The Role of the Inferior Parietal Lobule in Chinese Tone Perception: An fNIRS-Guided TMS Study*

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Abstract

左侧顶下叶（IPL）是语音范畴感知的重要脑区，它同样参与了汉语声调感知，但是对其功能认识还没有得到一致的结论。本研究使用功能性近红外光谱（fNIRS）技术对左侧 IPL 参与声调感知进行功能定位（实验一），然后使用经颅磁刺激（TMS）技术对左侧 IPL 进行虚拟损伤（实验二），建立左侧 IPL 与声调范畴感知的因果联系。实验一发现左侧 IPL 背侧通道不仅对声调范畴敏感，范畴间比范畴内刺激对诱发了更强的氧合血红蛋白（HbO）浓度变化；还对声学间隔敏感，小声学间隔比大声学间隔刺激对诱发了更强的 HbO 浓度变化。实验二分别虚拟损伤左侧 IPL 的背侧和腹侧通道，发现当左侧 IPL 背侧通道虚拟受损后，该通道对声调范畴的敏感性消失，而左侧 IPL 腹侧通道和前运动皮层通道对声学特征变得敏感。但是当左侧 IPL 腹侧通道虚拟受损后，仅左侧额下回通道出现了功能代偿性地对声调范畴敏感。结果表明左侧 IPL 背侧在汉语声调范畴感知中起到重要作用，而腹侧区域在语音感知的神经生理模型背侧通路中起着门控作用。研究结果从声调语言的角度丰富了语音感知加工的神经生理模型，阐明了背侧/腹侧语音加工通路在范畴感知中的协作机制。

Full Text

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Abstract The left inferior parietal lobule (IPL) is an important brain region for phonetic categorical perception, and it is likewise involved in Mandarin Chinese tone perception; however, no consistent conclusion has yet been reached regarding its function. In this study, functional near-infrared spectroscopy (fNIRS) was used to functionally localize the involvement of the left IPL in tone perception (Experiment 1), and transcranial magnetic stimulation (TMS) was then used to induce a virtual lesion in the left IPL (Experiment 2), establishing a causal link between the left IPL and categorical perception of tones. Experiment 1 found that the dorsal channel of the left IPL was not only sensitive to tone categories, with between-category stimulus pairs eliciting stronger changes in oxygenated hemoglobin (HbO) concentration than within-category stimulus pairs, but was also sensitive to acoustic interval, with small-acoustic-interval stimulus pairs eliciting stronger changes in HbO concentration than large-acoustic-interval stimulus pairs. In Experiment 2, virtual lesions were induced separately in the dorsal and ventral channels of the left IPL. The results showed that, after the dorsal channel of the left IPL was virtually lesioned, this channel' s sensitivity to tone category disappeared, whereas the ventral channel of the left IPL and the premotor cortex channel became sensitive to acoustic features. However, after the ventral channel of the left IPL was virtually lesioned, only the left inferior frontal gyrus channel showed functional compensatory sensitivity to tone category. These results indicate that the dorsal region of the left IPL plays an important role in categorical perception of Mandarin Chinese tones, while the ventral region serves a gating function in the dorsal pathway of the neurophysiological model of speech perception. From the perspective of a tonal language, the findings enrich the neurophysiological model of speech-perception processing and clarify the collaborative mechanism of the dorsal/ventral speech-processing pathways in categorical perception.

Keywords phonetic categorical perception, tone, inferior parietal lobule, fNIRS, TMS

Classification numbers B842; B845

1 Introduction

As a type of suprasegmental information, tone provides important information for speech recognition, especially for distinguishing lexical semantics. Tone processing has cognitive mechanisms (Yang & Chen, 2022; Zhao Rong et al., 2016) and neural mechanisms (Liang & Du, 2018; Luo et al., 2006) that differ from those for segmental information. Revealing the neural mechanisms of categorical perception of tones can enrich cognitive and neurophysiological models of speech processing and has therefore attracted extensive attention from researchers (Chien et al., 2021; Liang et al., 2023). The left inferior parietal lobule (Inferior Parietal Lobule, IPL) is an important brain region for categorical perception of segmental information (consonants and vowels) (Joanisse et al., 2007;

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Mahmud et al., 2021; Preisig et al., 2022). Studies have found that it is involved in the categorical perception of Mandarin tones (Chien et al., 2020; Feng et al., 2018), but its function remains controversial. This study combines functional near-infrared spectroscopy (fNIRS) and transcranial magnetic stimulation (TMS) to examine, from a causal perspective, the role of the left IPL in the categorical processing of Mandarin tones.

Existing cognitive neuroscience models regard the left IPL as an important brain region for speech processing, and a large body of empirical research has provided evidence for this view. The dual-stream model proposed by Hickok et al. (2011) holds that speech processing comprises a ventral pathway and a dorsal pathway. In the ventral pathway, preliminarily processed speech information passes through the middle temporal gyrus (MTG) and from the posterior to the anterior portion of the inferior temporal sulcus, supporting speech comprehension; information flowing through the ventral pathway is ultimately also conveyed to the inferior frontal gyrus (IFG). In the dorsal pathway, preliminarily processed speech information passes through the left IPL to the premotor cortex (PMC) and IFG, mapping sensory representations onto articulatory-motor representations and facilitating speech perception and discrimination. In the dorsal pathway, the left IPL connects the auditory cortex with articulatory motor areas and integrates sensorimotor information. Rauschecker and Scott (2009) also divided speech processing into an anterior ventral pathway, including the left superior temporal sulcus and IFG, and a posterior dorsal pathway, including the left IPL, PMC, and IFG; they regarded the left IPL as the hub of the posterior dorsal pathway, responsible for the relay of sensorimotor information. Empirical studies indicate that the left IPL is involved in speech perception. For example, a TMS study found that virtual lesions of the IPL affect discrimination of the number of syllables (Hartwigsen et al., 2016). Brain-lesion studies have found that impaired acoustic speech-processing ability is associated with damage to the left IPL (Caplan et al., 1995; Rogalsky et al., 2022). Other studies have found that the left IPL participates in the categorical perception of speech (Al-Fahad et al., 2020; Preisig et al., 2022). However, the involvement and function of the left IPL in the categorical processing of tones remain controversial.

Because Mandarin tones are suprasegmental information, exploring the neural mechanisms of their categorical perception has become a question of broad interest to researchers. On the basis of findings from studies of segmental information, researchers have focused, from the perspective of local brain-region function, on the role of brain regions such as the temporal lobe in tone processing, while overlooking the function of the left IPL in tone processing. For example, Zhang et al. (2011) used magnetic resonance imaging and lexical tone continua with equal pitch changes both between and within categories to examine the sensitivity of the bilateral temporal lobes to categorical and acoustic information. Li et al. (2021) used electrocorticography, with natural speech streams as materials, and employed multivariate pattern classifiers and representational similarity analysis to investigate the sensitivity of the temporal lobe to tone categories; they likewise did not examine the sensitivity of the left IPL to tone categories.

From the perspective of whole-brain activity, studies have found that the left IPL participates in the categorical processing of Mandarin tones. Activation of the left IPL has been found when participants judged whether the tones of the final syllables in paired sentences were the same or different (Gandour et al., 2003), judged whether the tones of disyllabic words were the same or different (Kwok et al., 2019), and identified the tones of Chinese characters (Kwok et al., 2015). Native Mandarin speakers elicited stronger activation of the left IPL than native English speakers when performing tone same–different judgment tasks (Gandour et al., 2004; Klein et al., 2001). After native English speakers received training in learning tone categories in a lexical context, they showed significantly enhanced activation in the left IPL during a word-pair tone discrimination task compared with a non-speech pitch discrimination task (Wong et al., 2007).

However, the function of the left **IPL** in Mandarin tone perception remains a matter of debate. On the one hand, when the same tone same–different judgment task has been used, some researchers have not found activation in this brain region. For example, when participants were similarly asked to complete tone same–different judgments for paired syllables (Wong et al., 2004), tone same–different judgments for disyllabic words (Kwok et al., 2016), and tone same–different judgment tasks involving sequentially presented syllables (Hsieh et al., 2001), no **IPL** activation was found in the left hemisphere; instead, activation was observed in regions such as the **IFG**, **PMC**, and superior temporal gyrus, while activation in regions such as the **MTG** was found in the right hemisphere. Likewise, tone-category training based on a sound–meaning matching task (Yang et al., 2015) and a tone-category identification task (Wang et al., 2003) did not enhance left **IPL** activation in native English speakers during tone-category processing; rather, increased activation was found in regions such as the superior temporal gyrus.

