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Categorical perception of lexical tones in Mandarin-speaking seniors

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Abstract

Purpose: This study aims to investigate the different degeneration processes of categorical perception (CP) of Mandarin lexical tones in the normal aging population and the pathological aging population with mild cognitive impairment (MCI).

Method: In Experiment I, we compared the identification and discrimination of Tone 1 and Tone 2 across young adults, seniors aged 60-to-65 years, and older seniors aged 75-to-80 years with normal cognitive abilities. In Experiment II, we compared lexical tone identification and discrimination across young adults, healthy seniors, and age-matched seniors with MCI.

Results: In Experiment I, tone perception was intact in seniors aged below 65 years. Those aged above 75 years could also maintain normal tone identification, whereas they showed poorer tone discrimination, correlated with age-related poorer hearing level. In Experiment II, healthy seniors showed normal CP of Mandarin tones. Tone identification was also normal in those with MCI, whereas their tone discrimination had significantly degenerated.

Conclusions: In the normal aging population, age-related hearing loss decreased signal audibility, accounting for poorer discrimination of Mandarin lexical tones in seniors above 75 years. In the pathological aging population with MCI, the poorer discrimination of lexical tones may be attributed to the additive effect of age, hearing loss, and cognitive impairment (e.g., impaired working memory and long-term phonological memory). This study uncovered the roles of low-level sensory processing and high-level cognitive processing in lexical tone perception in the Chinese aging population.

Introduction

Speech perception plays an important role in social communication. Within the speech chain, people understand others' speech and monitor their own speech via speech perception (Denes & Pinson, 2015). Once the ability of speech perception is degraded, people would have difficulty in engaging in social communication, which is often the case happening in seniors. Aging is always accompanied by progressive degeneration of organs, tissues, and cells in bodies. Among these, brain atrophy and presbycusis negatively affect speech perception in seniors. For example, if seniors suffered from conductive hearing loss, the transduction of the mechanical energy of sounds in their ears would be degraded. If they had sensorineural hearing loss, the mechanoelectrical conversion of sounds and the transmission of these electrical nerve impulses to their brain would be devastated. The degeneration of the central auditory pathway also influences the preliminary neural encoding of sounds. These changes can decrease signal audibility in older listeners. In addition to the low-level acoustic processing, cortical or subcortical senescence also interferes with higher-level cognitive processing (e.g., working memory, inhibition, and executive function) related to speech perception. In empirical studies, more and more evidence has indeed shown that seniors have deficits in speech perception because of reduced hearing sensitivity and inefficient cognitive processing (e.g., Cerella, 1990; Gordon-Salant & Fitzgibbons, 1997; Gordon-Salant et al., 2006). All of these difficulties in speech perception severely decrease the self-efficacy of seniors. In recent decades, researchers have made great efforts to investigate the normal and pathological aging processes, in the desire to help seniors live with grace.

Categorical perception in the normal aging population

As one aspect of speech perception, categorical perception (CP) is a basic speech processing ability to map continuous acoustic signals to finite phonological categories in mental phonological knowledge (Liberman et al., 1957). Previous studies have well-documented the characteristics of CP (e.g., Repp, 1984; Xu et al, 2006): 1) a sharp transition appears around category boundary position in identification function; 2) a between-category discrimination peak appears around the category boundary position; 3) within-category discrimination is near the chance level. Listeners with normal CP ability could enhance between-category discrimination and inhibit within-category discrimination.

Accumulated evidence has shown that seniors suffer from a decline in CP of segments and suprasegments, and temporal and spectral processing of speech signals (Harkrider et al., 2005; Ning, 2018; Strouse et al., 1998; Tremblay et al., 2002). For the CP of consonants, Gordon-Salant et al. (2006) found that seniors only showed the impaired perception of specific temporal cues associated with the consonant manner of articulation (e.g., the silent duration for DISH/DITCH, and the transition duration for BEAT/WHEAT), and not those related to consonant voicing (e.g., voice onset time for BUY/PIE, and vowel duration for WHEAT/WEED). For the CP of vowels, Bidelman et al. (2014) found that older listeners needed longer reaction time and showed less clear categorical boundary than younger listeners in the identification of English vowels /u/ and /a/ which differed in formants. Roque et al. (2019) also observed a less clear distinction in seniors between WHEAT and WEED which differed in vowel duration.

The research on the CP of segments mentioned above mainly focused on the aging population speaking English, which is a non-tonal language. Mandarin is a tonal language with four tones differing in pitch height and slope. These tones are suprasegments and can distinguish lexical meanings. For example, syllable /t^{h}u/ is '秃 bald' with high-level tone (Tone 1), '图 figure' with mid-rising tone (Tone 2), '土 soil' with falling-rising tone (Tone 3), and '兔 rabbit' with falling tone (Tone 4) (Chao, 1968; W. S.-Y. Wang, 1976). In China, there are more than 264 million senior citizens older than 60 years of age, and they account for 18.7% of the total population. Among them, more than 190 million seniors are above 65 years old, accounting for 13.5% of the total population (National Bureau of Statistics of the People's Republic of China, 2021). Thus, the degeneration of lexical tone perception has attracted researchers' attention recently (Y. Wang et al., 2021; Y. Wang, Yang, & Liu, 2017; Y. Wang, Yang, Zhang et al., 2017; Xiao et al., 2020). Y. Wang, Yang, Zhang et al. (2017) explored the CP of lexical tones (Tone 2 vs. Tone 3) among 13 Chinese seniors between the ages of 60 and 70 years. Significantly shallower slopes in the tone identification and smaller peakedness in the discrimination accuracy were found in the seniors, compared with young adults. In addition, tone perception in real-life communication is more challenging for seniors because of signal distortion (e.g., noisy environment). CP of lexical tones in such adverse conditions was also explored in seniors. Y. Wang, Yang,

& Liu (2017) investigated whether signal duration influenced lexical tone perception (Tone 1 vs. Tone 2, and Tone 1 vs. Tone 4) in native seniors. Those authors observed that short signal duration impaired perceptual ability in seniors. Furthermore, Y. Wang et al. (2021) explored the effect of speech-shaped noise on the CP of Mandarin lexical tones (Tone 1 vs. Tone 2, and Tone 1 vs. Tone 4) in 12 60-to-70-year-old adults and found that noise degraded the older listeners' tone perception significantly.

