is producing evidence that rhythm class is a continuum rather than a discrete entity, with all languages more or less stress based, and Japanese no longer seen as occupying a rhythm class of its own (e.g., Grabe & Low, 2002). Nevertheless, rise time is the main auditory cue to rhythmic timing in speech, irrespective of the rhythm class of the language (Hoequist, 1983), and rise time is intimately connected with syllable stress. A stressed syllable has a larger rise time. Hence, a perceptual insensitivity to rise time would impede accurate syllabic segmentation of the speech stream across languages. As rise times in speech are determined by the amplitude rise time associated with vowel onsets, a perceptual insensitivity to rise time would also affect the efficient division of syllables into onset–rime units. Hence, a sensory difficulty in perceiving the onsets of amplitude envelopes could affect phonological development (Goswami et al., 2002).

Although the literature exploring auditory sensory deficits in developmental dyslexia has focused on the rapid changes in frequency and intensity that characterize formants (e.g., Tallal, 2004), the importance of the slower amplitude modulations in the speech stream for speech perception is being increasingly recognized. Modern auditory science has shown that selectively degrading modulation frequencies near the syllabic rate (4–16 Hz) degrades participants' ability to identify consonants and to understand sentences (Drullman, Festen, & Plomp, 1994). In contrast, speech stimuli that are processed to leave only the slower temporal modulations enable almost-perfect speech intelligibility (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). Therefore, accurate perception of the slowly varying amplitude envelope cues is now thought to be important for phonological development (Nittrouer, 2006). Indeed, children given cochlear implants, which supply envelope information but not fine time structure cues, can develop age-appropriate phonological systems (Johnson & Goswami, 2009).

This theoretical analysis is at variance with traditional assumptions in linguistics, according to which phonemes are the primary elements of spoken words across languages and are the building blocks of the phonological system (phonemes are the individual sounds represented by letters, such as F and PH for the phoneme /f/). Formants (rapid changes in frequency and intensity) were once thought to be the auditory correlates of phonemes (Blumstein & Stevens, 1981). Yet importantly, adults find speech quite intelligible even when no formant structure is present (Remez, Rubin, Pisoni, & Carrell, 1981). This suggests that other acoustic cues also contribute to phoneme perception and that the ability to perceive rapid changes in frequency or intensity may be less critical for phonological development than previously assumed (Gillam et al., 2008). As speech is intelligible without formant structure, sensory difficulties with rapid and transient auditory cues seem unlikely to impair the development of reading across languages (Tallal, 1980). Instead, a sensory difficulty in perceiving acoustic cues to rhythmic timing may underpin the phonological difficulties found in developmental dyslexia across languages (see Goswami, 2009).

Once children begin to learn to read, however, the print–sound correspondences that they learn begin to have a reciprocal effect on phonological development (Perfetti, Beck, Bell, & Hughes, 1987). Orthographic learning will affect phonological development differently across languages because languages also differ in their orthographic systems. Essentially, different orthographies use different "grain sizes" (for a review, see Ziegler & Goswami, 2005). Whereas Chinese characters represent units of meaning that are syllable sized, alphabetic orthographies use symbols that represent sound elements within syllables. Numerous developmental studies show that as soon as children begin learning to read, phonological processing is changed forever (see Frith, 1998). Awareness of the phonological units reflected by the alphabet (phonemes) only develops in children learning to read alphabetic languages. Adults who have never learned to read an alphabetic script lack awareness of phonemes (Read, Zhang, Nie, & Ding, 1986), as do children learning to read character-based scripts like Chinese by rote (Huang & Hanley, 1994). As phonological difficulties are found in developmental dyslexia irrespective of whether the orthography is alphabetic (most European languages), syllabic (e.g., Japanese Kana), or morphosyllabic (like Chinese), the orthographic choices made by a particular language do not seem to change the developmental trajectory for dyslexia.

Differences in orthographic consistency seem instead to affect the manifestation of developmental dyslexia across languages (for a review, see Ziegler & Goswami, 2005). In transparent languages like Italian and Spanish, both reading and nonword reading can be extremely accurate. This is because each letter maps uniquely to one sound, and children with developmental dyslexia can learn these connections. Nevertheless, recoding print to sound remains so effortful and slow that affected children are functionally dyslexic. Therefore, timed measures of single word reading are necessary to identify dyslexia in transparent languages. In nontransparent languages like English and Danish, word reading and nonword reading are usually quite inaccurate. Letters and letter clusters can have multiple pronunciations, for example, the letter cluster—*ough* in English has many different correspondences to sound (as in *bough*, *cough*, *dough*, *tough*, *through*; see Ziegler, Stone, & Jacobs, 1997). Children with developmental dyslexia in English are both slow and inaccurate readers. The partly logographic nature of Chinese led some to claim that developmental dyslexia would not be found in Chinese, as the orthography could be acquired on a visual basis (Flores-d'Arcais, 1992; Makita, 1968). This claim has proved misplaced, and Chinese children with dyslexia have been found to show impaired phonological awareness and impaired phonological recoding to sound (Cheung et al., 2008; Ho, Chan, Tsang, & Lee, 2002). Hence, the ease of orthographic learning per se does not appear to eliminate the phonological processing difficulties experienced by children with dyslexia across languages, although it can affect their reading accuracy. Again, this suggests that the primary impairment in developmental dyslexia is phonological. A sensory precursor of difficulties in establishing high-quality phonological representations could be impaired auditory processing. This impairment should manifest similarly across languages with different orthographic systems.

