Mechanisms of Tone and Intonation Processing and Their Modulation by Musical Disorders

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Abstract

Background: In tonal languages, both intonation and lexical tone rely on pitch cues. Intonation helps listeners comprehend speaker intent, while lexical tone indicates word meaning. These two elements also interact within sentences. However, the hierarchical temporal order in which they are processed by the brain during dynamic processing remains unclear. Furthermore, music and language are two closely related domains. How musical disorders affect the perception of intonation and lexical tone in speech, and whether similar effects exist in adults and children, also awaits investigation.

Purpose: This study primarily investigates the mechanisms of intonation and lexical tone processing in native Mandarin speakers and their relationship with musical disorders, addressing two research questions: (1) the temporal hierarchy of intonation and lexical tone processing; (2) the impact of musical processing disorders on intonation and lexical tone recognition.

Methods: The participant groups in this study included 11 adult participants with musical disorders, 13 adult control participants, 21 child participants with musical disorders, and 23 child control participants. The experimental materials consisted of audio recordings of Mandarin sentences read by speakers with standard Mandarin pronunciation. In the first experiment, 13 adults with normal musical ability were presented with Mandarin sentences expressing different intonations and lexical tones, and were asked to judge intonation/lexical tone, while their behavioral performance and EEG were recorded. Experiment two focused on the influence of musical ability on intonation and lexical tone judgment abilities. Sentences containing both intonation and lexical tone information were presented to 11 adult participants with musical ability disorders and child participants with varying musical abilities, and their accuracy rates in intonation and lexical tone recognition were recorded.

Results: Experiment one found that in the intonation task, neural responses to intonation information emerged within a very early time window, while responses to lexical tone information appeared later. In the lexical tone task, however, the earliest effect observed in the EEG was an interaction between intonation and lexical tone, revealing the significant involvement of intonation information in both intonation and lexical tone judgments. Experiment two found that musical disorders primarily affected intonation processing rather than lexical tone judgment ability in both adult and child groups. Additionally, data from children showed that intonation processing abilities mature earlier than lexical tone, a result that may be related to the importance of intonation for human social communication.

Full Text

Preamble

Mechanisms of Intonation and Tone Processing and Their Modulation by Musical Disorders

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Background

In tonal languages, both intonation and lexical tone rely on pitch cues. Intonation helps listeners understand speaker intent, while lexical tone indicates word meaning, and these two dimensions interact within sentences. However, the temporal hierarchy of how the brain processes them during dynamic speech perception remains unclear. Moreover, while music and language are closely related domains, how musical disorders affect speech intonation and tone perception in both adults and children, and whether similar effects exist across age groups, are questions that await investigation.

Purpose: This study investigates the mechanisms of intonation and tone processing in native Mandarin speakers and their relationship with musical disorders, addressing two primary research questions: (1) the temporal sequence of intonation and tone processing; and (2) the impact of musical processing disorders on intonation and tone identification.

Method: Participants included 11 adult amusics, 13 adult control subjects, 21 children with musical disorders, and 23 child controls. Experimental materials consisted of audio recordings of Mandarin sentences read by a native speaker with standard pronunciation. In Experiment 1, 13 adults with normal musical ability listened to Mandarin sentences expressing different intonations and tones, judging either intonation or tone while their behavioral performance and EEG were recorded. Experiment 2 examined how musical ability affects intonation and tone judgment by presenting sentences containing both intonation and tone information to the 11 adult amusics and to child participants with varying musical abilities, recording their accuracy in intonation and tone identification.

Results: Experiment 1 revealed that in the intonation task, brain responses to

intonation information appeared in a very early time window, with tone-related responses emerging later. In the tone task, however, the earliest ERP effect was an interaction between intonation and tone, demonstrating that intonation information actively participates in both intonation and tone judgments. Experiment 2 found that musical disorders primarily affected intonation processing rather than tone identification ability in both adult and child groups. Additionally, children' s data showed that intonation processing abilities mature earlier than tone processing, a result likely related to the importance of intonation for human social communication.

Keywords: intonation, lexical tone, Mandarin, congenital amusia, musical ability

ABSTRACT

Background: Intonation and lexical tone both rely on F0 in tonal languages. While the former can indicate speaker intention (e.g., asking a question or stating a fact), the latter helps determine word meaning. These two interact within sentences, yet the order in which the brain accesses them remains unknown. Additionally, as a domain closely related to language, music may influence the processing of intonation and tones. Whether musical disorders affect adults' and children' s intonation and tone identification abilities remains unclear.

Purpose: The current study aimed to investigate: (1) the access order of intonation and lexical tones in Mandarin Chinese; and (2) whether individuals impaired in pitch perception perform differently from those with normal musical ability in intonation and tone identification tasks.

Method: Eleven adults and twenty-one children with pitch disorders, along with thirteen adult controls and twenty-three child controls, participated. They listened to Mandarin sentences containing both intonation and lexical tone in the same syllable, judging either intonation (in the intonation task) or tone (in the tone task). In Experiment 1, thirteen adults with normal musical ability participated, with behavioral reactions and ERP mean amplitudes recorded and analyzed. In Experiment 2, the intonation and tone identification of adult and child amusics (and child controls) were investigated, with behavioral performance recorded and compared.

Results: In Experiment 1, ERP results showed that in the intonation task, participants responded to intonation first and then to lexical tone. In the tone task, participants showed sensitivity to both intonation and tone through an early interaction beginning at 100ms. Participants were alert to intonation and processed it regardless of task, indicating intonation' s important role in human communication. In Experiment 2, musical disorder impaired intonation identification rather than lexical tone identification in both adults and children. Additionally, lexical tone perception was not fully developed in 9-year-old children, while their intonation identification ability was mature, suggesting that intonation identification may mature earlier than tone identification in humans.

Keywords: Intonation, lexical tone, Mandarin, amusia, music ability

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Chapter 1 Introduction

1.1 Temporal Hierarchy of Intonation and Tone Processing

Pitch is a crucial feature in language. At the syntactic level, it relates to intonation and can indicate intonational phrase boundaries and grammatical boundaries [1, 2]; at the lexical level, it relates to tone and can determine word meaning in tonal languages [3]. Both intonation and tone rely on F0 cues, making their interaction inevitable during speech processing [see Mandarin studies 4, 5, 6; Cantonese studies 7]. Previous research has thoroughly investigated tone’ s influence on intonation, revealing conflicts between falling tones (e.g., Mandarin Tone 4) and rising question intonation [5, 6, 8-11]. However, both intonation and tone processing unfold over time, and this temporal dynamic must be considered when studying their interaction and judgment. To date, it remains unclear when intonation and tone are processed in an utterance and what their processing order is. Therefore, the first experiment of this study explores the temporal hierarchy of intonation and tone processing to better understand the dynamic process of speech prosody processing.

To investigate the processing order of intonation and tone in tonal languages, we propose two hypotheses: the task-relevant hypothesis and the intonation-priority hypothesis. (1) **Task-relevant hypothesis:** Language processing in real-time has long been found to depend on task content [12]. Using identical speech signals (consonant-vowel-consonant syllable pairs), phonetic discrimination tasks enhance activity in left Broca’ s area, while pitch discrimination tasks activate right prefrontal cortex [12]. If the temporal hierarchy of intonation and tone is essentially task-dependent, then tone-related effects should be observed first in tone tasks, while intonation effects should have temporal priority in intonation tasks. (2) **Intonation-priority hypothesis:** Intonation may have a higher temporal hierarchy than tone in speech processing. Four reasons support this hypothesis. First, prosodic cues may have deeper evolutionary roots than lexical tone and can exist independently of human language. For Bengalese finches, prosody discrimination is a primary ability. Research shows they can detect prosodic differences in Japanese sentences rather than content differences, despite having both discrimination abilities [13]. Spierings and ten Cate found that zebra finches are sensitive to the same series of prosodic cues in human speech (pitch, duration, amplitude), with pitch receiving more prominent processing, similar to human speech prosody perception [14]. Furthermore, a cross-fostering experiment [15] found that the temporal structure of zebra finch song prosody is innate.

