INTERSPEECH 2020
October 25–29, 2020, Shanghai, China

Age-related differences of tone perception in Mandarin-speaking seniors

Yan Feng[1], *Gang Peng*[1,2], *William Shi-Yuan Wang*[1,3]

[1]Research Centre for Language, Cognition, and Neuroscience, Department of Chinese and Bilingual Studies, The Hong Kong Polytechnic University, Hong Kong, China
[2]Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Guangdong, China
[3]Department of Electronic Engineering, Chinese University of Hong Kong, Hong Kong, China
yanny.feng@connect.polyu.hk, gpengjack@gmail.com, wshiyuanw@gmail.com

Abstract

This study examined age-related differences in categorical perception of Mandarin lexical tones through comparing identification and discrimination performance among young adults, seniors aged 60-65 years, and older seniors aged 75-80 years. Results showed a significantly wider boundary and smaller peakedness in older seniors. There was also a positive correlation between the hearing level at 125 Hz and boundary width, and a negative correlation between hearing level (125 Hz) and peakedness in older seniors, indicating that the decline of tone perception in this population might be associated with degradation of hearing sensitivity. However, there was no significant difference between young adults and seniors aged 60-65 years, which might reveal that younger seniors could maintain normal ability to perceive tones categorically.

Index Terms: Mandarin, categorical perception, tone, age-related decline

1. Introduction

Distinct from the common European languages, for tonal language like Mandarin, the lexical tone is a suprasegmental feature that can distinguish different meanings of words. There are four tones in Mandarin differing in fundamental frequency (F0): high-level tone (Tone 1), mid-rising tone (Tone 2), falling-rising tone (Tone 3), and falling tone (Tone 4) [1, 2]. F0 here not only reflects the spectral pitch information in the general acoustic domain, but also includes phonological information in the language-specific domain. Thus, the perception of lexical tone in native listeners is a combination of spectral signal processing and phonemic category knowledge retrieving.

Categorical perception of speech is a basic cognitive ability to perceive continuous acoustic signals as discrete phonemes [3]. Repp [4] summarized several characteristics of categorical perception: 1) a sharp boundary between two categories in identification function, 2) an accuracy peak at category boundary in discrimination function predicted from identification function, and 3) discrimination accuracy for within-category pairs is near chance level. Previous literature has well-documented that Mandarin lexical tones could be perceived categorically by native listeners [5, 6].

Because of hearing loss, cognitive decline, structural and functional brain senescence, elderly listeners are reported to have difficulty with speech perception in daily communication [7, 8]. There are more than 249 million seniors aged above 60 years in China, which account for 17.9% of the total population [9]. More and more studies focus on the perceptual decline in Chinese seniors, rather than only those from western, educated, industrialized, rich and democratic countries [10]. Wang et al. [11] investigated the categorical perception of Mandarin lexical tones (Tone 2 vs. Tone 3) among 13 older adults aged 60-70 years and found that older adults showed a significant decline in tone identification and discrimination, with young adults as a comparison. They further examined the impact of signal duration on Mandarin tone perception (Tone 1 vs. Tone 2, Tone 1 vs. Tone 4) in native older adults [12], and indicated that this cohort was more sensitive to sound duration: Short duration impaired seniors' perceptual ability. Recently, Feng et al. [13] investigated lexical tone perception (Tone 1 vs. Tone 2) of Mandarin-speaking seniors aged 60-81 years with normal cognitive ability and those with mild cognitive impairment (MCI). A significant decline was observed in MCI seniors, rather than normal seniors, which indicated that general cognitive decline might be associated with perceptual impairment of tone. However, these studies did not allow for a direct comparison across ages in the aging population.

Besides behavioral tests mentioned above, some recent research measures electroencephalograms to observe cortical changes of event-related potentials when older adults perceive Mandarin tones. Xiao et al. [14] compared mismatch negativity (MMN) between young adults and older adults aged 55.6-79.6 years with normal cognitive ability when they perceived between/within-category lexical tones (Tone 2 vs. Tone 4) and nonspeech tone without attention. They discovered that the amplitude of MMN decreased and latency increased in older adults when perceiving between-category lexical tones. Older adults maintained the perceptual ability of within-category lexical tones by increasing latency of MMN, while no compensation was found in the nonspeech tone condition. The MMN findings provided neural evidence for the speech-specific preservation in processing pitch information and the decline in retrieving tone category knowledge. There are also some subcortical changes being observed in the elderly. All four lexical tones in Mandarin could elicit frequency-following responses (FFRs), emphasizing the important role of phase-locking ability in neural encoding of tones [15]. Some previous studies on FFR observed a decreased pitch discrimination and reduced FFR phase coherence and amplitude with increased age, indicating that the declined phase-locking ability involving the brainstem and the impaired neural representation of frequency in the elderly was associated with the age-related deficit in pitch perception [16].

