Fundamental Frequency Variation in Crying of Mandarin and German Neonates

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Summary: Objectives. This study examined whether prenatal exposure to either a tonal or a nontonal maternal language affects fundamental frequency (fo) properties in neonatal crying.

Study Design. This is a population prospective study.

Participants. A total of 102 neonates within the first week of life served as the participants.

Methods. Spontaneously uttered cries (N = 6480) by Chinese (tonal language group) and German neonates (nontonal group) were quantitatively analyzed. For each cry utterance, mean fo and four characteristic variation measures (fo range, fo fluctuation, pitch sigma, and pitch sigma fluctuation) were calculated, averaged for individual neonates, and compared between groups.

Results. A multiple analysis of variance highlighted a significant multivariate effect for language group: Wilks $\lambda = .76$, $F(6, 95) = 4.96$, $P < .0001$, $\eta_p^2 = .24$. Subsequent univariate analyses revealed significant group differences for fo variation measures, with values higher in the tonal language group. The mean fo did not differ between groups.

Conclusions. Data regarding fo variation in infant cries have been suggested as providing critical insight into the maturity of neurophysiological vocal control. Our findings, alongside with auditive perception studies, further underscore the assumption of an early shaping effect of maternal speech, particularly fo-based features, on cry features of newborns. Further studies are needed to reexamine this observation and to assess its potential diagnostic relevance.

Key Words: crying–infant–fundamental frequency–melody variation–tonal language.

INTRODUCTION

Neonates' spontaneous (mitigated) crying, uttered within pain-free circumstances, has already been demonstrated to exhibit an impressive richness of variation among its melodic and rhythmic elements.[1–8] This melodic richness requires well-coordinated respiratory-laryngeal activity. Indeed, infant crying is the most highly coordinated and finely regulated motor behavior available to neonates.[9] The muscles of the larynx function as part of the respiratory system before birth, and, like all other respiratory muscles, have undergone considerable use before birth.[10]

The precocious maturity of the auditory-vocal system and the high speed at which neurophysiological control mechanisms underlying phonation operate justify assumptions that cry properties, particularly fundamental frequency (fo), carry information about brain dysfunctions.[2,11–15] There is a large body of outstanding research in the field of cry diagnosis.[2,7,11,14–28] However, far too little is still known about the influence of endo- and exogenous factors on the fo properties of healthy infants' crying. This lack of knowledge has limited the clinical value of previous findings.

In particular, recent findings with respect to fetal auditory learning and memory[29–32] require systematic cross-linguistic studies. Fetuses are highly attracted to their mother's voice and the melodic features of her speech.[29,33–35] Moreover, maternal language has been found to shape the perceptive preferences of foetuses and newborns.[30,32,36–38] Unlike other voices, that of the mother is not dampened by the abdominal walls and is the most important acoustic speech source for a fetus[34,39,40]; the fo features of maternal speech are the most salient stimuli for the fetus.[31,41,42] Moreover, there is evidence that linguistic and prosodic language properties are processed by distinct neural networks within the first day of life.[43]

As a consequence, it makes sense that the fetal auditory system becomes especially attuned to the dominant salient input of the acoustic environment. Particularly interesting is the fact that "fetal learning" includes input characteristics that seem to affect output characteristics. For example, it has been found that prenatal exposure to maternal language seems to shape neonates' cry melodies, that is, the fo properties of infant crying.[4,44] If this is true, then the influence of maternal language on infant crying must be regarded as an important variability source in any fo-based diagnostic efforts.

In lexical tonal languages like Mandarin, fo patterns are quite variable, but are less so in nontonal languages like German or English.[45] The analysis presented here considered the potential influence of a tone language, with its typical high variations on fo properties in the crying of neonates. The study was prompted by a first report of crying in the neonates of mothers speaking an African tone language (*Lamnso*), which found that there was a higher fo variation among these neonates than those from a nontonal language background.[44] The preliminary finding was interpreted as being indicative of the imprinting effect of long-term prenatal stimulation from the complex tone language used by Lamnso-speaking Nso mothers from Northwest Cameroon.

