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LETTER TO THE EDITOR

Evidence of Altered Cortical Processing of Dynamic Lexical Tone Pitch Contour in Chinese Children with Autism

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Dear Editor,

Autistic people often show enhanced pitch-processing skills involving complex tones and musical tones. However, when it comes to tones that carry linguistic meaning such as lexical tones in tonal languages and speech intonation, they tend to display reduced discrimination sensitivity [1, 2]. One possible account for the striking contrast between linguistic and non-linguistic pitch processing is that the auditory system affected by autism might not be adequately specialized for the detection of linguistic structures in sounds [3, 4]. In other words, the linguistic pitch might not be as perceptually salient for autistic individuals as it is for neurotypical individuals.

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Significantly, large populations of autistic individuals reside in tonal-language-speaking countries such as China [5]. A more complete picture of autism must rely on the knowledge gained from these linguistically and culturally diverse communities. Tonal languages such as Chinese can serve as a unique testbed for understanding pitch processing in autism. In Chinese, syllabic fundamental frequency (f_0) changes are employed to differentiate word meaning, and these phonemic f_0 categories are referred to as lexical tones. For example, the syllable /da/ in Chinese means "answer" when spoken with a rising f_0 (Tone 2), and the same syllable means "big" when pronounced with a falling f_0 (Tone 4). The linguistic function requires Chinese listeners to develop perceptual templates and specialized neural processing schemes for such phonemic tonal information [6]. Research in the past has provided strong evidence that native Chinese speakers have auditory advantages for f_0 coding at subcortical and cortical levels compared to speakers of non-tonal languages [7, 8], indicating language-dependent auditory processing of pitch information. Despite the enhanced pitch processing skills associated with autism, evidence about language-specific processing of pitch is still rare, especially from individuals who use tones phonemically in everyday life.

F_0 curvilinearity is a defining feature of lexical tones. The f_0 contour of a canonical Tone 2 is curvilinear and dynamic. Studies of lexical tone processing have used tones with the canonical curvilinear f_0 contours that are closely modeled after the f_0 contour of naturally spoken Tone 2. Others used tones with linear f_0 contours as Tone 2 approximations. Both types of stimuli can be reliably perceived as Tone 2 by native listeners, however, recent research has shown that the curvilinear f_0 elicits a greater neural response amplitude than the linear f_0 in adults with normal hearing [9]. Interestingly, such an effect of f_0

contour is more prominent in native Chinese listeners than in native English listeners. This phenomenon fits with the idea that the curvilinearity is not simply acoustic in nature but can reflect linguistically-relevant perceptual coding. That is, unlike the curvilinear f_0, a linear f_0 in Tone 2 is somewhat unnatural for a Chinese listener [9].

We were curious about the language-dependent auditory processing of pitch in autism, therefore we used stimuli similar to those used by Krishnan *et al*. (2014) to examine the cortical encoding of f_0 curvilinearity in school-age Chinese-speaking children with autism ($n = 22$, mean age = 12.1, ± 1.4 years) and typically developing (TD) peers ($n = 27$, mean age = 11.7, ± 0.8 years; Table S1). EEG was recorded during passive listening to curvilinear and linear tones. The curvilinear f_0 was dynamically changing and the linear tone was a linearly rising f_0 contour with the same onset and offset frequency as the curvilinear tone (Fig. 1). Instead of using speech sounds, the tones were carried by iterated ripple noise (IRN). The non-speech IRN carrier eliminates the influence of speech context and allows for precise examination of neural coding of the pitch features without confounds from semantic and phonetic processes (see Supplementary Materials).

Prominent P1 and N2 components were elicited in both groups (Figs. 2 and S1). Regardless of tone conditions, the autism group displayed prolonged latency and attenuated amplitude of N2 relative to the TD group. Auditory N2 attenuation has recently been confirmed by a meta-analytic study [10]. Previous work with autistic children has suggested that this late processing stage might be more prone to auditory hypo-responsivity [11]. One theory about the functional significance of child N2 is that it reflects auditory "sensitization" in building up the neural representations of sound features [12]. Thus, the attenuated N2 in the autism group might implicate basic auditory learning abnormalities associated with under-powered neural circuitry in higher-order auditory cortex.

To increase the reliability of detecting tone effects beyond discrete measures of the P1 and N2 peaks, we used the non-parametric cluster-based permutation test. We found that reliable ERP amplitude differences between curvilinear and linear conditions were present in the TD group but not in the autism group. No cluster in the autism group survived the permutation test (Fig. 2). Similarly, an earlier study with Chinese-speaking autistic children reported reduced discrimination sensitivity for lexical tone contrasts compared to TD peers, despite increased sensitivity to pitch contrasts of pure tones and hummed sounds [1], which raised the possibility of a less committed auditory system for detecting the linguistic relevance of pitch information. Assuming that the tone curvilinearity was linguistically relevant, the lack of curvilinear *vs* linear ERP differences here in autism can serve to verify this possibility in the light of the auditory encoding of subtle but critical pitch characteristics. Further testing of this hypothesis would benefit from the inclusion of a curvilinear non-lexical tone condition and non-tonal language participants.