Nonetheless, the age ranges of the seniors in these studies limited the generalization of the findings to those aged above 70 years in terms of increased life expectancy. We know that life expectancy increases with better sanitation and medical innovations across the years, and the global life expectancy was 72 years in 2016, according to the World Health Organization (World Health Organization, 2020). In fact, the life expectancy in China is above 76 years (Chen et al., 2020), so it is necessary to include more seniors aged above 70 years in age-related studies. Furthermore, all of the studies mentioned above failed to conduct a direct age comparison between younger seniors and older seniors. Some literature on normal aging has well documented that the prevalence of hearing loss increases in older seniors, and hearing loss becomes more severe with increasing age (Walling & Dickson, 2012). In China, the prevalence of age-related hearing loss is 75.85% in seniors between the ages of 75 and 80 years, which is much higher than 44.88% in younger ones aged 60-to-65 years (Gong et al., 2018). Therefore, it is expected that categorical speech perception in younger seniors is different from that in older seniors. The first target of this study is to solve the age comparison of CP of lexical tones in the Mandarin-speaking normal aging population.

CP in the aging population with mild cognitive impairment

Compared with the normal aging population, speech perception may be more challenging in the pathological aging population. In general, seniors with different degrees of cognitive decline are divided into several clinical stages on a dementia continuum. For example, the National Institute on Aging – Alzheimer's Association research framework in the U.S. outlines a novel clinical staging scheme of dementia, with a total of six stages ranging from a preclinical stage without overt clinical symptoms to a stage of severe dementia (Jack et al., 2018). Mild cognitive impairment (MCI) in the dementia continuum is a transitional stage from normal aging to dementia (Petersen, 2000). Seniors suffering from MCI show apparent cognitive abnormalities and detectable mild functional impairment. Bidelman et al. (2017) studied the perception of English vowels (/u/-/a/) in seniors with MCI. Although they observed no significant difference in the behavioural identification of vowels between healthy seniors and those with MCI, those authors found a hypersensitivity of cortical and subcortical responses in the MCI group.

Although CP could be automatically processed without attention (Zheng et al., 2014), Feng et al. (2021) found that extra cognitive load negatively affected CP of lexical tones because of the competition of attention and memory resources. This revealed that CP also recruited some high-level cognitive functions. Xu et al., (2006) proposed a multistore model of CP: auditory input was processed hierarchically, beginning from sensory memory trace which processed raw auditory information, and then analyzed sensory memory which contained fine-grain analyzed acoustic encoding. To reduce the working memory load, there was also a short-term categorical memory parallel to the analyzed sensory memory, which captured critical acoustic features for perceptual categorization. All of the three components mentioned above were subject to memory decay. Long-term phonological memory was finally recruited for phonemic identification and between-category discrimination. Such cognitive load of CP may not be high for young adults, whereas the situation may be different for seniors with MCI. In numerous studies on patients with MCI, working memory is one of the cognitive components receiving the most interest, which refers to the ability to temporarily store and manipulate information essential for complex cognitive tasks, such as speech comprehension (Baddeley, 2007). Previous studies have well-documented that working memory in seniors with MCI was impaired (e.g., Jutten et al., 2021; Kessels et al., 2011; Saunders & Summers, 2010). In addition, seniors' retrieval of long-term memory and the phonological representation in the long-term memory was also reported to be impaired (Du et al., 2016; Grönholm-Nyman et al., 2010; Oh & Ha, 2015). Thus, it is expected that seniors with MCI may show degradation of CP because of impaired working memory and long-term phonological memory.

It is reported that approximately 14.71% of seniors in China suffer from MCI (Xue et al., 2018). However, limited attempts have been made to investigate the perceptual ability of seniors with MCI in China, especially their perception of lexical tones. Considering the effect of language background on categorical speech perception (Peng et al., 2010; W. S.-Y. Wang, 1976), the findings about the effect of cognitive impairment on categorical speech perception from the English-speaking population could not be generalized to the Chinese population. Besides, research on patients with MCI may provide implications to clinical intervention, and appropriate and timely treatment may help them by palliating their cognitive decline and decreasing their risk for developing dementia. Thus, the second target of this study is to explore the CP of lexical tones in Mandarin-speaking seniors with MCI.

To solve the two research questions, in Experiment I, we assessed the CP of Mandarin lexical tones in native seniors aged 60-to-65 years and older ones aged 75-to-80 years with normal cognitive ability. In Experiment II, we investigated the CP of lexical tones in healthy seniors and those with MCI.

