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Cross-linguistic contributions of acoustic cues and prosodic awareness to first and second language vocabulary knowledge

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Background: Several studies have revealed that prosody contributes to reading acquisition. However, the relation between awareness of prosodic patterns and different facets of language ability (e.g., vocabulary knowledge) in school-age children remains unclear. This study measured awareness of prosodic patterns using non-speech and speech stimuli.
Methods: Hierarchical regression equations were computed to examine links among auditory cues (e.g., amplitude rise time, pitch contour and interval), language-specific prosodic awareness and children's vocabulary knowledge in Mandarin as a first language (L1) and English as a second language (L2) after controlling for age and nonverbal IQ.
Results: Results revealed that (1) amplitude envelope rise time discrimination predicted Mandarin L1 and English L2 vocabulary knowledge, (2) Mandarin tone perception and rhyme awareness did not predict Mandarin L1 vocabulary and (3) English rhyme awareness better predicted English L2 vocabulary than did stress production.
Conclusion: Our findings suggest that (1) amplitude rise time, which signals syllable boundaries, is a cross-linguistic predictor of vocabulary knowledge and (2) the development of English L2 vocabulary may depend on phonological more than prosodic awareness.

Keywords: auditory perception, suprasegmental phonology, lexical stress, lexical tone, Mandarin

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Highlights

What is already known about this topic

- Rise time discrimination is important to reading acquisition.
- Prosodic awareness is important to word reading.
- Phonological awareness is more important to English L2 word reading than is English stress production.

What this paper adds

- Rise time discrimination is important to not only Mandarin L1 but also English L2 vocabulary knowledge.
- Pitch discrimination is not a significant predictor of L1 vocabulary knowledge in a tone language like Mandarin.
- Phonological awareness is more important to English L2 vocabulary knowledge than is English stress production.

Implications for theory, policy or practice

- The mechanism(s) of the links between prosodic and phonological awareness, vocabulary and reading in a second language should be further examined.
- English L2 reading instruction might put emphasis on phonological awareness first and on prosodic awareness later.
- L2 learners' prosodic awareness should be assessed with perception and production tasks taken into consideration.

Previous studies have suggested that word reading ability is predicted by prosodic awareness in English-speaking monolingual children (Goswami, Gerson, & Astruc, 2010; Holliman, Wood, & Sheehy, 2008; Jarmulowicz, Taran, & Hay, 2007; Whalley & Hansen, 2006). Prosodic awareness appears to help bootstrap children's spoken word recognition for vocabulary development, and their vocabulary knowledge in turn supports the development of phonological awareness for reading acquisition (Holliman et al., 2014; Wood, Wade-Woolley, & Holliman, 2009). However, it remains unclear (1) if acoustic features can transfer between prosodic systems to better enable language acquisition in a non-native language and (2) if prosody plays a more vital role in spoken word learning than does phonological awareness. To this end, we examined links among auditory processing of different acoustic cues signalling prosodic patterns, language-specific prosodic awareness and vocabulary knowledge in both first (L1; Mandarin) and second languages (L2; English) among school-age Taiwanese children. Mandarin-speaking English learners are a particularly interesting population because the prosodic systems across the two languages are very different: pitch features dominate in their native L1, Mandarin, but they must also exploit other acoustic features to understand the stress patterns of English (their L2). Our cross-linguistic design also allowed us to examine (1) whether Mandarin L1 and English L2 vocabulary acquisition relies on unique acoustic cues and (2) the differential roles of prosodic and phonological awareness in Mandarin L1 and English L2 vocabulary acquisition.

Acoustic features signalling prosodic patterns at the word level and language learning

Linguistic prosody may serve as a bridge between speech–language processing and how language is organised. In the speech stream, syllables are organised based on prosodic patterns specific to a given language (Frazier, Carlson, & Clifton, 2006). For example, syllables could be arranged as contiguous sound units varying in English stress or Mandarin tone patterns. Individuals are predisposed to a periodicity bias (e.g., a stressed syllable preceding an unstressed syllable in English) towards the fluctuations of native prosodic patterns (Cutler & Mehler, 1993). These patterns provide a basic skeleton to store auditory information in short-term memory (Reeves, Schmauder, & Morris, 2000; Sturges & Martin, 1974) and deliver a perceptually salient cue for both speech segmentation (Cutler, 1996; Echols, 1996) and phoneme perception (Mehta & Cutler, 1988; Wood & Terrell, 1998).

Speech segmentation and phoneme perception are important for vocabulary development because detailed segmental representations are needed to discriminate words with increasingly similar phoneme sequences. As stipulated by the lexical restructuring hypothesis (Metsala, 1997a, 1997b), children's vocabulary growth requires a phonological re-representation process from lexical items to syllables, onsets/rhymes and finally phonemes. This suggests that speech segmentation driven by prosodic patterns at the word level could trigger children's vocabulary development for the phonological restructuring process. In the following sections, we discuss different acoustic features that signal prosodic patterns at the word level and their relation with language learning.