On the other hand, researchers also disagree about the functional role of the left **IPL** in Mandarin tone-category processing. Some researchers have argued that the left **IPL** is sensitive to the acoustic features of Mandarin tones. In a study in which participants completed category-identification tasks for tone, intonation, and speaker gender, tone and intonation identification elicited stronger left **IPL** activation than gender identification, suggesting that this region may show selective activation for suprasegmental information (Chien et al., 2020). A further contrastive study found that stimuli with clear tone and intonation categories elicited stronger activation in the bilateral temporal lobes than categorically ambiguous stimuli, whereas no difference was found in the left **IPL** (Chien et al., 2021). This result suggests that the involvement of the **IPL** in tone and intonation processing reported by Chien et al. (2020) may not reflect the processing of abstract categorical information, but rather sensitivity to specific acoustic features. Feng et al. (2021) asked participants to complete a tone-identification task and found that the left **IPL** represented tone categories; however, after acoustic features such as pitch height and pitch direction were included as covariates in a partial-correlation analysis, tone category was no longer significantly correlated with the neural representational similarity matrix in the left **IPL**, whereas the two remained significantly correlated in the middle portion of the left superior temporal gyrus. This provides direct evidence that, in tone processing, the left **IPL** is sensitive to the specific acoustic features of tones rather than to abstract categorical information.

However, some studies have found that, in tone-category processing, the left **IPL** is not only sensitive to specific acoustic features but also processes more abstract information. Feng et al. (2018) found that when participants completed three tasks—passive listening, repetition, and tone identification—the left **IPL** could distinguish tone categories in all cases. Further analysis showed that the left **IPL** was sensitive to pitch height and pitch direction; even when these acoustic features were entered as covariates in a partial-correlation analysis, the **IPL** neural similarity matrix was still significantly correlated with a multidimensional model constructed on the basis of these two dimensions. This indicates that the **IPL** is sensitive both to specific acoustic features and to abstract categorical information based on acoustic features. Research on categorical perception of segmental information has also found that activation patterns in the left **IPL** can distinguish different syllables but cannot distinguish formant features, suggesting that the left **IPL** may represent abstract categorical information that is not influenced by acoustic features (Preisig et al., 2022).

Understanding of the functional role of the left **IPL** in Mandarin tone-category processing remains controversial; in sum, this controversy is reflected in two respects. First, **IPL** activation has not been reported in the categorical perception of tones, whereas activation has been found in brain regions of the dorsal pathway, **PMC-IFG**, as well as in brain regions of the ventral pathway, **MTG-IFG**. Second, the **IPL** has been reported to be sensitive to both acoustic features and tone categories. However, bas···

Within the dual-stream theory, this debate can be interpreted in another way: the IPL, together with the PMC and IFG, are all dorsal- and ventral-stream brain regions involved in the perception of tone categories (Chien et al., 2020; Feng et al., 2021; Kwok et al., 2016), but they differ in their division of labor. For example, the PMC is considered responsible for perceiving articulatory motor features (Gandour et al., 2003; Si et al., 2017), whereas the IFG is engaged in higher-level category-based decision processing (Feng et al., 2018; Feng et al., 2021). The previously reported involvement of these brain regions in tone-category perception is the result of specific task demands. These regions may operate through a mechanism of dynamic cooperation during tone-category perception: if the function of one brain region is inhibited or impaired, other brain regions are activated to assume a greater load and complete the task. Drawing on previous theories (Hickok et al., 2011; Hickok & Poeppel, 2007; Rauschecker & Scott, 2009), the present study defines the dorsal pathway as the neural pathway that passes through the left IPL to the PMC and IFG, and defines the ventral pathway as the neural pathway that runs from the superior temporal sulcus and posterior MTG to the anterior region and then to the IFG. Applying TMS neuromodulation to induce a virtual lesion in the left IPL can not only reveal its role in tone-category perception, but also elucidate the mechanism of dynamic cooperation between the dorsal and ventral pathways during speech perception.

The present study also manipulated both the tone-category information of paired stimuli (between-category vs. within-category) and their acoustic interval features (large vs. small). By examining acoustic information and tone-category effects in the left IPL and in brain regions associated with the dorsal and ventral pathways, the study can not only reveal the role of the left IPL in tone perception, but also indicate the role of the left IPL within the dual-stream model, thereby clarifying the mechanism of cooperation between the dorsal and ventral pathways. Specifically, two experiments were conducted. Experiment 1 used functional near-infrared spectroscopy (fNIRS) to investigate whether the left IPL is sensitive to abstract tone-category perception or to acoustic features. On this basis, the following prediction can be made: if the left IPL is sensitive both to acoustic features and to tone categories, then it will show differential activation when processing different stimulus pairs. Experiment 2 combined fNIRS and TMS on the basis of Experiment 1 to induce a virtual lesion in the left IPL, and examined whether the PMC of the dorsal pathway and the IFG, which is reached by both the dorsal and ventral pathways, would participate in activation and complete tone-category perception through a compensatory mechanism, thereby revealing dynamic cooperation between the IPL and the dorsal PMC, as well as between dorsal and ventral pathways. Based on the dual-stream model of speech processing, the following prediction can be made: if the IPL is a region of the dorsal pathway, its activation should show an inhibitory pattern similar to that of the dorsal PMC; whereas for the IFG, which can be reached through both dorsal and ventral pathways, functional compensation may manifest as enhanced activation, allowing it to assume more of the processing load in speech perception.

2 Experiment 1

2.1 Method

2.1.1 Participants Sample size was calculated using G-Power 3.1. To estimate the effect size of a medium-sized (2 ×2) interaction ((f = 0.30), Cohen, 1992), ( ) was set to 0.05 and statistical power was set to 0.95 (Faul et al., 2009), yielding a required sample size of 26 participants. More than 30 participants were recruited for each group to ensure sufficient statistical power. Experiment 1 recruited 31 university students [[unclear: number of participants]] (18 female), with a mean age of 20.45 years (18–26 years). All participants were native speakers of Chinese, right-handed, had normal hearing and normal or corrected-to-normal vision, and had no history of neurological or psychiatric disorders. Each participant carefully read and signed the *Participant Informed Consent Form* and received appropriate compensation after completing the experiment. The experiment was approved by the Human Research Ethics Committee of the School of Psychology, Shaanxi Normal University.

2.1.2 Experimental Design and Materials

The original experimental material was speech recorded by a female native speaker of Chinese (stereo, 44.1 KHz). Praat software (http://www.fon.hum.uva.nl/praat/) was used to standardize the intensity and duration of the speech (75 dB, 300 ms). The speech was recorded as the Tone 1 syllable [a55], and was synthesized into a tonal continuum from Tone 1 to Tone 4 using the PSOLA (pitch-synchronous overlap and add) method (Valbret et al., 1992). The continuum contained 15 stimuli, each represented by a number, and the pitch of the stimuli was equally spaced on the equivalent rectangular bandwidth scale. Detailed fundamental-frequency information for the continuum is shown in Figure 1A.

The experimental stimuli were selected using classic tasks from research on speech categorical perception—identification and discrimination tasks. Twenty university students who did not participate in the formal experiment completed the material-screening task (10 female, 18–25 years old), with the same recruitment criteria as in the formal experiment. In the identification task, the 15 stimuli of the continuum were presented individually in random order, with each stimulus presented 20 times. Participants judged whether each stimulus was Tone 1 or Tone 4 and responded by pressing a key. In the discrimination task, the 15 stimuli of the continuum formed 15 identical stimulus pairs, and each stimulus was also paired with the stimulus one step away from it to form 13 different stimulus pairs (e.g., 1-3, 2–4). Each different stimulus pair was presented 18 times, and each identical stimulus pair was presented 9 times. Participants were required to judge whether the stimulus pair was the same and to respond by pressing a key.

Following previous research (Xu et al., 2006), in the identification task, the proportion with which each speech stimulus (e.g., 1, 2) was identified as Tone 1 was calculated. In the discrimination task, the discrimination score for each comparison unit (e.g., 1-3) was calculated according to (P = P(“S” S) P(S) + P(“D” D) P(D)), where (P(S)) and (P(D)) refer, respectively, to the proportions of same trials (1-1, 3-3) and different trials (1-3) within each comparison unit; in the present experiment, both were 0.5. (P(“S” S)) and (P(“D” D)) refer, respectively, to the proportion of same trials responded to as same and the proportion of different trials responded to as different. The psychometric functions obtained from the two tasks are shown in detail in Figure 1B. The experiment manipulated the tonal category of paired stimuli (between-category, within-category) and acoustic interval (large, small), forming a (2 ×2) within-participant experimental design. For between-category stimulus pairs, the 5–9 (small interval) and 4–10 (large interval) pairs were selected; for within-category stimulus pairs, 1–5 and 9–13 were selected as small-acoustic-interval pairs, and 9–15 as the large-acoustic-interval pair. Repeated presentation of each stimulus formed identical stimulus pairs (e.g., 1–1, 4–4), which were used as filler stimuli. The stimuli in each experimental condition were presented 48 times, for a total of 192 trials; together with 48 presentations of the filler condition consisting of identical stimulus pairs, the entire experiment contained 240 trials.

A

End frequency (Hz)

Stimulus	End frequency (Hz)
1	230
2	225
3	219
4	214
5	209
6	204
7	199
8	194
9	189
10	183
11	179
12	174
13	170
14	165
15	161

0 ms 300 ms

B

Ratio (%)

Stimulus number

Legend: identification task; discrimination task

Figure 1. Pitch-pattern diagram of the tone continuum (A); and results of the identification task and discrimination task (B). In the identification task, the ordinate indicates the percentage of responses identified as Tone 1; in the discrimination task, it indicates the discrimination score. The ratio corresponding to a stimulus is the discrimination score for the comparison unit composed of that stimulus and its two adjacent stimuli.