Method

Participants

Experiment I

We recruited 67 participants in this experiment: 24 young adults between the ages of 20 and 30 years (15 males, M_{age} = 24.58, SD = 2.73), 24 seniors aged 60-to-65 (9 males, M_{age} = 62.71, SD = 1.37), and 19 older seniors from 75 to 80 years old (12 males, M_{age} = 77.74, SD = 2.00). All participants were from northern China and could speak Mandarin fluently in daily life. None of them reported having formal experience learning music, language impairments, psychiatric illness, nervous system medications, or surgery involving the ears or head. To test their general cognitive abilities, the Beijing version of Montreal Cognitive Assessment (MoCA) (Yu et al., 2012) was conducted by a trained experimenter. There are several subtests in MoCA to assess different cognitive abilities, such as executive function, visuospatial function, short-term memory, working memory, language abilities, long-term memory, attention, and abstract thinking. All participants obtained MoCA scores between 26 and 30 points (see Figure 1A), indicating they had normal cognitive ability. No significant differences were found in the MoCA scores across the three groups, F (2, 64) = 2.883, p = .063. The total years of the participants' formal education (t = 0.935, p = .355) and their socioeconomic status were matched in the two groups of elders. The elder participants had obtained Bachelor's degree or Master's degree, and were engineers, doctors, or teachers before retirement. All were compensated for their voluntary participation in this study. Consent forms were obtained from all participants with the protocol approved by the Human Subjects Ethics Subcommittee of The Hong Kong Polytechnic University.

We used an audiometer (GSI 18) to examine the participants' hearing level in a quiet room, and the results are shown in Figure 1B. The hearing threshold of the young adults was normal (≤ 20 dB HL) between 125 Hz and 8,000 Hz. The hearing threshold of the seniors below 65 years was normal between 125 Hz and 2,000 Hz, and they showed mild hearing loss (20-40 dB HL) between 3,000 Hz and 8,000 Hz. The older seniors, above 75 years, showed mild hearing loss between 125 Hz and 2,000 Hz and moderate hearing loss (≥ 40 dB HL) between 3,000 Hz and 8,000 Hz. There was no ear asymmetry of the hearing level in the three groups (all ps > .05).

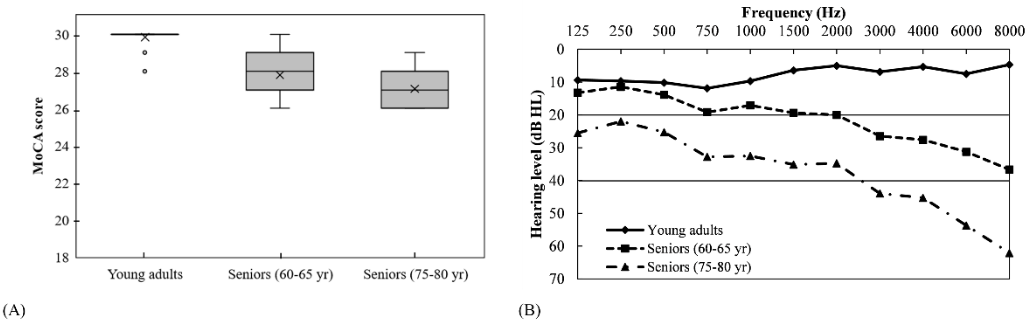

Figure 1. (A) MoCA scores, and (B) hearing level of young adults, seniors below 65 years old, and those above 75 years.

Experiment II

We recruited a total of 66 participants in this experiment: 24 young adults aged 20-30 years (15 males, M_{age} = 24.58, SD = 2.73), 25 healthy seniors between the ages of 60 and 81 years with normal cognitive ability (14 males, M_{age} = 73.79, SD = 5.82), and 17 seniors from 63 to 81 years of age with MCI (10 males, M_{age} = 72.93, SD = 6.23). One normal older participant with severe hearing loss and two illiteracy participants with MCI were excluded from data analysis. All participants were from northern China and could speak Mandarin fluently in daily communication. They reported having no experience of formal musical training, no history of psychiatric illness, and no surgery involving the ears or head. The age (t = 0.424, p = .674) and total years of formal education (t = 1.904, p = .065) were matched in the two elder groups.

Figure 2A shows the MoCA scores for the three groups. All of the young adults and healthy seniors obtained MoCA scores between 26 and 30 points. The scores of the MCI participants were within the range from 19 to 25 points. Figure 2B illustrates the participants' hearing levels. The hearing thresholds of young adults were normal (≤ 20 dB HL) from 125 Hz to 8,000 Hz. The hearing thresholds of the two elder groups were near normal from 125 Hz to 500 Hz, but those participants showed mild-to-moderate hearing loss (20 – 60 dB HL) from 750 Hz to 8,000 Hz. There was no significant difference in the hearing level between the two elder groups (t = 1.649, p = .108), nor was there a significant ear asymmetry in the three groups (all ps > .05).

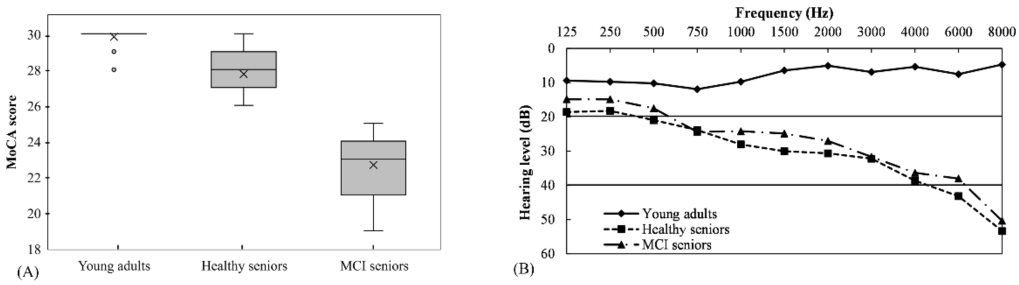

Figure 2. (A) MoCA scores, and (B) hearing level of young adults, healthy seniors, and those with MCI.

