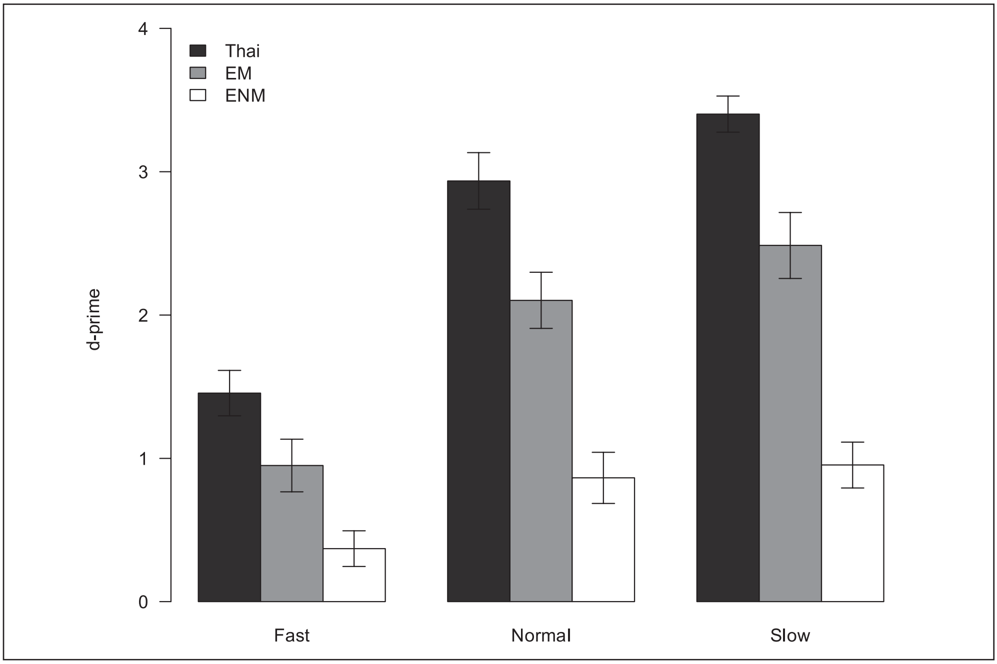

Figure 2. Mean *d′* scores (+/− 1 standard error) in discriminating long and short vowels for Between Category–Same Rate condition by rate and group.

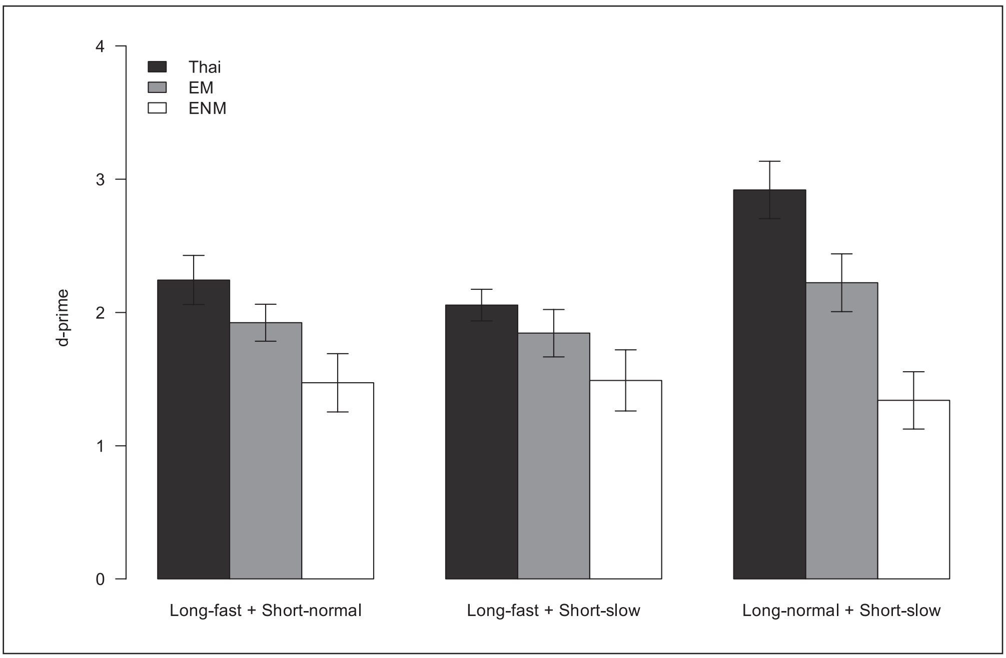

Figure 3. Mean *d′* scores (+/− 1 standard error) for Between Category–Different Rate condition of the discrimination task by length-rate pattern and group.