2.1.3 Experimental procedure

Participants sat in a quiet testing room approximately 60 cm from the computer screen. In each trial, a "+" fixation symbol first appeared at the center of the screen for 300 ms, reminding participants that the auditory stimulus was about to be presented. This was followed by a blank screen for 200 ms, after which the pair of speech stimuli was played sequentially through headphones with an interval of 500 ms. Participants were asked, after clearly hearing the second stimulus, to judge quickly and accurately whether the tones of the stimulus pair were the same and to respond by pressing a key. After the participant's keypress, the next trial began after 7-10 s (mean 8.4 s). The 240 trials were divided into 4 runs; trials from each condition were evenly assigned to each run, and stimulus pairs were presented in a pseudorandom order. Participants received sufficient practice and began the formal experiment only after they were familiar with the experimental procedure. The total duration of the experiment was within 50 minutes. Stimulus presentation and recording of behavioral responses were implemented using E-prime 2.0.

2.1.4 fNIRS data acquisition

While participants completed the behavioral task, this study used fNIRS to measure changes in brain activity. The spatial resolution of fNIRS can reach 2-3 cm, with a measurement depth of 1.5-2 cm (Pinti et al., 2020). Previous studies have used this technique to investigate the neural mechanisms of speech processing (Lawrence et al., 2018; Zinszer et al., 2015). In the present study, a Hitachi ETG-7100 functional near-infrared spectroscopy imaging system was used to record changes in the concentrations of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) in participants, with dual wavelengths (695 nm and 830 nm) and a sampling rate of 10 Hz. The experiment used a 4 × 4 holder, on which 8 emitters and 8 detector optodes were placed in an interleaved arrangement. The distance between optodes was 3 cm, forming a total of 24 channels. A 3D digitizer (FASTRAK, Polhemus, ColChester, VT, USA) was used to localize the channels for each participant, ensuring that the holder simultaneously covered the left-hemisphere IPL, PMC, and IFG. The holder placement was basically the same in the two experiments of this study. Channel-localization data from all participants in the two experiments were averaged, and the SPM spatial registration function was used to obtain the mean brain-location information for the channels (Ye et al., 2009).

2.1.5 Data processing and analysis

The fNIRS data were analyzed using the Homer2 software package (Huppert et al., 2009), with the processing pipeline referring to previous studies.

(Brigadoi et al., 2014; Lawrence et al., 2018). For each participant' s data, the raw light-intensity data were first converted into optical-density data; motion components in the optical-density data were then identified and corrected; next, band-pass filtering with a cutoff frequency of 0.01–0.2 Hz was applied to reduce slow drift and high-frequency noise; after filtering, the optical-density data were converted into HbO and HbR concentration data using the Beer–Lambert law. Studies have shown that HbO is more closely related to fMRI-BOLD and is a more suitable parameter for investigating cortical activity; therefore, only HbO data were used in the subsequent analyses (Stoeckel & Binkofski, 2010).

Based on the MRIcro registration results in NIRS-SPM (Wan et al., 2018) and visual inspection, the channels of interest selected in this study were Channel 11 and Channel 15, representing the left IPL; Channel 20 and Channel 23, representing the left PMC; and Channel 14 and Channel 17, representing the left IFG. Because the left IPL was the brain region of primary interest in this study, the data from its two channels were examined separately, whereas for the PMC and IFG, the results were based on the average of the two channels.

For each region/channel of interest, a 4–9 s interval was selected as the peak time window based on visual inspection, and the mean value within 1 s before and after the peak for each participant in each condition was calculated for subsequent analysis. A 2 (acoustic interval: large, small) × 2 (tone category: between-category, within-category) repeated-measures ANOVA was then conducted for the regions/channels of interest. The results were visualized using EasyTopo software (Tian et al., 2013). For the behavioral results, participants' discrimination accuracy for stimulus pairs was examined, likewise using a 2 × 2 repeated-measures ANOVA.

2.2 Results

2.2.1 Behavioral results

All participants completed the task and were included in the data analysis. Participants' mean discrimination accuracy across all conditions was 56.96%, similar to the mean accuracy reported by Yu et al. (2014). Specifically, the mean accuracy was 76.14% in the small-acoustic-interval between-category condition, 29.64% in the small-acoustic-interval within-category condition, 91.73% in the large-acoustic-interval between-category condition, and 30.31% in the large-acoustic-interval within-category condition.

The ANOVA on discrimination accuracy showed a significant main effect of acoustic interval ($F(1, 30) = 20.50, p < 0.001, \eta_p^2 = 0.41$): participants showed higher discrimination accuracy for large-acoustic-interval stimulus pairs ($M = 0.61, SD = 0.02$) than for small-acoustic-interval stimulus pairs ($M = 0.53, SD = 0.02$). The main effect of category information was significant ($F(1, 30) = 333.82, p < 0.001, \eta_p^2 = 0.92$): participants showed higher discrimination accuracy for cross-category stimulus pairs ($M = 0.84, SD = 0.02$) than for within-category stimulus pairs ($M = 0.30, SD = 0.02$). The interaction between acoustic interval and category information was significant ($F(1, 30) = 11.91, p = 0.002, \eta_p^2 = 0.28$). Further simple-effects analyses showed that the tone-category effect was significant in both the small-acoustic-interval condition ($F(1,30) = 169.06, p < 0.001, \eta_p^2 = 0.85$) and the large-acoustic-interval condition ($F(1,30) = 269.52, p < 0.001, \eta_p^2 = 0.90$); in both conditions, discrimination accuracy was higher for between-category stimulus pairs than for within-category stimulus pairs.

2.2.2 fNIRS results

Figure 2A shows heat maps of brain-region activation for the main effects of acoustic interval and tone category, as well as their interaction; the four interes –

The changes in HbO concentration in the regions of interest under the four conditions are shown in Figure 2B. Detailed statistical results are provided in Supplementary Table 1; here, only statistically significant results are reported.

For the dorsal left IPL (channel 15), the main effect of acoustic interval was significant ($F(1,30) = 4.67$, $p = 0.039$, $\eta_p^2 = 0.13$): small acoustic-interval stimuli ($M = 0.09$, $SD = 0.01$) elicited stronger activation than large acoustic-interval stimuli ($M = 0.07$, $SD = 0.01$). In addition, a significant main effect of tone category was found in the dorsal channel of the left IPL ($F(1,30) = 7.29$, $p = 0.011$, $\eta_p^2 = 0.20$): between-category stimuli ($M = 0.09$, $SD = 0.01$) elicited stronger activation than within-category stimuli ($M = 0.07$, $SD = 0.01$).

For the ventral left IPL (channel 11), PMC, and IFG channels, no significant main effects or interactions were found ($ps > 0.05$).

A Acoustic interval; tone category; interaction; dorsal IPL (15); $F = 0$–5.
B Dorsal IPL (15); ventral IPL (11); PMC; IFG; ΔHbO (μM); small; large; between-category; within-category.

Figure 2. The fNIRS results show, in the F-value heat maps of brain activation (A), that the IPL is sensitive to acoustic-interval and tone-category effects; further, the changes in HbO concentration under different conditions (B) also demonstrate the role of the dorsal IPL in tone-category perception.

2.3 Discussion

Experiment 1 constructed a continuum of Mandarin tone stimuli varying from Tone 1 to Tone 4, manipulated changes in tone category and acoustic interval, and examined oxygenation changes in channels within the three regions of interest: the left IPL, PMC, and IFG. The behavioral results revealed effects of acoustics, category, and their interaction; the fNIRS results showed main effects of acoustic interval and tone category in the dorsal left IPL (channel 15).

The results of Experiment 1 replicated the classic categorical-perception effect. Behaviorally, participants were sensitive not only to acoustic features but also to tone categories, as reflected in better discrimination of between-category stimulus pairs than within-category stimulus pairs. This is consistent with previous findings. For example, behavioral studies have found that native Mandarin speakers show sensitivity to tone-category perception, and that their ability to perceive tone categories is stronger than that of non-tone-language native speakers (Peng et al., 2010; Shen & Froud, 2016; Xu et al., 2006). ERP studies have also found that between-category stimuli with equivalent acoustic changes elicit stronger mismatch negativity, or stronger N2b and P3b components, than within-category stimuli (Xi et al., 2010; Zhang et al., 2012). The behavioral results of Experiment 1 also revealed a significant interaction between acoustic interval and tone category, indicating that, during tone-perception processing, acoustic information and categorical information influence each other. This finding is consistent with that of Zhang et al. (2011), who also found an interaction in the processing of tone-category information and acoustic information.

function, whereby high-level category processing exerts a top-down influence on low-level acoustic processing. The interaction pattern in Experiment 1 showed that although the tone-category effect was significant under different acoustic-interval conditions, under the large acoustic-interval condition, accuracy was higher for stimulus pairs crossing tone-category boundaries. In other words, under the small acoustic-interval condition, the increased ambiguity of the acoustic information made it more difficult for listeners to perceive tone categories.