Materials

We selected two words ('衣' /i/ with Tone 1, *clothes* – '姨' /i/ with Tone 2, *aunt*) that are frequently used in Chinese. The words were naturally uttered by a male native Mandarin speaker from northern China. Speech samples were recorded by Praat (Boersma & Weenink, 2020) with a 44.1 kHz sampling rate and 16-bit resolution. The tone continuum with nine stimuli was generated by TANDEM-STRAIGHT software (Kawahara & Morise, 2011). The duration of each stimulus was adjusted to 350 ms by using PSOLA (i.e., pitch synchronous overlap and add). This technique can divide sound waveform into several overlapping segments, and increase the duration of stimulus by repeating some segments or decrease its duration by removing some segments. The intensity of each stimulus was calibrated to 70 dB SPL by adjusting the root-mean-square amplitude in Praat. Stimuli in the tone continuum differed in F0. Syllables /i/ with Tone 1 (stimulus 1, ‘衣’) and /i/ with Tone 2 (stimulus 9, ‘姨’) were selected as two endpoints. The F0 onset of stimulus 1 was 151 Hz, and that of stimulus 9 was 109 Hz, as shown in Figure 3. The onset of F0 decreased from 151 Hz to 109 Hz at a step size of approximately 5 Hz.

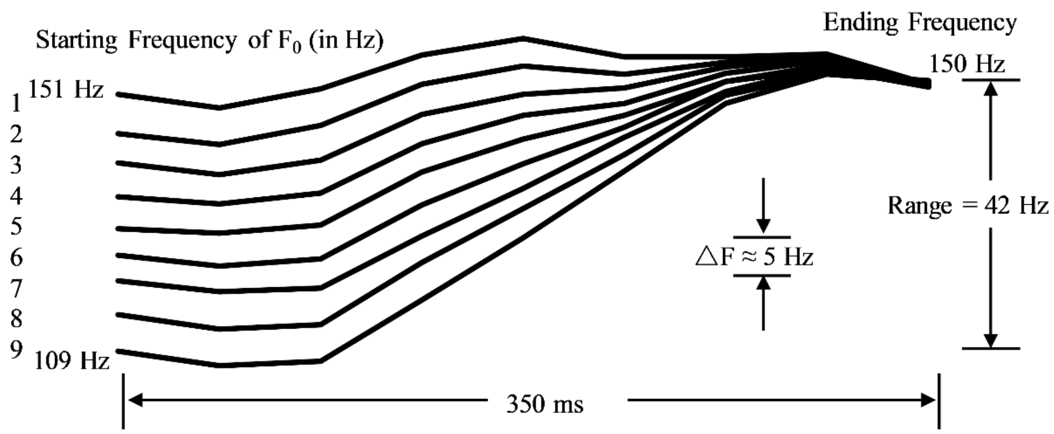

Figure 3. F0 contours of the tone continuum.

Procedure

The classic paradigm of CP (Liberman et al., 1957) was adopted in this study, including identification and discrimination tasks. A laptop with E-Prime 2.0 was used to conduct the experiment. All sound stimuli were presented by the laptop via a headphone. Participants wearing the headphone were seated in a soundproofed room.

Before the experiment, the volume was adjusted to a comfortable level for each participant. The identification task was a two-alternative forced-choice task. Participants needed to determine the sound stimulus as Sound 1 (‘衣’) or Sound 2 (‘姨’) by pressing two keys on a keyboard. Number key ‘1’ for Sound 1 and number key ‘2’ for Sound 2. In the testing block, to avoid tiredness, there were only five repetitions of all randomly presented stimuli. In the discrimination task, participants needed to judge whether the two stimuli were the same or different, using number key ‘1’ for ‘the same’ and number key ‘2’ for ‘different’. There were 23 stimuli pairs: nine stimuli paired with themselves (i.e., 1-1, 2-2, 3-3,…8-8, 9-9) and 14 pairs of different stimuli separated by two steps 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). All pairs of stimuli were randomly presented with five repetitions in the testing block. The interstimulus interval (ISI) was 500 ms. To help participants become familiar with all procedures and ensure that they had understood the tasks, there was a practice block with feedback before each testing block. The testing block was only released when they obtained an accuracy above 80% in the practice block.

Data Analysis

For the identification task, responses of Tone 1 were analyzed. We conducted a Probit analysis on the identification responses to calculate the position of category boundary and boundary width (Finney, 1971). We defined the boundary position as the 50% crossover point of the identification curve, and the boundary width as the distance between the 25^{th} and the 75^{th} percentiles of the identification curve. A narrower boundary width reflected a clearer distinction of phonological categories.