To the best of our knowledge, the present study is the first to describe the fo properties of Chinese neonates' crying. The study

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was motivated on the assumption that the characteristic variations in fo contour and fo level of Mandarin[45,46] could provide a salient, pitch-based stimulus for the developing fetal brain.[31,47] In tone languages, syllables and words are characterized by tones that are defined by their relative fo height and contour.[46–49] This generates a high fo variation in time that is similar to a musical melody, to which fetuses and infants are highly sensitive.[50–54] Prenatal music exposure was also found to induce long-term neural effects.[55]

This study compared fo properties in the spontaneous crying of Chinese neonates of Mandarin-speaking mothers from Beijing with those of neonates of German-speaking mothers from Berlin. Prenatal exposure to Mandarin was assumed to increase fo variation in Chinese neonates' crying as a result of auditory learning and its shaping effect on sound production.

MATERIALS AND METHODS

Participants and procedure

A total of 110 healthy, full-term German (N = 55) and Chinese neonates with normal hearing from a monolingual family background (middle-class families) were investigated during their first week of life (mean age: German: 3.5 days [±0.95], range 1–5 days; Chinese: 3.79 [±0.68], range 2–5 days). Three German neonates and one Chinese neonate were excluded from the final analysis, as the melodies of their cries exhibited disturbed and irregular (high short-term fo perturbation) patterns, which is indicative of a nonoptimal vocal control state at the time of recording. A further three Chinese neonates were excluded because the accompanying recording protocols contained information that indicated a potential additional influence of a surrounding nontonal influence (English, German) in connection with the maternal profession. As a consequence of the above, a total of 52 German and 50 Chinese neonates were included in the final analysis. Both neonatal groups had a mean gestational age of 39 weeks (German: 39.6 ± 0.94, Chinese: 39.2 ± 1.27). Birth weights were also similar, with a mean of 3460 g (±370) for the German and 3421 g (±435) for the Chinese neonates.

Mothers of neonates were contacted at maternity units of hospitals in Beijing (China) and Berlin (Germany) and asked to participate in the research according to the institutions' informed consent procedures. All the parents gave written informed consent. Only neonates exhibiting a normal course of intrauterine development were selected to participate by pediatricians in the respective project teams.

German neonates were recorded at the Children's Hospital Lindenhof (Sana Klinikum), Berlin, within the framework of a broader study after receiving approval from the clinic director and the research ethics committee of the University Clinics (Charité) of the Humboldt University of Berlin, Germany. The Chinese neonates were recorded at two main hospitals in the center of Beijing after receiving the approval of the respective clinic directors and the research ethics committee of the Beijing Normal University, China.

Cry recordings and analysis

The recording protocol was principally identical for the two neonatal groups. Recording began when a neonate started to fuss at a time when the mother would normally feed the child. Only spontaneous cries were recorded (eg, when the neonates were hungry) and no cries were induced through the infliction of pain. The cry recordings had a maximum duration of 2 minutes per session depending on the neonate's crying behavior (fussing was not recorded). In total, 6480 cry utterances from the 102 neonates were recorded. The Chinese neonates were participants in a broader ongoing study, which required a repeat recording during the neonates' first few days of life. Here, the data of the two neonatal recording sessions were pooled for the analysis, which explains the larger cry number in the Chinese neonates. The average number of recorded cry utterances per neonate was 66 (range 11–278) per child in the Chinese neonates and 36 (range 11–75) per child in their German counterparts. A cry utterance was defined as the onset and offset of identifiable acoustic energy in the waveform that occurred on the expiratory phase of a single respiratory cycle.[56,57]

The cry analysis was performed in the signal analysis laboratory of the Center for Pre-speech Development and Developmental Disorders, Department of Orthodontics, University of Würzburg. In a preprocessing routine, the manual segmentation of single cry utterances was based on amplitude-by-time waveforms. The time-consuming manual segmentation was applied to achieve a high degree of reliability. In the next step, narrow (45 Hz) band frequency spectrograms were calculated for all single cry utterances using a commercially available system (CSL 4400; KayPENTAX, division of PENTAX medical, 2 Bridgewater Lane 07035-1439 Lincoln Park, NJ, USA). Phonatory noise phenomena and phenomena like sudden fo shifts or subharmonics were identified based on visual inspections of the spectrograms. These phenomena occur regularly, including healthy infants' crying,[7] owing to nonlinearities in the restoring forces resulting from an extremely large amplitude-to-length ratio of very young infants' vocal folds.[58,59] Only completely noisy, voiceless cry utterances were excluded (N: German = 429, N: Chinese = 812), because the fo contour cannot be reliably determined in those signals. Accordingly, 5239 harmonic cries (Chinese group: 3341 ÷ 80% of recorded cries; German group: 1898 ÷ 82%) with well-identifiable fo contours (melody) were ultimately analyzed. For each of these cry utterances, phenomena like short-time noise, fo shifts, and fo subharmonics required the interactive verification of the fo contour (melody) for reasons of the reliability of the fo determination. This verification followed automatic fo measurement using *PRAAT* v. 5.2.[60] In cases of obvious fo-tracking problems of the automatic routine, the fo analysis was manually repeated using *PRAAT*. Finally, we applied a low-pass filter (Gaussian filtering) with a cutoff frequency of 40 Hz to eliminate high-frequency modulation noise and artifacts.[3]