The present experiment found that the left IPL is involved in the categorical-perception processing of Mandarin tones. The dorsal portion of the left IPL showed sensitivity both to acoustic features and to tone-category information. This result is consistent with previous findings. For example, Gandour et al. (2003) found that the left IPL was activated when participants performed a tone discrimination task. In addition, Feng et al. (2018) found that, when participants performed different tasks, the left IPL showed cross-task sensitivity to tone categories. Compared with a gender-identification task, activation in the left IPL was stronger during a tone-category task (Chien et al., 2020). Together with the results of Experiment 1, these findings indicate that the left IPL plays an important role in the categorical perception of tones.

The present experiment finely distinguished the categorical information and acoustic features involved in tone perception, and found that the left IPL participates not only in the processing of tone-category information but also in the processing of tone-acoustic information. To further examine the role of the left IPL in Mandarin tone perception, Experiment 2 combined transcranial magnetic stimulation (TMS) with functional near-infrared spectroscopy (fNIRS). After inducing a virtual lesion in the left IPL, we examined changes in participants' behavior and patterns of brain activity, thereby investigating, from the perspective of neural causality, the role of this region in tone-category processing.

3 Experiment 2

3.1 Method

3.1.1 Participants On the basis of Experiment 1, which found differential sensitivity to tone categories in the dorsal portion (Channel 15) and ventral portion (Channel 11) of the left IPL, Experiment 2 applied TMS stimulation separately to the two channels to induce virtual lesions. On the one hand, the lesion effects of the two channels could serve as mutual references. On the other hand, although Experiment 1 did not find sensitivity to acoustic features or tone categories in the ventral portion of the left IPL, previous research has found that the temporoparietal junction, which includes the ventral left IPL, is an obligatory route for speech-information transmission in the dorsal pathway (Murakami et al., 2015). Thus, inducing virtual lesions in the dorsal and ventral portions of the left IPL is conducive to a fine-grained examination of the roles of different subregions of the left IPL in the categorical perception of tones. Sixty-four university students (36 women), none of whom had participated in Experiment 1, were recruited, with a mean age of 19.83 years (18-26 years). They were divided into two groups, receiving TMS stimulation applied to the dorsal portion (Channel 15) and ventral portion (Channel 11) of the left IPL, respectively. There were 31 participants (18 women) who received dorsal TMS stimulation, with a mean age of 19.19 years (18-24 years). There were 33 participants (18 women) who received ventral TMS stimulation; the data from 2 participants were removed because the light intensity during data collection was too weak, and the mean age was 20.42 years (18-26 years). The recruitment criteria for participants were the same as in Experiment 1, and none had any contraindications for TMS. Before the experiment, each participant carefully read the *Participant Informed Consent Form* and signed to indicate consent,

After completing the experiment, participants received appropriate compensation. This experiment was approved by the Human Research Ethics Committee of the School of Psychology, Shaanxi Normal University.

3.1.2 fNIRS Experiment

The materials, procedure, and data acquisition and processing in Experiment 2 were identical to those in Experiment 1.

A three-factor mixed experimental design was adopted: 2 (TMS stimulation site: dorsal IPL, ventral IPL) × 2 (tone category: between-category, within-category) × 2 (acoustic interval: large, small interval). TMS stimulation site was the between-subjects factor. The two groups of participants received stimulation over the dorsal IPL (channel 15) and ventral IPL (channel 11), respectively, and the data from the two groups of participants served as mutual references. When comparing the data from the two groups of participants, activation in four regions of interest—the dorsal IPL, ventral IPL, PMC, and IFG—was still examined simultaneously.

3.1.3 TMS Parameter Settings

TMS stimulation was delivered using a Magstim Rapid^2 repetitive transcranial magnetic stimulator, with a figure-of-eight coil with a radius of 70 mm. Before the formal experiment began, the center of the coil was manually aligned tangentially with the stimulation location and kept immobile during stimulation. The stimulation target for the left dorsal IPL was channel 15, and the stimulation target for the ventral IPL was channel 11. A continuous theta-burst stimulation (cTBS) protocol was used. The pulse frequency of stimulation was 50 Hz, with three consecutive pulses constituting one burst unit; the burst frequency was 5 Hz, and stimulation lasted 40 s, for a total of 600 pulses (Huang et al., 2005). For all participants, the stimulation intensity was uniformly set to 50% of the machine' s maximum stimulator output. After stimulation ended, participants began the fNIRS experiment.

3.2 Results

After preliminary data analysis, in the group receiving stimulation over the left ventral IPL, the data from one participant were entirely excluded because the participant moved their head excessively during the experiment and were not included in the final data analysis. The final dataset comprised valid data from 31 participants in the dorsal IPL group and 30 participants in the ventral IPL group.

3.2.1 Behavioral Results

After the left dorsal IPL was virtually lesioned, the mean accuracy of the 31 participants was 59.16%. Specifically, the mean accuracy in the small-acoustic-interval between-category condition was 72.58%, the mean accuracy in the small-acoustic-interval within-category condition was 30.98%, the mean accuracy in the large-acoustic-interval between-category condition was 91.80%, and the mean accuracy in the large-acoustic-interval within-category condition was 41.26%.

After the left ventral IPL was virtually lesioned, the mean accuracy of the 30 participants was 63.21%. Specifically, the mean accuracy in the small-acoustic-interval between-category condition was 77.36%, the mean accuracy in the small-acoustic-interval within-category condition was 32.13%, the mean accuracy in the large-acoustic-interval between-category condition was 93.06%, and the mean accuracy in the large-acoustic-interval within-category condition was 50.30%.

A three-factor analysis of variance was conducted on participants' discrimination accuracy: 2 (TMS stimulation site: dorsal IPL, ventral IPL) × 2 (tone category: between-category, within-category) × 2 (acoustic interval: large, small acoustic interval). The statistical results are shown in Appendix Table 4. The results revealed a significant main effect of acoustic interval ($F(1, 59) = 88.52$, $p < 0.001$, $\eta_p^2 = 0.60$): large-acoustic-interval stimuli had ($M =$

((M = 0.69, SD = 0.02)) was higher than that for stimulus pairs with a small acoustic interval ((M = 0.53, SD = 0.02)). The main effect of tone category was also significant ((F(1,59) = 211.88, p < 0.001, _p^2 = 0.78)): discrimination accuracy for between-category stimulus pairs ((M = 0.84, SD = 0.02)) was higher than that for within-category stimulus pairs ((M = 0.39, SD = 0.02)).

In the behavioral results, the main effect of TMS stimulation site and all two-way interactions were not significant. The three-way interaction among TMS stimulation site, acoustic interval, and tone category was significant ((F(1,59) = 4.43, p = 0.04, _p^2 = 0.07)). Simple-simple effects analyses showed that, under the four types of materials, the two TMS stimulation groups (dorsal vs. ventral) did not differ in the accuracy of their behavioral responses.

To examine the influence of TMS stimulation on participants' behavioral results, the data from the two groups of participants who received TMS stimulation in Experiment 2 were compared between groups with the data from the participants who received no stimulation in Experiment 1. One-way fully randomized ANOVAs were conducted separately under the four stimulation conditions. The results showed that, under the three stimulation conditions of small acoustic interval between-category, small acoustic interval within-category, and large acoustic interval between-category, the differences in behavioral-response accuracy among the three groups of participants were not significant (small acoustic interval between-category: (F(2,89) = 0.67, p = 0.513); small acoustic interval within-category: (F(2,89) = 0.17, p = 0.843); large acoustic interval between-category: (F(2,89) = 0.20, p = 0.817)). Only in the large acoustic interval within-category condition was the difference among the three groups of participants significant ((F(2,89) = 6.09, p = 0.003, _p^2 = 0.12)). Specifically, there was no difference in behavioral accuracy between the two groups that received TMS stimulation ((t(59) = 1.47, p = 0.357)), and the difference between the group receiving IPL dorsal TMS stimulation and the no-stimulation group was also not significant ((t(60) = 1.88, p = 0.172)). Only the difference between the group receiving IPL ventral TMS stimulation and the no-TMS-stimulation group was significant ((t(59) = 3.89, p = 0.002, Cohen d = 1.00)), with the mean accuracy of the group receiving TMS stimulation being higher than that of the no-stimulation group. These results indicate that inhibitory TMS stimulation did not have a significant effect on participants' behavioral responses.

3.2.2 fNIRS results

For HbO changes in the four regions of interest, a three-factor ANOVA of 2 (TMS stimulation site: IPL dorsal, IPL ventral) × 2 (tone category: between-category, within-category) × 2 (acoustic interval: large interval, small interval) was conducted. The statistical results are shown in Table 1. Results reaching statistical significance ((p < 0.05)) are reported in detail below.