For the discrimination task, all stimuli pairs were grouped into seven comparison units, each of which included four types of stimuli pairs: A-A, B-B, A-B, and B-A (e.g., 1-1, 3-3, 1-3, and 3-1). Discrimination accuracies of seven comparison units were calculated by the formula proposed by Xu et al. (2006):

$$P = P\,(\text{‘}S\text{’}|S) \times P\,(S) + P\,(\text{‘}D\text{’}|D) \times P\,(D) \tag{1}$$

In Equation 1, $P\,(S)$ is the percentage of the same stimuli pairs (e.g., 1-1, 3-3) and $P\,(D)$ refers to the percentage of different stimuli pairs (e.g., 1-3, 3-1). Here, $P\,(\text{‘}S\text{’}|S)$ and $P\,(\text{‘}D\text{’}|D)$ respectively index the percentage of ‘the same’ responses to the same stimuli pairs, and the percentage of ‘different’ responses to different stimuli pairs. Based on the boundary position, the discrimination accuracies were further divided into between- and within-category accuracy. The between-category accuracy was the average accuracy of two comparison units straddling the categorical boundary. The within-category accuracy was the average accuracy of the remaining comparison units. Discrimination peakedness is an indicator of one’s discrimination ability to enhance between-category discrimination and inhibit within-category discrimination (Xu et al., 2006). Thus, it referred to the difference between within- and between-category accuracy.

Linear mixed-effect models (LMMs) in R (R Core Team, 2019) were adopted to compare lexical tone identification and discrimination across different groups, given the potential individual differences across subjects. The package of lme4 (Bates et al., 2015) was used to create the LMMs. Bonferroni correction was used to conduct multiple comparisons. Although all participants obtained accuracy above 80% in the practice block and entered into the testing block successfully, the identification accuracies of the two endpoints of the tone continuum, i.e., Stimulus 1 (typical Tone 1) and Stimulus 9 (typical Tone 2), of two older seniors in Experiment I and one senior with MCI in Experiment II were found below 80%. The relatively low identification accuracy indicated that those three participants might have not paid full attention to the task, since participants (114 in 130 in this study) usually identified Stimulus 1 as Tone 1 and Stimulus 9 as Tone 2 with 100% accuracy, respectively if they paid full attention to the identification task. Therefore, the data from these three participants were excluded from further data analysis.

Table 1. Boundary positions and boundary widths of tone identification in young adults, seniors below 65 years old, and those above 75 years.

Groups	Boundary position (SD)	Boundary 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	5.29 (0.52)	1.10 (0.66)

Results

Experiment I

Figure 4A shows the identification responses of Tone 1 among young adults, seniors aged 60-65 years, and older seniors aged 75-80 years. Table 1 lists the boundary positions and boundary widths (means) of lexical tone identification in the three groups. Two LMMs were separately created to describe the identification boundary width and boundary position as a function of *age group*. Both models consisted of a fixed factor of *age group* [young adults vs. seniors (60-65 yr) vs. older seniors (75-80 yr)], and a random factor of *subject*. There was no significant effect of *age group* on boundary width, $F(2, 62) = 1.58$, $p = .214$, or on boundary position, $F(2, 62) = 2.951$, $p = .060$.

Figure 4C presents the between- and within-category accuracies in the three groups. We used an LMM to describe the discrimination accuracy as a function of *age group* and *category* (within-category vs. between-category). The model included two fixed factors of *age group* and *category*, and a random factor of *subject*. We found a significant effect of *category* ($\chi^2 = 126.43$, $p < .001$), and a significant interaction effect ($\chi^2 = 10.82$, $p = .004$) on discrimination accuracy. In each group, the between-category accuracy was higher than within-category accuracy (all ps < .0001). Between-category accuracy in the older seniors ($M = 0.67$) was significantly lower than that in the young adults ($M = 0.75$) ($\beta = 0.079$, $SE = 0.024$, $t = 3.364$, $p = .003$) and the seniors aged below 65 years ($M = 0.76$) ($\beta = 0.086$, $SE = 0.024$, $t = 3.675$, $p = .001$). However, no significant difference was found in between-category accuracy between young adults and the seniors aged below 65 years ($\beta = -0.007$, $SE = 0.021$, $t = -0.341$, $p = 1.000$). There was no significant difference in within-category accuracy across the three groups [young adults: $M = 0.54$; seniors (60-65 yr): $M = 0.54$; older seniors (75-80 yr): $M = 0.55$; all ps = 1.000]. Since the within-category accuracy was near the chance level, the absence of the within-category discrimination difference may be attributed to the floor effect.

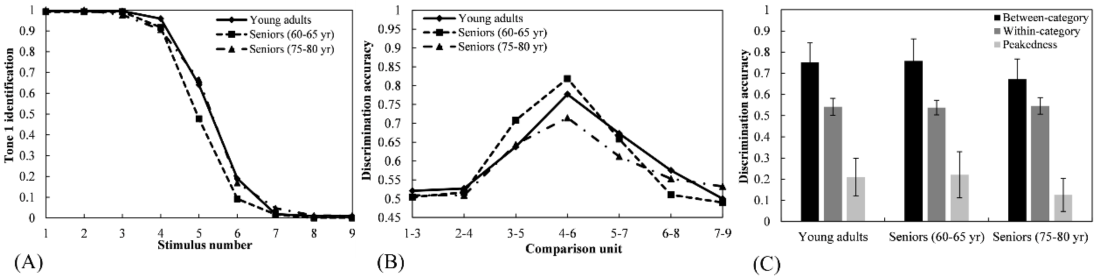

Figure 4. (A) Identification curves, (B) discrimination curves, (C) discrimination accuracy and peakedness of lexical tones in young adults, seniors below 65 years old, and those above 75 years. Error bars = ± 1 *SD*.