Accordingly, we developed here a task to measure psychoacoustic sensitivity to sound rise time in children and also used it to measure sensitivity to sound frequency, sound intensity, and sound duration. We compared 229 children with and without developmental dyslexia learning English (a stress-timed language with many plosives and a complex syllable structure), Spanish (a syllable-timed language with many sonorant sounds and a simple syllable structure), and Chinese (syllable timed and tonal, with a simple syllable structure). These languages also have very different spelling systems (English = opaque alphabetic, Spanish = transparent alphabetic, Chinese = morphosyllabic). The children were approximately matched in age (10–11 years) and were also given tests of reading attainment and phonological awareness that were appropriate for their language. In English, reading develops over a relatively long period, and so a standardized test of single word reading and a test of rhyme awareness were used. As both reading and phonological awareness develop very rapidly in Spanish, similar tests would be performed at ceiling level by Spanish children. Indeed, we have shown that rhyme awareness approaches ceiling levels in Spanish-speaking children by the age of 6 years (Guardia & Goswami, 2009), and piloting with a phoneme deletion task for the current study also revealed ceiling performance (note that phoneme deletion tasks can be performed by using orthographic images and hence may not provide a pure measure of phonological processes). The Spanish children therefore received a complex onset/coda substitution task (spoonerism task) for phonological awareness and a standardized timed nonword decoding measure. Chinese is both character based and tonal—a key aspect of phonological structure is that identical syllables are spoken in one of four pitches or tones, and tone awareness is a unique predictor of reading acquisition in Chinese (McBride-Chang et al., 2008). Accordingly, the Chinese participants were given a test of tone awareness and a standardized reading test of character recognition. Finally, in some Chinese studies, the dominant phonological characteristic in Chinese dyslexia has been a difficulty in the rapid naming of familiar digits, colors, or objects (Ho et al., 2002). Accordingly, we also tested rapid automatized naming in Chinese and in the other two languages for comparative purposes.

METHODS

Participants

Ninety-six children from England, 73 children from Taiwan, and 60 children from Spain participated, ranging in age from 7 years 0 months (youngest English RL child) to 13 years 7 months (oldest Spanish CA child; see Table 1 for mean ages and *SD* by language). One hundred twenty-nine of the participants were boys (English = 54, Spanish = 33, Chinese = 42). Eighty-eight of the children in the study had either been identified as having developmental dyslexia by their local education authority or showed severe literacy and phonological deficits according to our own test battery. As phonological deficits were part of the inclusion criteria for the study, it is possible that children whose difficulties

Table 1. Participant Details

English	*Dyslexic (n = 44)*	*CA Controls (n = 27)*	*RL Controls (n = 25)*	*F(2, 93)*
Chronological age (*SD*), months	125.88 (12.93)	124.48 (11.74)	98.52 (7.28)	51.52***[a]
Reading age (*SD*), months	99.0 (18.5)	136.8 (19.6)	104.0 (14.5)	39.87***[b]
WISC, short-form IQ[c] (*SD*)	105.95 (15.21)	107.18 (10.42)	106.28 (12.13)	0.07

Spanish	*Dyslexic (n = 18)*	*CA Controls (n = 21)*	*RL Controls (n = 21)*	*F(2, 57)*
Chronological age (*SD*), months	133.50 (10.63)	130.62 (14.21)	98.48 (5.58)	66.56***[a]
Nonword reading speed (*SD*), sec	82.50 (17.47)	55.62 (15.68)	80.76 (18.75)	15.33***[b]
Non-verbal Intelligence Quotient standard score (*SD*) (standard = 10, *SD* = 1.5)	10.06 (1.63)	10.48 (2.04)	9.14 (2.03)	2.63

Chinese	*Dyslexic (n = 26)*	*CA Controls (n = 29)*	*RL Controls (n = 18)*	*F(2, 70)*
Chronological age (*SD*), months	119.46 (8.77)	120.97 (6.13)	102.94 (5.57)	40.92***[a]
Character recognition (*SD*) (raw score, maximum = 200)	57.58 (18.69)	90.55 (17.62)	58.89 (13.45)	31.43***[b]
Character percentile rank (*SD*)	29.81 (22.86)	71.07 (16.50)	61.78 (23.11)	
WISC, short-form IQ[c]	102.85 (8.96)	107.16 (7.67)	108.14 (7.00)	2.95

DYS = children with dyslexia; CA = chronological age controls; RL = reading level controls.

