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The pitch of synchronized spontaneous otoacoustic emission does not sound familiar to ears that emit it

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ABSTRACT

Spontaneous otoacoustic emissions (SOAE) are sounds that originate from the cochlea and escape the ear. Computer simulation predicts that, given the typical sound pressure level of SOAE measured in the ear canal, the vibration on the basilar membrane should be in the audible range. The aim of this study is to find out whether humans can hear this vibration in quiet. Sixty-three subjects were recruited and synchronized SOAE (SSOAE) were found in 50 ears. These subjects were instructed to spend extra time quietly while paying attention to "sounds in the ear" (SinE). Next, each subject listened to five randomized tones, and was forced to select the one that sounded closest to the SinE. The frequencies of the tones are 88%, 94%, 100%, 106%, and 112% times the frequency of the largest peak in the SSOAE spectrum, respectively. If a subject has SSOAE in both ears, the procedure was repeated for the two ears. Results show that the five choices received 11, 12, 8, 9, and 10 votes, respectively, so none of them was significantly higher than by chance. Hence, the present study falls short of supporting the theoretical prediction that SOAE is audible to the ear that emits it.

Keywords: Otoacoustic Emissions, Cochlea, Spontaneous Oscillation

1. INTRODUCTION

Spontaneous otoacoustic emissions (SOAE) are acoustic waves coming out from the cochlea to the ear canal and have reportedly been found in 30-70% of human ears (1-4). Exactly how SOAE is generated in mammalian ears has been an issue under debate (5). In one theory, SOAE is regarded as a choreographed interplay between cochlear wave amplification and Bragg diffraction-like wave reflection (6,7). Thus, accompanying the spontaneous emission, there must be sustained standing waves inside the cochlea and the working principle is akin to that of a laser. In another theory, SOAE is explained by localized oscillation inside the cochlea without the need to couple to a global standing wave (8-10). The site of local oscillation is likely to be the outer hair cells (11,12). Nevertheless, regardless of the disagreement on the underlying theory, the fact that an ear could produce spontaneous emissions implies the existence of autonomous mechanical oscillation inside the cochlea. This leads us to question whether such autonomous vibration could be sensed by the person who has it in the ear. Further, if the vibration is perceptible, should the sensation be categorized as a kind of *objective* tinnitus?

The term *objective tinnitus* (13) was coined before the discovery of OAE (14). A boy under age 3 was found to produce long-lasting tones from both ears at approximately 5500 Hz and 8000 Hz, respectively. The tone intensities were so high that they could be heard by his parents. The research team (13) ruled out the possibility of "neuro-acoustic transduction from the internal ear" due to lack of mechanisms that would explain such transduction. The origin of the tones from the boy's ears was deemed to be vascular instead. One decade later and after the discovery of click-evoked OAE (14), spontaneous emissions were also confirmed (15) and soon known to exist in 2/3 of normal-hearing ears (16). It was once hoped that SOAE would provide a physical explanation of tinnitus; however, investigations on whether tinnitus pitch coincided with SOAE frequencies yielded mixed results (17).

In the light of recent theoretical progress on the understanding of SOAE, we sought to re-investigate whether one can hear his own autonomous cochlear vibration if one's ear produces spontaneous emission. SOAE frequencies were measured, and the subjects were asked to stay in the sound booth quietly and pay attention to ringing "sound in the ear" (SinE), if there was any. Afterwards, while the memory was still afresh, they listened to a series of 5 tones and selected the one that sounded the most similar to the SinE. While one of the tones was exactly at the frequency of the largest peak in the subject's synchronized OAE (SSOAE) spectrum, we aimed to see if that one tone would receive more votes than other tones. The rest of this paper is organized as follows. Section 2 describes subject recruiting, OAE measurement, and the design of the psychoacoustical experiment. Results and discussions are given in Sec. 3; particularly, a comparison to computer simulation is also given. Section 4 concludes this paper and points to future research directions.

2. METHODS

2.1 Subjects and OAE measurements

Sixty-six subjects (32 male and 34 female) of age 20 to 29 years were recruited to participate in the study. For some technical reasons we decided to measure spontaneous OAE in the click-stimulated manner. The peak sound pressure level of the click was about 74 dB relative to 20 uPa. Click-evoked OAE was measured from both ears for each subject in a sound booth. The click was presented every 59 ms for about three minutes, and the total number of clicks was 3000 for each ear. The ER-10C probe (Etymotic Research Inc., Elkgrove Village, IL, USA) was used for recording the acoustic responses in the ear canal. A 24-bit UltraLite-mk3 Hybrid external sound card (MOTU, Cambridge, MA, USA) was used for analog-to-digital (A/D) and digital-to-analog (D/A) conversion. The sampling rate was set to 44.1 kHz.

