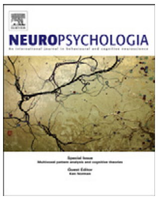
Neuropsychologia 50 (2012) 2849–2859

Contents lists available at SciVerse ScienceDirect

Neuropsychologia

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



Relationship between brainstem, cortical and behavioral measures relevant to pitch salience in humans

Ananthanarayan Krishnan[a,*], Gavin M. Bidelman[b], Christopher J. Smalt[c], Saradha Ananthakrishnan[a], Jackson T. Gandour[a]

[a] Department of Speech Language Hearing Sciences, Purdue University, West Lafayette, IN 47907-2038, USA
[b] Rotman Research Institute, Baycrest Centre for Geriatric Care, Toronto, ON, Canada
[c] School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907-2038, USA

ARTICLE INFO

Article history:
Received 11 June 2012
Received in revised form
1 August 2012
Accepted 15 August 2012
Available online 23 August 2012

Keywords:
Fundamental frequency
Pitch encoding
Auditory brainstem
Frequency-following response
Auditory cortex
Cortical pitch response
Pitch discrimination

ABSTRACT

Neural representation of pitch-relevant information at both the brainstem and cortical levels of processing is influenced by language or music experience. However, the functional roles of brainstem and cortical neural mechanisms in the hierarchical network for language processing, and how they drive and maintain experience-dependent reorganization are not known. In an effort to evaluate the possible interplay between these two levels of pitch processing, we introduce a novel electrophysiological approach to evaluate pitch-relevant neural activity at the brainstem and auditory cortex concurrently. Brainstem frequency-following responses and cortical pitch responses were recorded from participants in response to iterated rippled noise stimuli that varied in stimulus periodicity (pitch salience). A control condition using iterated rippled noise devoid of pitch was employed to ensure pitch specificity of the cortical pitch response. Neural data were compared with behavioral pitch discrimination thresholds. Results showed that magnitudes of neural responses increase systematically and that behavioral pitch discrimination improves with increasing stimulus periodicity, indicating more robust encoding for salient pitch. Absence of cortical pitch response in the control condition confirms that the cortical pitch response is specific to pitch. Behavioral pitch discrimination was better predicted by brainstem and cortical responses together as compared to each separately. The close correspondence between neural and behavioral data suggest that neural correlates of pitch salience that emerge in early, preattentive stages of processing in the brainstem may drive and maintain with high fidelity the early cortical representations of pitch. These neural representations together contain adequate information for the development of perceptual pitch salience.

1. Introduction

Voice pitch, an important information-bearing perceptual component of language and music, provides an excellent window for studying experience-dependent effects on both brainstem and cortical components of a well-coordinated, hierarchical processing network. There is growing empirical evidence to support the notion that the neural representation of pitch-relevant information at both brainstem and cortical levels of processing is influenced by one's experience with language and/or music (Kraus & Banai, 2007; Krishnan & Gandour, 2009; Patel & Iversen, 2007). It is well known from animal studies that neural processes mediating experience-dependent plasticity for pitch at the brainstem and cortical levels may be well-coordinated based on neuroanatomical evidence of ascending and descending pathways (Huffman & Henson, 1990; Kelly & Wong, 1981; Saldana, Feliciano, & Mugnaini, 1996) and physiological evidence of improved signal representation in subcortical structures mediated by the corticofugal system (Suga, Ma, Gao, Sakai, & Chowdhury, 2003; Yan & Suga, 1998; Zhou & Jen, 2000). Human electrophysiological studies have also shown enhanced brainstem neural activity in individuals with short-term auditory training (Russo, Nicol, Zecker, Hayes, & Kraus, 2005; Song, Skoe, Wong, & Kraus, 2008), long-term linguistic experience (Krishnan & Gandour, 2009; Krishnan, Gandour, & Bidelman, 2012; Krishnan, Xu, Gandour, & Cariani, 2005), and musical training (Bidelman, Gandour, & Krishnan, 2011a; Bidelman & Krishnan, 2009; Musacchia, Sams, Skoe, & Kraus, 2007; Wong, Skoe, Russo, Dees, & Kraus, 2007). Results showing correlation between brainstem and cortical responses in musicians suggest that brainstem neural representations of pitch, timing and timbre cues and cortical

---

* Corresponding author. Tel.: +1 765 494 3793; fax: +1 765 494 0771.
E-mail addresses: rkrish@purdue.edu (A. Krishnan), gbidelman@rotman-baycrest.on.ca (G.M. Bidelman), csmalt@purdue.edu (C.J. Smalt), sanantha@purdue.edu (S. Ananthakrishnan), gandour@purdue.edu (J.T. Gandour).