The discrimination peakedness was described in the LMM as a function of *age group*. The model consisted of a fixed factor of *age group*, and a random factor of *subject*. We found a significant effect of *age group* ($F(2, 62) = 5.614$, $p = .0057$). The discrimination peakedness in the older seniors ($M = 0.13$) was significantly smaller than that in the young adults ($M = 0.21$) ($\beta = 0.083$, $SE = 0.030$, $t = 2.777$, $p = .0217$) and seniors aged below 65 years ($M = 0.22$) ($\beta = 0.094$, $SE = 0.030$, $t = 3.146$, $p = .0076$). Pearson correlation analysis demonstrated a significant negative correlation between peakedness of discrimination and hearing level in the older seniors ($r = -.532$, $p = .028$). No significant difference was observed between young adults and seniors aged below 65 years ($\beta = -0.011$, $SE = 0.027$, $t = -0.405$, $p = 1.000$).

To conclude, seniors aged below 65 years maintained an intact CP of tones. The older seniors aged above 75 years could also maintain normal tone identification.

However, they showed a reduced tone discrimination ability. In addition, the poorer their hearing sensitivity was, the poorer their discrimination ability was in this population.

Experiment II

Identification curves of Tone 1 in young adults, healthy seniors, and those with MCI are shown in Figure 5A. Table 2 lists the boundary positions and boundary widths (means) of tone identification in the three groups. We created two LMMs separately to describe the identification boundary width and boundary position as a function of *group*. Both models consisted of a fixed factor of *group* (young adults vs. healthy seniors vs. seniors with MCI), and a random factor of *subject*. There was no significant effect of *group* on boundary width, $F(2, 59) = 1.973$, $p = .148$, or on boundary position, $F(2, 59) = 0.098$, $p = .907$.

Table 2. Boundary positions and boundary widths of tone identification in young adults, healthy seniors, and those with MCI.

Groups	Boundary position (SD)	Boundary width (SD)
Young adults	5.31 (0.48)	1.02 (0.51)
Healthy seniors	5.26 (0.63)	1.42 (1.23)
Seniors with MCI	5.23 (0.67)	1.56 (0.72)

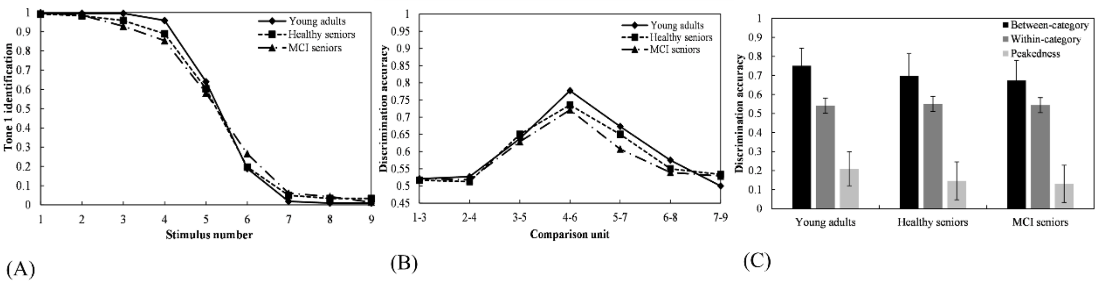

Figure 5. (A) Identification curves, (B) discrimination curves, (C) discrimination accuracy and peakedness of lexical tones in young adults, healthy seniors, and those with MCI. Error bars = ±1 *SD*.

Discrimination curves for each tone comparison unit are shown in Figure 5B, and Figure 5C presents the within- and between-category discrimination accuracies for lexical tones in the three groups. The discrimination accuracy was described in an LMM as a function of *group* and *category*. The model consisted of two fixed factors of *group* and *category*, and a random factor of *subject*. There was a significant effect of *category* ($\chi^2 = 92.39, p < .001$) and interaction effect ($\chi^2 = 7.96, p = .019$). A significant difference between the within- and between-category accuracy was observed in all of the three groups (all *p*s < .0001). There was also a significant difference in between-category accuracy between the young adults ($M = 0.75$) and the seniors with MCI ($M = 0.67$) ($\beta = -0.078$, $SE = 0.027$, $t = -2.912$, $p = .013$). However, no significant difference was found in between-category accuracy between healthy seniors ($M = 0.70$) and those with MCI ($\beta = 0.024$, $SE = 0.027$, $t = 0.885$, $p = 1.000$). Although healthy seniors did not differ significantly from young adults in between-category accuracy ($\beta = -0.054$, $SE = 0.023$, $t = -2.361$, $p = .059$), they showed a trend toward poorer between-category discrimination ability. It was noteworthy that the group of the healthy seniors in

Experiment II covered the age ranges of the two senior groups in Experiment I. There was no significant difference in within-category accuracy across the three groups (young adults: *M* = 0.54; healthy seniors: *M* = 0.55; seniors with MCI: *M* = 0.54; all *p*s = 1.000). Since the within-category accuracy was near the chance level, the absence of the within-category discrimination difference may be attributed to the floor effect.

We used an LMM to describe the discrimination peakedness as a function of *group*. The model included a fixed factor of *group*, and a random factor of *subject*. A significant effect was observed, $F(2, 59) = 4.044$, $p = .0226$. The peakedness in the seniors with MCI (*M* = 0.13) was smaller than that in the young adults (*M* = 0.21) (β = -0.080, *SE* = 0.032, $t = -2.492$, $p = .047$). However, no significant difference in peakedness was found between the healthy seniors (*M* = 0.15) and the young adults (β = -0.063, *SE* = 0.028, $t = -2.306$, $p = .074$), and between the healthy seniors and those with MCI (β = 0.016, *SE* = 0.032, $t = 0.513$, $p = 1.000$).

To summarise, both healthy seniors and those with MCI maintained normal tone identification ability. Seniors with MCI showed significantly reduced discrimination ability because of the additive effect of age, hearing loss, and cognitive impairment.

