Hearing Research 354 (2017) 9–15

Contents lists available at ScienceDirect

Hearing Research

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

Research Paper

No auditory experience, no tinnitus: Lessons from subjects with congenital- and acquired single-sided deafness

Sang-Yeon Lee [a, 1], Dong Woo Nam [a, 1], Ja-Won Koo [a], Dirk De Ridder [b], Sven Vanneste [c], Jae-Jin Song [a, *]

[a] Department of Otorhinolaryngology-Head and Neck Surgery, Seoul National University Bundang Hospital, Seongnam, Republic of Korea
[b] Unit of Neurosurgery, Department of Surgical Sciences, Dunedin School of Medicine, University of Otago, Dunedin, New Zealand
[c] Lab for Clinical and Integrative Neuroscience, School of Behavioral and Brain Sciences, The University of Texas at Dallas, USA

ARTICLE INFO

Article history:
Received 16 April 2017
Received in revised form
10 June 2017
Accepted 9 August 2017
Available online 15 August 2017

Keywords:
Tinnitus
Single-sided deafness
Bayes

ABSTRACT

Recent studies have adopted the Bayesian brain model to explain the generation of tinnitus in subjects with auditory deafferentation. That is, as the human brain works in a Bayesian manner to reduce environmental uncertainty, missing auditory information due to hearing loss may cause auditory phantom percepts, i.e., tinnitus. This type of deafferentation-induced auditory phantom percept should be preceded by auditory experience because the fill-in phenomenon, namely tinnitus, is based upon auditory prediction and the resultant prediction error. For example, a recent animal study observed the absence of tinnitus in cats with congenital single-sided deafness (SSD; Eggermont and Kral, Hear Res 2016). However, no human studies have investigated the presence and characteristics of tinnitus in subjects with congenital SSD. Thus, the present study sought to reveal differences in the generation of tinnitus between subjects with congenital SSD and those with acquired SSD to evaluate the replicability of previous animal studies. This study enrolled 20 subjects with congenital SSD and 44 subjects with acquired SSD and examined the presence and characteristics of tinnitus in the groups. None of the 20 subjects with congenital SSD perceived tinnitus on the affected side, whereas 30 of 44 subjects with acquired SSD experienced tinnitus on the affected side. Additionally, there were significant positive correlations between tinnitus characteristics and the audiometric characteristics of the SSD. In accordance with the findings of the recent animal study, tinnitus was absent in subjects with congenital SSD, but relatively frequent in subjects with acquired SSD, which suggests that the development of tinnitus should be preceded by auditory experience. In other words, subjects with profound congenital peripheral deafferentation do not develop auditory phantom percepts because no auditory predictions are available from the Bayesian brain.

1. Introduction

Non-pulsatile tinnitus is a common otological symptom, characterized by a conscious auditory perception in the absence of an external stimulus; this is often called a 'phantom sound' because there is no corresponding genuine physical source of the sound (Jastreboff, 1990). Although previous researchers have suggested possible mechanisms of the development of tinnitus that can be summarized into 3 broad categories; 1) peripheral auditory deafferentation and central maladaptive plastic changes, 2) spontaneous neuronal hyperactivity, and 3) increased cross-fiber synchrony (Preece et al., 2003; Eggermont and Roberts, 2012; Tyler, 2006), the exact pathophysiology of tinnitus has yet to be clearly elucidated. A recent study suggested that an established tonotopic map that leads to a corresponding auditory memory is necessary to generate tinnitus (Eggermont and Kral, 2016). According to a similar concept, the Bayesian brain model, the brains of subjects with peripheral hearing loss-induced auditory deafferentation constantly generate predictions about the environment to minimize sensory uncertainty that results from a limited amount of auditory information (De Ridder et al., 2014a). Thus, phantom auditory perceptions following auditory deafferentation are the

* Corresponding author. Department of Otorhinolaryngology-Head & Neck Surgery, Seoul National University Bundang Hospital, 300 Gumi-dong, Bundang-gu, Seongnam, Gyeonggi-do, 13620, Republic of Korea.
E-mail addresses: jjsong96@snubh.org, jjsong96@gmail.com (J.-J. Song).
[1] These two authors contributed equally to this work.

http://dx.doi.org/10.1016/j.heares.2017.08.002
0378-5955/

consequence of an active process during which the brain updates predictions. From this perspective, sensations due to both external stimuli and prediction-driven interpretation and organization are required for the perception of tinnitus (Joos et al., 2014). Previous human studies have reported a relationship between tinnitus pitch and maximum hearing loss frequency, which suggests that tinnitus is a fill-in phenomenon for homeostasis (Norena et al., 2000; Schaette et al., 2012; Schecklmann et al., 2012). In other words, missing auditory information due to hearing loss can induce auditory phantom percepts that correspond to the missing auditory information (De Ridder et al., 2014a; McMillan et al., 2014). Thus, tinnitus can be explained as an intentional compensatory auditory perception. In a recent study, subjects with tinnitus and severe acquired hearing loss exhibited increased cortical activity in the parahippocampal gyrus relative to non-tinnitus controls, and it was suggested that this increase may be associated with abnormal activity aimed at reducing environmental uncertainty (Vanneste and De Ridder, 2016).