[a] DYS = CA better than RL.

[b] DYS worse than CA, DYS = RL.

[c] Standard score = 100, *SD* = 15.

****p* < .001.

were visual and not phonological were excluded from the sample. Seventy-seven age-matched control children (CA control group) and 64 reading-level matched control children (RL control group) were recruited from local schools in each country. Only children who had no additional learning difficulties (e.g., dyspraxia, ADHD, autistic spectrum disorder, SLI) and nonverbal IQ within the normal range were included. All English participants received a short hearing screen using an audiometer. Sounds were presented in both the left or the right ear at a range of frequencies (250, 500, 1000, 2000, 4000, and 8000 Hz), and all subjects were sensitive to sounds within the 20-dB HL range. Participant details are shown in Table 1.

Procedures

Children were given reading and IQ tests standardized in each language, experimental phonological awareness tasks (see below), and psychoacoustic tasks assessing auditory thresholds for sound rise time, duration, frequency, and intensity. The psychoacoustic tasks were made by the last author using a cartoon "Dinosaur" threshold estimation interface originally created by Dorothy Bishop (Oxford University). A novel adaptive staircase procedure (Levitt, 1971) using a combined 2-up 1-down and 3-up 1-down procedure was used with a test run terminating after eight response reversals or the maximum possible 40 trials. The threshold was calculated using the measures from the last four reversals using the 3-up 1-down procedure. This indicated the smallest difference between stimuli at which the participant could still discriminate with a 79.4% accuracy rate. To confirm that children were attending throughout the procedure, we randomly presented four attention trials during each test run, using the maximum contrast of the respective stimuli. The children were assessed individually in a quiet room within their school or at home. A rigorous practice procedure was applied before the presentation of the experimental stimuli. In the dinosaur tasks, the children were instructed to focus on a stimulus contrast (e.g., pitch) by using verbal descriptions and five practice trials. Both verbal and nonverbal (pointing) responses were accepted. Practice trials were also given before the phonological tasks. Chronologically, the Spanish children were tested before we had access to the Chinese and English samples used in this study. Therefore, the Spanish children did not receive the frequency discrimination task.

Tasks

Standardized Reading and IQ Tests

These comprised the British Ability Scales single word reading test for English (Elliott, Smith, & McCullogh, 1996), the PROLEC-R standardized test for Spanish (Cuetos, Rodríguez, Ruano, & Arribas, 2007), and the Graded Chinese Character Recognition Test for Chinese (Huang, 2001). Four subtests of the standardized form of the Wechsler Intelligence Scale for Children (WISC) were administered in England and Taiwan: block design, picture arrangement, similarities, and vocabulary. IQ scores were prorated following the procedure adopted by Sattler (1982) for the English sample and Chen (1999) for the Chinese sample. The Spanish WISC has different subtests, and so the block design measure was used as a representative nonverbal IQ measure.

Psychoacoustic Tasks

Amplitude envelope onset (rise time) task (1 rise). This was a rise time discrimination task in AXB format. Three 800-msec tones were presented on each trial, with 500-msec ISIs. Two (standard) tones had a 15-msec linear rise time envelope, a 735-msec steady state, and a 50-msec linear fall time. The third tone varied the linear onset rise time logarithmically with the longest rise time being 300 msec. Children were introduced to three cartoon dinosaurs. It was explained that each dinosaur would make a sound and that the child's task was to decide which dinosaur's sound was different from the other two and had a softer rising sound (longer rise time). The child then participated in five practice trials. As an integral part of the software program, feedback was given after every trial on the accuracy of performance. During the practice period, this was accompanied by further verbal explanation and reinforcement by the researcher. Schematic depiction of the stimuli can be found in Richardson, Thomson, Scott, and Goswami (2004), although note that this study used a different standard tone and threshold estimation procedure from the current study.

Rise time from a carrier task (2 rise). For this two-interval forced choice (2IFC) task, a continuum of 40 stimuli was created using a sinusoidal carrier at 500 Hz amplitude-modulated at the rate of 0.7 Hz (depth of 50%). Children were required to discriminate amplitude changes with different rates of onset within sounds comprising two amplitude envelopes rising from a steady state. Each stimulus was 3573 msec long (2.5 cycles). Rise time was again varied logarithmically from 15 to 300 msec, and the fall time was fixed at 350 msec. The longest rise time sound was the standard sound, and children were asked to choose the dinosaur who made the sound that had the sharper beat (i.e., the shorter rise time). Schematic depiction of the stimuli can again be found in Richardson et al. (2004).