Discussion

CP of lexical tones in the normal aging population

In the normal aging population, this is the first study conducting an age comparison of lexical tone perception between seniors below 65 years and those above 75 years. We observed a steep boundary in the identification curves, a peak at category boundary in the discrimination curves, and a significant difference between within- and between-category accuracy in all groups. These findings indicated that all participants could perceive lexical tones categorically, in accord with Repp (1984).

There was no significant age difference in the tone identification and discrimination between young adults and seniors from 60 to 65 years old, suggesting that these seniors maintained normal CP of lexical tones. This finding was inconsistent with previous studies on CP of Tone 1 and Tone 2 in seniors between the ages of 60 and 70 years (Y. Wang, Yang, & Liu, 2017; Y. Wang et al., 2021), where those authors observed an impaired CP in the seniors. One possible reason is that the duration of tone stimuli in our study was 350 ms and ISI was 500 ms, whereas those in Y. Wang et al. (2021) were only 200 ms and 400 ms. Y. Wang, Yang, and Liu (2017) have found that the seniors' CP improved with a longer duration of stimuli. The duration of 350 ms in our study might be long enough to convey a clear and intelligible lexical tone for seniors to make a correct response. The longer ISI may also help seniors to process the stimuli considering their slower processing speed as reported in Bidelman et al. (2014). Besides the duration of tones, the aging effects on the perception of different lexical tones may also differ in pitch dimensions and levels of processing (e.g., bottom-up processing or top-down processing). Y. Wang, Yang, and Liu (2017) explored the CP of Tone 1-4 and Tone 1-2, and Y. Wang, Yang, Zhang et al. (2017) examined that of Tone 2-3 in seniors. Combining their findings and our observation, it seems that the tone contrasts between different pitch dimensions may modulate the difficulty of CP, and thus aging effects on the CP of more difficult ones (e.g., Tone 2-3) would be more evident than less difficult ones (e.g., Tone 1-4). On the other hand, although the age-related physiological disadvantages may hinder the efficient bottom-up processing of CP in seniors, some previous studies have reported that seniors possessed more abundant language experience and long-term language knowledge (Matzen & Benjamin, 2013; Wulff et al., 2019), which may help them maintain a normal CP via top-down processing. Furthermore, our study controlled the factors of normal cognitive ability indicated by MoCA score, high education level, and high socioeconomic status in seniors, indicating that they had relatively higher cognitive reserves (Stern, 2009; Tucker & Stern, 2011), whereas previous studies did not. The hypothesis of cognitive reserve assumes that the human brain is able to actively utilize pre-existing cognitive processes or recruit compensation mechanisms to cope with age-related physiological disadvantages (e.g., brain atrophy) (Stern, 2009). This hypothesis also indicates that people with more cognitive reserve have more efficient neural networks, greater capacity, and better flexibility to cope with brain atrophy than those with less cognitive reserve do. Thus, the seniors in our study could maintain normal behavioural performance via cognitive reserve or neural compensation.

Besides, our results indicated that seniors above 75 years with normal cognitive ability could also maintain an intact tone identification despite the age-related hearing loss. The multistore model of CP proposed by Xu et al. (2006) assumed that long-term categorical memory of phonology could provide top-down processing. Therefore, their maintenance of normal tone identification may be attributed to the top-down compensation of long-term phonological memory for the decreased signal clarity resulting from age-related hearing loss. Previous research has also demonstrated that older listeners with hearing loss could rely more on some high-level cognitive abilities (e.g., memory and attention) to realize the top-down strengthening of auditory input (e.g., Wong et al., 2009; Wong et al., 2010).

However, the top-down compensation mentioned above may not work for all tasks. Compared with the identification task, the discrimination task may rely more on low-level auditory processing of the two sounds. We observed that seniors above 75 years showed significantly poorer ability to enhance between-category discrimination and inhibit within-category discrimination. We further found that such impaired discrimination of lexical tones may be attributed to age-related hearing loss. The correlation between tone discrimination and hearing loss supported the information degradation hypothesis, which proposed that the age-related sensory organ degeneration impaired sensory processing and further influenced cognitive processing (Humes et al., 2013; Schneider & Pichora-Fuller, 2000). The age-related hearing loss decreases signal audibility and influences the primary auditory encoding of speech signals, so that those with more severe hearing loss performed more poorly in the discrimination of lexical tones than their peers did. The acoustic information of Mandarin lexical tones is resolvable by low-frequency harmonics (Liu et al., 2014). The human's auditory pathway is organized tonotopically (Kandel et al., 2013) and Krishnan et al. (2004) found that the neural encoding of Mandarin lexical tones in the low-frequency range depends on phase-locking ability. It is reported that the phase-locking ability in seniors degenerated with age (Clinard et al., 2010). Thus, seniors may show impaired tone discrimination because of their decreased phase-locking ability. In addition, Bidelman et al. (2019) also found that the neural pathway was abnormal and less efficient in seniors with hearing loss, providing a possible neural mechanism underlying the impact of hearing loss on speech perception. Our finding was consistent with previous research reporting that the hearing level can predict speech perception in seniors with normal cognitive ability (Gordon-Salant et al., 2006; Fostick et al., 2013). Gordon-Salant et al. (2006) suggested that the perception of consonants was impaired in seniors from 64 to 80 years old with hearing loss. Molis and Leek (2011) also found that those with hearing impairment (61-80 years old) could not distinguish different vowel categories (/ɪ/, /ʊ/, and /ɝ/) clearly. Our study further extended the impact of age-related hearing loss to the perception of suprasegments – Mandarin lexical tones.