In English, prosodic patterns are fluctuations of multi-dimensional acoustic features cuing stressed and unstressed syllables. Stressed syllables may have higher fundamental frequency, higher intensity or longer duration compared with unstressed syllables (Fry, 1958; Kehoe, Stoel-Gammon, & Buder, 1995; Morton & Jassem, 1965). English speakers must process these collective features to determine alternations of stressed and unstressed syllables to segment words held in auditory working memory and in turn acquire vocabulary. Similar to English speakers, Mandarin speakers use pitch variations in their native prosodic system (i.e., lexical tone) for vocabulary acquisition. However, reliance on pitch cues is especially important in Mandarin L1 given the unique lexical role of pitch in tonal languages (Howie, 1976). Thus, it is worthwhile to examine if perceptual processing of different acoustic cues plays a differential role in Mandarin (L1) and English (L2) vocabulary development due to different weightings of acoustic features signalling Mandarin and English prosody.

Recently, individual variability in prosodic awareness has been assessed using non-speech (e.g., pure tones) and speech stimuli (e.g., prosodic patterns embedded in words). In a rhythm discrimination task, pure tones varying in timing (i.e., duration), accent (i.e., increasing intensity) and grouping (i.e., chunking tone sequences into beats) can be manipulated to resemble alternations between strong and weak beats as in English stress. Rhythmic discrimination of these non-speech stimuli had a close association with foreign language learning in French speakers (Bhatara, Yeung, & Nazzi, 2015). This suggests that French speakers with better perception of timing, accent, and grouping information appear to be better at learning foreign languages, which presumably builds on the good perceptual discrimination of rhythmic patterns pertaining to given languages. In an L1 tone language such as Cantonese, a relationship emerged between rhythmic discrimination and narrative (i.e., story retelling) (Antoniou, To, & Wong, 2015), suggesting that perception of rhythmic patterns that are not specific to native tone systems may be linked to native language acquisition.

At a rudimentary level, rhythmic discrimination requires at least the continuous monitoring of signal intensity and duration. Indeed, intensity and duration cues of English prosody have also been examined for links with vocabulary in several studies. For example, amplitude envelope rise time (i.e., rate of signal onset intensity) is critical for accurate perception of English prosodic patterns (Goswami & Leong, 2013) due to the fact that stressed syllables tend to have steeper amplitude onsets than unstressed syllables. Sensitivity to amplitude rise time is also a significant predictor of English L1 vocabulary knowledge even after controlling for listeners' age and performance IQ (Corriveau, Pasquini, & Goswami, 2007). These findings suggest that amplitude envelope rise time plays a role in English L1 vocabulary acquisition because it signals the patterns of stressed and unstressed syllables, which provide an analysable unit for phoneme perception and working memory. The important connection between rise time processing and language is supported by recent neuroimaging studies, which demonstrate that this cue helps to encode speech signals in the auditory cortex (Doelling, Arnal, Ghitza, & Poeppel, 2014; Gross et al., 2013).

Although amplitude envelope rise time is an important acoustic marker for rhythmic languages like English, its role in tone languages like Mandarin remains less clear. In tone languages, speakers might rely more heavily on pitch cues than amplitude envelope rise time in acquiring language. Along these lines, Antoniou, To, and Wong (2015) proposed a language-specific auditory cue hypothesis, which states that sound cues specific to a given language are only important for learning that language. Under this framework, amplitude envelope rise time may be more specific to English word learning, whereas pitch may be more specific to Mandarin word learning. Contrary to Antoniou, To, and Wong's (2015) hypothesis, several studies suggest languages might fall in a rhythmic continuum rather than strict dichotomy between rhythmic and nonrhythmic languages (Arvaniti, 2012; Grabe & Low, 2002; Nespor, 1990). Envelope rise time distinguishes three minimal pairs of affricate–fricative contrasts in Mandarin (i.e. /tsh/-/s/, /t.shk;h/-/ʂ/ and/t.ccrl;h/-/ɕ/) (Tsao, Liu, & Kuhl, 2006). This suggests that rise time, a perceptual correlate of stress, may also be important to learning languages like Mandarin that does not rely on linguistic stress.

Previous studies have shown that pitch contour processing (i.e., global detection of rising/falling pitch patterns) as an acoustic marker of prosody (Patel, Peretz, Tramo, & Labreque, 1998) contributes to word reading (Chung & Bidelman, 2020; Foxton et al., 2003). Building on this, Chung, Jarmulowicz and Bidelman (2017) further tested links between pitch contour discrimination and word reading abilities in Mandarin-speaking children. This study revealed that Mandarin L1 word reading was significantly predicted by pitch contour discrimination but not amplitude envelope rise time discrimination. This suggests that pitch may be more important than amplitude envelope rise time to learning tone languages like Mandarin, lending support to Antoniou, To and Wong's (2015) language-specific hypothesis. However, Chung, Jarmulowicz and Bidelman (2017) focused on early reading, not vocabulary acquisition. It remains unclear whether auditory cues used in language-specific ways (i.e., pitch cues for Mandarin and amplitude rise time for English) is observable across different language tasks (e.g., word reading and vocabulary knowledge).