For all other tasks, the standard was a pure tone with a frequency of 500 Hz and a duration of 200 msec. Intensity ranged from 55 to 75 dB SPL in the *intensity discrimination* task, duration ranged from 400 to 600 msec in the *duration discrimination task*, and the frequency range for the *frequency discrimination task* was 3 semitones. For the 1-rise, frequency, and duration tasks, the AXB format was used whereas the 2-rise and intensity tasks used a 2IFC format. The children were asked to choose the softer rise, higher pitch, longer sound, sharper beat, and softer sound, respectively. The auditory thresholds for frequency were not continuously distributed but formed two clusters for both English and Chinese. A group of children in each language were sensitive to frequency, and a group were very insensitive to frequency (English, 23/44 dyslexics and 3/27 controls insensitive to frequency; Chinese, 13/26 dyslexics and 5/29 controls insensitive to frequency). Therefore, frequency sensitivity was treated as a dichotomous variable (thresholds $\geq$ 1.18 semitones treated as insensitive).

Phonological Tasks

Phonological awareness. The English children received a rhyme oddity task using digitized speech (e.g., kick, pick, tip; see task in Thomson & Goswami, 2008). The maximum score was 20. In prior work, the split-half reliability for this kind of measure was .80. The Spanish children received a spoonerism task created for this study, requiring them to either substitute the onsets in two words (e.g., *rasgo-lenta* becomes *lasgo-renta*, 20 trials) or codas (e.g., *mujer-balon* becomes *mujen-balor*, 20 trials). The maximum score was 40. Reliability was estimated by computing the correlation between the onset and the coda trials, $r = .65$, $p < .001$. The Chinese children received an oddity tone awareness task modified from Siok and Fletcher (2001). They were asked to select the monosyllable with a different tone to the others (from sets of four monosyllables). The maximum score was 16. The coefficient of internal consistency (Cronbach's α) for this task was .75.

Rapid automatized naming. For English and Spanish, experimental rapid automatized naming (RAN) tasks were used on the basis of familiar objects whose names occupy dense phonological neighborhoods (see Kuppen, Huss, Fosker, Mead, & Goswami, submitted). The English children were asked to name line drawings of the familiar objects *gate*, *wheel*, *shop*, and *tie*. The Spanish children were asked to name line drawings of *gato* (cat), *luna* (moon), *mesa* (table), and *boca* (mouth). In each language, children were first introduced to the names of the pictures and then shown a page with the same pictures repeated 40 times in random order. The children were asked to produce the names as quickly as possible, performance was timed, and errors were counted. An estimate of reliability for this task was gained by computing the correlation between RAN dense and RAN sparse version also administered in both languages, in which items were drawn from sparse phonological neighborhoods, $r = .79, p < .001$ for English, $r = .86, p < .001$ for Spanish. For Chinese, the object-naming task from the naming-speed test battery (a standardized assessment suitable for primary school students in Taiwan) was used (Tzeng, 1997). The test has strong interrater reliability (.963) and parallel-forms reliability (.795–.956) (Tzeng, 1997). Children were given fifty stimuli printed on a 200 × 130 mm card and were asked to name the stimuli as accurately and as quickly as possible.

Data Analysis

The major focus of interest in this article is the role of basic auditory processing in developmental dyslexia across languages. As individual differences in sensory skills might be expected to depend on maturation only, it has been argued that the appropriate control group for children with dyslexia is CA controls only ("a reading age [and therefore younger] control group could only have poorer sensorimotor performance"; Ramus, White, & Frith, 2006, p. 266). On a developmental hypothesis, auditory sensory processing skills might also be expected to be affected by being taught to read (Goswami, Gerson, & Astruc, 2009). Therefore, the performance of a younger group of typically developing children equated for reading level with the dyslexics (RL match) is also of interest. For the current study, a conservative strategy was used, in which only statistical analysis of the data from the children with dyslexia and their CA controls were used for theoretical interpretation. The RL data are provided for comparative purposes. The data (including the auditory threshold data) were continuously distributed and met criteria for normality (checked for kurtosis and skew). The data were explored by group using the SPSS box plot function to check for outliers. Outliers were defined as scores falling outside three interquartile ranges from the further edge of the box and were removed (English: 1 CA control removed for 1 rise, 1 dyslexic, and 2 CA controls removed for intensity, 1 CA control removed for frequency; Spanish: 1 CA control removed for intensity; Chinese, no outliers). Parametric statistics (ANOVA and multiple regression) were then applied, and two-tailed tests were used.