http://dx.doi.org/10.21437/Interspeech.2020-2194

In order to solve the issues on the age comparison of the spectral and suprasegmental perception at the phonological level in the aging population, this study aims to investigate the age-related decline trajectory of the categorical perception of Mandarin lexical tones among native elderly listeners with normal cognitive ability. Three groups for age comparison consist of young adults, seniors aged 60-65 years and older seniors aged 75-80 years.

2. Method

2.1. Participants

Twenty-four young adults aged 20-30 years (15 male, mean age = 24.58 yr, SD = 2.73), 24 younger seniors aged 60-65 years (9 male, mean age = 62.71 yr, SD = 1.37), and 19 older seniors aged 75-80 years (12 male, mean age = 77.74 yr, SD = 2.00) were recruited from northern China who could fluently speak Mandarin in daily life. Participants in two elder groups also lived in northern China during childhood and tone systems (especially high-level tone and mid-rising tone) in their northern dialects are similar to that in Mandarin. No participant reported language impairments or psychiatric illness, surgery in ear or head, nervous system medications, or formal music learning experience. Beijing Version of Montreal Cognitive Assessment (MoCA) [17] was conducted and all participants matched in MoCA score (F (2, 64) = 2.883, p = 0.063) representing normal cognitive ability (26-30 points). Two elderly groups also matched in total years of formal education (t (1, 41) = 0.935, p = 0.355) and social-economic status. They were compensated for voluntary participation in this study, and consent forms were obtained from them with a protocol approved by the Human Subjects Ethics Sub-committee of The Hong Kong Polytechnic University.

2.2. Material

Speech samples /i/ with Mandarin high-level tone ('衣', clothes) and /i/ with mid-rising tone ('姨', aunt) were uttered by a native male speaker from northern China and recorded using Praat [18] with a 44,100 Hz sampling rate and 16-bit resolution. Two words (i.e., '衣', '姨') are frequently used in spoken and written Chinese. TANDEM-STRAIGHT [19] was used to generate the tone continuum with nine stimuli from the high-level tone (Sound 1) to the mid-rising tone (Sound 2) (see Figure 1). The step size between two adjacent stimuli was around 5 Hz. All stimuli were adjusted to 350 ms in duration and 70 dB SPL in intensity.

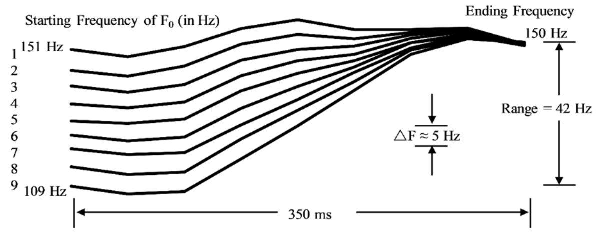

Figure 1: *Schematic diagram of tone continuum.*

2.3. Procedure

In order to exclude participants with severe hearing impairment, a hearing level test was conducted in all participants using an audiometer (GSI 18), with results shown in Figure 2. For young adults, the hearing threshold was normal at all frequencies (≤ 20 dB HL). For seniors aged 60-65 years, the hearing threshold was normal at low-to-mid frequencies (125-2000 Hz), and they showed mild hearing loss at high frequencies (3000-8000 Hz) (20-40 dB HL). For older seniors aged 75-80 years, they showed mild hearing loss at low-to-mid frequencies and moderate hearing loss at high frequencies (≥ 40 dB HL). No ear asymmetry of the hearing level was found in three groups (all ps > 0.05).