0028-3932/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.neuropsychologia.2012.08.013

response timing are shaped in a coordinated manner through corticofugal modulation of subcortical afferent circuitry (Musacchia, Strait, & Kraus, 2008). However, little is known about how language (music) experience shapes pitch at each level of the processing hierarchy or how it modulates the nature of the interplay between them. The scalp-recorded brainstem frequency following response (FFR) and the cortical pitch onset response (POR) representing neural activity relevant to pitch at brainstem and cortical levels, respectively, provide a physiologic window to evaluate the hierarchical organization of pitch processing along the auditory pathway.

The FFR reflects sustained phase-locked activity in a population of neural elements within the rostral brainstem (see Chandrasekaran & Kraus, 2010; Krishnan, 2007, for reviews). It has provided numerous insights into pitch encoding of ecologically-relevant stimuli including speech (Krishnan & Gandour, 2009) and music (Bidelman, Krishnan, & Gandour, 2011). Furthermore, the FFR has revealed that experience-dependent plasticity enhances neural representation of pitch in native speakers of a tone language (Krishnan, Swaminathan, & Gandour, 2009; Krishnan et al., 2005) and individuals with extensive music experience (Bidelman, Gandour, & Krishnan, 2011b; Lee, Skoe, Kraus, & Ashley, 2009; Wong et al., 2007). Finally, pitch-relevant information preserved in the FFR is strongly correlated with perceptual pitch measures (Bidelman & Krishnan, 2011; Krishnan, Bidelman, & Gandour, 2010; Krishnan & Plack, 2009; Parbery-Clark, Skoe, Lam, & Kraus, 2009) suggesting that acoustic features relevant to pitch are already emerging in representations at the level of the brainstem.

The POR, as recorded using magnetoencephalography (MEG), is thought to reflect synchronized cortical neural activity specific to pitch (Chait, Poeppel, & Simon, 2006; Krumbholz, Patterson, Seither-Preisler, Lammertmann, & Lutkenhoner, 2003; Seither-Preisler, Patterson, Krumbholz, Seither, & Lutkenhoner, 2006). For example, POR latency and magnitude has been shown to depend on specific features of pitch (e.g., salience, fundamental frequency). A more robust POR with shorter latency is observed for stimuli with stronger pitch salience compared to ones with weaker pitch salience. In order to disentangle the POR from the obligatory onset responses (P1–N1–P2), Krumbholz et al. (2003) utilized a novel stimulus paradigm in which a continuous sound is constructed using an initial segment of noise with no pitch (that evokes only the onset components), followed by a pitch-eliciting segment of iterated rippled noise (IRN) matched in intensity and overall spectral profile. Interestingly, the POR is evoked only for this noise-to-pitch transition and not for the pitch-to-noise stimulus transition. Source analyses (Gutschalk, Patterson, Rupp, Uppenkamp, & Scherg, 2002; Gutschalk, Patterson, Scherg, Uppenkamp, & Rupp, 2004; Krumbholz et al., 2003), corroborated by human depth electrode recordings (cf. 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; Penagos, Melcher, & Oxenham, 2004; Zatorre, 1988). Given both its sensitivity and consistency across a number of studies, the POR offers an excellent window for studying early cortical representations of pitch. Our preliminary POR data, extracted from scalp-recorded EEG, yielded multiple peaks in addition to pitch onset. We therefore have chosen to designate this scalp-recorded neural activity as cortical pitch response (CPR).