The second reason supporting the intonation-priority hypothesis is that prosodic skills, which develop early, play a crucial role in infants’ speech learning. Studies show that five-month-old infants respond differently to approval/disapproval [16] and positive/negative expressions [17], and infants develop preferences for prosodic features between six and nine months [18]. Infants may rely on prosodic cues (e.g., stress patterns) to segment words from fluent speech [19]. Third, intonation is a universal expressive feature across languages [20], conveying not only linguistic information but also paralinguistic information about the speaker’ s emotion, attitude, and intent [20-23]. People can even extract emotional prosody from unfamiliar Western or non-Western languages [24]. Such social information is crucial for human social communication and survival [e.g., 25], suggesting it may have higher processing priority than lexical information in the brain. Fourth, previous research found that people have categorical perception for lexical tone [26, 27] but not for intonation [28]. Given that our brain prioritizes limited resources for the most important tasks, even subtle intonation changes may be important for humans. In Liu and Rodriguez’ s study examining English intonation (question/statement) categorical perception in English and Chinese native speakers, Chinese speakers showed steeper intonation identification functions and different intonation boundaries than English speakers. However, the resulting discrimination function was not typical of categorical perception, with neither group showing (or showing only very small) discrimination peaks [28].

Given intonation’ s advantages and social significance compared to tone, people may be more sensitive to intonation than tone. However, most previous studies focused on how intonation and tone interact, lacking comparison of their temporal hierarchy during dynamic processing. Researchers widely believe that tone can affect intonation identification, with question intonation better identified when the final syllable is Tone 4 than Tone 2, while no tone effect was found for statement intonation identification [5, 6]. The falling Tone 4 conflicts with the rising contour of question intonation, making question intonation easier to identify and strengthening the difference between question and statement intonation for Tone 4 stimuli [see MMN for question and statement intonation on Tone 4 rather than Tone 2 in 8, 9; P300 component in 10; P600 component in 11]. Regarding intonation’ s effect on tone, previous studies suggested that intonation does not affect tone contours in Mandarin [29] and has almost no effect on tone perception [4]. Mandarin infant-directed speech (with exaggerated intonation contours) also does not distort lexical tones [30]. Given Tone 4’ s strong interference effect on question intonation identification, Yuan took a local perspective viewing intonation as tone-dependent, concluding that tone identification may precede intonation identification or at least be processed simultaneously [6]. However, a Cantonese study found that question intonation caused most low tones to be misidentified as high tones [31], suggesting that F0 contour changes caused by intonation may affect tone identification.

Investigating the temporal hierarchy of intonation and tone processing is important for clarifying which has priority in tonal languages. We need real-time understanding of subtle differences in intonation and tone processing at high temporal resolution throughout the dynamic process. Event-related potentials (ERP) are an excellent tool for examining this process due to their high temporal resolution, allowing detection of how auditory cues may affect brain activity. Researchers can discover when intonation and tone become involved in auditory processing and compare their temporal order. To give intonation a fair comparison opportunity, this study also included a tone identification task, not just an intonation task, so that intonation cues' effect on tone identification could also be examined. Liu and colleagues also included both intonation and tone tasks in their study [10], but their ERP data analysis mixed data from both tasks without separate analysis, making it difficult to compare intonation and tone processing separately and determine which is more sensitive and more easily perceived by Mandarin native speakers. Therefore, to compare their effects and explore top-down processing, both intonation and tone identification tasks should be studied and analyzed.

1.2 Intonation and Tone Processing in Individuals with Musical Processing Disorders

Music plays an important role in people' s lives [32-34]. Many studies show that music can influence skills and cognitive abilities in other domains, such as language [35-38], mathematics [39], and spatial reasoning [40-44]. However, Kalmus et al. [45] reported that nearly 4% of the UK population has a disorder affecting musical pitch processing, known as congenital amusia [46]. Similarly, in China, the proportion of pitch processing disorders reaches 3.4% [47]. Congenital amusia is a disorder involving difficulties in music perception and production [48, 49], characterized primarily by pitch processing difficulties [50]. Amusics have deficits in perceiving, remembering, and appreciating music [46], and this musical disorder cannot be attributed to differences in hearing, intelligence, or musical experience [49, 51]. The most widely used test for identifying amusia is the Montreal Battery of Evaluation of Amusia (MBEA) developed by Peretz et al. [52]. This battery includes six subtests: three pitch-related subtests (scale, contour, interval), two rhythm-related subtests (rhythm and meter recognition), and one memory subtest (melody recognition).

As essential foundations of human life, music and language are closely linked in evolution and cognitive processing [53]. They share many similarities, including acoustic-physical characteristics and syntactic structures [33, 34, 54, 55], and partially share cognitive and neural mechanisms [53]. Pitch processing is fundamental for both melody in music and prosody in language [56]. Research shows that pitch experience can transfer between these two domains [57-59]. However, researchers have not reached consensus on the extent to which pitch processing overlaps between music and language. Therefore, studying pitch perception may help explore similarities and differences between music and language. Examining amusics' performance in language-related tasks provides an opportunity to explore similarities and differences in pitch processing across these domains.

Previous research has found that amusics show poorer abilities in tone perception, speech processing, intonation and emotional prosody processing, and sentence comprehension [47, 60-66]. Nan et al. found that nearly one-third of tested Mandarin-speaking amusics had impairments in tone identification and discrimination [47], and Nguyen et al. found that French-speaking amusics performed worse than controls in discriminating Mandarin tones [67].

In intonation identification and discrimination, Ayotte et al. [51] found in their Montreal study that amusic groups did not differ significantly from normal participants in tasks identifying speech intonation (i.e., identifying statement vs. question intonation) and discriminating intonation (judging whether intonation was the same). However, when all speech information was removed from sentences, amusics showed decreased ability. Similarly, Patel et al. [66] found that amusics' ability to distinguish sentences based on intonation was far better than their ability to distinguish discrete-pitch analogs representing intonation contours, and they also showed deficits in discriminating gliding-pitch analogs. Meanwhile, other research has revealed deficits in speech intonation judgment among amusics. For example, researchers found that British amusics had problems distinguishing, identifying, and imitating statements and questions, where the main difference was the pitch direction of the final word [64]. Building on this, Hutchins et al. explored whether differences between amusics' performance on speech and non-speech tasks related to the range of pitch changes, suggesting that such changes are relatively coarse in speech but finer in music [68]. When amusic participants classified sentences as statements or questions, researchers manipulated the F0 value of the final note (from level 1 to level 11) and found that amusics used the same stimulus classification criteria as normal participants, though with lower accuracy and internal consistency. Amusics seemed to have problems with fine changes between endpoints, suggesting that pitch perception deficits affect their ability with pitch contours, thus confirming the authors' hypothesis that amusics' different perceptual abilities for music and language mainly result from pitch differences in language not being as fine as in music.

These findings highlight the importance of exploring domain-specificity in amusia [53]. However, research on intonation in tonal language contexts is relatively scarce. Notably, in tonal languages, pitch variation is a distinctive feature for individual words, so studying tonal language native speakers with amusia can help explore whether pitch processing deficits transfer to the language domain [68]. Next, we introduce these few studies on tonal language amusics' performance in intonation judgment.

Jiang et al. (2010) conducted two experiments in China, asking amusic participants to complete discrimination and identification tasks for melodic contours and speech intonation. In the intonation task, stimuli were two-syllable Mandarin verb-object phrases, and participants needed to distinguish between statement and question intonation stimuli. Results showed that compared to normal participants, amusics had deficits not only in discriminating melodic contours but also in processing intonation in both speech and non-speech analogs [69].