To investigate whether prenatal exposure to Mandarin will increase fo variation in Chinese neonates' crying as a result of auditory learning and its postulated shaping effect on sound production, adequate fo measurements were made and values averaged over the neonates for each neonate's cry utterance (Figure 1):

(1) ***Mean fo***: defined as the arithmetic average of all the fo values of a cry utterance.

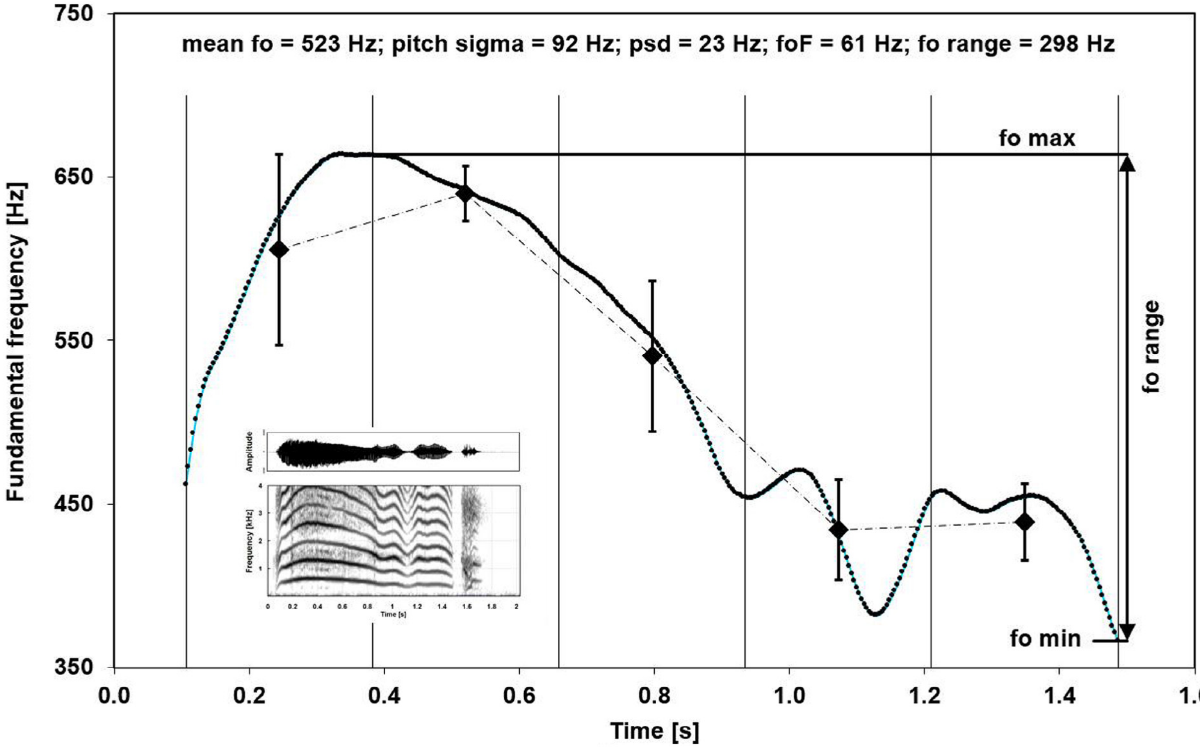

FIGURE 1. Example of a cry melody from a Chinese neonate to illustrate the determination of the fo properties (see explanation in the text). The insert (*bottom left*) displays the corresponding narrow band frequency spectrum.

(2) ***fo range***: defined as the subtracted difference between the maximum and the minimum fo within a cry utterance.
(3) ***Pitch sigma***: defined as the standard deviation in the mean fo within a cry utterance.
(4) ***fo fluctuation*** (foF): defined as the measure of the mean fo variation between five consecutive time sections of equal length per cry utterance. This measure is calculated by (1) subdividing each cry utterance into five time sections of equal length, (2) determining the mean fo across each time section, (3) calculating the difference of the mean fo values of the five consecutive sections in time, and (4) computing the average of the four differences.
(5) ***Pitch sigma fluctuation***: calculated by applying an analog approach, as described for the foF.
(6) ***fo min***: the minimum fo value of a cry utterance. This measure was specifically included to investigate the potential influence of the low-dipping tone 3 in Mandarin.