In the left IPL dorsal region (channel 15), the main effect of acoustic interval was significant: stimulus pairs with a large acoustic interval ((M = 0.11, SD

= 0.01)) elicited stronger HbO changes in this brain region than stimulus pairs with a small acoustic interval ((M = 0.10, SD = 0.01)). This effect interacted significantly with TMS stimulation site, because the acoustic-interval effect in the left IPL dorsal region remained significant even when this brain region received TMS virtual-lesion stimulation ((F(1,59) = 12.34, p = 0.001, _p^2 = 0.17)), manifested as stimulus pairs with a large acoustic interval ((M = 0.13, SD = 0.02)) eliciting stronger HbO changes than stimulus pairs with a small acoustic interval ((M = 0.10, SD = 0.02)). However, when the left IPL ventral region (channel 11) received TMS virtual-lesion stimulation, the acoustic-interval effect in the left IPL dorsal region was no longer significant ((F(1,59) = 0.18, p = 0.671)).

In the left IPL ventral region (channel 11), the main effect of acoustic interval was significant: stimulus pairs with a large acoustic interval ((M = 0.08, SD = 0.01)) elicited stronger HbO changes in this brain region than stimulus pairs with a small acoustic interval ((M = 0.07, SD = 0.01)). In this brain region, the acoustic…

The acoustic interval also interacted significantly with the TMS stimulation site. This was because, when TMS virtually lesioned the dorsal pathway of the left IPL, the acoustic-interval effect in the ventral left IPL was significant ((F(1, 59) = 12.00, p = 0.001, _p^2 = 0.17)): stimulus pairs with a large acoustic interval ((M = 0.10, SD = 0.02)) elicited stronger HbO changes than stimulus pairs with a small acoustic interval ((M = 0.08, SD = 0.01)). However, when TMS virtually lesioned the ventral pathway of the left IPL, the acoustic-interval effect in this brain region was no longer significant ((F(1, 59) = 0.09, p = 0.772)). In the ventral left IPL, a significant interaction between acoustic interval and tone category was also found; that is, the tone-category effect in this brain region reached significance only under the small-acoustic-interval condition ((F(1, 59) = 4.79, p = 0.033, _p^2 = 0.08)), showing that between-category stimulus pairs ((M = 0.08, SD = 0.01)) elicited stronger HbO changes than within-category stimulus pairs ((M = 0.06, SD = 0.01)). Under the large-acoustic-interval condition, however, the tone-category effect was not significant ((F(1, 59) = 0.02, p = 0.884)).

In the left PMC, only the interaction between TMS stimulation site and acoustic interval reached significance. Specifically, when TMS virtually lesioned the dorsal pathway of the left IPL, the acoustic-interval effect was significant ((F(1, 59) = 7.14, p = 0.010, _p^2 = 0.11)): the large acoustic interval ((M = 0.12, SD = 0.01)) elicited stronger HbO changes in this brain region than the small acoustic interval ((M = 0.10, SD = 0.01)). When TMS virtually lesioned the ventral pathway of the left IPL, however, the acoustic-interval effect in the left PMC was no longer significant ((F(1, 59) = 2.36, p = 0.130)).

In the left IFG, the main effect of tone category was significant: within-category stimulus pairs ((M = 0.08, SD = 0.01)) elicited stronger HbO changes in this brain region than between-category stimulus pairs ((M = 0.06, SD = 0.01)). Moreover, the interaction between the tone-category effect and the TMS stimulation site was significant. When TMS virtually lesioned the dorsal pathway of the left IPL, the tone-category effect in the left IFG was not significant ((F(1, 59) = 0.02, p = 0.887)); whereas when TMS virtually lesioned the ventral pathway of the left IPL, a significant tone-category effect was found in the left IFG ((F(1, 59) = 11.01, p = 0.002, _p^2 = 0.16)), showing that within-category stimuli ((M = 0.07, SD = 0.01)) elicited stronger HbO changes in the IFG than between-category stimuli ((M = 0.04, SD = 0.01)).

Table 1. Results of the 2 × 2 × 2 ANOVA for the four regions of interest

Source of variation	(df)	Dorsal IPL (15) (F)	Dorsal IPL (15) (p)	Dorsal IPL (15) (_p^2)	Ventral IPL (11) (F)	Ventral IPL (11) (p)	Ventral IPL (11) (_p^2)	PMC (F)	PMC (p)	PMC (_p^2)	IFG (F)	IFG (p)	IFG (_p^2)
Acoustic interval	((1,59))	**4.66**	**0.035**	**0.07**	**4.94**	**0.030**	**0.08**	0.61	0.439	0.01	1.75	0.191	0.03
Tone category	((1,59))	1.45	0.233	0.02	1.50	0.225	0.02	1.78	0.187	0.03	**5.13**	**0.027**	**0.08**
TMS stimulation site	((1,59))	1.21	0.276	0.02	2.93	0.092	0.05	1.75	0.191	0.03	3.14	0.082	0.05
Acoustic × category	((1,59))	1.86	0.177	0.03	**4.64**	**0.035**	**0.07**	2.60	0.112	0.04	1.98	0.165	0.03
TMS × acoustic	((1,59))	**7.66**	**0.008**	**0.11**	**6.96**	**0.011**	**0.11**	**8.81**	**0.004**	**0.13**	0.11	0.737	0.00
TMS × category	((1,59))	0.08	0.779	0.00	1.80	0.185	0.03	0.90	0.346	0.02	**6.08**	**0.017**	**0.09**

Source of variation	(df)	Dorsal IPL (15) (F)	Dorsal IPL (15) (p)	Dorsal IPL (15) (_p^2)	Ventral IPL (11) (F)	Ventral IPL (11) (p)	Ventral IPL (11) (_p^2)	PMC (F)	PMC (p)	PMC (_p^2)	IFG (F)	IFG (p)	IFG (_p^2)
TMS × acoustic × category	((1,59))	0.12	0.728	0.00	0.34	0.562	0.01	1.15	0.288	0.02	0.34	0.563	0.01

Note: Boldface indicates statistically significant results (($p < 0.05$)).

To provide a more intuitive illustration of the different effects of TMS-induced virtual lesions to the dorsal left IPL (channel 15) and ventral left IPL (channel 11), Figure 3 presents heat maps of brain regions showing the acoustic-interval effect and the tone-category effect when TMS virtual lesions were applied to different sites. As shown in the figure, when TMS virtually lesioned the dorsal channel (15) of the left IPL (Figure 3A), the tone-category effect in this region disappeared, whereas the acoustic-interval effect was observed in the dorsal/ventral left IPL and the PMC. When TMS virtually lesioned the ventral channel (11) of the left IPL (Figure 3B), the acoustic-interval effect disappeared, whereas the tone-category effect was observed in the left IFG.

Figure 3. Heat maps of fNIRS F values showing that, when TMS virtually lesioned the dorsal (A) and ventral (B) IPL channels, the brain regions sensitive to acoustic interval and tone category differed.

3.3 Discussion

Experiment 2 built on Experiment 1 by incorporating TMS neuromodulation to virtually lesion the functions of the dorsal (channel 15) and ventral (channel 11) regions of the left IPL, thereby examining the role of the left IPL in the categorical processing of Mandarin tones from a neural-causal perspective. In Experiment 1, the behavioral results revealed both main effects of acoustic information and tone category, as well as an interaction between the two; however, in the fNIRS results, main effects of both acoustic information and tone category were found only in the dorsal channel of the IPL. In Experiment 2, the effects of virtually lesioning the dorsal versus ventral IPL differed significantly: after lesioning the dorsal IPL channel, the dorsal IPL was no longer sensitive to tone category, whereas both the dorsal and ventral channels, as well as the PMC, were sensitive to acoustic interval; after lesioning the ventral IPL channel, the dorsal and ventral IPL, as well as the PMC, were no longer sensitive to either acoustic information or tone-category information, whereas the IFG showed sensitivity to tone category. These results indicate that, in the categorical processing of Mandarin tones, the dorsal and ventral portions of the left IPL play different roles.

From a neural-causal perspective, Experiment 2 clarified the important role of the dorsal channel of the left IPL in the categorical perception and processing of Mandarin tones. Previous studies have shown that the left IPL is involved in the categorical processing of Mandarin tones (Chien et al., 2020; Feng et al., 2018). In Experiment 1 of the present study, we also found that the left IPL was sensitive both to the acoustic features of tones and to tone-category information. Experiment 2 further applied a neuromodulation technique, using TMS stimulation to virtually lesion the left IPL; the results clearly showed that damage to the left IPL causally affects neural activity in the categorical processing of Mandarin tones. This indicates that, under normal conditions, the dorsal IPL plays a very important role in the categorical perception of tones.

Experiment 2 also yielded a new finding regarding the left IPL: this brain region may exhibit a dorsal/ventral role in Mandarin tone perception

⋯the functional dissociation of the dorsal/ventral-channel brain regions. The dorsal portion of the left IPL showed sensitivity to tone-category processing in Experiment 1; when the function of this brain region was inhibited by TMS stimulation, it was no longer sensitive to category processing. By contrast, in the ventral portion of the left IPL, under normal circumstances sensitivity to acoustic or category information is not required (Experiment 1). When the dorsal function of the IPL was inhibited, the ventral IPL region was recruited and exhibited sensitivity to acoustic information; when its own function was inhibited, it was no longer sensitive to either category or acoustic information. This pattern of results demonstrates a dissociation in the left IPL, with the dorsal and ventral portions corresponding respectively to sensitivity to tone categories and to acoustic information.