RESULTS

Auditory discrimination data, phonological awareness data and rapid-naming times for age-matched English, Spanish, and Chinese children with and without dyslexia are provided in Table 2, along with the performance of younger reading-level matched children for comparison. One-way ANOVAs for the phonological awareness tasks using number correct as the dependent variable and comparing children with dyslexia to age-matched controls in each language (English, $n = 71$; Chinese, $n = 55$; Spanish, $n = 39$) showed significantly poorer performance by the dyslexic children for each language compared with CA controls, as would be expected; English rhyme awareness, $F(1, 69) = 24.1, p = .000$; Spanish spoonerisms, $F(1, 37) = 9.7, p = .004$; Chinese tone awareness, $F(1, 53) = 87.3, p = .000$. Similar one-way ANOVAs for the age-matched groups using auditory thresholds as the dependent variable showed significantly higher thresholds for both rise time (English: 1-rise and 2-rise measures; Spanish and Chinese: 1-rise measure) and duration in each language: English 1 rise, $F(1, 68) = 15.2, p = .000$; Spanish 1 rise, $F(1, 37) = 5.0, p = .03$; Chinese 1 rise, $F(1, 53) = 8.6, p = .005$; English 2 rise, $F(1, 69) = 14.3, p = .000$; English duration, $F(1, 69) = 4.6, p = .035$; Spanish duration, $F(1, 36) = 8.7, p = .005$; and Chinese duration, $F(1, 53) = 10.1, p = .003$. Simple frequency discrimination was also impaired in Chinese, the tonal language, $F(1, 53) = 10.2, p = .002$. English dyslexics were impaired in discriminating frequency, $F(1, 68) = 37.4, p = .000$, and intensity, $F(1, 65) = 5.1, p = .03$. When the RL children were included in the auditory ANOVAs for each language, the performance of these younger children was almost always statistically equivalent to that of the children with dyslexia.

If poorer discrimination of aspects of amplitude envelope structure, notably rate of amplitude envelope onset or rise time, were associated with phonological and literacy difficulties, then variance in measures of auditory sensitivity should predict both phonological awareness in a given language and literacy attainment. This was also investigated using the dyslexics and age-matched controls (English, $n = 71$; Chinese, $n = 55$; Spanish, $n = 39$). A series of three-step fixed entry multiple regression equations were created for each language so that the independent effects of age and IQ could be controlled before exploring the relationships between auditory discrimination, phonological awareness, and literacy. For each regression, the Cook's distance was used to check for influential or unusual data points; no data points were excluded. The independent variables were (in a fixed order) (a) age, (b) IQ measure, and (c) one of the auditory threshold measures. Results are shown in Table 3 for phonological awareness and in Table 4 for literacy acquisition.

Rise time (1-rise and 2-rise measures) was a consistent predictor of phonological awareness across languages, explaining 17% ($p = .004$) and 10% ($p = .036$) of unique variance, respectively, for Spanish, 26% ($p = .000$) and 6% ($p = .033$) of unique variance for English, and 12% ($p = .008$) and 9% ($p = .024$) of unique variance for Chinese. Frequency discrimination predicted phonological awareness in English and Chinese, and duration discrimination predicted phonological awareness in Spanish and Chinese (see Table 3). The intensity measure predicted phonological awareness in English, Spanish, and Chinese. The largest proportion of unique variance was predicted by rise time discrimination for English (1-rise measure, 26% of unique variance), duration discrimination

Table 2. Mean Discrimination Thresholds (Auditory Tasks) and Mean Naming Time or Percent Correct (Phonological Tasks) (*SD* in Parentheses)

Group	*English* *44 DYS*	*English* *27 CA*	*English* *25 RL*	*Spanish* *18 DYS*	*Spanish* *21 CA*	*Spanish* *21 RL*	*Chinese* *26 DYS*	*Chinese* *29 CA*	*Chinese* *18 RL*
Phon. Aw.[a]	59.0 (16.5)	78.0 (14.6)[b]	64.8 (14.7)	49.2 (19.7)	68.1 (18.2)[b]	20.30 (19.7)	34.0 (14.7)	78.0 (19.3)[b]	72.0 (20.7)
RAN (sec)	41.3 (9.6)	34.6 (5.7)[b]	41.7 (6.8)	38.7 (10.6)	29.5 (6.3)[b]	40.9 (6.9)	52.8 (10.4)	40.5 (7.9)[b]	42.9 (5.9)
1 Rise[c]	109.6 (80.4)	36.5 (14.6)[b]	87.7 (73.0)	124.2 (73.1)	73.0 (43.8)[b]	175.4 (51.1)	153.5 (84.3)	87.7 (58.5)[b]	154.2 (69.7)
2 Rise[c]	244.6 (151.7)	189.5 (110.8)[b]	241.3 (173.3)	253.5 (143.7)	233.2 (137.7)	267.1 (124.8)	245.9 (154.7)	224.3 (149.9)	239.7 (160.1)
Duration[c]	103.4 (41.8)	75.7 (45.6)[b]	90.8 (41.0)	92.3 (38.8)	56.4 (24.5)[b]	97.4 (32.6)	123.1 (45.0)	82.0 (35.9)[b]	112.8 (46.2)
Intensity[d]	2.8 (0.7)	2.2 (0.6)[b]	2.8 (1.1)	3.1 (1.1)	2.4 (0.4)	3.1 (1.1)	3.6 (1.8)	2.7 (0.7)	3.9 (1.7)
Frequency[e]	1.3 (0.5)	0.4 (0.3)[b]	0.99 (0.56)	–	–	–	1.1 (0.6)	0.6 (0.4)[b]	0.8 (0.6)

DYS = children with dyslexia; CA = chronological age controls; RL = reading level controls; Phon Aw. = phonological awareness measure.

[a] English: rhyme oddity; Spanish: spoonerisms; Chinese: tone awareness.