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Phonological representation and vocabulary acquisition

Several longitudinal studies have revealed that early phoneme discrimination predicts later language acquisition in infants (Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005; Kuhl et al., 2008; Tsao, Liu, & Kuhl, 2004; Vouloumanos & Curtin, 2014). Studies with preschool and school-age children also found that native phoneme discrimination was closely related with vocabulary knowledge in their first language (Tsao, Lee, Hsieh, & Chiu, 2009; Vance, Rosen, & Coleman, 2009). Among Cantonese–English bilingual children, Cheung et al. (2010) found that speech perception (i.e., the ability to discriminate consonants varying in acoustic features such as voice onset time) in Cantonese (L1) accounted for significant variance in Cantonese L1 vocabulary knowledge, and English (L2) speech perception explained significant variance in English L2 vocabulary knowledge. These findings suggest that language-specific phoneme discrimination might play an important role in L1 and L2 vocabulary acquisition. Together, there is a close relationship between phoneme discrimination and phonological representation, both of which are key elements in language acquisition. Compared with phonemes, prosodic patterns are larger sound units that span across individual sounds. However, the role of prosodic pattern discrimination in language acquisition, particularly second language acquisition, is still unclear.

There is evidence to suggest that prosody influences vocabulary acquisition across languages. A study with 5-month-old English-speaking infants reported that increased interest in strong–weak stress patterns was significantly associated with native vocabulary knowledge at 12 months of age (Ference & Curtin, 2013). Turning to tone languages, tone perception was significantly correlated with vocabulary knowledge in Cantonese (Wong, Ciocca, & Yung, 2009) and Mandarin (Wang, Chen, Chiang, Lai, & Tsao, 2016). Recently, Tong, Tong, and McBride-Chang (2015) found that Cantonese tone recognition (tone to picture naming) accounted for more variance in Cantonese expressive vocabulary than did phonological awareness after controlling for age and nonverbal IQ. Studies also found similar results in Mandarin-speaking children where tone perception was more important to Mandarin L1 word reading than phonological awareness (Chung, Jarmulowicz, & Bidelman, 2017; Chung & Bidelman, 2020). The findings support the following propositions: (1) prosodic awareness at the word level has an indirect effect on phonological awareness through vocabulary (Holliman et al., 2014; Wood, Wade-Woolley, & Holliman, 2009) and (2) there is a bidirectional relationship between phonological awareness and vocabulary development (McBride-Chang et al., 2005). In contrast, phonological awareness made more contribution to English L2 word reading than did English stress perception and production (Chung, Jarmulowicz, & Bidelman, 2017). Together, these findings suggest that prosodic and phonological awareness may also play different roles in Mandarin L1 and English L2 vocabulary development.

The aims of the present study

The present study examined links among auditory processing of different acoustic features of speech prosody, language-specific prosodic awareness, and Mandarin L1 and English L2 vocabulary. Specifically, we aimed to determine the contribution of separate auditory processing abilities (rise time and pitch discrimination) to children's Mandarin L1 and English L2 vocabulary knowledge. We also controlled for several potentially confounding variables, including age and nonverbal IQ. Based on previous work (Chung, Jarmulowicz, & Bidelman, 2017), we hypothesised that pitch contour discrimination would contribute to

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Mandarin L1 vocabulary knowledge, and amplitude envelope rise time discrimination would predict English L2 vocabulary knowledge. We also expected that prosodic awareness would predict Mandarin L1 vocabulary knowledge better than phonological awareness predicts Mandarin L1 vocabulary knowledge, whereas the reverse would be observed for L2.

Methods

Participants

Sixty-one fourth graders (29 boys, 32 girls; *M* = 9.82 years, *SD* = 0.25) were recruited in Taipei, Taiwan. All children passed a bilateral hearing screening at audiometric frequencies between 1 and 4 kHz (i.e., thresholds ≤25-dB hearing level). The children were native speakers of Mandarin and did not have many opportunities to speak English in daily conversation except for in the classroom setting. In Taipei, the instruction medium is Mandarin, with compulsory English education beginning in first grade at the age of 7. However, the children's mean onset age of English learning was around 4.5 years (*M* = 4.87 years, *SD* = 1.13), because some began learning English through tutoring programmes. The children did not have any speech, language, emotional or physical problems as reported by classroom teachers. Both children and their parents gave written informed consent in compliance with a protocol approved by the University of Memphis Institutional Review Board, and children received school supplies for their participation.

Materials

Nonverbal intelligence. Raven's Standard Progressive Matrices (Chen & Chen, 2006) was used to assess nonverbal intelligence. The *Raven's Standard Progressive Matrices* consists of 60 black-and-white test items. Children selected among six to eight choices the missing element that best completed the geometric design.