Researchers found that amusics have deficits in tasks primarily relying on pitch sensitivity, such as distinguishing smooth pitch sequences extracted from statements and questions, but not in tasks requiring multiple acoustic cues to derive meaning, such as word identification tasks and natural speech statement-question identification and discrimination tasks [62]. Similar to the previous study [69], Liu et al. used pairs of words with identical single characters but different intonation, though their words ranged from three to seven syllables. Statement intonation words and corresponding question intonation words differed not only in F0 but also in duration and intensity. Paired t-tests showed that statement intonation stimuli had significantly lower mean F0, lower mean intensity, and wider pitch range than question intonation stimuli, both for the entire word stimulus and for the final syllable. Moreover, statement intonation final syllables had significantly shorter duration than question intonation syllables. In Jiang et al.' s (2010) study [69], they used two-syllable word pairs that differed only in the F0 curve of the second syllable. Differences in stimuli between these two studies may explain why they obtained different results (i.e., why Mandarin amusics in Jiang et al.' s study did not perform as well as controls on intonation tasks). This suggests that other acoustic cues, such as duration and intensity, may help Mandarin-speaking amusic groups with speech-related processing.

Unlike these two studies on Chinese amusics' intonation processing that used phrases as test materials, Jiang et al. [60] used dialogues rather than single words or phrases as experimental stimuli in their 2012 study. This study explored amusics' brain responses to prosody-syntax mismatches in everyday speech comprehension. Participants needed to judge the semantic acceptability of dialogues including question/answer pairs. Answer sentences contained "yes" or "no," a reason clause, and a final clause with statement or question intonation that was semantically related. The final syllable was spoken with either question or statement intonation, making the overall intonation appropriate or inappropriate. Amusics performed worse on this task than controls. Additionally, amusics did not show significant differences in N100 and P600 components between semantically inappropriate and appropriate conditions, while controls showed larger P600 and smaller N100 components for inappropriate stimuli.

These recent studies on amusics' intonation judgment performance have contributed significantly to exploring amusics' language abilities and the relationship between music and language. However, in sentence intonation processing, besides the widely used pitch cues, other cues such as intensity also play important roles and may provide substantial compensatory support for amusics' speech comprehension, warranting consideration in research. Second, due to the close connection between intonation and tone summarized above, when examining amusics' intonation and tone judgment, the interaction between tone and intonation should also be considered to explore whether amusics differ from normal participants when identifying tones affected by intonation (e.g., Tone 4 in question intonation) and intonation affected by tone. Furthermore, research on language processing abilities in children with musical disorders is lacking, necessitating studies examining how musical disorders affect intonation and tone identification in tonal language-speaking children.

Chapter 2 Research Questions

2.1 Temporal Sequence of Intonation and Tone Processing

Lexical tone and intonation interact with each other in real-time speech perception. Previous studies have not explored the temporal characteristics of how tone and intonation are processed within the same syllable. In this study, we designed two tasks (intonation identification and tone identification) to investigate the order in which our brain processes this information.

Therefore, in this study, the timing of ERP effects is an important dependent variable, with independent variables including the auditory stimuli' s intonation and tone information. We needed stimulus materials that could simultaneously represent both intonation and tone information, a requirement met by Mandarin Chinese, where tone and intonation can be carried by the same final syllable. Indeed, previous research has shown that intonation perception in Mandarin relies more on the F0 characteristics of the final syllable than on the pitch level of the entire sentence [70]. F0 is the primary cue for tone, while for intonation, researchers believe questions have higher F0 and intensity than statements [5], though the contribution of intensity to intonation identification remains under discussion [71]. To thoroughly investigate when and how auditory cues for intonation appear in the processing stream, this study manipulated both pitch and intensity cues. We decomposed intonation changes into F0 and intensity variations while controlling for duration cues and sentence content. Thus, there were three independent variables: intonation-pitch (question pitch vs. statement pitch), intonation-intensity (question intensity vs. statement intensity), and tone (Tone 2 vs. Tone 4). We used Tones 2 and 4 because of their special characteristics. As Jiang and colleagues summarized, in Mandarin, for question intonation, all tones except Tone 4 have rising contours, while only Tone 4 has a falling pitch contour; for statement intonation, Tone 2 has a rising trend while other tones are falling [69]. Although question intonation generally has a rising pitch pattern and statement intonation corresponds to falling contours, Mandarin Tones 2 and 4 maintain their own characteristics, facilitating exploration of how tone and intonation are processed individually and how they influence each other.

The hypotheses for Experiment 1 were: (1) In both Mandarin intonation identification and tone identification tasks, intonation would be processed first; and (2) Auditory cues for tone would affect intonation identification, while intonation would also affect tone identification.

2.2 Effects of Musical Disorders on Intonation and Tone Processing

Music and language are closely connected domains. Previous research shows that musical disorders may affect intonation judgment, but how they specifically affect pitch and intensity factors in intonation is not well understood. This study explores sentence intonation processing using not only the widely used F0 cue from previous research but also other linguistic cues such as intensity, providing good control over various cues involved in intonation judgment (pitch, intensity, duration). Intensity likely provides substantial compensatory support for amusics' speech comprehension, and this design helps us better understand how musical disorders affect amusics' language perception.

Through the orthogonal design of our stimulus materials (statement pitch-statement intensity, question pitch-question intensity, statement pitch-question intensity, question pitch-statement intensity), we can explore which materials amusics and control participants judge well and which stimulus types hinder intonation identification. If groups differ in intonation identification ability, we can determine whether these differences exist across all materials or only for certain stimulus types. Additionally, by including a tone task, this experiment also explores whether amusics and controls differ in tone judgment and whether their tone judgment is affected by intonation factors.

Furthermore, most previous studies examining how musical ability affects intonation and tone judgment were based on adult participants. This experiment also recruited elementary school children to investigate whether effects of musical disorders found in adults also exist in children. By comparing performance of children with different musical abilities on intonation and tone identification tasks, we can examine the impact of musical processing disorders on children' s language processing. By comparing children and adults with normal musical ability on both tasks, we can analyze the development and maturation of human tone and intonation processing abilities.

Chapter 3 Experiment 1: Temporal Hierarchy of Intonation and Tone Processing

3.1.1 Participants

Researchers recruited 13 participants with normal musical ability, native Mandarin speakers who had not received more than two years of formal music training (5 male, 8 female) through campus forum postings. None reported any neurological or psychological disorders, and all had good hearing with minimum hearing thresholds below 20 dB at 250-8000 Hz. They were all right-handed as measured by questionnaire [72] and scored in the normal range (above the cutoff of 71.7%) on the Montreal Battery of Evaluation of Amusia (MBEA) [52].

3.1.2 Stimuli

This study used 39 pairs of single Chinese characters in Mandarin, where characters in each pair had identical vowels and consonants but differed only in tone (one was Tone 2, one was Tone 4), creating 78 single-character stimuli that were all real characters. Experimental materials consisted of a neutral semantic sentence frame "这个字念" (This character is pronounced) followed by one of the single characters as the final word (e.g., "这个字念'替'"). A young female native Mandarin speaker recorded the 78 sentences, reading each twice–once with statement intonation and once with question intonation–resulting in 156 sentences. Researchers then extracted the final character from each sentence, obtaining 156 single-character audio materials. For each character, there were two tones, each with two intonations, creating four stimulus types. Using Praat audio processing software [73], researchers normalized the duration of the four stimulus types for each character by extracting their durations, calculating the mean, and applying this average duration to all four stimuli. This controlled the linguistic factor of duration while maintaining ecological validity. A statement intonation sentence frame "这个字念" (duration: 989 ms) was then recombined with these characters (duration: 405-584 ms), yielding 156 sentences with identical frames differing only in the final character.