In this paper, the first 20 ms of the response is regarded as the transient-evoked (TE) OAE and any signal that remains prominent after 20 ms is regarded as the synchronized SOAE (SSOAE). The click responses contaminated by artifacts were excluded first, and TEOAE and the SSOAE part of the signal was extracted by averaging the remaining click responses to improve the signal-to-noise ratio (SNR). The artifact rejection criterion was the same as described by Liu et al. (18). Figure 1 shows two different ways to visualize the resulting estimate of the OAE signals from a typical subject; by inspection, this subject produced SSOAE in both ears with multiple frequencies. The frequency of the largest peak was manually saved for further exploration in the psychoacoustic part of this research.

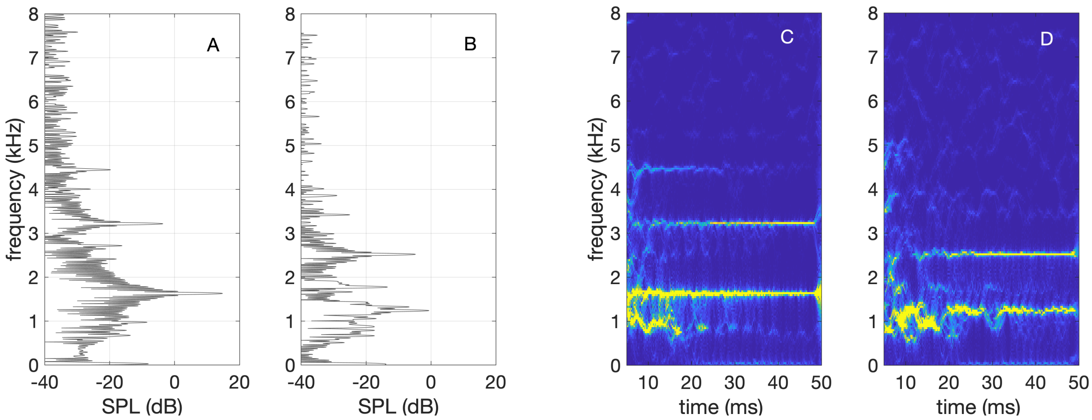

Figure 1 – An example of a subject producing SSOAE in both ears. **A** and **B**: the magnitude spectrum of SSOAE for the left ear and the right ear, respectively. **C** and **D**: the same SSOAE signal from the left and the right ear, respectively. The signal is visualized in the time-frequency plane via a nonlinear signal modeling technique called conceFT (19,20).

2.2 Psychoacoustic experiments

Before starting the SSOAE measurement, the subjects completed a questionnaire in which they were asked to recall if there had been any incidence of "feeling a sound generated inside the ear"; 19 out of 63 responded with a positive answer. Most of them freely described that the sound was at a high frequency and they had heard it in a quiet environment.

After measuring the SSOAEs but without revealing the results to the subjects, they were instructed to stay in the sound booth for 3 minutes. The ER10C earphone remained inserted in the ear canal. The subjects were told that, during the 3 minutes, the earphone would play no sound and their task was to pay attention to any faint ringing sound in the ear (SinE) and be familiarized with the pitch of the sound. The subjects were told that, if they could not hear any SinE, they could please stay in the booth. However, they were also informed that they could terminate the experiment whenever they did not wish to continue.

After the three minutes ended, a sequence of 5 single tones would be played through the ear phone to the ear. If the ear had SSOAE, the frequencies of the 5 tones would be 88%, 94%, 100%, 106%, and 112% times the frequency of the ear's largest SSOAE peak but the order was randomized. If the ear did not have SSOAE, the 5 tones were 880, 940, 1000, 1060, and 1120 Hz, also in a randomized order. In either case, the subject was asked to determine which of the 5 tones sounded most familiar or similar to the SinE.

Out of the 66 subjects, 63 were able to complete the experiment and answer the question for both ears. One subject made more than one choice and another one could not make any choice. Yet another subject could not complete the experiment due to influence by tinnitus based on self-report. Their data are excluded from further analyses.