The classic paradigm of categorical perception [3, 5, 6] was adopted in this study, including identification and discrimination tasks, and all participants were asked to complete both tasks. In the identification task, participants were required to determine the stimulus they heard as Sound 1 (i.e., '衣') (pressing key '1' on keyboard) or Sound 2 (i.e., '姨') (pressing key '2'), which was a two-alternative forced choice task. In the testing block, all stimuli were presented randomly with only five repetitions to avoid older participants being tired. The discrimination task required participants to judge whether the two stimuli they heard were the same (pressing key '1') or different (pressing key '2'). There were 23 pairs of stimuli with five repetitions in total, including 9 pairs of same stimuli (i.e., 1-1, 2-2, 3-3,…8-8, 9-9) and 14 pairs of different stimuli in forward order (i.e., 1-3, 2-4, 3-5,…6-8, 7-9) or reverse order (i.e., 3-1, 4-2, 5-3,…8-6, 9-7) with two steps difference. All pairs of stimuli were randomly presented in the testing block. The interstimulus interval was 500 ms. A practice block with feedback was available for participants to be familiar with all procedures before all testing blocks.

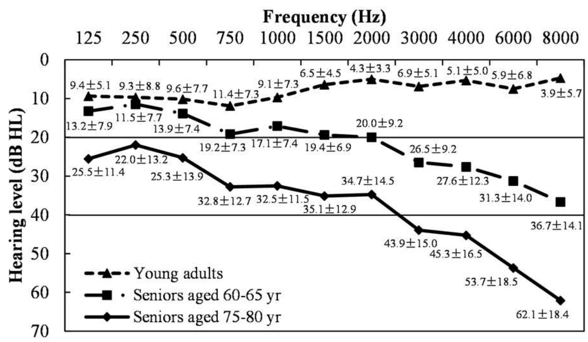

Figure 2: *Hearing level of the three groups (Data label: mean ±SD).*

2.4. Data analysis

For tone identification, the percentage of responses on high-level tone was defined as the identification score. Boundary position and boundary width were further calculated based on the identification score using Probit analysis [20] according to the procedure in [6]. Boundary position was defined as the 50% point of identification score, and boundary width was defined as the linear distance between 25% and 75% percentiles of identification score. Narrower boundary width means sharper categorical transition in tone identification near the boundary.

For tone discrimination, all 23 pairs of stimuli were divided into seven comparison units, each consisting of four types of stimuli pairs (A-A, B-B, A-B, B-A). Discrimination accuracy was analyzed using the formula proposed in [21]:

$$P = P(\text{'S'}|S) \times P(S) + P(\text{'D'}|D) \times P(D) \quad (1)$$

where P (S) and P (D) represented the percentage of same pairs (e.g., 1-1, 3-3) and different pairs (e.g., 1-3, 3-1), respectively. P ('S'|S) represented the percentage of 'the same' responses to the same pairs. P ('D'|D) represented the percentage of 'different' responses to different pairs. Discrimination accuracy was further divided into between-category discrimination accuracy and within-category accuracy. Between-category accuracy was defined as the mean of discrimination accuracies of the comparison units straddling the category boundary, and within-category accuracy was defined as the mean of discrimination accuracies of the remaining comparison units. Discrimination peakedness was further defined as the difference between within-category accuracy and between-category accuracy. Wider boundary and smaller peakedness represented the lower degree of categoricalness of perception.

3. Results

3.1. Tone identification

Boundary position and width of Mandarin lexical tone perception among young adults, seniors aged 60-65 years, and older seniors aged 75-80 years are shown in Table 1. Identification responses of high-level tone in the three groups are presented in Figure 3. One-way ANOVA with a Bonferroni post-hoc test revealed a significant group difference in boundary width ($F(2, 64) = 3.737$, $p = 0.029$). Pairwise comparison showed that the boundary width of older seniors aged above 75 years was significantly wider than that of seniors aged below 65 years ($p = 0.029$). No significant difference was found between younger seniors and young adults nor between young adults and older seniors (both *p*s > 0.05). For older seniors, there was also a marginally positive correlation between boundary width and hearing level at 125 Hz ($r = 0.441$, $p = 0.059$). No significant difference was found in boundary position ($F(2, 64) = 2.534$, $p = 0.087$).