The finding of functional dissociation between the dorsal and ventral channels of the left IPL reconciles previous debates concerning the role of the left IPL in the perception and processing of Mandarin tones. On the one hand, prior studies have reported conflicting functional accounts of the left IPL in categorical perception of tones: some studies have proposed that it is responsible for categorical perception (Gandour et al., 2004; Feng et al., 2018), whereas others have argued that, during tone processing, this brain region is sensitive to the specific acoustic features of tones rather than to abstract category information (Feng et al., 2021). On the other hand, previous studies have reported inconsistent activation loci within the left IPL for Mandarin tone-category processing. For example, Feng et al. (2018) found that both the anterior and posterior portions of the IPL participated in Mandarin tone-category processing. Gandour et al. (2004), however, found that a ventral IPL location near the temporoparietal junction participated in Mandarin tone-category processing. The results of Experiment 2 clearly demonstrate a functional dissociation between dorsal channel 15 and ventral channel 11 in the left IPL, with the dorsal side being more sensitive to category information, thereby reconciling discrepancies in prior findings.

Experiment 2 also yielded another important finding: tone perception and processing may result from cooperative processing between the dorsal and ventral pathways. First, judging from the behavioral accuracy results of Experiment 2, TMS stimulation did not affect participants' completion of the speech-perception task. Compared with the response accuracy in Experiment 1, although participants in Experiment 2 received inhibitory TMS stimulation of brain regions, their behavioral response accuracy did not decrease. Comparing the two groups of participants who received TMS stimulation at different sites in Experiment 2, the two groups showed no significant differences attributable to TMS stimulation site across the four types of materials. These results indicate that although TMS stimulation affected the activation patterns in participants' brain regions, it did not exert a significant influence on their overall behavioral performance in speech perception and processing. This suggests that the functional inhibition of specific brain regions by TMS may be compensated for by the functions of other brain regions, making the behavioral effects inconspicuous.

Second, results at the neurophysiological level indicate that a dynamic cooperative mechanism may exist between the dorsal and ventral pathways for speech perception. By using TMS stimulation to produce virtual lesions in the dorsal and ventral IPL channels, Experiment 2 found that participants could rely on different neural circuits to complete the task during categorical perception of tones. When the dorsal IPL channel was virtually lesioned, the brain regions sensitive to tone categories disappeared; at this point, participants relied on sensitivity to acoustic information in the dorsal IPL, the ventral channel, and the PMC within the dorsal pathway to complete processing. When the ventral IPL channel was virtually lesioned, the dorsal IPL, the ventral channel, and the PMC within the dorsal pathway all failed to show sensitivity to either tonal acoustic information or category information; at this point, processing was completed solely through the IFG region—accessible via both the dorsal and ventral pathways—which was sensitive to tone categories. This result may demonstrate compensation by the ventral pathway when speech processing in the dorsal pathway is impaired. These patterns of results indicate that a cooperative mechanism between the dorsal and ventral pathways may exist in tone-category perception and processing.

4 General Discussion

Using fNIRS-guided TMS virtual-lesion techniques, the present study examined, from the perspective of neural causality, the role of the left IPL in the processing of Mandarin lexical-tone categories. The following specific results were obtained: (1) the dorsal IPL was sensitive to both acoustic distance and tone category, whereas the ventral IPL was not; (2) TMS stimulation of either the ventral or dorsal IPL did not significantly affect participants' behavioral performance; (3) TMS stimulation of the dorsal IPL significantly suppressed the sensitivity of this brain region to tone category, while the ventral IPL at this point showed sensitivity to tone category; (4) TMS stimulation of the dorsal IPL did not affect this region' s sensitivity to acoustic distance, but enhanced the sensitivity of the ventral IPL and PMC to acoustic distance; (5) TMS stimulation of the ventral IPL caused the IPL to lose sensitivity to both acoustic distance and tone category, but enhanced the sensitivity of the IFG to tone category. On the one hand, the experimental results confirm previous findings that the left IPL is involved in the categorical perception of Mandarin tones; on the other hand, the new findings indicate a functional dissociation between the dorsal and ventral portions of the left IPL in Mandarin tone-category perception. Thus, at the theoretical level, these findings enrich neurophysiological models of speech perception and processing from the perspective of tone languages. These issues are discussed in detail below.

4.1 The Role of the Left IPL in Tone-Category Perception

Exploring the role of the left IPL in Mandarin tone-category processing was the primary aim of the present study. The cognitive neural mechanisms of Mandarin tone perception have received extensive attention from researchers, but no consistent conclusion has been reached regarding the role of the left IPL in this process. Some studies have suggested that it is sensitive to multidimensional information in tones, such as pitch height and pitch direction (Feng et al., 2021). In the fNIRS results of Experiment 1, the present study likewise found sensitivity-related activation in the left IPL in response to acoustic-distance information. The fNIRS results of Experiment 1 also revealed sensitivity-related activation in the left IPL in response to tone category. Consistent with the present findings, previous studies have found that the left IPL is sensitive to both acoustic features and categorical information. Feng et al. (2018) found that the neural similarity matrix of the left IPL was correlated with models of pitch height and pitch direction, indicating that the left IPL processes acoustic features. They also found that even after pitch height and pitch direction were entered as covariates in a partial-correlation analysis, the neural similarity matrix of the left IPL was still significantly correlated with a multidimensional model constructed on the basis of these two dimensions, indicating that the left IPL processes abstract information generated by the integration of specific acoustic features.

By manipulating the acoustic distance and tone category of paired stimuli, the present study found that the left IPL processes both acoustic information and categorical information. It should be noted that some studies have argued that comparing between-category and within-category stimulus pairs with equal acoustic changes can better reflect the processing of categorical information, and that changes in within-category acoustic information are often used to examine the processing of acoustic information (Xi et al., 2010; Zhang et al., 2012). However, when examining the neural representation of phoneme-category information, Alho et al. (2016) also compared between-category and within-category stimulus pairs with both equal and unequal acoustic changes; when examining the neural representation of phoneme acoustic information, they compared large and small acoustic stimulus pairs both across categories and within categories. In addition, when using ERP techniques to examine the roles of tonal acoustic information and categorical information in tone processing, some studies have adopted the same experimental design as the present study, using the main effect of acoustic distance to reflect the processing of acoustic information and the main effect of categorical information to reflect the processing of categorical information (Yu et al., 2014).

The left IPL showed sensitivity to both acoustic features and categorical information, which is very likely related, to a large extent, to functionally segregated subregions within this brain area. First, previous studies have found that the IPL actually comprises multiple subregions of the supramarginal gyrus and angular gyrus. Some researchers have subdivided the IPL into seven subregions on the basis of cytoarchitecture (Caspers et al., 2006), whereas others have subdivided it into six subregions according to fiber-tract connections between IPL voxels and other brain regions (Wang et al., 2012). Moreover, functional segregation among IPL subregions is formed through functional connectivity with different brain regions (Igelstrom et al., 2015).

Second, studies of speech perception and processing provide evidence for functional segregation in the left IPL. Some studies have found that the left IPL represents important acoustic information used to distinguish segmental information, such as place-of-articulation information (Correia et al., 2015) and other noncategorical information (Hartwigsen et al., 2016). Other researchers have found that the left IPL is sensitive to abstract categorical information; for example, between-category stimuli with equal acoustic intervals elicited stronger IPL activation than within-category stimuli (Joanisse et al., 2007). Still other researchers have found that activation patterns in the left IPL can distinguish different syllables but cannot distinguish the acoustic features of formants, leading them to propose that the left IPL represents abstract segmental categorical information (Preisig et al., 2022). Unfortunately, studies based on segmental information have not finely distinguished subregions of the left IPL; consequently, the functional understanding of the left IPL remains controversial.

An important finding of the present study is that the left IPL exhibited functional segregation among different brain regions during the categorical processing of Mandarin tones. Specifically, Experiment 1 found only that the dorsal IPL region was sensitive to both acoustic information and tone categories, whereas the ventral region showed no effect. When Experiment 2 used TMS to induce virtual lesions separately in the dorsal and ventral portions of the left IPL, the results showed distinct patterns of effects. When speech information can be processed via the dorsal pathway, the dorsal IPL plays a key role in categorical tone perception. That is, under normal circumstances, the dorsal IPL alone can support categorical tone perception while processing both acoustic information and categorical information, without the involvement of the PMC and IFG regions. When this region is damaged, however, it becomes necessary to rely on the sensitivity of dorsal-pathway regions (such as the PMC) to acoustic information, completing categorical tone perception through functional compensation. The ventral IPL may play an important gating role in Mandarin tone category perception, controlling whether speech information requires the involvement of the dorsal pathway to complete the categorical tone perception task. Damage to this brain region leads the entire dorsal speech pathway regions (dorsal IPL, PMC) to become insensitive to both acoustic information and tone categories, such that categorical tone perception can only be completed through the IFG region, which can also be reached via the ventral pathway.