Alternatively, the co-existence of noise in the IRN stimuli might have reduced the ability of autistic children to extract the f_0 features. Compared to speech tones and harmonic tones, the IRN-based tone was degraded in terms of temporal regularity, which could impose greater demands on neuronal synchronization to reliably track the f_0, especially when the f_0 trajectory was dynamically changing and time-varying. This interpretation is supported by the evidence of reduced processing efficiency for auditory stimuli with temporal modulation [13] and increased neural variability in responses to complex sensory input in autism [11]. The inclusion of noise-free conditions would further clarify the role of noise. Notably, given that the N2 peak in autism showed a similar tone effect along with the visible trend of such an effect in the ERP waveforms, it is plausible that the lack of curvilinear *vs* linear distinction only represented a subset of autistic children.

Auditory processing and the associative ability to extract information from co-occurring sounds are essential to speech understanding in challenging situations such as in background noise. Difficulty with speech-in-noise (SIN)

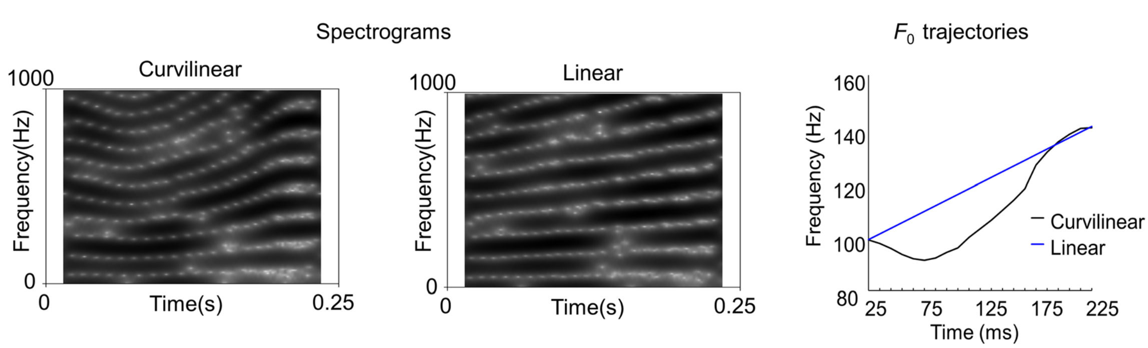

Fig. 1 Spectrograms and pitch contours of the curvilinear and linear stimuli.