CP of lexical tones in the aging population with MCI

To explore the CP of lexical tones in the aging population with MCI, we compared healthy seniors and those with MCI. There was a steep boundary in the identification curves, a peak around the boundary position in the discrimination curves, and a significant difference between within- and between-category accuracy across all groups. According to Repp (1984), these results revealed that all participants could perceive Mandarin lexical tones categorically.

The process of aging is multi-dimensional in nature: the hearing level and cognitive ability of seniors usually become worse with age. In Experiment I, the older seniors maintained normal cognitive ability, but showed obvious age-related hearing loss in comparison to young adults and younger seniors. Results of Experiment I demonstrated a reduced tone discrimination ability for the older seniors, implying that age-related hearing loss plays a significant negative role in tone discrimination ability. In Experiment II, seniors with MCI showed a hearing level that was poorer than that of the young adults but was similar to that of the healthy seniors, and obvious cognitive impairment compared to the other two groups. Results of Experiment II demonstrated a significantly reduced tone discrimination ability for the seniors with MCI, implying that cognitive impairment also plays a significant negative role in tone discrimination ability, besides the age-related hearing loss. Taken together, both age-related hearing loss and cognitive impairment influence tone discrimination ability in the aging population. The findings suggested that both factors should be considered in the aging research.

Since age-related hearing loss has been discussed in detail in Experiment I, we may pay more attention to the discussion of cognitive impairment here. On the one hand, only tone discrimination degraded in seniors with MCI, but their tone identification was normal. It is noteworthy that the cognitive requirements of phonemic identification and discrimination are different. In the phonemic identification task, listeners need to encode one sound stimulus only. For the phonemic discrimination task in this study, listeners need to maintain the first sound until the release of the second sound and then compare the two sounds. Therefore, compared with identification, phonemic discrimination requires extra cognitive resources for the maintenance and manipulation of sound stimuli in working memory and is thus relatively more complex. It has been reported that seniors with MCI showed impaired working memory (e.g., Jutten et al., 2021; Kessels et al., 2011; Saunders & Summers, 2010). The cognitive processing load of the relatively complex phonemic discrimination may increase more for those with MCI than healthy ones. Therefore, their poorer phonemic discrimination may be partially attributed to the impaired working memory. Considering the different degeneration processes of phonemic identification and discrimination, it is necessary to examine identification and discrimination abilities simultaneously in seniors.

On the other hand, seniors with MCI performed worse in the between-category discrimination of lexical tones, supporting that long-term phonological memory may degrade in seniors with MCI. Their phonological representations in long-term memory may be less precise. Du et al. (2016) found an overall less distinctive phoneme representations, so-called phoneme dedifferentiation, in speech-related cortical regions when seniors perceived English consonants via functional magnetic resonance imaging technique. Previous studies have also observed the impairment in the retrieval of the long-term phonological memory in the pathological aging population, such as patients with MCI and Alzheimer's disease (Grönholm-Nyman et al., 2010; Oh & Ha, 2015). Such impairment influences not only speech perception, but also speech production (e.g., tip-of-the-tongue phenomenon, and phonemic fluency). Thus, the less precise phonological representations and the impaired retrieval of long-term phonological memory of MCI participants may profoundly influence their tone discrimination.

Since speech perception is important in daily communication, scholars and clinicians devote more and more efforts to developing training regimens to help seniors with cognitive impairments to facilitate their speech perception and further improve the quality of daily life. Our study suggested that clinical intervention for those with MCI should pay special attention to phonemic discrimination. Smith et al. (2009) proposed a computer-based auditory discrimination training including pitch/frequency discrimination and phonemic discrimination, and was proved to be effective in seniors. The training effect also transferred to real-life improvements and could even sustain for three months after the training (Smith et al., 2009; Strenziok et al., 2014). Additionally, our findings supported that cognitive training on working memory for seniors with MCI may be helpful to improve their speech perception. Ingvalson et al. (2015) proved that 10 days of working memory training could improve speech perception in Mandarin and English listeners.

All of the elder participants that we recruited lived in urban areas and had high levels of education and socioeconomic status. However, there are many Chinese elders who have not had such generous educational opportunities when they were young. Some of them stayed in rural areas for their whole life. Previous studies have observed that both low educational levels and living in rural areas can negatively influence cognitive abilities in the elderly (e.g., Xue et al. 2018). Therefore, our findings cannot be generalized directly to those people. Demographic diversity and individual variation should be considered in more depth in further studies. Power analysis with an effect size of 0.25, an alpha level of 0.05, and a power of 0.8 also indicated that the total sample size should be 159. Therefore, a larger number of participants may be involved in future studies to increase the statistical power. Besides, in Experiment II, working memory and long-term phonological memory were not separately assessed for seniors. Future research should include more detailed cognitive assessments to figure out the relationship between cognitive decline and CP.

Conclusions

In this study, we investigated different degeneration processes of CP of Mandarin lexical tones in the normal aging population and the pathological aging population with MCI. In the normal aging population, seniors aged below 65 years maintained intact categorical tone perception. Those aged above 75 years could also maintain normal tone identification, whereas they showed impaired discrimination of lexical tones associated with age-related hearing loss. These suggested that the decreased signal audibility impaired their tone discrimination. In the pathological aging population with MCI, tone discrimination also showed a significant degeneration, suggesting that lexical tone discrimination was vulnerable to the additive effect of age, hearing loss, and cognitive impairment (e.g., impaired working memory and long-term phonological memory).

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