In other words, the dorsal and ventral regions of the left IPL may correspond to different functions. The dorsal IPL region plays an important leading role in tone perception, but when it is damaged, it requires functional compensation from the ventral IPL region. The ventral IPL region not only provides functional compensation for the dorsal region, but may also play an important gating role, controlling whether the information involved in categorical tone perception and processing is processed via the dorsal or the ventral pathway.

4.2 The Left IPL and the Dorsal/Ventral Neural Pathways of Speech Perception

On the basis of studies of the brain mechanisms of segmental processing, researchers have proposed a dual-pathway model of speech processing (Hickok et al., 2011;

(Hickok & Poeppel, 2007). Studies have found that categorical processing of Mandarin tones involves not only regions in the ventral pathway, such as the MTG (Si et al., 2017; Zhang et al., 2011; Zinszer et al., 2015), but also dorsal-pathway regions including the IPL, PMC, and IFG (Chien et al., 2020; Si et al., 2017). The present study is therefore of great significance for elucidating the role of the left IPL in the dorsal/ventral pathways of speech perception. On the one hand, the ventral region of the left IPL plays an important gating role in the dorsal pathway for categorical perception of tones. Previous studies have found that the ventral IPL shows significant functional connectivity with the PMC and IFG during speech perception and processing (Buchsbaum et al., 2001; Buchsbaum et al., 2005). The present study not only dissociated the functions of the dorsal and ventral regions of the IPL; more importantly, it found that when the ventral region was disrupted, neither the IPL nor the PMC remained sensitive to tonal acoustic information or categorical information. This indicates that the ventral IPL plays an important gating role in the dorsal pathway of tone perception: once this region is disrupted, the entire dorsal pathway no longer participates in the categorical perception and processing of tones. Previous research has shown that speech perception induces excitability in the primary motor cortex. Applying inhibitory TMS to the temporoparietal junction alone significantly reduced this excitability, whereas applying inhibitory TMS to the IFG or PMC alone had no significant effect; only simultaneous virtual lesions to these two regions produced a significant reduction. The researchers argued that speech information reaches the primary motor cortex via the temporoparietal junction, a necessary posterior input node of the dorsal pathway, together with the parallel IFG and PMC (Murakami et al., 2015). Together, that study and the present study demonstrate the gating role of the left ventral IPL in the dorsal pathway of speech processing.

On the other hand, the present study reveals a mechanism of dynamic cooperation between the dorsal and ventral pathways in tone perception. The results of Experiment 2 showed that when the ventral IPL was virtually lesioned, the dorsal pathway was no longer sensitive to tonal acoustic information or categorical information, while the IFG became sensitive to categorical information. This result suggests that when the ventral IPL is virtually lesioned and dorsal-pathway processing of tonal information is affected, the ventral pathway may play a compensatory role, manifesting as sensitivity-related activation to tonal information in the IFG. This finding is consistent with previous studies, which suggest that categorical perception of tones may simultaneously activate information reaching the IFG via the dorsal PMC region and via the ventral MTG region (Chien et al., 2020; Feng et al., 2021; Kwok et al., 2016). Earlier studies of speech processing have found a dynamic cooperation mechanism between the dorsal and ventral pathways. Specifically, pseudoword repetition elicited greater activation than real-word repetition in dorsal-pathway brain regions, whereas comprehension of meaningful sentences elicited greater activation than comprehension of meaningless sentences in ventral-pathway brain regions (Saur et al., 2008). Further research has shown that when ventral speech-semantic features are ambiguous, processing relies more heavily on the participation of motor regions in the dorsal pathway that are responsible for sensorimotor information (Michaelis et al., 2021; Osnes et al., 2011; Wild et al., 2012). For example, Michaelis et al. (2021) manipulated the signal-to-noise ratio and asked participants to complete auditory lexical recognition under easy and difficult conditions. They found that under the easy condition, auditory lexical recognition did not involve dorsal motor regions, whereas under the difficult condition, activity in dorsal motor regions increased. When semantic features are increased, processing relies more heavily on participation of the ventral pathway (Kwok et al., 2016; Michaelis et al., 2021). Kwok et al. (2016) found that when participants completed a tone discrimination task using meaningful lexical materials, the bilateral superior temporal gyri, right MTG, and left IFG were activated, whereas activation was not observed in dorsal-pathway regions such as the IPL and PMC, which had been more commonly reported in previous studies. The present study found that during categorical processing of tones, when dorsal sensorimotor information is unavailable, information reaches the IFG via the ventral pathway,

provided evidence for the mechanism by which the dorsal and ventral pathways dynamically cooperate and functionally complement one another in tone perception.

4.3 Theoretical Contributions to Neurophysiological Models of Speech Perception

Investigating the neural mechanisms of categorical perception of lexical tone can enrich and advance neurophysiological models of speech processing. The findings of this study make theoretical contributions to neurophysiological models of speech perception in the following three respects. First, this study enriches the empirical evidence for these models from the perspective of a tone language. Dual-stream theoretical models of speech perception (Hickok et al., 2011; Hickok & Poeppel, 2007; Rauschecker & Scott, 2009) were proposed on the basis of findings on the perception and processing of segmental information. Research on the categorical perception of suprasegmental information, such as Mandarin lexical tones, can enrich and develop neurophysiological models of speech perception from a cross-linguistic perspective. Second, the findings of this study further deepen neurophysiological models of speech perception. The left IPL is an important brain region in neurophysiological models of speech perception and is regarded as part of the dorsal pathway. However, researchers have disagreed about its function. By combining neuromodulation techniques, this study not only clarified in depth that functionally dissociable subregions exist within the left IPL, but also elucidated its gating mechanism within the dorsal/ventral pathways. Finally, from the perspective of neural causality, this study also clarified the cooperative mechanism between the dorsal and ventral pathways in speech perception, thereby enriching the theoretical interpretation of the model.

4.4 Limitations

This study has two limitations. First, most TMS studies use sham stimulation and add the results of a blank control group. In the present study, TMS was used to induce virtual lesions separately in the dorsal/ventral channels of the left IPL so that they could serve as mutual references. The results showed that the effect patterns produced by stimulating the two channels differed, allowing them to be compared with one another. However, the influence of the presence versus absence of TMS stimulation cannot be ruled out, and future research may examine this technique in greater depth.

On the other hand, the functional inferences drawn in this study regarding the dorsal/ventral channels of the left IPL at different processing stages of categorical tone perception involve some risk, because fNIRS technology, after all, cannot reveal the process of information processing in depth. Future studies could combine magnetoencephalography, which has relatively high temporal and spatial resolution, to further verify the inferred gating role of the ventral region of the left IPL in this study.

5 Conclusion

This study found that the left IPL plays an important role in the categorical processing of Mandarin lexical tones. From the perspective of neural causality, it revealed a functional dissociation between the dorsal and ventral channels of the left IPL: the ventral portion of the left IPL may play an important gating role in the dorsal pathway during categorical tone perception, whereas the dorsal portion of the left IPL plays an important role in the speech dorsal pathway' s completion of categorical tone perception. These findings are of great significance for the neurophysiological model of categorical tone processing and indicate the cooperative and complementary roles of the dorsal and ventral pathways in categorical perception.

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fNIRS-guided TMS technique reveals a critical role of the left inferior parietal lobule in Chinese tone perception

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Abstract

The left inferior parietal lobe (IPL) is a critical brain region for categorical perception of speech, and some studies have shown that it is involved in the categorical perception of Chinese tones. However, its specific role in tone perception remains unclear.

The current study manipulated both tonal categories (intercategory vs. intracategory) and acoustic features (large vs. small acoustic intervals) in successively presented stimulus pairs to examine whether the IPL is sensitive to acoustic features or to the abstract representation of tonal categories during Chinese tone perception. Experiment 1 used functional near-infrared spectroscopy (fNIRS) to localize functional activation in the IPL during tone perception. Experiment 2 used transcranial magnetic stimulation (TMS) to virtually impair the IPL and establish a causal neural link between the IPL and tonal categorical perception.

Experiment 1 showed that the dorsal IPL channel was sensitive to tonal categories, exhibiting more robust IPL activation induced by intercategory stimulation than intracategory stimulation. This region was also sensitive to acoustic intervals, with stronger activation induced by small acoustic intervals than by large ones. In Experiment 2, the dorsal and ventral IPL channels were virtually disrupted separately using TMS. When the dorsal IPL channel was inhibited, its

sensitivity to tonal categories disappeared. In contrast, the ventral IPL channel and the left premotor cortex (PMC) channel were sensitive to acoustic intervals, with stronger activation induced by large acoustic intervals than by small ones. However, when TMS inhibited the ventral IPL channel, only functional compensation in the left inferior frontal gyrus channels showed sensitivity to tonal categories and induced greater intercategory activation than intracategory stimulation did.