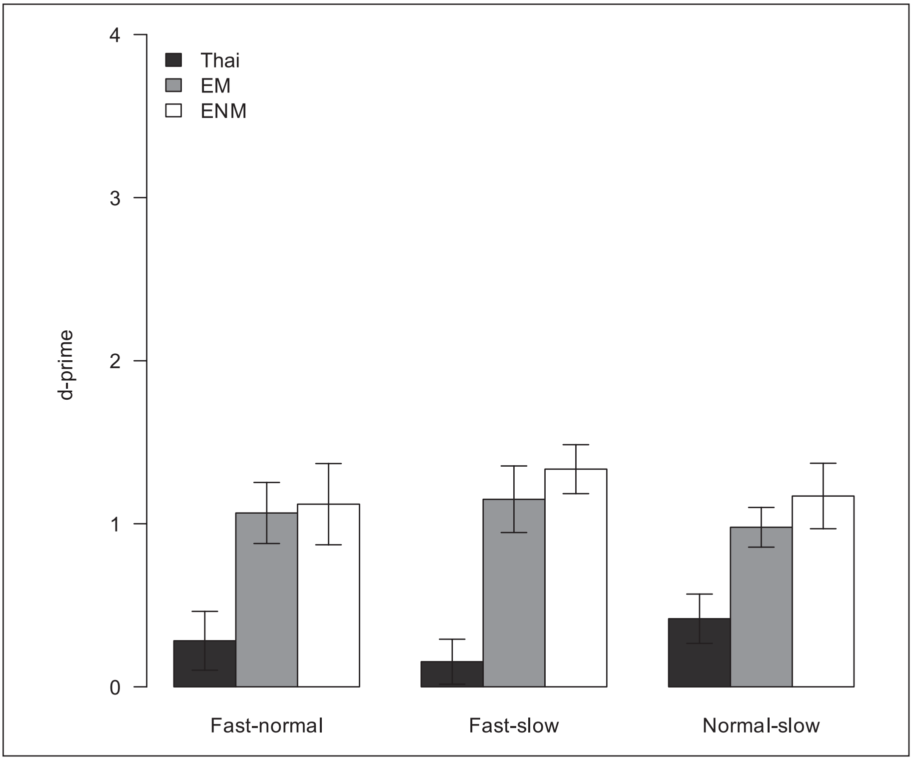

Figure 4. Mean *d′* scores (+/− 1 standard error) for the Within Category–Different Rate condition of the discrimination of short vowels by rate pattern and group.

Thai listeners were significantly more accurate than ENM at discriminating Long–normal + Short–slow ($p < 0.001$) and Long–fast + Short–normal pairs ($p = 0.026$); however, they did not differ significantly from EM ($p > 0.118$). It should be noted that neither EM nor Thai listeners showed significantly better discrimination than the ENM listeners in the Long–fast + Short–slow condition where the mean duration for the long vowels (115 ms) was shorter than that for the short vowels (130 ms), indicating that the EM and Thai listeners' perception was based on category information rather than absolute durational differences. Together, the findings from the Between Category–Different Rate condition indicate that EM and Thai listeners, compared to ENM, were more accurate at discriminating short and long vowels despite the challenge of having to adjust for speaking rate within a single discrimination pair, demonstrating EM as well as Thai listeners' sensitivity to between-category differences.

Listeners' within-category discrimination abilities were examined in the Within Category–Different Rate condition, using a 3-way mixed ANOVA with Rate pattern (Fast–normal, Fast–slow, or Normal–slow) and Length (long, short) as repeated measures and Group (Thai, EM, or ENM) as a between-subjects factor. Significant main effects were obtained for Rate pattern, $F(2, 32) = 7.194$, $p = 0.002$, Length, $F(1, 32) = 32.027$, $p < 0.001$, and Group, $F(2, 32) = 5.407$, $p = 0.009$.