Researchers recruited 11 Mandarin-speaking university students to judge these sentences. Each participant completed two tasks: in the intonation judgment task, they indicated whether the sentence expressed statement (press F) or question (press J) intonation; in the tone judgment task, they indicated whether the final character was Tone 2 (press 2) or Tone 4 (press 4). Task order was randomized. Stimuli with accuracy below 0.72 for either intonation or tone judgment were eliminated, removing 28 sentences and leaving 128 sentences (32 character pairs × 2 tones × 2 intonations). Mean intonation judgment accuracy was 0.93 (min: 0.73; max: 1.00; SD: 0.09), and mean tone judgment accuracy was 0.98 (min: 0.82; max: 1.00; SD: 0.05). Additionally, Tone 2 and Tone 4 single-character materials did not differ significantly in word frequency ($t(57) = 1.617$, $p = 0.111$). Acoustic analysis revealed significant differences between question and statement stimuli for each character in F0 level ($t(63) = 25.046$, $p < 0.001$) and intensity ($t(63) = 6.783$, $p < 0.001$). Mean F0 level, intensity, and duration are shown in Table 1 . Figure 1 [Figure 1: see original paper] shows the F0 contour for an example stimulus ("fei").

Additionally, researchers calculated the F0 interval as the semitone difference between 0% and 100% time points (100% time point - 0% time point). ANOVA on all final character stimuli revealed significant main effects of intonation (for F0 level: $F(1,31) = 592.736$, $p < 0.001$, $p^2 = 0.950$; for F0 interval: $F(1,31) = 82.936$, $p < 0.001$, $p^2 = 0.728$) and tone (for F0 level: $F(1,31) = 539.493$, $p < 0.001$, $p^2 = 0.946$; for F0 interval: $F(1,31) = 431.720$, $p < 0.001$, $p^2 = 0.933$), see Figure 2 [Figure 2: see original paper]. However, for both Tone 2 and Tone 4, statement stimuli had lower F0 level ($ps < 0.001$) and F0 interval ($ps < 0.001$) than question stimuli. For both question and statement intonation, Tone 2 stimuli had lower F0 level ($ps < 0.001$) and higher F0 interval ($ps < 0.001$) than Tone 4 stimuli. No meaningful interaction existed between intonation and tone (Figure 3 [Figure 3: see original paper]).

To investigate the role of pitch and intensity in intonation processing, researchers used Praat [73] to swap the pitch between statement and question intonation materials for each final character while leaving other cues including intensity unchanged. This created 128 new single-character audio files (32 character pairs

× 2 tones × 2 manipulated intonations) that were neither pure statement nor question intonation. The same sentence frames were added to these new characters, creating 128 new sentences. These unnatural sentences plus the previous 128 natural sentences made 256 total experimental stimuli. For each character and tone, there were four intonation stimuli (statement intonation material, question intonation material, statement intonation material with question intonation pitch, question intonation material with statement intonation pitch). Thus, this study had eight experimental stimulus types: four natural stimuli (q2: Tone 2 question, q4: Tone 4 question, s2: Tone 2 statement, s4: Tone 4 statement) and four unnatural stimuli (s2(q): Tone 2 question with statement pitch, s4(q): Tone 4 question with statement pitch, q2(s): Tone 2 statement with question pitch, q4(s): Tone 4 statement with question pitch). Table 1 shows the acoustic parameters for these eight stimulus final characters.

3.1.3 Stimulus Presentation

Participants first saw an instruction screen, then a fixation point (250 ms) at the center of the screen, followed by audio sentence presentation. The sentence frame “这个字念” lasted 989 ms, and the final character lasted 405-584 ms. EEG triggers were placed before the final character appeared. There was a 1200 ms interval between final character onset and the response phase; the screen did not turn after the final character finished playing but waited for the 1200 ms period to end before entering the response phase, when “请按键” (Please press a key) appeared. Participants were instructed to respond as quickly and accurately as possible on the keyboard, with a maximum response duration of 3000 ms.

3.1.4 Procedure

The experiment consisted of two tasks: intonation judgment and tone judgment, with task order randomized. Both tasks used the same stimuli. In the intonation judgment task, participants indicated whether the sentence was statement (press F) or question (press J) intonation. In the tone judgment task, they indicated whether the final character was Tone 2 (press 2) or Tone 4 (press 4). Participants sat in a testing room at Beijing Normal University’ s Behavioral Laboratory facing a computer screen. The experimenter explained the instructions, and the experiment began. Each task included 10 practice trials with feedback on correctness. For the intonation judgment task, these 10 trials used only statement (s) or question (q) materials without pitch-swapped stimuli, so correct answers existed. After practice, there was a short break, followed by the formal test phase where the 256 sentences were presented twice in random order, totaling 512 sentences. Each task’ s formal test consisted of four blocks with 128 sentences per block, with breaks between blocks. Each task lasted about half an hour, and the entire experiment lasted about one hour, controlled by E-prime software.

During the behavioral experiment, researchers recorded participants’ EEG signals using a 64-channel (Ag/AgCl) NeuroScan system with SynAmps EEG amplifier, bandpass filter set to 0.05-200 Hz, and sampling rate of 1000 Hz. The 64 channels were located on a Quick-Cap, with the ground electrode between FPz and Fz and the reference electrode at the nose tip. Vertical EOGs were recorded from electrodes above and below the left eye, and horizontal EOGs from electrodes lateral to the left and right eyes. Electrode impedance was kept below 10 kΩ during recording.

3.1.5 Data Analysis

First, researchers calculated participants’ response accuracy for each condition in both tasks. For the intonation judgment task, pitch-swapped statement materials (q(s)) and pitch-swapped question materials (s(q)) had no standard answers. For calculation convenience, researchers chose the speech cue (pitch or original intonation) that participants tended to use as the correct answer based on their judgment tendencies. Since data showed participants overall tended to judge pitch-swapped statement materials (q(s)) as question intonation and pitch-swapped question materials (s(q)) as statement intonation—meaning they relied on pitch as the judgment standard—researchers used this tendency as the standard for correct answers for these two conditions to facilitate further calculations.

For EEG data, preprocessing used NeuroScan software [74] to process blinks, then filtered the data (low-pass filter of 30 Hz, zero-phase, 24 dB/octave), segmented it (1400 ms, 200 ms pre-stimulus, 1200 ms post-stimulus), and performed baseline correction. Researchers selected nine electrodes from the 64 channels (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) and used Scan software to calculate mean amplitudes for each participant in each stimulus type and each electrode. These nine electrodes were divided into left, middle, and right regions, and frontal, central, and parietal regions by location, with each region containing three electrodes.

3.2.1 Investigating the Role of Intensity Cues in Intonation and Tone Processing

Since pitch is widely considered the primary cue in intonation identification, when evaluating participants’ accuracy for unnatural stimuli, researchers judged results based on consistency with pitch cues. Analysis showed that participants’ intonation identification accuracy for all eight stimulus types, including four unnatural stimuli, was significantly above chance (50%) (all $ps < 0.005$), see Table 2 . For the four unnatural stimuli where intensity cues indicated intonation opposite to pitch cues, the significantly above-chance accuracy based on pitch cues confirmed pitch’ s (not intensity’ s) primary role in intonation identification.