Because environmental uncertainty is based on auditory experience, tinnitus may not be generated without prior auditory experiences. Using an animal model of congenital single-sided deafness (SSD), a recent investigation failed to find evidence of auditory phantom percepts in the deaf ear (Eggermont and Kral, 2016). This result suggests that auditory deafferentation that induces phantom percepts should be preceded by auditory experience because the fill-in phenomenon is based upon an auditory prediction and the resultant prediction error (Eggermont and Kral, 2016). To the best of our knowledge, no human studies have investigated the presence and characteristics of tinnitus in subjects with congenital SSD. Thus, the present observational study aimed to determine the presence and characteristics of tinnitus in human SSD subjects to evaluate the replicability of the abovementioned animal study. The present study sought to determine the role that auditory experience plays in the development of tinnitus by analyzing and comparing the presence and characteristics of tinnitus in patients with congenital with those in patients with acquired SSD.

2. Materials and methods

2.1. Participants

This study retrospectively reviewed the records of patients with congenital or acquired SSD who visited the outpatient clinic at Seoul National University Bundang Hospital between January 2016 and December 2016. SSD was defined as follows: (1) pure-tone average of 500, 1000, 2000, and 4000 Hz greater than 90 dB hearing level (dB HL) in the affected ear in conjunction with (2) pure-tone average at the same frequencies lower than 20 dB HL in the non-affected ear. Patients with the uncertain subjective onset of hearing loss, radiological abnormalities (such as a unilateral enlarged vestibular aqueduct) that may have resulted in progressive SSD, or a history of operations or auditory interventions for the treatment of hearing loss were excluded from the study; ultimately, 20 subjects with congenital SSD were enrolled.

After meticulous reviews of subject history, laboratory tests, radiological evaluations, and medical records, seven subjects who had definite clinical or radiological evidence of congenital SSD were classified as “definitely congenital” SSD; this group included a documented congenital infection with the mumps virus (one subject) and several cases of unilateral cochlear nerve deficiency (six subjects). The remaining 13 subjects who did not have definite evidence of a congenital onset but exhibited the subjective onset of hearing loss as “under school age” or “childhood” were classified as “probably congenital” SSD. Subjects with no definite evidence of congenital onset or the ambiguous subjective onset of hearing loss (e.g., “more than 20 years ago”) were excluded from the analysis. The acquired SSD group included 60 patients with no history of tinnitus prior to the onset of idiopathic sudden sensorineural hearing loss (ISSNHL), who were recruited during a retrospective random screening of recently visited patients. None of the subjects in the acquired SSD group had a history of objective tinnitus or etiologies such as Meniere's disease, head injury, brain surgery, or neurological disorders. This study was approved by the Seoul National University Bundang Hospital Institutional Review Board and was conducted in accordance with the Declaration of Helsinki (IRB-B-1703-385-105).

2.2. Audiological and psychoacoustic evaluations

At the initial visit, a structured history of the characteristics of tinnitus on the affected side and the psychoacoustic nature (pure-tone or narrow-band noise) of the tinnitus were obtained. All subjects underwent pure-tone audiometry (PTA) testing that included psychoacoustic tests of tinnitus such as tinnitus pitch matching, tinnitus loudness matching, and the minimum masking level test. The hearing thresholds for seven different octave frequencies (0.25, 0.5, 1, 2, 3, 4, and 8 kHz) were evaluated using PTA in a soundproof booth, and each subject's audiometric configurations were classified into the following three categories based on the PTA results: flat, i.e., thresholds across frequencies did not vary more than 20 dB from each other; high tone, i.e., thresholds showed levels equal to or lower than 250–8000 Hz, and differences between the thresholds at 250 and at 8000 Hz were more than 20 dB; and low tone, i.e., thresholds showed at equal or higher levels from 250 to 8000 Hz and the differences between the thresholds at 250 and 8000 Hz were more than 20 dB (Liu et al., 2011). The mean hearing threshold was calculated using the average of the hearing thresholds at 0.5, 1, 2, and 4 kHz, and the frequency of each subject's maximum hearing loss was determined based on the results of the PTA. In cases where maximum hearing loss was evident at multiple frequencies, the lowest such frequency was recorded. The range of SSD was determined by summing up the audiometric frequencies with a threshold >70 dB (Vanneste and De Ridder, 2016). Due to poor compliance, 16 subjects in the acquired SSD control group were not screened using the tinnitogram, and as a result, the analysis of tinnitus characteristics included 44 subjects from the acquired SSD group.

2.3. Statistical analysis

All data were analyzed using the Statistical Package for Social Sciences software (SPSS 22.0 K, IBM; Seoul, Korea). To determine significant differences between the two groups in the screened continuous and categorical variables, independent *t*-tests, Chi-square tests, and linear-by-linear association analyses were performed, as appropriate. To analyze the relationships between the audiometric variables and the tinnitus characteristics, Spearman's correlation analysis were performed. *P*-values <0.05 were considered to indicate statistical significance.

3. Results

3.1. Demographic characteristics

Subjects’ demographic and clinical characteristics are summarized in Table 1. There were no significant differences between the two groups, except in terms of the SSD etiology; subjects in the acquired SSD control group had idiopathic SSD, whereas those in the congenital SSD group included cases of congenital SSD