RESULTS

The results of the acoustic analysis of the crying are set out in Table 1. A multiple analysis of variance was calculated to examine differences in fo properties between the German and the Chinese neonates. The multiple analysis of variance revealed a significant multivariate effect for language group: Wilks $\lambda = .76$, $F(6, 95) = 4.96$, $P < .001$, $\eta_p^2 = .24$ (large effect size after Cohen).

Subsequent univariate analyses revealed significant group differences for three fo variation measures, with medium effect sizes: fo range, $F(1, 100) = 4.8$, $P < .05$, $\eta_p^2 = .05$; pitch sigma, $F(1, 100) = 5.6$, $P < .05$, $\eta_p^2 = .05$; and pitch sigma fluctuation, $F(1, 100) = 6.4$, $P < .05$, $\eta_p^2 = .06$. One variation measure (foF) just barely missed the significance between the groups, $F(1, 100) = 3.9$, $P = .052$, $\eta_p^2 = .04$. Figure 2 contains an exemplary presentation for fo range distribution in semitones to illustrate observed group differences.

The results indicated that neonates from the two language backgrounds did not differ with respect to their mean fo. At the same time, the findings suggest that Mandarin neonates produce cries with more fo variation than their German counterparts (Table 1). Moreover, the averaged minima of the fo were found to significantly differ between the language groups: fo min, $F(1, 100) = 4.8$, $P < .05$, $\eta_p^2 = .05$. In contrast to the fo variation measures and fo min, mean fo did not differ between groups: $F(1, 100) = .006$, $P = .94$. There were also no differences with respect to sex.

TABLE 1.
Averaged Values and 95% Confidence Intervals [CI]

	Tonal Language Group (Chinese Neonates)	Nontonal Language Group (German Neonates)
mean fo (Hz)	406 [396–417]	407 [393–422]
fo min* (Hz)	293 [285–300]	311 [296–325]
fo range* (Hz)	171 [161–181]	157 [148–166]
pitch sigma* (Hz)	39 [6–42]	35 [33–37]
foF (Hz)	33 [30–35]	29 [27–32]
psd* (Hz)	13 [2–14]	12 [11–13]

* Significant ($P < .05$).
Abbreviation: psd, pitch sigma fluctuation.

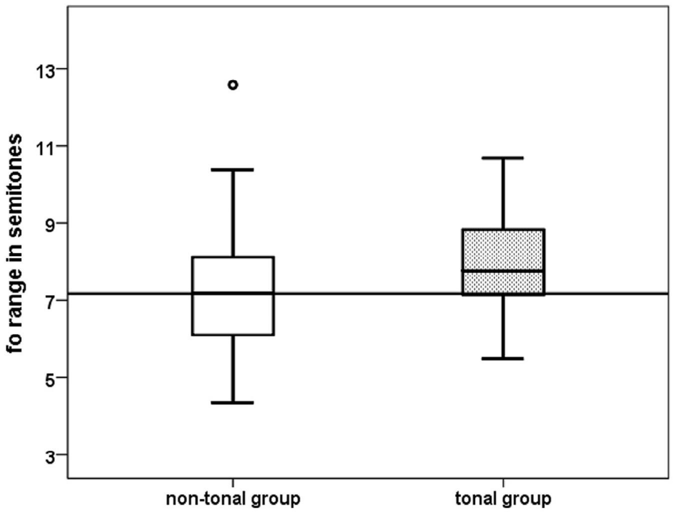

FIGURE 2. Boxplot diagram showing the fo range distribution in semitones for the two language groups. The Chinese neonates had a mean fo range in their crying that was one to two semitones higher than that of the German neonates.

DISCUSSION

Early auditory learning processes in neonates are reflected in perceptual preferences for melodies to which they are repeatedly exposed prenatally.[31,50] The current findings underscore the previous notion that early auditory learning processes shape neonates' vocal outputs, especially their fo properties.[4,44] In line with the previous report for Cameroon (Nso) neonates,[44] the Chinese neonates, like the Nso neonates (with surrounding Lamnso language), exhibited higher values in all fo variation measures than German neonates, whereas the mean fo was almost identical.