[b] Dyslexics significantly worse than CA.

[c] Threshold in milliseconds.

[d] Threshold in decibels.

[e] Threshold in semitones.

Table 3. Stepwise Regressions Showing the Unique Variance in Phonological Awareness Accounted for by the Auditory Measures

Step	*English Std Beta*	*English %R^2 change*	*Spanish Std Beta*	*Spanish %R^2 change*	*Chinese Std Beta*	*Chinese %R^2 change*
1. Age	.136	.019	.306	.094	.082	.007
2. WISC IQ[a]	.197	.039	.298	.088	.249	.061
3. 1 Rise	−.532	.255*	−.436	.172**	−.366	.123*
3. 2 Rise	−.252	.063***	−.356	.098***	−.303	.089***
3. Duration	−.233	.051	−.545	.294*	−.494	.215*
3. Intensity	−.256	.061***	−.352	.119***	−.290	.080***
3. Frequency[b]	.371	.120*	–	–	.427	.175*

Std Beta = standardized Beta coefficient; R^2 change = unique variance accounted for by that step.

[a] Spanish measure = WISC blocks.

[b] Dichotomous measure, 0 = sensitive, 1 = insensitive.

*$p < .001$.

**$p < .01$.

***$p < .05$.

for Spanish (29% of unique variance, $p = .000$), and duration discrimination for Chinese (22% of unique variance, $p = .000$). Table 4 shows that only the 1-rise measure was a consistent predictor of reading development across language, accounting for 9% of unique variance for Spanish reading ($p = .048$), 26% of unique variance for English reading ($p = .000$), and 14% of unique variance for Chinese reading ($p = .004$). In addition, intensity and duration detection were significant predictors of reading development for Spanish and rise time (2-rise measure), intensity, and frequency for English (see Table 4). These data suggest that basic auditory processing is important for reading development across languages. The auditory cue of rise time is consistently important.

However, rapid naming has been suggested to be the most dominant cognitive phonological deficit in Chinese, and so the contribution of individual differences in auditory sensory processing to rapid naming was also investigated. As shown in Table 2, the children with dyslexia in all languages showed the classic pattern of being significantly slower to name objects than their chronological age controls. If rapid access to and output of word forms depends in part on the quality of the representations in the phonological lexicon, then individual differences in

Table 4. Stepwise Regressions Showing the Unique Variance in Reading Accounted for by the Auditory Measures

Step	*English Std Beta*	*English %R^2 change*	*Spanish Std Beta*	*Spanish %R^2 change*	*Chinese Std Beta*	*Chinese %R^2 change*
1. Age	−.027	.001	−.409[a]	.167*	.262	.069
2. WISC IQ[b]	.201	.041	−.048	.002	.159	.025
3. 1 Rise	−.532	.255**	.315	.089***	−.384	.135*
3. 2 Rise	−.388	.149*	.242	.045	−.157	.024
3. Duration	−.161	.024	.344	.100***	−.239	.050
3. Intensity	−.288	.078***	.458	.202*	−.059	.003
3. Frequency[c]	.531	.247**	–	–	.170	.028

Std Beta = standardized Beta coefficient; R^2 change = unique variance accounted for by that step.

[a] Beta value is negative as speeded measure, older children are faster readers.

[b] Spanish measure = WISC Blocks.

[c] Dichotomous measure, 0 = sensitive, 1 = insensitive.

*$p < .01$.

**$p < .001$.

***$p < .05$.

basic auditory processing would be expected to contribute to individual differences in rapid naming. A series of three-step fixed entry multiple regression equations were created for each language, again controlling for age and IQ before exploring the relationships between auditory discrimination and RAN. The results are shown in Table 5. As can be seen, rise time discrimination contributed significant unique variance to rapid naming for English and Chinese, but not for Spanish (English: 1 rise, 10% of unique variance, $p < .05$, 2 rise, 7% of unique variance, $p < .05$; Chinese: 1 rise, 11% of unique variance, $p < .01$). Otherwise, the contributions were language specific, with frequency discrimination and duration discrimination making a significant contribution for English and intensity discrimination making a significant contribution for Chinese. None of the auditory measures reached significance for Spanish, although this was a smaller sample and so the equations had less power. The auditory measure that came closest was duration (8% of unique variance, $p = .066$). As will be recalled, duration also contributed the most unique variance to phonological awareness in Spanish (29%, $p < .001$). For Chinese, rise time was most strongly associated with rapid naming (11% of unique variance), whereas for English it was frequency discrimination (18% of unique variance). However, the negative Beta value shows that faster rapid naming in English was correlated with poorer frequency discrimination skills. The largest predictor in terms of impaired RAN performance in English was therefore rise time, as in Chinese (1-rise measure, 10% of unique variance).