Table 1: *Boundary position and width of the three groups.*

Group	Position (SD)	Width (SD)
Young adults	5.31 (0.48)	1.02 (0.51)
Seniors aged 60-65 yr	4.98 (0.57)	0.82 (0.45)
Seniors aged 75-80 yr	5.25 (0.60)	1.62 (1.68)

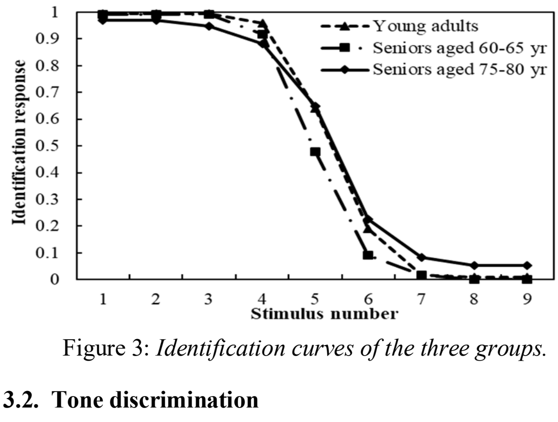

Figure 3: *Identification curves of the three groups.*

3.2. Tone discrimination

Discrimination accuracy of three groups is shown in Figure 4. A two-way repeated-measures ANOVA was conducted to determine the impact of *group* (young adults, seniors aged 60-65 yr, and older seniors aged 75-80 yr) and *category* (between-category and within-category), with *group* as the between-subject factor and *category* as the within-subject factor. The Greenhouse-Geisser correction was used when appropriate. Significant main effects of *group* ($F(2, 64) = 4.825$, $p = 0.011$) and *category* ($F(1, 64) = 238.465$, $p < 0.001$) were found. There was also a significant interaction effect between *group* and *category* ($F(2, 64) = 7.781$, $p = 0.001$). Simple main effect analysis indicated that between-category discrimination accuracy was higher than within-category discrimination accuracy in all groups (*p*s < 0.001) (see Figure 5). For within-category accuracy, no significant difference was found among the three groups (*p*s > 0.05). However, for between-category accuracy, older seniors performed worse than young adults ($p = 0.008$) and seniors aged below 65 years ($p = 0.004$).

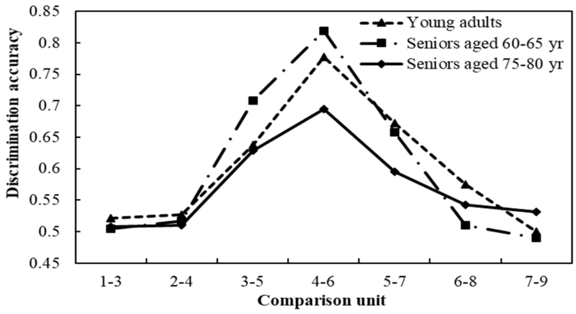

Figure 4: *Discrimination curves of the three groups.*

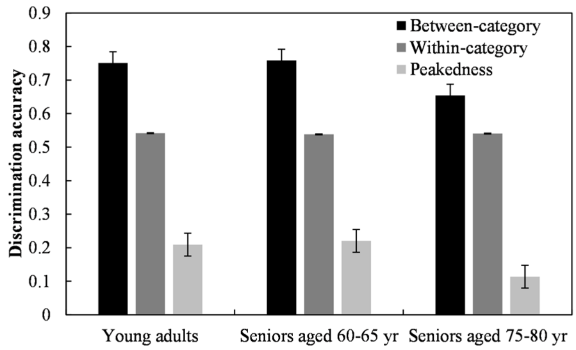

Figure 5: *Between/within-category discrimination accuracy and peakedness in the three groups.*

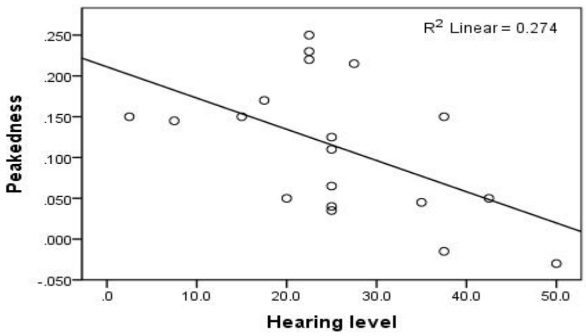

Figure 6: *Correlation between peakedness and hearing level at 125 Hz in older seniors.*

Besides, results of one-way ANOVA indicated a significant group difference in discrimination peakedness of tone perception ($F(2, 64) = 7.781$, $p = 0.001$). The pairwise comparison revealed that peakedness in older seniors was significantly smaller than that in young adults ($p = 0.005$) and seniors aged below 65 years ($p = 0.002$). For older seniors, a significant negative correlation between peakedness and hearing level at 125 Hz was found (r = -0.524, p = 0.021) (see Figure 6).