Recently, Krishnan, Gandour, Smalt, and Bidelman (2010) demonstrated that the degree of neural periodicity (i.e., pitch-relevant phase-locked neural activity) as reflected in the brainstem FFR accurately predicts the perceptual salience of IRN pitch. Moreover, strong correlations were observed between neural and behavioral measures of pitch. These findings support the notion that early sensory level representations of pitch relevant information in the brainstem may play an important role in formulating and/or shaping pitch percepts (Baumann et al., 2011; Langner, 1983; Pantev, Hoke, Lutkenhoner, & Lehnertz, 1989; Zatorre, Evans, & Meyer, 1994). While previous research has documented details of pitch encoding mechanisms at brainstem, cortical, and perceptual levels of processing separately, we are not cognizant of any published accounts that examine the interplay and coordination across subcortical and cortical levels of processing.

In an effort to increase our understanding of the organization of the hierarchical network underlying pitch processing and the nature of the interplay between levels of processing along the hierarchy, we introduce herein a novel experimental approach whereby neural representation of pitch-relevant information at brainstem (FFR) and cortical (CPR) levels can be recorded simultaneously in response to IRN stimuli varying in pitch salience. We further compare these neural indices to perceptual measures of pitch salience. This combined approach gives us a unique window to examine the coordination between different levels of pitch processing in real time, which may otherwise be obscured by inferences drawn from separate evaluation of neural responses evoked by different stimulation/acquisition paradigms or comparisons across studies.

2. Materials and methods

2.1. Participants

Thirteen Purdue University students (five male, eight female) were recruited to participate in the experiment. All exhibited normal hearing sensitivity at octave frequencies between 500 and 4000 Hz and reported no previous history of neurological or psychiatric illnesses. Participants were closely matched in age (23.9 ± 3.1 years), years of formal education (17.9 ± 2.2 years), and were strongly right handed (90.4 ± 15.6%) as measured by the Edinburgh Handedness Inventory (Oldfield, 1971). Two participants had more than 10 years of instrumental musical training; all others, less than three years. Participants were paid and gave informed consent in compliance with a protocol approved by the Institutional Review Board of Purdue University.

2.2. Stimuli

Four IRN stimuli were employed, each consisting of two segments: an initial 500 ms segment followed by a 250 ms segment (Fig. 1). For each stimulus, the two segments were crossfaded with 5 ms cos2 ramps to produce the following four transitions: Noise eac (read "no-pitch IRN" IRNitch IRNitch IRN, the two segments were crossfaded with 5 ms co nIRN0, IRN8, IRN32, and pIRN0, respectively). The overall RMS level of each segment was equated such that there was no discernible difference in intensity between initial and final segments. Temporal and spectral characteristics of the stimuli are shown in Fig. 1.

IRN is a complex pitch-evoking stimulus which has been widely used for examining temporal pitch mechanisms and pitch salience, as it allows one to systematically manipulate the temporal periodicity and hence pitch salience of a stimulus. Yet, IRN lacks the prominent temporal envelope typical of most signals carrying pitch. Studies show that the pitch of IRN corresponds to the reciprocal of the delay ($1/d$) and that its salience grows with the number of iterations (Krishnan et al., 2010; Patterson, Handel, Yost, & Datta, 1996; Yost, 1996a; Yost, 1996b). IRN stimuli were created by delaying Gaussian noise (80–4000 Hz) and adding it back on itself in a recursive manner, producing a pitch percept corresponding to the reciprocal of the delay (d) (Yost, 1996a). To examine the effects of changing pitch salience on the FFR, CPR, and behavioral measures of pitch, two different iterations steps were used to create the sensation of either a weak ($n=8$) or a strong ($n=32$) steady state pitch corresponding to 100 Hz ($d=10$ ms).

In addition to the Noise control stimulus (matched in bandwidth to experimental stimuli), IRN0 served as a second control stimulus. Informal listening to IRN0 by trained musicians confirmed that it does not support the production/identification of musical melody. It therefore does not satisfy the most conservative definition of pitch (ASA, 1960; Plack, 2005, p. 2). Like noise, it should not evoke an electrophysiologic response specific to pitch. IRN0 was created by manipulating an IRN32 segment by moving a sliding window (length equal to d) across its temporal waveform and randomizing the phase within each window, thereby removing fine temporal structure (Barker, Plack, & Hall, 2012). While this manipulation removes the sensation of pitch, it retains the broad spectro-temporal features germane to IRN. Here, utilizing IRN0 removes any concomitant