A repeated-measures ANOVA with task (intonation, tone), pitch (question, statement), intensity (question, statement), and tone (Tone 2, Tone 4) as within-subject variables found no significant main effect of intensity ($F(1,12) = 2.446$, $p = 0.144$, $p^2 = 0.169$), but a significant three-way interaction of task × pitch

× intensity ($F(1,12) = 87.161$, $p < 0.001$, $p^2 = 0.879$), see Figure 4 [Figure 4: see original paper]. Specifically, for the intonation task, the pitch × intensity interaction was significant ($F(1,12) = 122.884$, $p < 0.001$, $p^2 = 0.911$). For question-pitch stimuli, question-intensity stimuli had higher identification accuracy than statement-intensity stimuli ($p < 0.001$); for statement-pitch stimuli, statement-intensity stimuli had higher accuracy than question-intensity stimuli ($p < 0.001$). This indicates that intonation is easier to identify when pitch and intensity cues are consistent than when inconsistent, and this interaction exists only in the intonation task, not the tone task. Besides intensity-related effects, the ANOVA also found significant main effects of task ($F(1,12) = 57.631$, $p < 0.001$, $p^2 = 0.509$), tone ($F(1,12) = 38.594$, $p < 0.001$, $p^2 = 0.828$), pitch ($F(1,12) = 12.462$, $p = 0.004$, $p^2 = 0.763$), and a task × tone interaction ($F(1,12) = 51.453$, $p < 0.001$, $p^2 = 0.811$). Since these effects are unrelated to intensity, they will be discussed in the following analysis investigating intonation and tone effects in both tasks.

These behavioral results demonstrate that pitch is the primary and most important cue in intonation identification, though intensity also influences intonation processing through interaction with pitch. However, in tone identification, no role for intensity was found. Having examined intensity's importance and considering its non-core role in intonation and tone identification, researchers removed unnatural stimuli in subsequent analyses to better investigate how intonation and tone cues participate in the dynamic processes of natural intonation and tone identification.

3.2.2 Investigating Effects of Intonation and Tone in Both Tasks

For behavioral data, a repeated-measures ANOVA with task (intonation identification, tone identification), intonation (question, statement), and tone (Tone 2, Tone 4) as within-subject variables revealed significant main effects of task ($F(1,12) = 28.215$, $p < 0.001$, $p^2 = 0.702$), with higher accuracy in the tone task than the intonation task. The main effect of intonation was also significant ($F(1,12) = 10.166$, $p = 0.008$, $p^2 = 0.459$), with lower accuracy for question than statement intonation across both tasks (intonation task $p = 0.008$, tone task $p = 0.043$; Figure 5 [Figure 5: see original paper]). A significant task × tone interaction was also found ($F(1,12) = 20.911$, $p = 0.001$, $p^2 = 0.635$), see Figure 6 [Figure 6: see original paper]. In the intonation task, Tone 2 final stimuli had lower intonation identification accuracy than Tone 4 stimuli ($p < 0.001$), but in the tone task, no significant difference existed between Tone 2 and Tone 4 ($p = 0.165$).

To explore the relationship between final character auditory features and identification accuracy in both tasks, researchers conducted a linear regression analysis with F0 level and F0 interval as independent variables. For intonation identification, the regression model including F0 interval and excluding F0 level was significant ($p < 0.001$). Conversely, for tone identification, the significant model included F0 level but not F0 interval ($p < 0.001$). This suggests that although auditory analysis shows both F0 level and F0 interval can distinguish intonation and tone, when listening to these natural stimuli containing both, intonation identification may be primarily affected by F0 interval, while tone identification relates more to F0 level.

For EEG data, researchers analyzed mean amplitudes across nine electrodes in 50 ms time windows from 0-800 ms after keyword onset, performing repeated-measures ANOVA on mean amplitudes while listening to natural stimuli, with intonation (question, statement), tone (Tone 2, Tone 4), region (frontal, central, parietal), and hemisphere (left, middle, right) as within-subject variables. Results for continuous 50 ms time windows are shown in Table 3 . Continuous 50 ms time windows showing the same effect in ANOVA were merged and re-analyzed (only effects found in more than two consecutive 50 ms windows were discussed). Results below are reported based on merged time windows.

In the intonation task, ANOVA on mean amplitudes across nine electrodes in the 150-250 ms window found a significant intonation × region interaction (F(2,24) = 27.958, p < 0.001, p^2 = 0.700). In the parietal region, question intonation evoked a larger negative component than statement intonation (p = 0.017). No other effects were significant. In the 250-400 ms window, a significant intonation × region interaction was also found (F(2,24) = 12.886, p < 0.001, p^2 = 0.518). In the parietal region, question intonation showed a larger negative component than statement intonation (p = 0.012). In this window, a significant tone × region effect was also found (F(2,24) = 3.607, p = 0.043, p^2 = 0.231), with Tone 2 evoking a larger negative component than Tone 4 in the parietal region (p = 0.038). In the 450-650 ms window, a significant intonation × tone interaction was found (F(1,12) = 6.733, p = 0.023, p^2 = 0.359). For Tone 4 final stimuli, statement intonation showed a smaller positive component than question intonation (p = 0.001); for Tone 2 final stimuli, no significant difference existed between intonations (p = 0.868). In the 650-750 ms window, significant intonation × region (F(2,24) = 3.987, p = 0.032, p^2 = 0.249) and tone × region (F(2,24) = 7.869, p = 0.002, p^2 = 0.396) effects were found. In the parietal region, question intonation showed a larger positive component than statement intonation (p = 0.031). In both central (p = 0.004) and parietal (p = 0.002) regions, Tone 4 evoked larger positive components than Tone 2. Figure 7 [Figure 7: see original paper] shows these significant effects. Since most effects appeared in the parietal region, ERP waveforms and significant effects in this figure (and Figure 8 [Figure 8: see original paper]) show mean amplitudes for the parietal region (averaged across P3, Pz, P4 electrodes).

In the tone task, a significant three-way interaction of intonation × tone × region was found in the 100-250 ms window (F(2,24) = 8.791, p = 0.001, p^2 = 0.423). For question sentences, Tone 4 showed a larger negative component than Tone 2 in the parietal region (p = 0.034); for statement sentences, no significant difference between tones was found (p > 0.05). No other effects were significant. Results are shown in Figure 8.

3.3 Discussion

Experiment 1 investigated the temporal hierarchy of intonation and tone processing in Mandarin, recording and analyzing participants' EEG responses to Mandarin sentences containing intonation and tone information in the same syllable during intonation and tone identification tasks. In the intonation task, ERP mean amplitude results showed that participants first responded to intonation (intonation main effect appeared in the 100-250 ms window), with tone-related effects appearing after 250-400 ms. In the tone task, the first detected effect was an intonation × tone interaction in the 100-250 ms window, where participants responded to both intonation and tone through an early interaction: in the 100-250 ms window, Tone 4 showed a larger negative component than Tone 2 in question intonation, while no significant difference between tones was found in statement intonation. This shows that the brain' s differential response to Tones 2 and 4 depended on intonation features; when intonation differed, the brain's response to tone also differed. If the initial task-relevant hypothesis were correct, tone effects should have been seen first in the tone task, but intonation effects were actually present in early time windows, indicating that intonation was already involved in tone task processing early on. This result reveals participants' sensitivity to intonation, tending more toward the second hypothesis that intonation has higher temporal hierarchy and shows early effects in both intonation and tone tasks.

Similar to the significant intonation and tone interaction in the tone task, the intonation task also showed a significant intonation × tone interaction in the 450-650 ms window, where Tone 4 final question stimuli showed a larger positive component than statement stimuli. Based on previous research, this may be due to the conflict between rising question intonation and falling tone [5, 6, 8-11]. In the subsequent 650-750 ms window of the intonation task, main effects of intonation and tone (larger positive components for question intonation and Tone 4) were also likely caused by such conflict between question intonation and Tone 4. The positive component found in this window can be considered a P600 component, which is seen as reflecting reprocessing [75, 76] and has been found in previous studies on tone-intonation interaction [11]. P600 reflects a process where participants reanalyze and check sentences to resolve detected conflicts and unexpected events [75]. In the current study, due to the strong conflict between Tone 4 and question intonation, participants may need to reprocess the final syllable with question intonation or Tone 4 before making an identification decision to resolve potential conflicts and avoid judgment errors.