4. Discussion

This study examined age-related differences of Mandarin lexical tone perception in native young adults, seniors aged 60-56 years, and older seniors aged 75-80 years using classic categorical perception paradigm. Compared with previous studies, our study enlarged sample size and divided the elderly population into two groups to thoroughly examine the age-related decline of the categorical perception of lexical tone. On the other hand, some recent research paid attention to the difference between chronological age and biological age, and they claimed that age-related differences of cognitive ability in the elderly could be predicted by biological age independent of chronological age [22]. As biological age is a comprehensive predictor considering impacts from gene and health conditions, it might advance the understanding of predictors of perceptual decline from the sole perspective of chronological age [23]. Therefore, in this study, we discussed the aged-related difference of tone perception with the combination of chronological age, hearing sensitivity and cognitive ability.

In this study, there was a steep boundary in the identification curve, a peak at category boundary in the discrimination curve, and a significant difference between within-category accuracy and between-category accuracy among the three groups, indicating that all participants perceived lexical tones categorically according to Repp [4].

Our results indicated that older seniors aged 75-80 years showed a wider boundary and smaller peakedness, revealing that the degree of categoricalness in older seniors was lower. Older seniors aged above 75 years showed a significant decline when perceiving Mandarin lexical tones. Many factors like hearing loss and reduction in functional connectivity have been discovered to partially account for the less distinctive phoneme representations in the aging brain [24, 25], so-called neural de-differentiation. The lower ability to perform fine-grained speech perception might be correlated with age-related neural de-differentiation in speech-relevant regions.

We also observed a positive correlation between boundary width and hearing level at 125 Hz, and a negative correlation between discrimination peakedness and hearing level at 125 Hz in older seniors. This indicated that those with hearing impairment at low frequency performed worse in tone identification and discrimination. The decline of lexical tone perceptual ability in this population might be associated with hearing loss. One noteworthy point is that 125 Hz is one of the fixed discrete frequencies provided by the audiometer (see Figure 2) and is the closest to the pitch range of the tone continuum in this study. Our finding was also consistent with previous research [7] supporting that for seniors with normal cognitive ability, hearing level played a more important role in predicting perceptual performance, but not cognitive ability. Bidelman et al. [26] found a less efficient information exchange and less integrated communication pathway in the full brain, and reverse flow of neural signal in the dorsal-ventral pathway in the left hemisphere among hearing-impaired seniors. This abnormal neural transmission might explain the impact of hearing loss on speech perception.

For tone discrimination, only between-category discrimination accuracy in older seniors was found to be lower than the other two groups, but within-category accuracies of the three groups were similar. This was consistent with the findings in [14], which proposed that perceptual ability of within-category speech tones in seniors was preserved through potential compensatory mechanisms (e.g., longer processing time demonstrated by longer latency in ERP in [14]), while that of between-category tones was impaired because of difficulty in utilizing phonemic category knowledge. Another possible explanation for this finding was the floor effect as within-category discrimination accuracy was close to the chance level (50%).

For seniors aged 60-65 years with normal cognitive ability and hearing sensitivity at low frequency, we found no significant difference in tone identification and discrimination, with young adults as a comparison. Some previous studies also observed that seniors could perform similarly or even better than young adults since seniors had more abundant language knowledge and language experience [27, 28]. Although seniors showed similar ability to young adults in behavioural performance, several brain-imaging research proposed that compensation mechanisms played an important role by recruiting more brain regions and functional brain networks in seniors to maintain the normal behavioural performance [24, 29, 30].

Some limitations could not be ignored in this study. First, the number of female and male participants was not balanced in the three groups because of the difficulty in participant recruitment. Thus, it is difficult to discuss any potential differences caused by gender in this paper, although some previous research documented the sex difference of cognitive ability in normal older adults [31, 32]. Second, in order to thoroughly examine the correlation between hearing loss and tone perception, we need to distinguish the impact of hearing sensitivity from that of age in further research.

5. Conclusions

This study explored the perceptual difference of Mandarin lexical tones among young adults, seniors aged below 65 years, and older seniors above 75 years with normal cognitive ability. Results revealed that older seniors performed worse in both identification and discrimination tasks. Older seniors also showed a positive correlation between the hearing level at 125 Hz and boundary width, and a negative correlation between hearing level (125 Hz) and discrimination peakedness, indicating that the decline of perceptual ability in older seniors might be correlated with hearing loss. However, seniors aged 60-65 years performed similar to young adults, revealing that they still maintained the normal perceptual ability of lexical tones. Our study demonstrated that not all seniors, but those who aged above 75 years showed a decline in tone perception.