The measurement of SSOAE and the psychoacoustic experiment were approved by the IRB of National Tsing Hua University under Record Number 10706HE044.

Table 1 – frequency distribution of largest SSOAE spectral peaks for different group of ears. The numbers of subjects are 32 male and 34 female. For each subject, both ears were measured.

Source	**1-2 kHz**	**2-3 kHz**	**3-4 kHz**	**4-7 kHz**
Female, Right ears	5	8	5	1
Male, Right ears	3	4	5	1
Female, Left ears	4	2	3	3
Male, Left ears	1	4	0	1
Total	13	18	13	7

3. RESULTS AND DISCUSSIONS

3.1 Spontaneous emissions and the psychoacoustic experiment

We judged whether an ear produced SSOAE by inspecting the conceFT plot (as in Fig. 1). If the conceFT plot has prominent horizontal traces in the interval of 20 to 50 ms, the ear is regarded as producing SSOAEs. Based on this definition, SSOAEs were found in 15/32 male and 19/34 female subjects. Among them, 5 male and 12 female subjects had SSOAEs in both ears. SSOAEs were found more often in the right ears than the left ears; 7/15 male subjects had SSOAE in the left ear and 13/15 had it in the right ear; to compare, 12/19 female subjects had SSOAE in the left ear while all 19/19 had it in the right ear. The gender (female > male) and lateral (right > left) differences in the prevalence of SOAE both agree with findings in the literature (1-3).

To evaluate the recording quality, an SNR was estimated for each ear. While the true OAE signal was estimated by averaging, the noise floor was estimated by calculating the energy of the following signal (21),

$$f_{\text{noise}}(t) = \{f_1(t) - f_2(t) + \cdots + (-1)^{N-1} f_N(t)\}/N, \tag{1}$$

where $f_j(t)$ denotes the response to the j^{th} click, and N denotes the number of clicks in the recording session. Then, the SNR was defined as the energy ratio of the average signal to the energy of $f_{\text{noise}}(t)$ in the interval of 20 to 50 ms. The mean SNR, calculated after artifact rejection and signal averaging, was 12.5 dB in all ears that produced SSOAE. To compare, the mean SNR was 4.8 dB in ears that do not exhibit prominent SSOAE traces in the conceFT plot.

For every ear that produced SSOAE, the location of largest spectral peak was recorded. All such peaks occurred between 1.0 to 7.0 kHz. By breaking into frequency bands, the counts of the peaks are listed in Table 1. The 2-3 kHz band turned out to be most likely for large SSOAEs to occur.

Results of the psychoacoustic experiment do not seem to suggest any familiarity of the SSOAE frequency by the subject who produces it. Among the two ears of the 63 subjects who completed the psychoacoustic experiment, 50 ears (39.7%) possessed SSOAE and 76 ears (60.3%) did not. The SSOAE from those 50 ears, when presented back to the ear at the frequency of its largest peak, did not sound particularly alike the SinE that the subject tried to pay attention and memorize; only in 8 out of 50 times, the subjects picked the SSOAE frequency to be the most similar to SinE. The other four choices received 10, 12, 9, and 10 votes, respectively (in the order of ascending frequency). Thus, the present results did not suggest that humans could hear one's own SOAE.

To compare, for the 76 ears that did not have SSOAE, the subjects picked the tones at 880, 940, 1000, 1060, and 1120 Hz as most alike their SinE for 15, 11, 18, 13, and 19 times, respectively.

3.2 Comparison to Computer Simulation

A cochlear mechanics model was adopted for computer simulation of spontaneous emission. The model is based on transmission line equations that describe passive wave propagation in the cochlea, and the equations couple to an active module describing the somatic motility in the outer hair cell (22). With 3.0% roughness in the mass of the basilar membrane, Wu and Liu (20) reported that the model could produce coherent reflection (23) and TEOAE. Here, the degree of roughness was further increased to 5.0%. A stronger coherent reflection can be expected, and if the round-trip gain is greater than one, the model should generate sustained oscillation based on the global standing-wave theory of SOAE (6).