The ANOVA also revealed a significant Length x Group interaction, $F(2, 32) = 5.199$, $p = 0.011$. Bonferroni-adjusted pairwise comparisons showed that, across rate patterns, Thai listeners were significantly worse than both English groups at within-category discrimination of short vowels ($p < 0.004$; Figure 4), while all groups performed similarly for the discrimination of long vowels

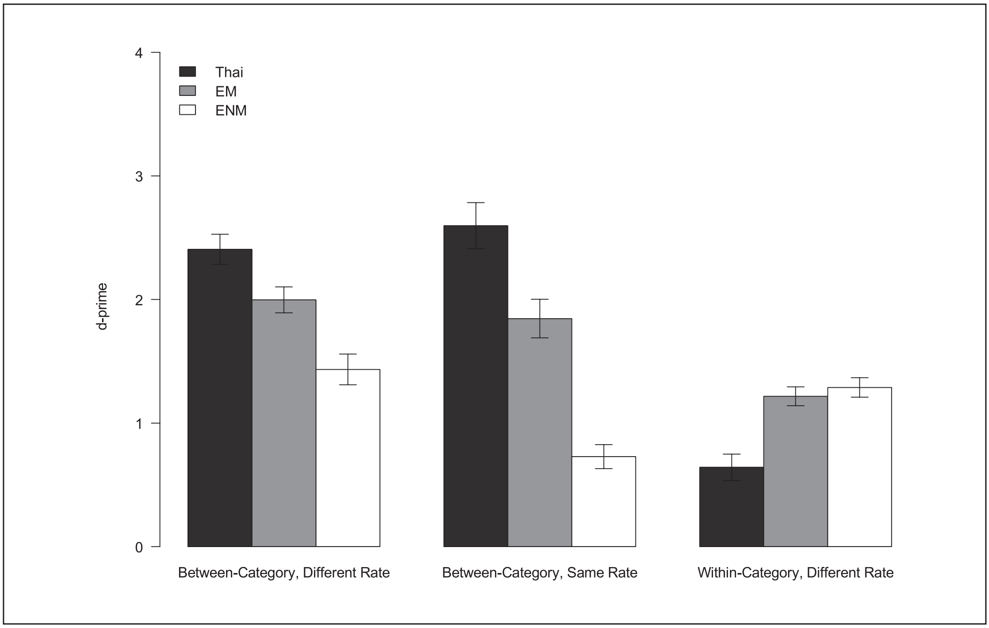

Figure 5. Mean *d′* scores (+/− 1 standard error) for each Category–Rate condition and group.

($p > 0.372$). A significant Rate x Length interaction was also found, $F(2, 32) = 6.907$, $p = 0.002$, with pairwise (Bonferroni) comparisons indicating that across groups, for long vowel pairs, discrimination scores were higher for the fast–slow rate pattern relative to the other rate patterns ($p < 0.002$), whereas performance was comparable for short vowel pairs at different rate patterns ($p > 0.05$). The remaining Rate pattern x Group and Rate pattern x Length x Group interactions did not reach significance ($p > 0.08$).

Finally, to compare overall discrimination performance by condition and group (Figure 5), a 2-way mixed ANOVA was constructed containing Category–Rate condition (Between Category–Same Rate, Between Category–Different Rate, Within Category–Different Rate) as a repeated measure and Group (Thai, EM, and ENM) as a between-subjects factor. Significant main effects of Category–Rate condition, $F(2, 32) = 45.799$, $p < 0.001$, and Group, $F(2, 32) = 9.059$, $p = 0.001$, were found, along with a significant Category–Rate condition x Group interaction, $F(4, 32) = 26.950$, $p < 0.001$. Pairwise (Bonferroni) comparisons of Category–Rate condition fixing each Group were performed. EM demonstrated significantly higher *d′* scores in both Between Category conditions relative to the Within Category condition ($p < 0.005$), with performance in Between Category–Same Rate and Between Category–Different Rate not differing significantly from each other ($p = 0.822$). Thai controls displayed a similar pattern of discrimination performance, with higher discrimination accuracy in the Between Category conditions than the Within Category condition ($p < 0.001$) and no difference between the two Between Category conditions ($p = 0.748$). ENM, on the other hand, showed significantly lower scores in the Between Category–Same Rate condition relative to the other conditions ($p < 0.013$) and no significant difference between the Between Category–Different Rate and the Within Category–Different Rate conditions ($p > 0.05$).

Pairwise (Bonferroni) comparisons of Group by Category–Rate condition found that in the Between Category–Same Rate condition, Thai controls had higher overall discrimination accuracy performance than both English groups ($p < 0.004$), and the EM group in turn had higher discrimination accuracy than ENM ($p < 0.001$). For the Between Category–Different Rate condition, the Thai group performed significantly better than ENM ($p = 0.003$), and EM performed marginally better than ENM ($p = 0.074$), while the Thai and EM listeners performed similarly ($p = 0.394$). Finally, for the Within Category–Different Rate condition, Thai listeners demonstrated significantly worse within-category discrimination than both English groups ($p < 0.042$), who did not differ significantly from each other ($p > 0.05$).