6. Acknowledgements

This study is partly supported by grants from National Natural Science Foundation of China (NSFC: 11974374), and Hong Kong Research Grants Council – General Research Fund (GRF: 15601718). We appreciate Shenzhen Associations of Senior Scientists and Technicians for assisting the recruitment of elder participants. Special thanks to Meng Yaru and Li Hanfei for assisting data collection.

7. References

[1] W. S.-Y. Wang, "The Chinese language," *Scientific American*, vol. 228, no. 2, pp. 50-63, 1973.

[2] G. Peng, "Temporal and tonal aspects of Chinese syllables: A corpus-based comparative study of Mandarin and Cantonese," *Journal of Chinese Linguistics*, vol. 34, no. 1, pp. 134-154, 2006.

[3] A. M. Liberman, K. S. Harris, H. S. Hoffman, and B. C. Griffith, "The discrimination of speech sounds within and across phoneme boundaries," *Journal of Experimental Psychology*, vol. 54, no. 5, pp. 358-368, 1957.

[4] B. H. Repp, "Categorical perception: Issues, methods, findings," In N.J. Lass (Ed.), *Speech and Language: Advances in Basic Research and Practice* (vol. 10) (pp. 243-335). New York: Academic Press, 1984.

[5] W. S.-Y. Wang, "Language change," *Annals of the New York Academy of Sciences*, vol. 208, no. 1, pp. 61-72, 1976.

[6] G. Peng, H.-Y. Zheng, T. Gong, R.-X. Yang, J.-P. Kong and W. S.-Y. Wang, "The influence of language experience on categorical perception of pitch contours," *Journal of Phonetics*, vol. 2010, no. 38, pp. 616-624, 2010.

[7] L. Fostick, E. Ben-Artzi, and H. Babkoff, "Aging and speech perception: Beyond hearing threshold and cognitive ability," *Journal of Basic and Clinical Physiology and Pharmacology*, vol. 24, no. 3, pp. 175-183, 2013.

[8] M. Bilodeau-Mercure, C. L. Lortie, M. Sato, M. J. Guitton, and P. Tremblay, "The neurobiology of speech perception decline in aging," *Brain Structure and Function*, vol. 220, no. 2, pp. 979-997, 2015.

[9] Ministry of Civil Affairs of the People's Republic of China, "Report on civil affairs development," http://www.mca.gov.cn/article/sj/tjgb, 2019.

[10] J. Henrich, S. J. Heine, and A. Norenzayan, "Most people are not WEIRD," *Nature*, vol. 466, no. 7302, pp. 29, 2010.

[11] Y. X. Wang, X. H. Yang, H. Zhang, L. L. Xu, C. Xu, and C. Liu, "Aging effect on categorical perception of Mandarin tones 2 and 3 and thresholds of pitch contour discrimination," *American Journal of Audiology*, vol. 26, no. 1, pp. 18-26, 2017.

[12] Y. X. Wang, X. H. Yang, and C. Liu, "Categorical perception of Mandarin Chinese tones 1–2 and tones 1–4: Effects of aging and signal duration," *Journal of Speech, Language, and Hearing Research*, vol. 60, no. 12, pp. 3667-3677, 2017.

[13] Y. Feng, Y. R. Meng, and G. Peng, "The categorical perception of Mandarin tones in normal aging seniors and seniors with Mild Cognitive Impairment," in *ICPhS 2019 – 19th International Congress of Phonetic Sciences, August 4-10, Melbourne, Australia, Proceedings*, 2019, pp. 909–913.

[14] R. Xiao, D. D. Liang, and S. P. Li, "Effects of aging on the Mandarin lexical tone perception: Evidence from ERPs," *Acta Psychologica Sinica*, vol. 52, no.1, pp.1-11, 2020.

[15] A. Krishnan, Y. Xu, J. T. Gandour, and P. A. Cariani, "Human frequency-following response: representation of pitch contours in Chinese tones," *Hearing Research*, vol. 189, no. 1-2, pp. 1-12, 2004.