Auditory processing. Children's auditory processing abilities were assessed by (1) amplitude rise time discrimination task and (2) two pitch discrimination tasks (Chung, Jarmulowicz, & Bidelman, 2017). Each auditory processing task included five practice trials and 40 experimental trials. During practice and experimental trials, visual feedback was presented by a graphic user interface via MATLAB. In the five practice trials, each child received extra verbal explanation and reinforcement. The three auditory processing tasks were run via a Mac laptop over headphones (Sennheiser HD 280) that were calibrated to 70 dB sound pressure level (binaurally).

Amplitude rise time discrimination. In the rise time task, stimulus parameters were modelled after Goswami et al. (2013). Each trial had three tones varying in rise time (rate of intensity and duration change at tone onset) presented in a three-interval forced choice task (3IFC). Two of the intervals had standard tones with a 300-ms rise time; the third contained a deviant which had a shorter rise time (e.g., 150 ms). Children decided which stimulus interval sounded different (i.e., 'odd-one-out'). Two consecutive correct responses resulted in a more difficult trial in which duration difference between rise time stimuli decreased; an incorrect response resulted in an easier trial in which duration

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difference between rise time stimuli increased. Thus, the duration of rise time was adaptively varied according to children's response in a two-down and one-up procedure, tracking 71% correct performance (Levitt, 1971). Using this procedure, differential thresholds were measured as the smallest difference in rise time that children could reliably detect. Smaller discrimination thresholds represent a higher sensitivity to intensity and duration changes of tone onset.

Pitch discrimination. Pitch contour and interval discrimination were modelled after Foxton et al. (2003). The pitch contour and interval tasks were presented in a two-interval forced choice (2IFC) paradigm. The task was to decide whether the pairs of six-tone sequences were the same or different. There were 40 pairs of six-tone sequences in which pitch values would change from one tone to another. Half of the pairs had identical tone sequences; the other half consisted of standard tone sequences and deviations in which a random tone mid-sequence was altered. The pitch contour discrimination task asked children to detect a random deviant tone violating pitch direction (e.g., pitch went down instead of up). In contrast, the pitch interval discrimination required children to detect a random deviant tone violating pitch distance between adjacent tones (e.g., pitch went up but did not reach the same value). Responses were quantified via *d*' [i.e., *d*' = z(H)-z (FA), where H and FA are the hit and false alarm rates, respectively]. A higher *d'* signals better discrimination sensitivity to contour/interval information.

Prosodic awareness. Prosodic awareness was assessed in four ways: English stress perception and production and Mandarin monosyllabic and disyllabic tone perception.

English stress perception. An English 'DEEdee' task (Goswami, Gerson, & Astruc, 2010; Whalley & Hansen, 2006) was used to measure English stress perception. Children completed four practice trials and 15 experimental trials. Six of 15 experimental trials were removed to improve task reliability. Each child heard three digitally recorded English phrases and then chose one of two DEEdee phrases that matched the stress patterns in a target phrase (e.g., DEEdee DEEdee corresponds with HUMPty DUMPty). Its Cronbach's alpha was 0.60.

English stress production. English stress production was assessed by an expressive DEEdee task (Chung, Jarmulowicz, & Bidelman, 2017). There were four practice trials and 12 experimental trials. In each trial, children produced a stress pattern with each syllable replaced by the syllable 'dee' for a low-frequency disyllabic spoken word (DEEdee for SOLvent and deeDEE for imPAIR). The first author and an English-speaking speech–language pathologist rated 15 children's (~25% of participants) English stress production. The resulting intra-class correlation (Hallgren, 2012) was excellent: 0.968 (Cicchetti, 1994), indicating high interrater reliability across coders. The task's Cronbach's alpha was 0.718.

Mandarin disyllabic tone perception. Disyllabic tone perception was assessed by a Mandarin version of the DEEDEE task (Chung, Jarmulowicz, & Bidelman, 2017). Children completed four practice trials and 15 experimental trials. Five of 15 experimental trials were removed to improve task reliability. In each trial, children were auditorily presented a target disyllabic word, and then required to select from two choices the DEEDEE phrase that matched the tone patterns in the target word (e.g., DEE^{4}DEE^1 for *qi*^{4}*che*^{1} 'car'). The task's Cronbach's alpha was 0.734.

Mandarin monosyllabic tone perception. Monosyllabic tone perception was examined using Liu and Hu's (2010) tone matching task. There were two practice trials and 20 experimental trials. In each trial, children heard three monosyllables (e.g., *gao*^{4}, *gan*^{3}, *gei*^{4}) and then selected from the second or the third syllable the one that matched the tone pattern in the first syllable. Relative to the disyllabic tone perception task, the monosyllabic tone perception task had shorter syllable length and retained phonemic information (not replaced by DEE) in each syllable. Cronbach's alpha for the task was 0.713.