Indeed, both the Chinese and the Nso neonates had experienced the typical acoustic cues of a tone language *in utero*, and both groups exhibited significantly more fo variation in their crying than the respective German control groups. However, the fo variation was slightly lower in the Chinese than in the Nso neonates, respectively: fo range: 171 *versus* 204 Hz; pitch sigma: 39 *versus* 46 Hz; and foF: 33 *versus* 39 Hz.

The finding that both neonatal groups from a tonal language background (Nso and Chinese) differ from German neonates (nontonal language background) in the same direction in terms of fo variation may simply reflect normal variability. However, it might also indicate a language-specific influence, because Lamnso and Mandarin are quite different in their tone characteristics. Although Mandarin is a contour tone language, Lamnso combines several register and contour tones[44] and hence, provides very complex fo-based stimuli for the fetus. Previous research demonstrated that the prenatal experience with the maternal language gained *in utero* influences the response of the newborn brain to language across brain regions sensitive to speech processing.[29,30,33,35] This finding is further supported by the work of Yeung et al[61] who demonstrated that infants as young as 4 months are able to differentiate language-specific tonal differences between Cantonese and Mandarin.

The larger fo range in Chinese neonates' crying (as in Nso infants' crying[44]) align nicely with findings from adults showing that speakers of tonal languages like Mandarin exhibit a greater fo range and fo variation in their speech than those who speak nontonal languages.[45,46,62–66] Chen[62(p170)] even suggested that native speakers of nontonal languages should learn to widen their normal pitch range to successfully produce Chinese tones. The properties of fo variation in tone languages seem to provide a robust perceptible stimulus for the fetus and the newborn. Both neonates and young infants (2- to 3-month-old) are clearly capable of perceiving fo level changes and fo direction (contour) as typical tone features.[67–69] Like the perception of musical melodies,[50–52] the typical fo variations of tone languages seem to leave memory traces.

In contrast to fo variation, the mean fo was similar between neonates of the two language groups. This finding reflects comparable neurophysiological control states underlying cry production: Mean fo and related entities in infant crying were found to vary with factors such as efficacy of adaptation to the external environment, occurrence of pre- or perinatal stress, intrauterine growth, gestational age, or integrity of vocal production circuitry in the brain.[1,2,14–16,25,28] In our study, all neonates were healthy and none of them showed signs of developmental disorder. Furthermore, neonate groups did not differ with respect to birth weight and gestational age. The high homogeneity with regard to those influencing factors together with the applied identical recording protocol in both countries explain the almost identical mean fo, exhibiting values well within the typical fo range of spontaneous crying of healthy neonates.

However, it is not easy to interpret the finding of a significantly lower mean minimum fo in Chinese neonates' crying. In the absence of any methodological or obvious neurophysiological explanation, one possibility is that the significantly lower minimal fo values in Chinese neonates' crying might be particularly linked to frequent exposure to tone 3 and tone 4, both of which have a falling contour over some portion of the tone.[46] Among the four lexical tones of Mandarin,[70] tone 3, with its low-dipping pitch, could provide the most salient acoustic cue in this respect.[61] More research is, however, needed to support the hypothesis and to understand any underlying external influences or even genetic factors.[71–74] It is indisputable that newborns are ready to acquire any of the world's languages and there are no "genes for Chinese" as Dediu and Ladd formulated.[72,73] However, among others it was particularly this group that has convincingly demonstrated that "tone is a stable characteristic of language because of its 'genetic anchoring' . . ." and, that "there are heritable differences of brain structure and function that affect language acquisition and usage."[72–74] From a developmental perspective, the precocious auditory learning and memory performances of human fetuses and young infants seem to have a similar powerful equivalent in neonates' vocal performances on their path to spoken language.[3–9] The data once more demonstrated an obvious influence of the surrounding speech prosody on newborns' cry melody, possibly *via* vocal learning based on biological predispositions.[4,6,44]

Although the tonal *versus* nontonal group differences may not yet have obvious clinical consequences, the identification of the surrounding language as a source of fo variation in crying, aside from frequently cited neurophysiological factors, is essential when trying to use fo properties to examine an infant's state of health.[13–15]

Although many questions remain unanswered, investigating factors that seem to shape neonates' crying will help to better understand the earliest developmental processes toward speech and language and to identify factors that have a robust predictive value for developmental disorders. The current study is reported with the intention to stimulate further cross-cultural research into pre-speech sound production.

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