These two interactions in intonation and tone tasks did not appear in behavioral results, possibly due to ceiling effects in the identification tasks themselves. In the tone task, mean tone identification rates for question Tone 2, question Tone 4, statement Tone 2, and statement Tone 4 stimuli were 0.98, 0.97, 0.99, and 0.99 (SDs: 0.02, 0.05, 0.01, and 0.01), respectively. In the intonation task, although identification rate for question Tone 2 stimuli was lower than other conditions (identification rate: 0.78, SD: 0.18), rates for question Tone 4, statement Tone

2, and statement Tone 4 stimuli were 0.95, 0.92, and 0.98 (SDs: 0.05, 0.07, and 0.03), respectively. These tasks may have been too easy for these Mandarin native speakers, so some effects appeared in ERP results but not in behavioral data.

ERP results may be caused by both top-down and bottom-up processing. Regarding bottom-up processing related to stimuli’ s auditory attributes, F0 level was significant in regression models for tone identification rate, while F0 interval was significant for intonation. However, the intonation × tone interaction could not be explained by either F0 level or interval. As shown in Figure 3, Tone 4 had higher F0 level than Tone 2 in both question and statement intonation, as did F0 interval. Therefore, this interaction cannot be explained by bottom-up processing of stimuli. Considering top-down modulation, the larger negative wave for question Tone 4 stimuli in the tone task can be explained by conflict between question intonation and Tone 4, which greatly changes Tone 4’ s F0 contour by flattening its falling slope (see Figure 1; also see Liu et al. 2016 [10]), making tone identification more difficult.

Besides the intonation × tone interaction, significant main effects were also found in the intonation task. In the 100-250 ms and 250-400 ms windows, question intonation showed larger negative components than statement intonation, which can be explained by question intonation being harder to identify behaviorally. As Yuan stated [5], statement intonation identification is simpler because statement intonation is a default, while question intonation is marked and requires specific features for identification. The larger negative component for Tone 2 than Tone 4 in the 250-400 ms window may be because Tone 2 final syllables create greater difficulty in intonation identification than Tone 4 final syllables.

Most EEG findings in this study concentrated in parietal regions, consistent with previous findings about intonation and tone effects in central-parietal areas [10, 11]. In Liu and colleagues’ study, differences between Tone 4 final question and statement stimuli were more significant in posterior than central regions [10]. In previous fMRI studies on speech processing, a dorsal frontoparietal network for tone processing was found [77], and parietal activation was also found when comparing active conditions (participants attended to intonation or tone and made discrimination judgments) to passive listening conditions [78]. In summary, the parietal region may play an important role in intonation and tone processing. Previous fMRI research [79] found parietal cortex activation when participants watched video clips related to social interaction, suggesting that parietal social cognitive functions may be related to its involvement in intonation and tone tasks found in this study.

To our knowledge, the current study provides the first evidence of brain processing order for intonation and tone within the same speech syllable. The finding of intonation’ s early effect in both intonation and tone identification processes highlights the importance of intonation and its social significance for human social communication.

Chapter 4 Experiment 2: Effects of Musical Disorders on Intonation and Tone Processing

4.1.1 Participants

First, researchers recruited 11 adult amusic participants (3 male, 8 female) through campus forum postings, in addition to the 13 control participants (5 male, 8 female) from Experiment 1. All participants were native Mandarin speakers who had not received more than two years of formal music training and had no history of neurological or psychological disorders. Hearing tests showed all participants had good hearing with minimum thresholds below 20 dB at 250-8000 Hz. All were right-handed as measured by the Edinburgh Handedness Inventory [72] and completed the Montreal Battery of Evaluation of Amusia (MBEA) [52] to identify amusia or tone agnosia, including three pitch-related subtests, two temporal subtests, and one memory subtest. Pure amusic participants scored below the cutoff of 71.7% on the MBEA, a criterion based on control scores minus two standard deviations [47], while control participants had normal musical ability (above 71.7% cutoff). Participants also completed a tone ability test during musical ability screening (tone test see [47]), including tone identification and discrimination. The two groups did not differ significantly on the tone test ($p = 0.773$). All participants also completed the Chinese version of the Wechsler Adult Intelligence Scale-Revised (WAIS-RC) [80], with no group differences in intelligence, see Table 4 .

Additionally, this experiment recruited 76 child participants, all third-grade students from two Beijing elementary schools. Their musical ability was tested using the Montreal Battery of Evaluation of Musical Abilities (MBEMA) [81], including subtests for scale, contour, interval, rhythm, and memory. Children scoring in the top 30% were selected as child controls, while those in the bottom 30% with poor musical ability were considered the child pitch disorder group. A total of 21 children were in the pitch disorder group (10 male, 11 female) and 23 in the control group (16 male, 7 female). Intelligence was tested using Raven' s Standard Progressive Matrices [82], with no significant group differences ($p > 0.10$). The groups also did not differ significantly in gender or age ($ps > 0.10$), see Table 5 . This study was approved by Beijing Normal University' s Ethics Review Committee, and all participants provided written informed consent.

4.1.2 Stimuli

To investigate adult amusics' intonation and tone identification abilities, Experiment 2 used the same stimuli as Experiment 1. For child participants, to reduce total testing time and maintain attention and testing quality, researchers randomly selected half of the 32 stimuli from Experiment 1 as materials for the intonation task and the remaining half for the tone task. Analysis of the stimuli found no significant differences between these two sets in intensity ($t(246) =$

-0.446, p = 0.656), F0 level (t(254) = -0.352, p = 0.725), F0 interval (t(254) = -0.527, p = 0.599), duration (t(249) = -1.110, p = 0.268), or word frequency (t(234) = 0.03, p = 0.976).

4.1.3 Stimulus Presentation

Same as Experiment 1.

4.1.4 Procedure

Participants completed an intonation identification task and a tone identification task, with task order randomized. For adult amusics, same as Experiment 1, each sentence was presented twice in random order. For children, to reduce testing time, each sentence was presented only once. One child in the pitch disorder group did not complete the intonation task due to time constraints; all other participants completed all tasks.

4.1.5 Data Analysis

To investigate whether each group' s judgment accuracy across the eight experimental conditions was significantly above chance, researchers conducted t-tests comparing accuracy to chance level (50%). Same as Experiment 1, for unnatural stimuli, since most participants judged based on pitch, data judged according to pitch were treated as correct. To examine whether pitch-impaired and control participants differed in accuracy across the two tasks and how different factors affected their judgments, repeated-measures ANOVA was performed with group as a between-subject variable and task (intonation, tone), intensity (statement, question), pitch (statement, question), and tone (Tone 2, Tone 4) as within-subject variables.

4.2.1 Results for Adult Control and Amusia Groups

Researchers conducted one-sample t-tests comparing accuracy to chance (50%) for both groups on intonation and tone tasks. In the intonation task, adult controls performed significantly above chance on all eight stimuli, but adult amusics did not differ significantly from chance when judging question intonation stimuli ending in Tone 2 (q2 and q2(s) conditions) (Table 6). First, for natural material q2, amusics could not correctly identify question intonation based on pitch or other intonation cues, indicating that Tone 2 significantly interfered with amusics' question intonation judgment. Second, for unnatural stimulus q2(s), amusics neither significantly identified intonation based on pitch nor tended to judge based on original intonation using cues like intensity, indicating Tone 2 also affected intonation identification for this unnatural stimulus (regardless of which cue participants used). A paired t-test comparing amusics' pitch-based identification rates for q2 and q2(s) found q2(s) identification rate was significantly lower than q2 (p = 0.004), indicating that although amusics could not identify clear intonation for either stimulus, they were even less likely to judge based on pitch when pitch and intensity were inconsistent—meaning intensity, besides tone, also affected intonation identification. In the tone task, both groups performed significantly above chance on all eight stimuli (Table 7).