Phonological awareness. Phonological awareness (PA) was assessed by sound oddity tests of rhyme contrasts in Mandarin (Hu & Catts, 1998) and English (Bowey, Cain, & Ryan, 1992). The Mandarin PA task included two practice trials and 10 experimental trials; the English PA task involved three practice trials and 12 experimental trials. Both PA tasks were to choose the token that sounded different from the others in final sounds (e.g., cat, dog and log). Cronbach alphas were 0.763 (Mandarin rhyme) and 0.750 (English rhyme).

Receptive vocabulary. Peabody Picture Vocabulary Test-Revised in Mandarin version (*PPVT-R*; Lu & Liu, 1998) and *Peabody Picture Vocabulary Test-IV* in English version (*PPVT-IV*; Dunn & Dunn, 2007) were used to measure receptive vocabulary in Mandarin and English, respectively. The PPVT-R in Mandarin version consisted of 125 test items, and the PPVT-IV in English version had 228 test items. Both tasks required children to select from four pictures the one that best matched the word that they heard. The internal consistency of both tasks is >0.90 for both the English and Mandarin versions. For the Mandarin PPVT-R, children started from the age 9 or 10 level. A basal set was obtained with the first eight consecutive correct items. The test was terminated once six errors were found in eight consecutive items or when all items were finished. For the English PPVT-IV, children started from the age 2:6–3:11 level. Children's basal and ceiling sets were observed based on published guidelines. For both tasks, raw scores were used to measure children's performance.

Results

Descriptive statistics for all measures are shown in Table 1. Pearson's correlations among variables are displayed in Table 2. Only amplitude envelope rise time discrimination was negatively associated with Mandarin L1 and English L2 vocabulary. Mandarin monosyllabic tone perception was significantly correlated with several measures, including Mandarin disyllabic tone perception, English stress perception and production, and Mandarin L1 and English L2 vocabulary. Finally, English stress production and L2 vocabulary were significantly correlated.

To examine the contributions of separate auditory processing abilities to Mandarin L1 and English L2 vocabulary knowledge after controlling for age and nonverbal IQ, three-step fixed-entry hierarchical regression equations were computed with the two vocabulary measures as dependent variables (i.e., separate models for Mandarin and English) and significance of the whole models were tested. In each fixed-entry hierarchical regression equation, age was entered at step 1, nonverbal IQ at step 2 and auditory processing at step 3. We then

TABLE 1. Descriptive statistics for all measures.

Measures	Highest possible score	Mean	SD
Age (in years)	—	9.82	0.25
Nonverbal IQ	60	43.57	6.26
Auditory processing (discrim.)			
Rise time thresholds (ms)	—	122.29	56.56
Pitch contour (*d'*)	—	1.92	1.06
Pitch interval (*d'*)	—	1.11	0.78
Prosodic awareness (scores)			
Monosyllabic tone perception	20	15.39	3.00
Disyllabic tone perception	10	8.08	2.10
English stress perception	9	6.61	1.93
English stress production	12	8.34	2.77
Phonological awareness (scores)			
Mandarin rhyme awareness	10	8.76	1.90
English rhyme awareness	12	9.80	2.32
Receptive vocabulary (PPVT)			
Mandarin	125	107.03	7.77
English	228	44.03	26.76

PPVT, Peabody Picture Vocabulary Test.

assessed each model's R^2 change to evaluate the additive predictive power of the additional task regressors. The whole model reached significance in Mandarin, $F(3, 57) = 4.48, p < .01$, and English, $F(3, 57) = 3.62, p < .05$. As shown in Table 3, amplitude envelope rise time discrimination thresholds made independent contributions to Mandarin L1 and English L2 vocabulary even after controlling for age and nonverbal IQ.

Table 4 shows the relative contributions of prosodic and phonological awareness to Mandarin L1 and English L2 vocabulary after partialling out age and nonverbal IQ. For this analysis, we used four-step, fixed-entry hierarchical regression equations, in which age was entered at step 1, nonverbal IQ at step 2, prosodic awareness at step 3 and phonological awareness at step 4. The entry order of prosodic and phonological awareness was also reversed as shown in previous studies (Chung, Jarmulowicz, & Bidelman, 2017; Chung & Bidelman, 2020). We aimed to examine whether prosodic and phonological awareness play different roles in Mandarin L1 and English L2 vocabulary development. Given the significant relationships between variables as shown in Table 2, prosodic and phonological awareness were entered by different tasks: (1) Mandarin monosyllabic tone perception and rhyme awareness when the dependent variable is Mandarin L1 vocabulary knowledge and (2) English stress production and rhyme awareness when the dependent variable is English L2 vocabulary knowledge. The whole models reached significance in Mandarin, $F(4, 56) = 2.59$, $p < .05$, and English, $F(4, 56) = 4.39$, $p < .01$. As revealed in Table 4, Mandarin monosyllabic tone perception and rhyme awareness, independent of age and nonverbal IQ, did not predict Mandarin L1 vocabulary knowledge. Turning

TABLE 2. Correlations between variables.