Taken together, these discrimination results indicate that the native Thai listeners were more sensitive to between-category vowel length distinctions than English listeners, evidenced by their superior identification and between-category (Same and Different Rate conditions) discrimination performance. In contrast, English non-musicians were more sensitive to within-category differences due to speaking rate variations, with significantly higher d' scores than the Thai listeners in the Within Category–Different Rate discrimination condition. The English musicians' performance was intermediate to the Thai and English non-musicians, showing enhanced sensitivity to categorical distinctions, as illustrated by their significantly higher identification and between-category (Same and Different Rate conditions) discrimination performance relative to the English non-musicians, while still maintaining within-category sensitivity, outperforming Thai listeners in the Within Category–Different Rate condition.

4 Discussion and conclusions

The present study examined whether musical experience would facilitate native English listeners' ability to normalize for speaking rate variation in the perception of Thai vowel length distinctions. The results of the identification task revealed that all groups, including the native Thai controls, were affected by speaking rate, such that they displayed poorer identification accuracy at fast relative to slower speaking rates. This is in line with prior research on the influence of speaking rate on phonemic length perception, whereby a fast speaking rate was found to yield significantly lower identification accuracy scores than slower rates, even for native speakers of the quantity language being tested (Tajima et al., 2008). A similar pattern of rate sensitivity was found in the discrimination task across groups, with poorer between-category discrimination accuracy at fast as compared to slower speaking rates.

As predicted, the English non-musicians were significantly less accurate overall in the identification task and at between-category discriminations than native Thai listeners, which is in line with previous studies demonstrating that non-native listeners whose L1s do not have phonemic temporal distinctions have difficulty perceiving phonemic vowel length in an L2 (Hisagi et al., 2010; McAllister et al., 2002; Tajima et al., 2008). Moreover, while the English non-musicians showed poor between-category discrimination when the pairs of vowels were at the same rate of speech (Between Category–Same Rate), they showed improved discrimination when the vowel pairs were at different rates of speech (Between Category–Different Rate), with performance in the latter condition being on par with the Within Category–Different Rate condition. The fact that the English non-musicians' discrimination performance was similar in the two conditions involving pairs of vowels at different speaking rates suggests that they were responding to rate differences rather than to phonemic length differences. It appears that non-musicians were latching onto the non-categorical cue, focusing on speaking rate differences bearing within-category temporal acoustic variations rather than categorical vowel length differences. These results are in line with the findings in non-native tone perception where, compared to native listeners, non-natives are more sensitive to within-category F0 differences, but less accurate in discriminating Chinese tones or classifying tonal exemplars into categories (Hallé, Chang, & Best, 2004; Peng, Zheng, Gong, Yang, & Kong, 2010; Xu, Gandour, & Francis, 2006). Indeed, Thai listeners were significantly worse than English listeners at discriminating within-category differences, though only for the short vowel pairs. Within-category differences as a function of speaking rate tend to be smaller for short relative to long vowels (Hirata, 2004a), and, in the present work, the average within-category difference for short vowels across rate patterns was 39 ms versus 100 ms for long vowels. Greater durational variation for the long vowels may have resulted in pairs containing items with sufficiently large enough differences that Thai listeners would be more likely to false alarm and perceive them as members of distinct length categories. Overall, these findings demonstrate that non-native listeners relative to native listeners are less capable of classifying exemplars bearing quantitative acoustic differences into categories.