[16] C. G. Clinard, K. L. Tremblay, and A. R. Krishnan, "Aging alters the perception and physiological representation of frequency: Evidence from human frequency-following response recordings," *Hearing research*, vol. 264, no. 1-2, pp. 48–55, 2010.

[17] J. Yu, J. Li, and X. Huang, "The Beijing version of the montreal cognitive assessment as a brief screening tool for mild cognitive impairment: a community-based study," *BMC Psychiatry*, vol. 12, no. 1, pp. 156-163, 2012.

[18] P. Boersma, and D. Weenink, "Praat: Doing phonetics by computer (Version 6.1.09)," http://www.praat.org, 2020.

[19] H. Kawahara, T. Takahashi, M. Morise, and H. Banno, "Development of exploratory research tools based on TANDEM-STRAIGHT," in *APSIPA ASC 2009 – 1st Asia-Pacific Signal and Information Processing Association: Annual Summit and Conference, October 4-7, Sapporo, Japan, Proceedings*, 2009, pp. 111-120.

[20] D. J. Finney, *Probit Analysis* (3rd ed.). Cambridge: Cambridge University Press, 1971.

[21] Y. Xu, J. T. Gandour, and A. L. Francis, "Effects of language experience and stimulus complexity on the categorical perception of pitch direction," *Journal of the Acoustical Society of America*, vol. 120, no. 2, pp. 1063-1074, 2006.

[22] S. W. MacDonald, R. A. Dixon, A. L. Cohen, and J. E. Hazlitt, "Biological age and 12-year cognitive change in older adults: findings from the Victoria Longitudinal Study," *Gerontology*, vol. 50, no. 2, pp. 64-81, 2004.

[23] C. A. DeCarlo, H. A. Tuokko, D. Williams, R. A. Dixon, and S. W. MacDonald, "BioAge: Toward a multi-determined, mechanistic account of cognitive aging," *Ageing Research Reviews*, vol. 18, pp. 95-105, 2014.

[24] Y. Du, B. R. Buchsbaum, C. L. Grady, and C. Alain, "Increased activity in frontal motor cortex compensates impaired speech perception in older adults," *Nature Communications*, vol. 7, no. 12241, pp. 1-12, 2016.

[25] J. O. Goh, "Functional dedifferentiation and altered connectivity in older adults: neural accounts of cognitive aging," *Aging and Disease*, vol. 2, no. 1, pp. 30-48, 2011.

[26] G. M. Bidelman, M. S. Mahmud, M. Yeasin, D. Shen, S. R. Arnott, and C. Alain, "Age-related hearing loss increases full-brain connectivity while reversing directed signaling within the dorsal-ventral pathway for speech," *Brain Structure and Function*, vol. 224, no. 8, pp. 2661-2676, 2019.

[27] L. E. Matzen, and A. S. Benjamin, "Older and wiser: Older adults' episodic word memory benefits from sentence study contexts," *Psychology and Aging*, vol. 28, no. 3, pp. 754-767, 2013.

[28] D. U. Wulff, S. D. Deyne, M. N. Jones, R. Mata, and The Aging Lexicon Consortium, "New perspectives on the aging lexicon," *Trends in Cognitive Sciences*, vol. 23, no. 8, pp. 686-698, 2019.

[29] P. A. Reuter-Lorenz, and K. A. Cappell, "Neurocognitive aging and the compensation hypothesis," *Current Directions in Psychological Science*, vol. 17, no. 3, pp. 177-182, 2008.

[30] V. S. Mattay, F. Fera, A. Tessitore, A. R. Hariri, K. F. Berman, S. Das, ... and D. R. Weinberger, "Neurophysiological correlates of age-related changes in working memory capacity," *Neuroscience Letters*, vol. 392, no. 1, pp. 32-37, 2006.

[31] A. C. McCarrey, Y. An, M. H. Kitner-Triolo, L. Ferrucci, and S. M. Resnick, "Sex differences in cognitive trajectories in clinically normal older adults," *Psychology and Aging,* vol. 31, no. 2, pp. 166-175, 2016.

[32] S. A. H. Van Hooren, A. M. Valentijn, H. Bosma, R. W. H. M. Ponds, M. P. J. Van Boxtel, and J. Jolles, "Cognitive functioning in healthy older adults aged 64–81: a cohort study into the effects of age, sex, and education," *Aging, Neuropsychology, and Cognition*, vol. 14, no. 1, pp. 40-54, 2007.