In summary, these findings demonstrate a critical role of the left dorsal IPL in the categorical perception of Chinese tone. In contrast, the ventral IPL plays an essential gating role in the dorsal stream of speech perception. The results enrich the neurophysiological model of speech perception from a tonal language perspective, elucidating the collaborative mechanism between dorsal and ventral speech streams in categorical perception.

Keywords speech category, tone, inferior parietal lobule, fNIRS, TMS

Appendix

Result 1: ANOVA Results for No TMS Stimulation in Experiment 1 and Single-Site TMS Stimulation in Experiment 2

Repeated-measures ANOVAs with a 2 (tone category: between-category, within-category) × 2 (acoustic interval: large, small acoustic interval) design were conducted on behavioral accuracy and brain-region activation, respectively, for the no-TMS condition in Experiment 1 and for the Experiment 2 TMS stimulation sites of dorsal IPL (channel 15) and ventral IPL (channel 11).

Supplementary Table 1. ANOVA results for behavioral accuracy and HbO concentration changes in each brain region in Experiment 1

Source of variation	df	Accuracy	Accuracy	Accuracy	Dorsal IPL (15)	Dorsal IPL (15)	Dorsal IPL (15)	Ventral IPL (11)	Ventral IPL (11)	Ventral IPL (11)	PMC	PMC	PMC	IFG	IFG	IFG
		F	p	η_p^2	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
Acoustic interval	(1,30)	20.50	**0.000**	0.41	4.67	**0.039**	0.13	1.07	0.310	0.03	2.99	0.094	0.09	2.39	0.133	0.07
Tone category	(1,30)	333.82	**0.000**	0.92	7.29	**0.011**	0.20	4.15	0.051	0.12	1.70	0.202	0.05	0.19	0.668	0.01

Source of variation	df	Accuracy F	Accuracy p	Accuracy η_p^2	Dorsal IPL (15) F	Dorsal IPL (15) p	Dorsal IPL (15) η_p^2	Ventral IPL (11) F	Ventral IPL (11) p	Ventral IPL (11) η_p^2	PMC F	PMC p	PMC η_p^2	IFG F	IFG p	IFG η_p^2
Acoustic × category	(1,30)	11.91	**0.002**	0.28	2.37	0.134	0.07	1.87	0.181	0.06	3.74	0.063	0.11	0.15	0.698	0.01

Note: Bold type indicates statistically significant results ($p < 0.05$).

Supplementary Table 2. ANOVA results for behavioral accuracy and HbO concentration changes in each brain region after TMS stimulation of dorsal IPL (15)

Source of variation	df	Accuracy F	Accuracy p	Accuracy η_p^2	Dorsal IPL (15) F	Dorsal IPL (15) p	Dorsal IPL (15) η_p^2	Ventral IPL (11) F	Ventral IPL (11) p	Ventral IPL (11) η_p^2	PMC F	PMC p	PMC η_p^2	IFG F	IFG p	IFG η_p^2
Acoustic interval	(1,30)	33.61	**0.000**	0.53	11.31	**0.002**	0.27	13.79	**0.001**	0.31	7.18	**0.012**	0.19	1.67	0.206	0.05
Tone category	(1,30)	97.04	**0.000**	0.76	1.88	0.180	0.06	4.54	**0.041**	0.13	3.81	0.060	0.11	0.02	0.895	0.00
Acoustic × category	(1,30)	4.27	**0.047**	0.12	0.41	0.527	0.01	1.05	0.313	0.03	3.43	0.074	0.10	1.88	0.181	0.06

Note: Bold type indicates statistically significant results ($p < 0.05$).

Supplementary Table 3. ANOVA results for behavioral accuracy and HbO concentration changes in each brain region after TMS stimulation of ventral IPL (11)

Source of variation	df	Accuracy F	Accuracy p	Accuracy η_p^2	Dorsal IPL (15) F	Dorsal IPL (15) p	Dorsal IPL (15) η_p^2	Ventral IPL (11) F	Ventral IPL (11) p	Ventral IPL (11) η_p^2	PMC F	PMC p	PMC η_p^2	IFG F	IFG p	IFG η_p^2
Acoustic interval	(1,29)	59.68	**0.000**	0.67	0.20	0.657	0.01	0.08	0.786	0.00	2.34	0.137	0.07	0.41	0.528	0.01
Tone category	(1,29)	119.46	**0.000**	0.80	0.30	0.591	0.01	0.01	0.942	0.00	0.06	0.815	0.00	13.09	**0.001**	0.31
Acoustic × category	(1,29)	0.59	0.449	0.02	2.04	0.164	0.07	4.59	**0.041**	0.14	0.15	0.697	0.01	0.36	0.552	0.01

Note: Bold type indicates statistically significant results ($p < 0.05$).

Result 2: Results of the 2x2x2 ANOVA

In Experiment 2, a three-factor ANOVA was conducted on discrimination accuracy: 2 (TMS stimulation site: IPL dorsal [channel 15], IPL ventral [channel 11]) × 2 (tone category: between-category, within-category) × 2 (acoustic interval: large, small acoustic interval). See Appendix Table 4.

Appendix Table 4. Results of the 2x2x2 ANOVA for behavioral accuracy

Source of variation	Simple-simple effect	df	F	p	(_p^2)
Acoustic interval		(1,59)	88.52	**0.000**	0.60
Tone category		(1,59)	211.88	**0.000**	0.78
TMS stimulation site		(1,59)	2.22	0.141	0.04

Source of variation	Simple-simple effect	df	F	p	(_p^2)
Acoustic interval*Tone category		(1,59)	1.42	0.238	0.02
TMS*Acoustic interval		(1,59)	0.42	0.520	0.01
TMS*Tone category		(1,59)	0.11	0.738	0.00
TMS*Acoustic interval*Tone category		(1,59)	4.43	**0.040**	0.07
	TMS stimulation site: small acoustic-interval between-category	(1,59)	1.05	0.309	0.02
	TMS stimulation site: small acoustic-interval within-category	(1,59)	0.06	0.800	0.00
	TMS stimulation site: large acoustic-interval between-category	(1,59)	0.24	0.623	0.00

Source of variation	Simple-simple effect	df	*F*	*p*	(_p^2)
	TMS stimulation site: large acoustic-interval within-category	(1,59)	2.15	0.148	0.04

Note: Bold type indicates statistically significant results (*p*<0.05).

Result 3: Results of the 3x2x2 ANOVA

In Experiment 2, for discrimination accuracy and activation in each brain region, the data from Experiment 1 were combined to conduct a three-factor ANOVA: 3 (TMS stimulation site: no stimulation, IPL dorsal [channel 15], IPL ventral [channel 11]) × 2 (tone category: between-category, within-category) × 2 (acoustic interval: large, small acoustic interval). See Appendix Table 5.

Appendix Table 5. Results of the 3x2x2 ANOVA for behavioral accuracy and the four regions of interest

Source of variation	df	Accuracy *F*	Accuracy *p*	Accuracy (_p^2)	IPL dorsal (15) *F*	IPL dorsal (15) *p*	IPL dorsal (15) (_p^2)	IPL ventral (11) *F*	IPL ventral (11) *p*	IPL ventral (11) (_p^2)	PMC *F*	PMC *p*	PMC (_p^2)	IFG *F*	IFG *p*	IFG (_p^2)
Acoustic interval	(1,89)	109.23	**0.000**	0.55	0.07	0.790	0.00	1.29	0.259	0.01	0.37	0.544	0.00	0.02	0.879	0.00
Tone category	(1,89)	443.40	**0.000**	0.83	6.34	**0.014**	0.07	4.28	**0.042**	0.05	3.46	0.066	0.04	4.60	**0.035**	0.05
TMS stimulation site	(2,89)	3.10	0.050	0.07	1.39	0.253	0.03	2.50	0.088	0.05	1.99	0.142	0.04	3.22	**0.045**	0.07

Source of variation	df	Accuracy F	Accuracy p	Accuracy (_p^2)	IPL dorsal (15) F	IPL dorsal (15) p	IPL dorsal (15) (_p^2)	IPL ventral (11) F	IPL ventral (11) p	IPL ventral (11) (_p^2)	PMC F	PMC p	PMC (_p^2)	IFG F	IFG p	IFG (_p^2)
Acoustic interval*Tone category	(1,89)	9.49	**0.003**	0.10	4.14	**0.045**	0.04	6.27	**0.014**	0.07	6.25	**0.014**	0.07	1.80	0.183	0.02
TMS*Acoustic interval	(2,89)	4.34	**0.016**	0.09	8.35	**0.000**	0.16	5.61	**0.005**	0.11	5.69	**0.005**	0.11	2.17	0.121	0.05
TMS*Tone category	(2,89)	1.78	0.175	0.04	1.10	0.338	0.02	1.23	0.297	0.03	0.50	0.609	0.01	3.73	**0.028**	0.08
TMS*Acoustic interval*Tone category	(2,89)	4.82	**0.010**	0.10	0.29	0.748	0.01	0.16	0.855	0.00	1.04	0.356	0.02	0.25	0.781	0.01

Note: Bold type indicates statistically significant results (p<0.05).

Note: Figure translations are in progress. See original paper for figures.

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