Our prediction of the facilitative effects of musical experience in vowel perception was borne out because the English musicians demonstrated superior performance relative to the non-musicians at identifying non-native long and short vowels at all speech rates. Similarly, musicians were significantly more accurate than non-musicians at between-category vowel length discriminations, both at same and different speaking rates. Moreover, in contrast to the non-musicians, English musicians patterned similarly to the native Thai listeners, showing greater accuracy at distinguishing Thai vowel length categories relative to within-category differences due to speaking rate variation. The present results are consistent with previous research demonstrating that musical experience can play a significant facilitative role in the perception of non-native speech categories (e.g., Lee & Hung, 2008, Milovanov et al., 2009; Sadakata & Sekiyama, 2011). While the pattern of results was similar between English musicians and Thai listeners, the Thai group's native language experience with these contrasts did result in enhanced accuracy rates in most conditions; however, group differences were neutralized in certain conditions. For example, no significant differences were found at the slow rate in the identification task between Thai and English musician groups, which may have resulted from the condition being sufficiently easy enough for these listeners, with the slow rate providing robust contextual and word-intrinsic cues for both musician and Thai listeners to have reached a performance ceiling. Moreover, the discrimination task saw a neutralization of Thai and English musician group differences at between-category discrimination at the fast speaking rate. This may have stemmed from Thai listeners doing equally poorly as English musicians as a result of relatively small acoustic differences between short and long vowels in this condition (M = 43 ms, a smaller difference even than certain within-category conditions such as short vowels at fast and slow rates, M = 58 ms). This may reflect the existence of absolute duration ranges in the native Thai listeners' internal system (that is, permissible minimum and maximum durations for short and long vowels). Indeed, Abramson and Ren (1990) noted that sufficiently compressing a long vowel would at some point result in listeners hearing its short counterpart, perhaps as a product of the long vowel being outside of the permissible long vowel category range. Long vowels at a fast speaking rate in the present work may have been compressed to such a degree that it became difficult for native listeners to discriminate them from short vowels.

It is also important to note that, unlike the Thai group, English musicians did maintain a degree of within-category sensitivity, as they outperformed Thai listeners at discriminating within-category differences as a result of speaking rate variation, indicating that their perception of this non-native temporal contrast was not yet completely native-like. As the stimuli pairs were from the same phonemic length category, native listeners normalized for rate differences (i.e., demonstrated less sensitivity to within-category differences). In contrast, English musicians showed enhanced perception of between-category differences (relative to non-musicians) and within-category differences (relative to Thai listeners), reflecting influences of both musical and linguistic experience.

The present findings indicate that the musician group demonstrated a formation of non-native length categories that were relatively robust and could withstand speaking rate variability. They were capable of tracking the speech rate of the carrier sentence and accounting for that rate, while abstracting over the acoustic variation, when considering the vowel length of the target item. Previous research has established that native listeners possess internal phonemic categories that are normalized for extrinsic acoustic variations, such as speaking rate or style, suggesting relational invariance for duration to maintain phonological length contrasts (Boucher, 2002; Hirata, 2004a; Smiljanic & Bradlow, 2008). That the musicians showed near native-like patterns of speaking rate normalization points to the enhancement of domain-general auditory abilities as a result of musical experience. Specifically, musicianship involves tracking the temporal context and normalizing for changes in musical tempo. Such experience with extracting sound units and tracking regularities within a complex auditory environment appeared to enhance their ability to acquire regularities in a speech environment in terms of perceiving phoneme-intrinsic cues to speech sound categories while normalizing for phoneme-extrinsic acoustic variations. Indeed, previous research has shown that musical experience may facilitate the perception of more linguistically-relevant acoustic dimensions of speech sounds. For example, musicians relative to non-musicians were found to be able to better track the F0 contour information that distinguishes phonemic tonal categories (Lee, Lekich, & Zhang, 2014). The current results are in line with these previous findings, revealing that general auditory processing mechanisms such as experience with spectral and temporal categories from musical training may positively transfer to aid perception of speech categories in a non-native language.

The present work provides insight into the nature of music-to-speech transfer in the temporal domain, in that musical experience influences non-native phonemic length perception at the linguistic categorical level rather than the physical quantitative level. While the musicians did outperform non-musicians in detecting phonemic vowel length contrasts, they did not show any advantage over non-musicians in discriminating within-category temporal differences due to speaking rate variations. Indeed, musicians have extensive experience normalizing for changes in musical tempo by extracting the length identities of a sequence of notes in such a way that these length identities remain constant across different tempos. This requires musicians to overlook non-categorical, quantitative variations despite the fact that their musical training also enhances their sensitivity to subtle acoustic differences. These mechanisms involved in musical perception appear to mediate musicians' perception of length contrasts in a non-native language. As they establish phonemic length categories they become less sensitive to subtle within-category acoustic durational differences. These patterns implicate common perceptual manifestations for music and linguistic categorical functions, suggesting that long-term exposure to contextual temporal variations may shape fundamental sensory circuitry in a domain-general manner.

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Note

1. Analyses were also conducted using linear mixed effects regression models. The results were comparable to those performed with the analyses of variance (ANOVAs), and thus for ease of reporting, the ANOVAs are reported here.

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