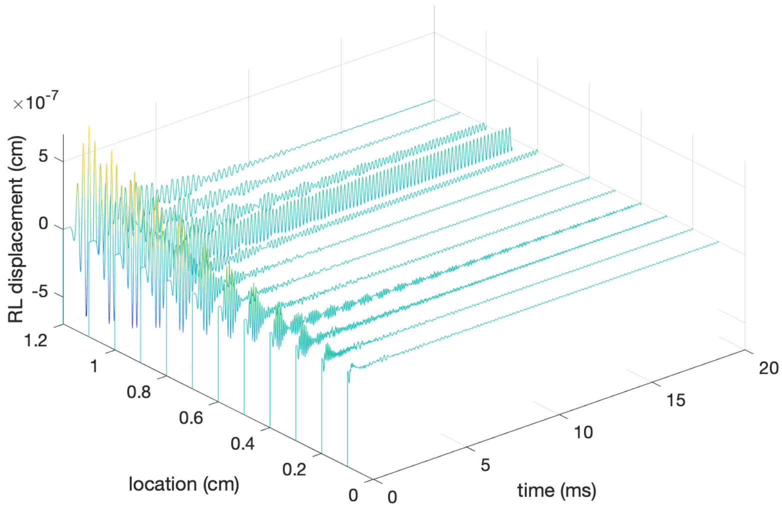

Figure 2 – An example of click-evoked autonomous vibration in the cochlea by simulation. Reticular-lamina (RL) displacement is plotted as a function of time in 12 locations in 0.1 cm steps from the stapes into the model cochlea.

It turns out that 5.0% roughness is sufficiently high to cause sustained vibration in the model. Figure 2 shows the intra-cochlear vibration triggered by a click in the ear canal. Note that near 0.9 cm from the stapes, the RL keeps vibrating during the entire 20 ms. Note that the sustained amplitude of the vibration at 0.9 cm is about 1.0 nm, which corresponds to the magnitude of vibration that a pure tone of a similar frequency at 20-30 dB SPL would cause at its best place in the cochlear (Ref. 22, Fig. 4). In a longer simulation, the vibration amplitude is stable and sustains further to at least 800 ms after the click. This agrees with early experimental findings in click-evoked OAE from human ears (24). During the same time course (after the TEOAE has already attenuated), the ear-canal sound pressure level is about 8.2 μPa (peak level), or -10.7 dB SPL, and the SSOAE frequency is 5.2 kHz for this simulation. Note that the amplitude and frequency are both typical of SSOAEs recorded from human ears. To summarize, the computer simulation suggests that if spontaneous emission is at the -10 dB SPL range when it travels back to the ear canal, the corresponding autonomous vibration in the cochlea would be as loud as a 20-30 dB tone.

3.3 General Discussions

On hindsight, a few factors and short-comings of the experimental design might explain the results we obtained from the present psychoacoustic experiment.

- First, the SSOAE frequency might not be exactly equal to the SOAE frequency (25).
- The SOAE spectrum tend to contain multiple peaks (10); therefore, presenting only the largest spectral peak might not sound similar to the combination of all prominent components.
- The subjects might not be musically capable of remembering the pitch of a sequence of tones that were separated apart by 6% in frequency. Note that 6% corresponds approximately to a semitone distance.
- Presently we test the two ears separately but the percept of SinE might not be lateral.

Quite peculiarly, even though only 19 in 63 subjects reportedly had felt SinE prior to their participation in this study, almost all subjects were able to complete the psychoacoustic tests with no hesitation. It is not clear whether the subjects had heard SinE with confidence during those three quiet minutes in the soundbooth, or they just did not mind to complete the psychoacoustic test and ended up guessing randomly most of the times. While the present results seem to suggest random guessing, nevertheless, it is possible that the SinE sensation was real but its percept did not correlate well with the frequency of the SOAEs (17). There are two possible ways to explain this lack of correlation. First, SOAE and the autonomous vibration in the cochlea might be so stable that the auditory nerves have adapted and been desensitized to it (16) unless the frequency somehow changes momentarily. Secondly, SinE is a percept due to electrical oscillation in the more central part of the auditory pathway. If the second explanation is right, then the present results suggest that most subjects in this group had a mild degree of subjective tinnitus that they could become aware of when they stay quiet for three minutes. Fortunately, none of the subjects were bothered by the SinE.

4. CONCLUSIONS

By recording SSOAE from ears and playing the frequency of the largest spectral peak back to the subjects, we did not find the subjects to be particularly familiar to the tones. Even though they were given a 3-minute period to pay attention to SinE, the present results, like in the literature, did not support a clear correlation between the SinE pitch and the most prominent SOAE frequency. While the present SSOAE measurement seemed robust from various perspectives, it may take a more sophisticated psychoacoustical experiment design in the future, to answer whether the cochlea has any contribution to the SinE “feeling” described in this study.

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