A repeated-measures ANOVA on accuracy across both tasks found the intonation task was significantly harder than the tone task ($F(1,22) = 102.839$, $p < 0.001$, $p^2 = 0.824$). Overall, question pitch was harder to judge than statement pitch ($F(1,22) = 18.143$, $p < 0.001$, $p^2 = 0.749$). A significant task × pitch × intensity interaction ($F(1,22) = 65.684$, $p < 0.001$, $p^2 = 0.806$) showed that intensity and pitch inconsistency only affected intonation judgment. When intensity and pitch cues were inconsistent, participants' judgments were significantly worse than when consistent ($ps < 0.001$; Figure 9 [Figure 9: see original paper]). Conversely, in the tone task, no significant accuracy difference existed between consistent and inconsistent conditions ($p > 0.05$; Figure 10 [Figure 10: see original paper]). The task × tone interaction was significant ($F(1,22) = 91.289$, $p < 0.001$, $p^2 = 0.811$), as was the task × pitch × tone interaction ($F(1,22) = 16.564$, $p = 0.001$, $p^2 = 0.430$). As shown in Figure 11 [Figure 11: see original paper], in the intonation task, Tone 2 stimuli were harder than Tone 4 stimuli for judging question intonation ($p < 0.001$), while in the tone task, for question pitch stimuli, Tone 4 was harder than Tone 2 for judging tone ($p = 0.026$). This indicates that Tone 4 combined with question pitch makes question intonation easier to identify but simultaneously makes Tone 4 harder to identify.

To investigate group differences within each task, researchers conducted separate ANOVAs for both tasks with group (adult amusia, adult control) as between-subject variable and intensity, pitch, and tone as within-subject variables. In the intonation task, a significant group main effect was found ($F(1,22) = 4.363$, $p = 0.049$, $p^2 = 0.166$; Figure 9), but in the tone task, amusics did not differ significantly from controls ($F(1,22) = 1.549$, $p = 0.226$; Figure 10). This indicates that pitch perception deficits in amusia negatively affect intonation identification but do not impair tone identification.

4.2.2 Results for Child Control and Pitch Disorder Groups

One-sample t-tests showed both child groups could successfully identify most intonation stimuli (Table 8). The child pitch disorder group did not show above-chance accuracy when judging Tone 4 final stimuli that were originally statement intonation but with question pitch (q4(s)). In the tone task, neither child controls nor pitch disorder children could successfully identify tone for two stimulus conditions containing question pitch and Tone 4 (q4 and q4(s)) (Table 9). This t-test result in the tone task indicates that overall, question pitch severely interfered with children' s Tone 4 identification, regardless of other cues like intensity and regardless of whether children had musical disorders. In the intonation task, child pitch disorder group could not identify intonation for q4(s), indicating that Tone 4 and statement intensity cues prevented pitch-impaired children from identifying question intonation based on question pitch. However, their intonation judgment for natural condition q4 was significantly above chance, further indicating that Tone 4 itself does not prevent child pitch disorder group from judging question intonation, but inconsistent intensity cues increase difficulty in identifying intonation for Tone 4 with question pitch, resulting in inability to identify intonation. This result demonstrates child pitch disorder group’ s reliance on intensity cues in intonation processing, possibly related to compensatory strategies for other cues due to their pitch impairment.

A repeated-measures ANOVA (between-subject variable: group; within-subject variables: task, pitch, intensity, tone) found that for children, the tone task was also easier than the intonation task (F(1,41) = 19.156, $p < 0.001$, $p^2 = 0.318$). A significant task × pitch interaction was found (F(1,41) = 7.684, $p = 0.008$, $p^2 = 0.158$): in the tone task, question pitch was harder than statement pitch for judging tone ($p < 0.001$), while in the intonation task, no significant accuracy difference existed between pitches ($p = 0.264$). The task × pitch × tone interaction was significant (F(1,41) = 7.440, $p = 0.009$, $p^2 = 0.154$): in the intonation task, for statement pitch, Tone 2 was harder than Tone 4 for judging intonation ($p < 0.001$), while for question pitch, no significant difference existed between tones ($p = 0.949$); in the tone task, for question pitch, Tone 4 was harder than Tone 2 for judging tone ($p < 0.001$), while for statement pitch, no significant difference existed ($p = 0.296$).

Additionally, the four-way interaction of task × intensity × pitch × group was significant (F(1,41) = 4.309, $p = 0.044$, $p^2 = 0.095$), see Figure 12 [Figure 12: see original paper]. In the intonation task, child pitch disorder group performed significantly worse than child controls for both natural and unnatural stimuli (ps < 0.05). In the tone task, pitch-impaired children only showed worse results than controls for unnatural stimuli (ps < 0.05). No significant group difference existed between child groups for natural stimuli in tone judgment, while a difference existed in intonation judgment, indicating that pitch processing disorder affects children’ s intonation judgment more than tone judgment.

4.2.3 Comparison Between Adult and Child Control Groups

t-tests showed that for both child and adult control groups, intonation identification rates for all eight stimulus types were significantly above chance (50%) (Table 10). For tone identification, adult controls performed significantly above chance, but child controls could not successfully identify Tone 4 stimuli with question pitch (q4 and q4(s) conditions, Table 11). The finding that child controls could successfully judge all intonation stimuli but not tone in some conditions reveals that children already have the ability to judge intonation based on pitch cues, but their tone judgment ability is not fully mature.

A repeated-measures ANOVA including both tasks found a significant group main effect (F(1,34) = 16.448, $p < 0.001$, $p^2 = 0.277$) and a group × pitch × task interaction (F(1,34) = 13.053, $p = 0.001$, $p^2 = 0.326$). In the intonation task, adult and child controls did not differ significantly in identifying question pitch intonation (p = 0.674), but child controls performed significantly worse than adult controls on statement pitch intonation (p = 0.002). In the tone task, child controls' tone identification was significantly worse than adult controls for both question and statement pitch stimuli (ps < 0.001). The group difference between adults and children in statement intonation identification in the intonation task will be analyzed in detail below.

A repeated-measures ANOVA on the intonation task showed child controls' intonation judgment accuracy was significantly lower than adult controls (F(1,34) = 5.251, p = 0.028, $p^2 = 0.134$). Additionally, previous research [5] found that statement intonation is easier to identify than question intonation, possibly because listeners identify statement intonation as default when insufficient cues prove the intonation is question, which is marked and requires specific features. In this study' s intonation task, an ANOVA on adult controls (with pitch, intensity, and tone as within-subject variables) found a main effect of pitch (F(1,12) = 11.663, p = 0.005, $p^2 = 0.493$). However, child controls showed no significant pitch main effect (F(1,22) = 0.250, p = 0.622). As shown in Figure 13 [Figure 13: see original paper], although children can judge intonation based on pitch cues, they have not yet developed a statement bias. However, the absence of statement bias does not mean children' s intonation judgment ability is immature, as this bias may simply be a strategy in intonation processing rather than an essential ability.

In the tone task, an ANOVA with pitch, intensity, and tone as within-subject variables and group as between-subject variable also found child controls' tone identification rate significantly lower than adult controls (F(1,34) = 23.994, p < 0.001, $p^2 = 0.414$). A significant three-way interaction of pitch × tone × group was found (F(1,34) = 7.499, p = 0.010, $p^2 = 0.181$; Figure 14 [Figure 14: see original paper]). Only for child pitch disorder group, when stimuli had question pitch, Tone 4 accuracy was significantly worse than Tone 2 (p < 0.001). No such pitch × tone interaction was found in adult controls, further supporting previous findings that adults have mastered the ability to identify Tone 4 with question pitch, a skill not yet mature in nine-year-old children (even those with high musical ability).