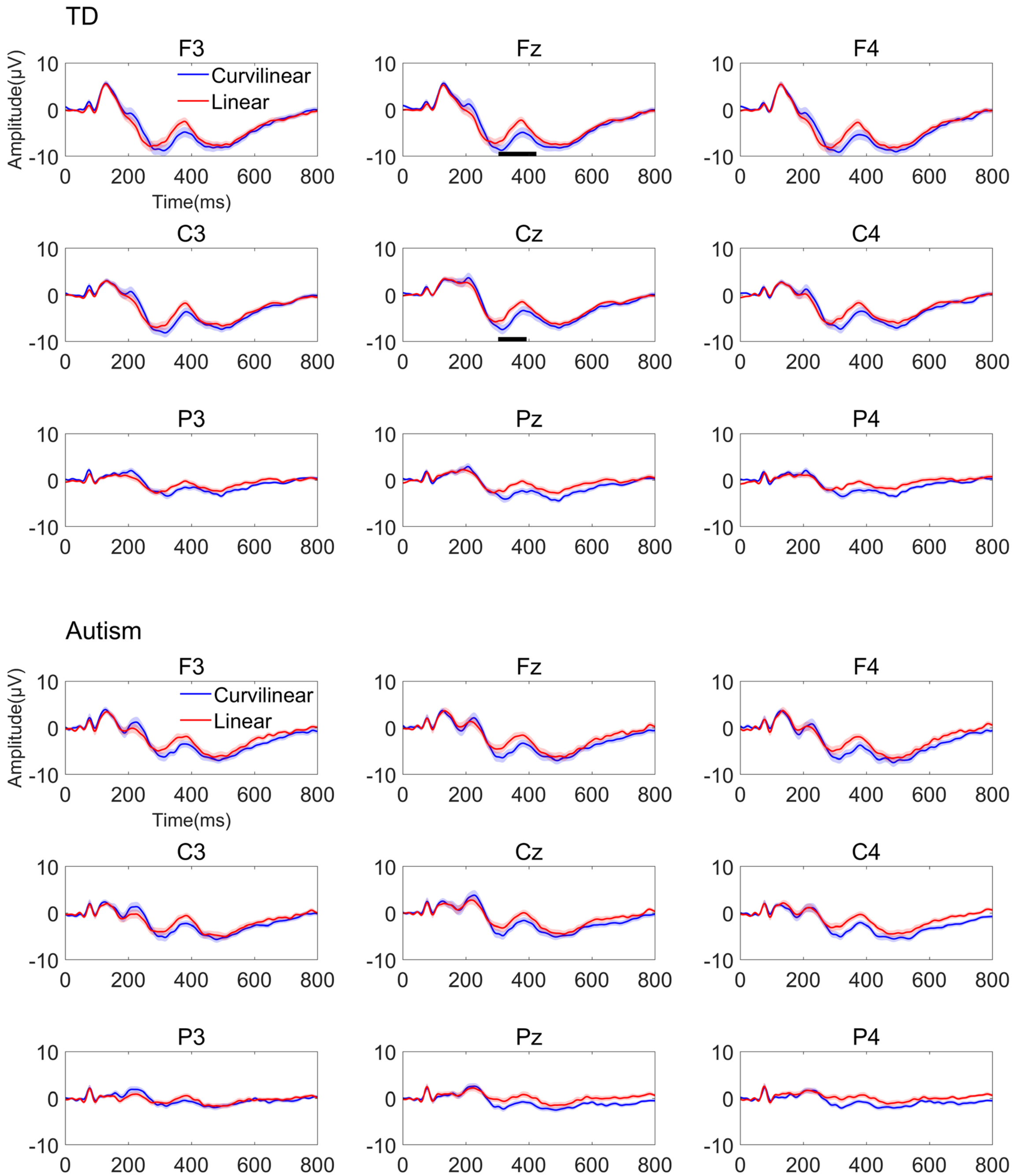

Fig. 2 ERP waveforms in the autism group and the TD group. Shaded areas represent the standard error at all sample points. Black bars on the horizontal axis are clusters showing significant curvilinear *vs* linear differences in cluster-based permutation tests.

perception is not uncommon in autism [14, 15]. Recent research has suggested that one potential contributor to the impaired SIN ability in autism might be atypical vocal pitch processing [16]. Thus, we also examined whether there was a general link between auditory pitch encoding and SIN perception of the participants. The Mandarin Speech Perception [17] system was used to assess the autistic children's SIN performance in the presence of steady-state noise. An estimate of the signal-to-noise ratio (SNR) threshold (SNR required to achieve 50% accuracy) was obtained for each child. A lower SNR indicates better SIN perception and vice versa. The mean SNR threshold of the autistic children ($-$ 5.99 $\pm$ 1.84 dB) did not differ from the TD norm ($-$ 5.75 $\pm$ 1.49 dB; P = 0.671). Although autistic individuals often display difficulty hearing in multi-speaker situations (informational masking) and in the presence of temporally modulated background noise, our finding is consistent with research demonstrating intact

SIN perception using steady-state background noise and purely energetic masker noise [14].

Our exploratory analyses indicated that a smaller N2 amplitude predicted better SIN perception in the autistic children ($P < 0.05$). A similar pattern was previously reported in school-age TD children, among whom those with better SIN perception had a significantly smaller speech-evoked N2 amplitude in background noise than children with poorer SIN perception. Moreover, in the poorer SIN group but not the better SIN group, N2 amplitude in the noise condition was significantly larger than that in the quiet condition [18]. In other words, better perceivers did not recruit more neural resources for SIN listening compared to quiet listening whereas poorer perceivers did. The similar pattern of N2–SIN relationship here might reflect an intact functional mechanism of N2 underlying SIN listening in the autistic children, which appears to be independent of the univariate N2 amplitude.

To summarize, this preliminary study provides two major findings. First, the curvilinear tone characteristic of a Chinese lexical tone, relative to a linear tone, elicited greater cortical responses in school-age children who spoke Chinese as their native language. One plausible interpretation is that the curvilinear tone has greater perceptual salience over the linear tone for an auditory system that has been shaped by a tonal language. If so, we should be cautious about f_0 contour characteristics in lexical tone research. Second, language-impaired Chinese children with autism failed to show a reliable tone curvilinearity effect, which is evidence of potentially disrupted neural specialization for lexical tone features and/or altered neural coding of stimulus periodicity embedded in complex noise.

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Conflict of interest The authors declare no conflict of interest.

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