Neuropsychologia 59 (2014) 1–12

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Cortical pitch response components index stimulus onset/offset and dynamic features of pitch contours

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ARTICLE INFO

Article history:
Received 9 November 2013
Received in revised form
12 March 2014
Accepted 11 April 2014
Available online 18 April 2014

Keywords:
Auditory
Pitch encoding
Iterated rippled noise
Cortical pitch response
Pitch onset response
Hemispheric laterality

ABSTRACT

Voice pitch is an important information-bearing component of language that is subject to experience dependent plasticity at both early cortical and subcortical stages of processing. We have already demonstrated that pitch onset component (Na) of the cortical pitch response (CPR) is sensitive to *flat* pitch and its salience. In regards to *dynamic* pitch, we do not yet know whether the multiple pitch-related transient components of the CPR reflect specific temporal attributes of such stimuli. Here we examine the sensitivity of the multiple transient components of CPR to changes in pitch acceleration associated with the Mandarin high rising lexical tone. CPR responses from Chinese listeners were elicited by three citation forms varying in pitch acceleration and duration. Results showed that the pitch onset component (Na) was invariant to changes in acceleration. In contrast, Na–Pb and Pb–Nb showed a systematic increase in the interpeak latency and decrease in amplitude with increase in pitch acceleration that followed the time course of pitch change across the three stimuli. A strong correlation with pitch acceleration was observed for these two components only – a putative index of pitch-relevant neural activity associated with the more rapidly-changing portions of the pitch contour. Pc–Nc marks unambiguously the stimulus offset. We therefore propose that in the early stages of cortical sensory processing, a series of neural markers flag different temporal attributes of a dynamic pitch contour: onset of temporal regularity (Na); changes in temporal regularity between onset and offset (Na–Pb, Pb–Nb); and offset of temporal regularity (Pc–Nc). At the temporal electrode sites, the stimulus with the most gradual change in pitch acceleration evoked a rightward asymmetry. Yet within the left hemisphere, stimuli with more gradual change were indistinguishable. These findings highlight the *emergence* of early hemispheric preferences and their functional roles as related to sensory and cognitive properties of the stimulus.

1. Introduction

Pitch is an important information-bearing perceptual attribute that plays an important role in the perception of language and music. There is considerable interest therefore in how this pitch-relevant information is extracted from speech and nonspeech sounds at both subcortical (Cariani & Delgutte, 1996a, 1996b; Cedolin & Delgutte, 2005; Meddis & O'Mard, 1997) and cortical levels (Walker, Bizley, King, & Schnupp, 2011). There is also growing interest in understanding the neural mechanisms that mediate *experience-dependent* shaping of pitch processing. Linguistic and musical pitch provide us with a window to evaluate how neural representation of pitch-relevant attributes emerge from early sensory levels of processing and interact with higher levels of cognitive processing in the human brain, and how language and music experience shapes these representations. Recent empirical data show that neural representation of pitch is shaped by one's experience with language and music at the level of the auditory brainstem as well as the cerebral cortex (Besson, Chobert & Marie, 2011; Gandour & Krishnan, 2014; Koelsch, 2012; Kraus & Banai, 2007; Krishnan, Gandour, & Bidelman, 2012; Meyer, 2008; Munte, Altenmuller, & Jancke, 2002; Patel & Iversen, 2007; Tervaniemi et al., 2009; Zatorre, Belin, & Penhune, 2002; Zatorre & Gandour, 2008). But we have yet to achieve a precise characterization of neural representation of pitch-relevant information associated with specific attributes of *dynamic* pitch contours that occur in natural speech.

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http://dx.doi.org/10.1016/j.neuropsychologia.2014.04.006
0028-3932/

At the cortical level, magnetoencephalography (MEG) has been used previously to study the sensitivity to periodicity, an essential requisite of pitch, by investigating the N100m component. However, a large proportion of the N100m is simply a response to the onset of sound energy, and not exclusively to pitch (Alku, Sivonen, Palomaki, & Tiitinen, 2001; Gutschalk, Patterson, Scherg, Uppenkamp, & Rupp, 2004; Lutkenhoner, Seither-Preisler, & Seither, 2006; Soeta & Nakagawa, 2008; Yrttiaho, Tiitinen, May, Leino, & Alku, 2008). In order to disentangle the pitch-specific response from the onset response, a novel stimulus paradigm was constructed with two segments – an initial segment of noise with no pitch to evoke the onset components only, followed by a pitch-eliciting segment of iterated rippled noise (IRN) matched in intensity and overall spectral profile (Krumbholz, Patterson, Seither-Preisler, Lammertmann, & Lutkenhoner, 2003). Interestingly, a transient pitch onset response (POR) was evoked from this noise-to-pitch transition only. The reverse stimulus transition from pitch to noise failed to produce a POR. It has been proposed that the human POR, as measured by MEG, reflects synchronized cortical neural activity specific to pitch (Chait, Poeppel, & Simon, 2006; Krumbholz et al., 2003; Ritter, Gunter Dosch, Specht, & Rupp, 2005; Seither-Preisler, Patterson, Krumbholz, Seither, & Lutkenhoner, 2006). POR latency and magnitude, for example, has been shown to depend on pitch salience. A more robust POR with shorter latency is observed for stimuli with stronger pitch salience as compared to those with weaker pitch salience. Source analyses (Gutschalk, Patterson, Rupp, Uppenkamp, & Scherg, 2002; Gutschalk et al., 2004; Krumbholz et al., 2003), corroborated by human depth electrode recordings (Griffiths et al., 2010; Schonwiesner & Zatorre, 2008), indicate that the POR is localized to the anterolateral portion of Heschl's gyrus, the putative site of pitch processing (Bendor & Wang, 2005; Griffiths, Buchel, Frackowiak, & Patterson, 1998; Johnsrude, Penhune, & Zatorre, 2000; Patterson, Uppenkamp, Johnsrude, & Griffiths, 2002; Penagos, Melcher, & Oxenham, 2004; Zatorre, 1988).