4.3 Discussion

Experiment 2 investigated the effects of musical disorders on intonation and tone identification. In adults, musical disorder participants performed significantly worse than normal participants on the intonation task but not on the tone task. In children, musically impaired participants showed lower accuracy on the intonation task. In the tone task, although overall accuracy was also lower, they did not differ significantly from normal participants in identifying natural stimuli. Results show that musical disorders primarily affect intonation identification rather than tone identification.

Adult amusics' intonation problems are consistent with previous findings [64, 69], showing that musical disorders affect intonation identification. t-tests found adult controls judged intonation based on pitch, and adult amusics also basically used pitch, but amusics had problems identifying question pitch when materials ended in Tone 2 (regardless of intensity). For tone identification, both adult controls and amusics performed significantly above chance, with no group differences. Additionally, for both adult amusics and controls, when intensity and pitch cues were inconsistent during intonation identification, judgments were worse than when consistent. In tone identification, consistent vs. inconsistent intensity and pitch stimuli did not produce accuracy differences, indicating intensity manipulation only affected intonation identification, not tone identification, in both groups.

In child groups, the significant four-way interaction of task × intensity × pitch × group showed that in intonation identification, child pitch disorder group performed worse than controls for both natural and unnatural stimuli. This demonstrates that child pitch disorder group' s pitch perception was overall worse than child controls. In the tone task, for natural stimuli, child pitch disorder group could judge tone normally, with no significant difference from child controls. For unnatural stimuli with swapped intonation pitch, child pitch disorder group' s tone judgment was worse than controls. This indicates that the pitch-swapping manipulation (making pitch and intensity inconsistent) clearly interfered with child pitch disorder group' s tone identification, suggesting child pitch disorder group may be sensitive to intensity factors, which are themselves cues in intonation. This result suggests that children may still need to rely on intonation for tone judgment, processing intensity cues from intonation even in tone judgment tasks. Additionally, t-tests showed both child groups could identify intonation for most stimulus types, but neither child controls nor pitch disorder children could successfully identify Tone 4 with question pitch, indicating children at this age cannot successfully perform tone judgment on such conflicting stimuli.

Comparing adult and child controls also revealed that child controls' tone identification rate was significantly lower than adult controls, and only for child controls was Tone 4 accuracy significantly worse than Tone 2 when stimuli had question pitch—no such pitch × tone interaction was found in adult controls. This also indicates that children' s tone processing abilities at this stage are not fully mature, differing from adults, and they have not yet mastered the ability to identify tone without intonation interference. In intonation identification, child controls performed significantly above chance on all eight stimuli, same as adult controls, indicating nine-year-old child controls can process intonation and also use pitch for intonation judgment like adults. Notably, ANOVA on both groups found that question intonation being harder to identify than statement intonation only appeared in adult controls, not child controls, suggesting nine-year-old children have not yet developed a statement bias. This bias may be a strategy for more efficient intonation processing, treating statement intonation as default and marking question intonation with required features. Although children have mature intonation identification ability, they have not yet developed this adult processing strategy.

Chapter 5 Summary

5.1 Conclusions and Significance

Through two experiments, this study investigated a series of questions about Mandarin intonation and tone processing, including: (1) whether intonation and tone show temporal hierarchy differences during Mandarin sentence processing and which variable is processed first by the brain—supporting task-relevant or intonation-priority hypotheses; (2) whether Mandarin native speakers primarily rely on pitch cues for intonation judgment and how other cues like intensity function; (3) whether intonation affects tone identification and whether tone affects intonation identification in Mandarin sentences; and (4) how musical disorder groups process intonation and tone and whether musical disorders affect intonation and tone processing.

5.1.1 Differences in Temporal Hierarchy Between Intonation and Tone

Results found that in intonation processing, intonation was the factor that first evoked ERP responses, while in tone processing, the brain processed both intonation and tone factors simultaneously very early, with an interaction between them. Participants' responses to tone stimuli were also based on intonation identification. Overall, the task-relevant hypothesis was not supported, and the intonation-priority hypothesis was not fully confirmed, but results generally tend to support intonation' s prioritized processing status. Due to intonation' s importance for meeting human social communication needs and further survival [25], and its potentially more ancient evolutionary origins, it is likely a type of stimulus that humans are more sensitive to and prioritize in processing. Future research should explore this issue further using more technologies and methods to examine whether intonation holds priority in processing.

5.1.2 Differences in Developmental Timing of Intonation and Tone

Research on children' s intonation and tone processing found that nine-year-old children already have relatively mature intonation identification ability and can successfully judge intonation for different stimulus types without tone interference. However, their tone processing is not fully developed and they cannot successfully identify Tone 4 with question intonation. This result suggests that tone likely matures later than intonation ability; at least for nine-year-olds, we observed earlier maturation of intonation processing. Intonation' s developmental advantage may be related to its important significance for human social interaction mentioned earlier. We hope future research will examine children' s intonation and tone processing at various ages before nine to further explore the relative developmental processes of tone and intonation and possible interactions.

5.1.3 Effects of Pitch, Intensity, and Tone on Intonation Identification

Results prove that Mandarin native speakers primarily rely on pitch for intonation judgment, but other cues like intensity still play a role. Identification is most accurate when pitch and intensity cues indicate the same intonation. When they indicate different intonations, participants mostly tend to judge based on pitch. Second, intonation and tone influence each other. For example, when intonation is question and tone is falling Tone 4, it is more conducive to successfully identifying question intonation but increases difficulty for tone identification. This is true for both musically normal and pitch-impaired participants, and both groups primarily use pitch as the cue for intonation and tone processing.

5.1.4 Effects of Musical Disorders on Intonation and Tone Processing

Although both intonation and tone use F0 as the primary identification factor, results from adults and children found that pitch ability disorders mainly affect intonation identification, with little effect on tone processing. Adult amusics' problems with intonation processing are consistent with previous findings [64, 69]. Research on musical disorders in children is limited, but similar intonation perception results were also found in cochlear implant studies [83]. In See and colleagues' experiment, cochlear implant users (mean age 10.57 years) had lower accuracy in intonation identification than normal-hearing children (mean age 7.96 years). Since cochlear implant users also have affected pitch perception, this result is similar to that of children with low musical ability in this study. Intonation identification may require precise pitch perception, causing lower identification accuracy in both special child groups and adult amusics. In tone identification (Tone 2 vs. Tone 4 in this study), although children could not judge some tones—Tone 4 stimuli with question pitch—this was a general age-related problem affecting both child groups. Musical disorder adults and children did not have greater difficulty in tone identification than normal participants, possibly because tone judgment is a gradually acquired ability, and congenital pitch processing disorder does not greatly affect it, thus musical deficits have less impact.

5.2 Future Research Directions

Intonation and tone both play very important roles in human understanding of conversation content and meaning, and more research should explore their processing mechanisms in the future. An important direction is the processing priority of intonation and tone. For example, in languages and dialects other than Mandarin, such as non-tonal languages (English) and tonal languages (Cantonese), whether intonation is a factor prioritized by the brain in early time windows. Meanwhile, we call for more cutting-edge brain research methods and tools to explore this issue. Second, whether all groups are sensitive to intonation is also worth exploring. For example, whether amusic groups also process intonation cues first in intonation and tone tasks, and whether they differ temporally from musically normal participants—these are future research directions.

Additionally, this study found immature tone processing abilities in children around age nine (third grade). When does tone processing mature so that behavioral performance is no longer interfered with by factors like intonation? This is a very meaningful research question. Moreover, this study found a statement bias in adults that was not present in nine-year-old children. When does this bias develop? Future research should answer these key questions, focusing on slightly older children and hopefully including longitudinal studies tracking this developmental process.

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