Accordingly, it was deemed of interest to explore the relative contributions of phonological awareness and RAN to reading development in the three languages and to examine whether rise time discrimination affected literacy via phonological processing or independently as well. Developmentally, an auditory insensitivity to rise time is hypothesized to have an effect on the development of the entire phonological lexicon, affecting both phonological awareness and RAN, leading consequently to a difficulty in acquiring fluent reading skills when an orthography is learned. If basic auditory sensory processing of rise time exerts an influence on reading solely through its developmental effect on phonology and rapid naming, then if either phonological awareness or RAN is entered into a multiple regression analysis before rise time, the predictive value of rise time for reading should no longer be significant. This question was also explored by creating a series of three-step fixed entry multiple regression equations for each language, this time controlling age at Step 1, either phonological awareness or RAN at Step 2, and then entering an auditory processing variable at Step 3. For completeness, the same equations were calculated for Spanish, although none of the auditory measures made a significant contribution to RAN in Spanish in this sample (here the Cook's distance indicated that one dyslexic should be removed, so these equations were based on 38 Spanish children). The auditory processing measure was either rise time discrimination (1 rise) or intensity, as these two variables had been significant predictors of RAN for Chinese (note that IQ was not controlled as it did not make a significant contribution to reading in the previous regression equations). The results are shown in Table 6.

As can be seen, for all three languages, both phonological awareness (of rime for English, phonemes for Spanish, and tone for Chinese) and object RAN contributed significant unique variance to reading development, as would be expected. The absolute amount of independent variance contributed by the phonological awareness measure was larger than the absolute amount of independent variance

Table 5. Stepwise Regressions Showing the Unique Variance in Rapid Naming Accounted for by the Auditory Measures

Step	*English Std Beta*	*English %R^2 change*	*Spanish Std Beta*	*Spanish %R^2 change*	*Chinese Std Beta*	*Chinese %R^2 change*
1. Age[a]	−.344	.119*	−.450	.203*	−.226	.051
2. WISC IQ	−.107	.011	−.009	.000	−.453	.202**
3. 1 Rise	.336	.102*	.168	.025	.339	.106*
3. 2 Rise	.269	.072***	.163	.021	.199	.038
3. Duration	.237	.053***	.278	.077	.175	.027
3. Intensity	.100	.009	.259	.065	.300	.086***
3. Frequency[b]	−.458	.176**	–	–	.054	.003

Std Beta = standardized Beta coefficient; R^2 change = unique variance accounted for by that step.

[a] Beta values are negative as speeded measure, so older children are faster.

[b] Dichotomous measure, 0 = sensitive, 1 = insensitive.

*$p < .01$.

**$p < .001$.

***$p < .05$.

Table 6. Stepwise Regressions Showing the Unique Variance in Reading Accounted for by Rise Time and Intensity after Controlling for Either Phonological Awareness or Rapid Naming

Step	*English Std Beta*	*English %R^2 change*	*Spanish Std Beta*	*Spanish %R^2 change*	*Chinese Std Beta*	*Chinese %R^2 change*
1. Age	−.027	.001	−.374[a]	.140*	.262	.069
2. PA[b]	.620	.377**	−.509[a]	.221***	.495	.328**
3. 1 Rise	−.267	.052*	.262	.047	−.198	.032
3. Intensity	−.149	.020	.329	.089*	.199	.038
2. RAN	−.516	.235**	.667	.353**	−.289	.079*
3. 1 Rise	−.382	.123***	.334	.089*	−.340	.092*
3. Intensity	−.255	.061*	.311	.088*	.028	.001

Std Beta = standardized Beta coefficient; R^2 change = unique variance accounted for by that step.

[a] Negative as dependent variable was reading speed (so age or better performance correlates with faster reading).

[b] English measure = rime awareness; Spanish measure = spoonerisms; Chinese measure = tone awareness.

*$p < .05$.

**$p < .001$.

***$p < .01$.

contributed by the RAN measure for English and Chinese (phonological awareness contributed 38% of unique variance to reading for English and 33% of unique variance for Chinese, RAN contributed 24% of unique variance for English and 8% of unique variance for Chinese). For Spanish, RAN contributed a larger amount of unique variance to reading (33%) than phonological awareness (22%), although it will be recalled that the Spanish reading measure was a timed test and RAN is also a timed test. For English, individual differences in sensitivity to rise time still contributed significant unique variance to single word reading skills after either phonological awareness was controlled (5%, $p < .05$) or RAN was controlled (12%, $p < .01$). For Chinese, this was only the case for RAN, where the 1-rise measure still contributed 9% of unique variance. For Spanish, the 1-rise measure still contributed significant unique variance to reading speed when RAN was controlled (9%), but not when phonological awareness was controlled (5%). For all languages, therefore, rapid naming affects reading development, and sensitivity to rise time affects reading development even when individual differences in rapid naming are controlled (Table 6). For Spanish and English, the same is true of intensity discrimination. The analyses for phonological awareness suggest that rise time affects reading development via its effect on phonological development for Chinese and Spanish, but for English it has an independent effect on reading as well. One explanation for these differences between languages is that rise time may make a broader contribution to phonological development than is measured by the particular phonological processing tasks used here. Further, English is at the "stress timed" end of the rhythm class continuum, whereas both Chinese and Spanish are closer to the "syllable timed" end of this continuum. As rise time is intimately connected with syllable stress, these prosodic differences between languages may also be important in understanding the data.