	1	2	3	4	5	6	7	8	9	10	11	12
1. Age	—	—	—	—	—	—	—	—	—	—	—	—
2. Nonverbal IQ	**.461**	—	—	—	—	—	—	—	—	—	—	—
3. Rise time discrimination	.008	−**.335**	—	—	—	—	—	—	—	—	—	—
4. Pitch contour discrimination	.027	**.336**	−.192	—	—	—	—	—	—	—	—	—
5. Pitch interval discrimination	.161	.237	−.109	**.694**	—	—	—	—	—	—	—	—
6. Monosyllabic tone perception	.188	**.324**	−.208	.060	.138	—	—	—	—	—	—	—
7. Disyllabic tone perception	**.262**	**.265**	−.054	.190	.104	**.488**	—	—	—	—	—	—
8. Mandarin rhyme awareness	**.311**	**.500**	−.041	.241	.168	.171	.090	—	—	—	—	—
9. English stress perception	.179	.173	.030	−.094	−.035	**.445**	**.390**	.145	—	—	—	—
10. English stress production	−.038	.125	−.196	.116	−.074	**.341**	**.396**	−.022	**.417**	—	—	—
11. English rhyme awareness	.019	.158	−**.268**	.046	.197	.243	**.280**	.008	.131	**.269**	—	—
12. Mandarin vocabulary	**.255**	**.312**	−**.340**	.190	.161	**.253**	.206	**.288**	.084	.137	−.028	—
13. English vocabulary	**.288**	.228	−**.275**	.002	.066	**.334**	**.301**	.189	.153	**.277**	**.342**	**.425**

Note. Significant values ($p < .05$) are marked in boldface.

TABLE 3. Hierarchical regressions showing unique variance in Mandarin (L1) and English (L2) vocabulary accounted for by auditory processing abilities (controlling for age and nonverbal IQ).

	Mandarin vocabulary		English vocabulary	
Step	Final β	R^2	Final β	R^2
1. Age	—	.065*	—	.083*
2. Nonverbal IQ	—	.048	—	.012
3. Auditory processing (+one of the following)				
Rise time	−.302*	.078*	−.277*	.066*
Pitch contour	.119	.012	−.052	.002
Pitch interval	.085	.007	.000	.000

$^{*}p < .05$.

TABLE 4. Hierarchical regressions showing unique variance in Mandarin (L1) and English (L2) vocabulary accounted for by prosodic and phonological awareness (controlling for age and nonverbal IQ).

	Mandarin vocabulary		English vocabulary	
Step	Final β	R^2	Final β	R^2
Model 1				
1. Age	.117	.065*	.277*	.083*
2. Nonverbal IQ	.124	.048	.031	.012
3. Prosodic awareness	.163	.024	.209	.075*
4. Rhyme awareness	.161	.019	.275*	.069*
Model 2				
1. & 2. (as above)				
3. Rhyme awareness		.020		.104*
4. Prosodic awareness		.024		.040
Total variance		.156*		.239**

Note. Prosodic and rhyme awareness refer to Mandarin monosyllabic tone perception and rhyme awareness when dependent variable is Mandarin vocabulary and to English stress production and rhyme awareness when dependent variable is English vocabulary.

$^{**}p < .01$.

$^{*}p \leq .05$.

to English L2 vocabulary, English rhyme awareness, independent of age and nonverbal IQ, accounted for more variance than did stress production irrespective of the entry steps. Additionally, significant proportions of variance in vocabulary knowledge (Mandarin: 15.6%; English: 23.9%) could be explained by prosodic and phonological awareness, age and nonverbal IQ together.

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Post-hoc analyses of linguistic and acoustic measures

Because the current study measured language-specific prosodic awareness using speech (i.e., Mandarin tone perception and English stress production) and non-speech stimuli (i.e., pitch contour and rise time discrimination), post-hoc analyses were conducted to determine if there were differences between the associations of the stimulus types and vocabulary knowledge in each language. As revealed in the free software package cocor (Diedenhofen & Musch, 2015), no significant difference was found across stimulus types in each language.

Discussion

Although several studies have examined links between prosody and reading, there have been few attempts to establish a direct relationship between prosody and different areas of language ability (e.g., vocabulary knowledge) in bilingual children. The current study examined relations among separate auditory processing abilities, language-specific prosodic and phonological awareness, and Mandarin L1 and English L2 vocabulary knowledge in Taiwanese fourth-grade children.

Rise time discrimination predicts vocabulary knowledge

Paralleling English monolingual children (Corriveau, Pasquini, & Goswami, 2007), we found that amplitude envelope rise time discrimination predicted both Mandarin L1 and English L2 vocabulary knowledge. This finding suggests that the ability to distinguish rudimentary properties of acoustic signals (envelope rise time) might play an important role in vocabulary acquisition not only in L1 (Corriveau, Pasquini, & Goswami, 2007) but also in L2. Specifically, individuals who are good at discriminating subtle differences in speech rise time might be better equipped to segment speech sequences and distinguish syllable boundaries, which in turn could help foster their vocabulary acquisition first and detailed phoneme representation later. This indirectly supports the proposition in the lexical restructuring hypothesis that children's vocabulary growth requires a phonological re-representation process from a coarse-grained phonological system to a fine-grained phonological system (Metsala, 1997a, 1997b).