We recently adopted Krumbholz et al.'s (2003) pitch onset response paradigm to demonstrate that a human cortical pitch response (CPR) can be extracted from scalp-recorded electroencephalogram (EEG) (Krishnan, Bidelman, Smalt, Ananthakrishnan, & Gandour, 2012). Indeed, neural responses evoked by IRN steady-state pitch stimuli steadily increased in magnitude with increasing IRN stimulus temporal regularity. Behavioral pitch discrimination also improved with increasing stimulus temporal regularity. This change in response amplitude with increasing stimulus temporal regularity was strongly correlated with behavioral measures of change in pitch salience (perceived strength of pitch). Furthermore, a robust CPR was evoked from both weak and strong IRN pitch-eliciting stimuli, but not to "no-pitch" IRN. We therefore conclude that the CPR is specific to pitch rather than simply a neural response to IRN elicited by slow, spectrotemporal modulations unrelated to pitch (Barker, Plack, & Hall, 2012).

In MEG/EEG studies of pitch processing, the primary focus was to characterize a single, transient pitch onset response to stimuli exhibiting a steady-state pitch. Whether or not their findings can be extrapolated to neural mechanisms that are associated with dynamic pitch contours is an empirical question. In this study, we utilize linguistically-relevant pitch stimuli with dynamic, curvilinear patterns. They represent *within-category* variants of the high rising lexical tone of Mandarin Chinese.

Linguistic and musical pitch provide an analytic window to evaluate how neural representations of important pitch attributes of a sound undergo transformation from early sensory to later cognitive stages of processing in the human brain, and how pitch-relevant experience shapes these representations. In the music domain, MEG/EEG studies have shown enhanced auditory cortical representations (Pantev et al., 1998; Shahin, Bosnyak, Trainor, & Roberts, 2003) and superior detection of weak pitch incongruities (Magne, Schon, & Besson, 2006; Marie, Delogu, Lampis, Belardinelli, & Besson, 2011) in musicians compared with nonmusician controls. Though providing convincing evidence in support of experience-dependent neural plasticity, none of their evoked response components were pitch-dependent. In the language domain, tonal languages are especially advantageous for studying pitch processing because of its functional load at the level of the syllable. Almost all previous EEG studies of lexical tone have investigated mismatch negativity (MMN) responses by using dynamic pitch contours with a passive oddball paradigm (cf. Gu, Zhang, Hu, Zhao, & Zhang, 2013; steady-state pitch; Zheng, Minett, Peng, & Wang, 2012; active oddball, P300). As measured by MMN amplitude, early, preattentive processing of lexical tone, relative to consonants, was lateralized to the right hemisphere (RH) (Luo et al., 2006). This RH preference was also observed in an MMN study of categorical perception of lexical tone (Xi, Zhang, Shu, Zhang, & Li, 2010). In their nonspeech condition that differed only in spectral components from the speech condition, no difference was observed between within- and between-category deviants, relative to standard stimuli, in the RH. Of special relevance to this study, *within-category* deviants elicited larger MMN in the RH regardless of speech/nonspeech condition. Lexical tone is of further interest because its primary auditory correlate is based on variations in pitch, a multidimensional perceptual attribute that relies on several acoustic features. MMN studies of tone languages have revealed that pitch contour and pitch height are two important features used in early, preattentive lexical tone processing (Chandrasekaran, Gandour, & Krishnan, 2007; Chandrasekaran, Krishnan, & Gandour, 2007; Tsang, Jia, Huang, & Chen, 2011). These findings notwithstanding, any definitive interpretations about cortical pitch processing must be tempered by the fact that the MMN is comprised of both auditory and *cognitive* mechanisms of frequency change detection in auditory cortex (Maess, Jacobsen, Schroger, & Friederici, 2007). The MMN itself is *not* a pitch-specific response.

Our overall objective therefore is to fill this knowledge gap by examining cortical, pitch-specific responses that are elicited by linguistically-relevant, dynamic pitch contours exemplary of those that occur in natural speech. To our knowledge there are no published reports that tie specific transient components of the cortical pitch response to selected portions of dynamic pitch contours. The specific aim of this paper is to first identify the multiple transient components of the CPR and label them in relation to specific aspects of our dynamic, curvilinear pitch stimuli (e.g., pitch onset, pitch offset, pitch acceleration). Our hypothesis is that the cortical representation of pitch, as reflected by the CPR, will be differentially sensitive to different attributes or features of dynamic pitch. To eliminate any potential interference of higher-order phonological categories, all three of our dynamic pitch stimuli fall within the limits of citation forms of Mandarin Tone 2. To enable us to focus primarily on the effects of changes in rate of acceleration during the rising portion of Tone 2, pitch height is constant; i.e., pitch onset and offset and pitch range are identical across stimuli. With respect to duration, the three stimuli represent short-, medium-, and long-duration variants of isolated productions of Tone 2.

2. Materials and methods

2.1. Participants

Ten native speakers of Mandarin Chinese (5 males, 5 females) were recruited from the Purdue University student body to participate in the experiment. All exhibited normal hearing sensitivity at audiometric frequencies between 500 and 4000 Hz and reported no previous history of neurological or psychiatric illnesses. They were closely matched in age (24.50 ± 3.53 years), years of formal education (16.90 ± 2.88 years), and were strongly right handed (laterality index $93.10 \pm 11.22\%$)