DISCUSSION

This study establishes rise time discrimination as a universal cross-language sensory deficit in developmental dyslexia. Rise time is an important temporal characteristic of the speech envelope and is linked to the metrical organization of speech and to the perception of stressed and unstressed syllables (Goswami et al., 2009). It is therefore an important auditory cue to prosodic structure and phonological awareness in languages with different phonological systems. Neurally, a difficulty in accurate rise time perception can be measured by using EEG, for example, via mismatch negativity (see Thomson, Baldeweg, & Goswami, 2009), or by using EEG to reveal the accuracy of phase-locking to the speech envelope (Abrams, Nicol, Zecker, & Kraus, 2009). Indeed, for English it was shown recently that individual differences in the timing, precision, and magnitude of cortical responses to the speech envelope predicted up to 50% of variance in phonological skills in 23 good, average, and poor readers aged 12 years (Abrams et al., 2009). These slower temporal modulations in the speech envelope provide essential information about syllable patterning. When the perception of these modulations was made difficult by presenting sentences as compressed speech, impaired phase-locking precision to the broadband speech envelope was revealed for poorer readers. In addition, Abrams et al. (2009) reported that individual differences in phase-locking precision and phase-locking amplitude explained up to 44% of variance in a single word reading measure for these 12-year-old children.

However, EEG methods are neither fast nor easy to administer to children, in contrast to the psychoacoustic threshold task developed here (which takes about 5 min to complete). Hence, auditory perception in the 1-rise task may be a useful sensory marker for developmental dyslexia across languages. A robust sensory correlate of phonological difficulties enables very early identification of risk for dyslexia and early targeted intervention to affect the trajectory of phonological development (Beddington et al., 2008). Such intervention could begin long before a child begins school and begins failing to learn to read. For Chinese dyslexia, rapid naming has been suggested to be the most useful screening and diagnostic tool (see Ho et al., 2002). Although this was not the case in our cohort of Chinese children, for whom tone awareness was the strongest phonological predictor of reading, multiple regression analyses nevertheless indicated a strong link between rise time discrimination and rapid naming in Chinese. Therefore, it seems that rise time plays a universal role in the developmental difficulties with phonology that are characteristic of developmental dyslexia, even if the particular phonological tasks that are most predictive in different languages are different. Rapid-naming tasks have also been suggested to be more predictive of reading in shallow orthographies such as German (Landerl & Wimmer, 2000). However, the most recent cross-language study to compare the predictive strength of phonological awareness tasks versus rapid-naming tasks across languages (using Dutch, Hungarian, Portuguese, Finnish, and French) did not support this view (Ziegler et al., 2010). Ziegler et al. (2010) reported that phonological awareness was a stronger predictor of reading than rapid naming for these languages, although these are all relatively shallow orthographies. Spanish is also a shallow orthography, and in the current study RAN was a stronger predictor of timed nonword reading than phonological awareness. Nevertheless, rise time still predicted reading in Spanish when RAN was controlled in multiple regression analyses. As rise time is also significantly related to phonological awareness in French, Hungarian, and Finnish (Hämäläinen et al., 2009; Surányi et al., 2009; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Dutch and Portuguese not so far tested), it is likely to be a useful tool for both screening and diagnosis across languages.

Rise time is also known to be important for the detection of musical rhythms and for perceiving the attack time of different instruments (Gordon, 1986). Therefore, accurate rise time perception may underpin the detection of periodic structure when perceiving both music and language. This suggests that research into novel remediation packages on the basis of rhythm and music may be of value for remediating the phonological deficit in developmental dyslexia. Liberman (1975) originally pointed out the importance of metrical organization in complex human behavior. He proposed that speech, music, and dance all conformed to the "metrical organization hypothesis," namely, that all temporally ordered human behavior is metrically organized. A number of recent studies suggest intimate connections between rhythm perception and production that span modalities. For example, Phillips-Silver and Trainor (2005) played infants the sound of a snare drum producing an ambiguous rhythm (three unaccented beats). They then asked parents to bounce their babies on their lap to the ambiguous drum rhythms using either duple or triple time. When the babies were then played an accented version of the same snare drum pattern (in duple or triple form), they showed a listening preference for the rhythm that matched the beats on which they had been bounced—their movement experiences influenced their auditory interpretation of metrical structure. As argued by Cummins and Port (1998), when individual action components are rhythmically coordinated, they are constrained in their relative timing—the degrees of freedom in the system are reduced. Therefore, musical activities that require coordination between linguistic rhythms and musical rhythms (e.g., singing to music, reciting metrical poetry to a drumbeat accompaniment, chanting and marching in time with syllable beats) may offer previously unsuspected benefits for phonological development (Corriveau & Goswami, 2009).

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