Our data further replicate and extend previous studies by showing that amplitude rise time is an acoustic marker of stress in rhythmic languages like English (Goswami & Leong, 2013), and amplitude rise time discrimination is a salient predictor of vocabulary knowledge in tone languages like Mandarin. Sensitivity to amplitude envelope rise time, which distinguishes syllable boundaries, is fundamental to all prosodic systems across languages. Syllables, particularly syllabic nuclei, are required elements through which stress or tone is expressed. Hence, rise time discrimination may be a type of fundamental perceptual ability upon which both rhythmic (i.e., lexical stress) and atypical rhythmic systems (i.e., lexical tone) are built. Additionally, children who are good at rise time discrimination would presumably be highly successful in distinguishing minimal pairs of affricate–fricative contrasts in Mandarin (i.e. /tsh/-/s/, /t.shk;h/-/ʂ/, and/t.ccrl;h/-/ç/) (Tsao, Liu, & Kuhl, 2006). As such, we posit that Mandarin may be a language that is not strictly nonrhythmic as usually conceived, but rather, a lexicon which falls into more of a rhythmic continuum (Arvaniti, 2012; Grabe & Low, 2002; Nespor, 1990).

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In contrast to rise time and our hypothesis, pitch contour discrimination failed to explain significant variance in Mandarin L1 vocabulary knowledge. This was surprising because pitch contour, an acoustic marker of linguistic prosody (Patel, Peretz, Tramo, & Labreque, 1998), is important for word reading (Chung, Jarmulowicz, & Bidelman, 2017; Chung & Bidelman, 2020; Foxton et al., 2003), which was significantly correlated with vocabulary knowledge in Mandarin-speaking children (Hu, 2013). Our results also challenge the language-specific auditory cue hypothesis, which states that dominant cues in a given language (e.g., pitch in Mandarin) are important to learning that language (Antoniou, To, & Wong, 2015). In the present study, the relationship between pitch discrimination and Mandarin vocabulary was not significant. One possible explanation is that the rate of intensity change tapped by our rise time discrimination task is a more salient cue for syllable boundaries in comparison with relative pitch height measured by the pitch contour discrimination task. In other words, amplitude envelope rise time signalling syllable boundaries is more critical to vocabulary acquisition than is pitch contour information. Collectively, we find that amplitude envelope onset is a cross-linguistic predictor of vocabulary development in Mandarin and English, whereas pitch contour is not a perceptually salient cue for Mandarin vocabulary acquisition.

Prosodic/phonological awareness and L1/L2 vocabulary knowledge

Mandarin monosyllabic tone perception was significantly correlated with Mandarin L1 vocabulary knowledge. However, Mandarin monosyllabic tone perception and rhyme awareness did not account for unique variance in Mandarin L1 vocabulary (after controlling age and nonverbal IQ). This contrasts with a recent study on Cantonese, which showed that independent of age and nonverbal IQ, tone perception (for Cantonese tones) can account for unique variance in vocabulary skills above and beyond phonological awareness (Tong, Tong, & McBride-Chang, 2015). Inconsistencies between studies may be attributable to two reasons. First, the number and complexity of tone patterns might influence the role of prosodic awareness in vocabulary knowledge. Children learning six tones in Cantonese may expend more cognitive resources than those learning four tones in Mandarin. This may result in more individual variability in Cantonese than in Mandarin prosodic awareness, which may account for the weaker association with vocabulary knowledge in Mandarin.

Second, different educational approaches to literacy between Taiwan and Hong Kong might be implicated in the development of prosodic awareness. Children in Hong Kong are taught to pronounce each character without the aid of a phonological coding system for pronouncing characters (Zhang & McBride-Chang, 2011). In contrast, children in Taiwan receive 10 weeks of intensive instruction in Mandarin phonetic symbols in first grade and become highly proficient in analysing Mandarin phonological structures. Thus, the more analytic educational approach in Taiwan may have resulted in uniformly proficient performance in Mandarin prosodic and phonological awareness, which reduced variability and cloaked the contributions to Mandarin L1 vocabulary acquisition. Collectively, children in Taiwan may use lexical tone to acquire vocabulary, but the contribution of Mandarin prosodic awareness to vocabulary acquisition may not be easily observable after the children receive the instruction in Mandarin phonetic symbols. Future cross-linguistic studies are needed to directly compare the influence of prosodic and phonological awareness on vocabulary acquisition in different tonal languages.

Turning to English L2, we found that English rhyme awareness (but not stress production) was a key predictor of oral vocabulary skills. This finding is compatible with a reading study in which English rhyme awareness was shown to be more important to English L2 reading ability than were stress perception and production (Chung, Jarmulowicz, & Bidelman, 2017). Taiwanese children may rely more heavily on phonological cues (i.e., segments or individual sounds) for English (L2) and/or may not have fully mastered its prosodic system. If this is the case, children may not be able to efficiently use nonnative prosodic patterns as a skeleton for auditory information in short-term memory (Reeves, Schmauder, & Morris, 2000; Sturges & Martin, 1974) or as a segmentation cue (Cutler, 1996; Echols, 1996) for vocabulary acquisition. Thus, the findings do not support the models that prosodic awareness has an indirect effect on phonological awareness through vocabulary in English monolingual children (Holliman et al., 2014; Wood, Wade-Woolley, & Holliman, 2009). The mechanism(s) of the links between phonological and prosodic awareness and vocabulary development in a second/foreign language should be further examined.

Although English stress perception and production were significantly correlated with each other, it is noteworthy that English L2 vocabulary was predicted by English stress *production*, but not stress *perception*. Possible explanations for this finding rest in the consistency of prosodic awareness measures and the difference between the stress perception and production tasks. First, the stress production task has a higher Cronbach's alpha value than does the stress perception task ($0.73 > 0.60$). This suggests that poorer reliability (i.e., more measurement errors) might lower the correlation coefficients observed between stress perception and vocabulary. Second, the two tasks were similar in that they used nonsense syllables (DEEdee). One key difference was that the perception task involved phrase-length sequences matched to actual English phrases, typically longer than two syllables, which may or may not have been familiar to the children. This put considerable load on working memory for the children, although they did perform similarly across the two tasks, $t(60) = 1.16$, $p = 0.25$, 96% CI [−0.08, 0.02]; 67% on the perception task, 69% on the production task. In contrast, the production task was limited to two-syllable words. An additional and perhaps critical difference was that the production task required both perception of stress patterns and production of accurate stress. Thus, the ability to integrate auditory information with oral-motor movement could be reflected in the English L2 stress production task. This ability to integrate across perception and production may be more important in L2 vocabulary development than perception alone. Future studies should consider titrating the difficulty of perception and production tasks to tease apart what exactly each task is tapping into and then examine their contributions to vocabulary acquisition.

Finally, the current study measured language-specific prosodic awareness using speech and non-speech stimuli. For the children in this study, speech stimuli (i.e., Mandarin tone perception and English stress production) are similar to non-speech stimuli (i.e., pitch contour discrimination and rise time discrimination) in their correlation to vocabulary knowledge. The association of pitch contour discrimination was similar as Mandarin tone perception with L1 vocabulary. For English L2, both rise time discrimination and stress production were equally associated with English vocabulary knowledge. However, only rise time discrimination and stress production are important predictors of vocabulary (in English). This may be a function of development such that individuals' difference in speech and non-speech perceptual skills diminish with exposure in L1 more than in L2.

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A curious aspect of our findings is the associations we observe across modalities, from perceptual judgement to stress production across the two languages. The perception tasks (1–2 syllables vs phrases) were not completely identical across Mandarin and English. Interestingly, Mandarin monosyllabic and disyllabic tone perception is significantly associated with both English stress perception and production. This suggests that individuals who are better at discriminating lexical tones would be better at employing pitch cues to perceive primary stress for stress production. This reflects prosodic transfer and some core language abilities associated with L1/L2 language learning.

Limitations and future directions

Although we have offered insight into the relations between prosody and L1/L2, our study only examined one area of language ability (i.e., vocabulary knowledge) and included bilinguals with two specific languages. Future studies could examine how children use prosodic patterns to acquire different areas of language ability (e.g., syntax and narrative). Considering potential differences across tone languages, it may also be interesting to examine the influence of different tone languages, different L2s, and/or different educational systems on vocabulary development, especially over time. Additionally, future studies might consider the consistency of prosodic awareness measures (i.e., reliability) (Holliman, Mundy, Wade-Woolley, Wood, & Bird, 2017). Lastly, special attention should be paid to how to measure awareness of prosodic patterns from the following perspectives: speech versus non-speech stimuli, perceptual judgement versus production and short versus long syllable length.

Conclusions

In summary, our findings indicate that amplitude envelope rise time (i.e., a cue that signals syllable boundaries) is a robust cross-linguistic predictor of vocabulary development in Mandarin (L1) and English (L2). Prosodic awareness, as measured in this study, does not contribute to Mandarin L1 vocabulary and makes minimal contributions to English L2 vocabulary compared with phonological awareness. This may reflect the effect of literacy instruction on the development of Mandarin L1 prosody, and different roles of prosodic and phonological awareness in English L2 vocabulary development. Prosodic transfer is observed between Mandarin L1 and English L2 as evidenced by the influence of Mandarin tone perception on English stress perception and production.

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Data Availability Statement

The authors have not been granted by children's parents in written consent to share data with other researchers. Thus, the data that support the findings of this study are not available in a public repository and on request. Future studies would secure data sharing in written consent.

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