Measuring the effects of medial olivocochlear efferents on the human hearing system during auditory selective attention

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Abstract

Findings from literature suggest that there may be an influence of auditory attention on the medial olivocochlear system, causing the gain of the cochlea to change due to outer hair cell innervation when a person attends or ignores an auditory stimulus. In an attempt to further investigate this effect, the paradigm of a previous pilot study was adapted and the experiment was rebuilt using more accurate measurement techniques. The results showed a minor effect that is a possible indication of attentional influences on the human hearing system. Due to complications in analysis and recordings, the results were not statistically significant and conclusive evidence on this effect still remains to be found.

Introduction

The medial olivocochlear system (MOCS) is an efferent auditory neural subsystem of the brain that originates from the primary auditory cortex. The neural bundles of the MOCS - olivocochlear neurons - are directly connected to the outer hair cells (OHCs) by means of synapses. The OHCs can reduce the gain of the cochlea by influencing the basilar membrane motion, which suggests that the MOCS is a system that can directly alter the gain of the cochlea by influencing OHCs [Guinan et al., 2006]. It is assumed that the pathway is responsible for the suppression of traumatic volume levels and thus serves as a protective system. However, from a biological and evolutional perspective, it is more likely that the main function of the MOCS is to innervate OHCs to improve signal-in-noise detection, as these traumatic volume levels only occur sporadically in nature [Smith & Keil, 2015].

In animal studies, the effects of the MOCS can directly be measured by using an invasive probe to detect the firing rate of the neurons while stimulating the neural bundles [Guinan, 1996]. However, such invasive research methods are not permitted in human subjects. Therefore non-invasive methods are necessary in order to be able to observe the effects of the MOCS in humans. In this study, otoacoustic emissions (OAEs) were used as a non-invasive method to measure the MOC effects. OAEs originate from inner ear [Probst et al., 1991], are influenced by the gain of the cochlea, and are therefore a perfect candidate for investigating the activity of the MOCS. There are different kinds of OAEs that are generally categorized in subgroups, characterized by the stimulus used in order to evoke them (e.g. distortion product otoacoustic emissions, stimulus frequency otoacoustic emissions). In this study, we will however only focus on spontaneous otoacoustic emissions (SOAEs), as they do not require the use of any external stimuli. SOAEs cannot be found in all human participants and therefore a prior screening is necessary in order to find participants with SOAEs of sufficient amplitude. If SOAEs are found to be sufficiently large in a certain participant, they can be studied and used to measure the gain of the cochlea in a non-invasive way, which in turn can then be related to the activation of the MOCS.

The MOCS can be activated by means of contralateral stimulation with an adequate stimulus sound intensity level [Zhao & Dhar, 2011]. When activation occurs, the amplitude of the SOAEs typically decreases and their corresponding frequency increases. When auditory attention is included, previous studies have shown that there can be differences in the amount of suppression that occurs when attention is focused either on or away from the stimulus. In some cases, studies have shown more suppression of OAEs during the non-attending condition [Giard et al. 1993], while others have observed more suppression during attending conditions [Maison et al., 2001 Froehlich et al., 1993]. To this day, the effect remains a topic of discussion and conclusive evidence about this phenomenon still remains to be found.

In this pilot study, we aim to investigate how the MOCS might improve signal-to-noise ratio by studying its behaviour during auditory selective attention tasks. It is expected that the MOCS adjusts the gain of the cochlea when attending to or ignoring auditory stimuli. In a previous pilot study by Wierenga, these effects had already been observed. In his study, small, but real differences were found between the attending and non-attending condition and the experiment has demonstrated a quantitative and qualitative method to measure these MOC effects. However, in this particular study only one participant was tested, not allowing for any statistical significance testing and therefore not granting the possibility of a proper conclusion. Additionally, they did not have access to the more modern and accurate microphones and amplifiers that are currently available. By adapting the previous paradigm and rebuilding the experiment, utilizing new equipment as well as improving on the way auditory attention is acquired during testing, we hope to provide novel insights into the efferent effects of the MOCS.

Methods

Materials

SOAEs were recorded in both ears, but only data from the contralateral ear to the stimulus ear was used. The recordings were obtained and pre-amplified (+20dB) using Etymotic Research 10B+ Low-Noise Microphones (sampling frequency = 48kHz). They were then further amplified (gain 50x), filtered (high-pass 300Hz 12dB/octave rolloff) and digitized with a Stanford Research Systems SR560 Low-Noise Amplifier. Data was then stored on a MacBook Pro 2011 laptop running the experiment in a MATLAB environment while simultaneously recording the data from each trial. The stimuli were pure sinusoidal tones generated with a MATLAB program, and were presented to the participant using EARTONE 3A Audiometric Insert Earphone speakers. Both the microphone system and speakers were connected to the laptop using an ESI U24XL 24bit USB sound interface.

Participants

Three participants - two males (age 23 and 53) and one female (age 20) – were tested in this experiment. Data from a previous study has shown that SOAEs were present in all of the participants. During the preliminary measurements of this study, participants were again tested for SOAEs. The SOAEs were found in either the right, left or both ears, but only the largest and most prevalent SOAE in one ear was chosen as the target emission of the experiment.

Experiment design

Regular SOAE measurements (120s continuous, silent) were conducted before and after the experiment. These measurements were not further used in the analysis of the data, but were used solely to confirm prevalence of SOAEs and to select a target emission.

The participants were asked to sit in a chair and listen to a total of 180 tones (50% high and 50% low tones, 1 octave below and 1 octave above target emission), and they were being instructed to focus on either the left or the right ear. Each of these tones were counted as one trial with a pre-stimulus and stimulus window (Fig.1). The pure tones were either short (1s), long (1.5s) or in the wrong ear (1.25s). The participants were then asked to ignore the tones in the wrong ear (non-attending condition) and to focus on the tones in the correct ear (attending condition). When a stimulus was presented in the correct ear, the participants were asked to press one of two buttons to indicate whether the tone was shorter or longer. When the stimulus was presented in the wrong ear, the participant was asked to ignore the tone and not press any of the buttons (for an example of the experiment paradigm, see figure 2). In order to make the task difficult and achieve maximal attention, the response time window was kept between 0.5s and 0.8s. Any button presses that were outside of the response window were counted as misses. Performance was then measured by counting the number of correct answers during the experiment relative to the total number of tones presented. SOAEs were measured during the stimulus tone and during the silent pre-stimulus period in the contralateral ear relative to the stimulus ear.

Analysis

The SOAEs were analysed in the spectral domain. The spectral analysis was performed on the recordings by using the built-in Welch windowing FFT algorithm in the MATLAB programming interface (pwelch.m, windowsize = 18kHz, 50% overlap). Only raw sound data was used, no filtering or artefact rejection was applied.

SOAE frequencies (f0) were then acquired for each trial separately by fitting a Lorentzian curve to the spectral data [van Dijk & de Kleine, 2011] (Fig.3). The total MOC effect was determined by calculating the difference between the f0 of the SOAE during the stimulus and the f0 of the SOAE during the pre-stimulus periods. Noisy trials were then removed manually, and the means and standard errors were calculated for each condition. The same procedure was repeated for all participants, across all conditions.

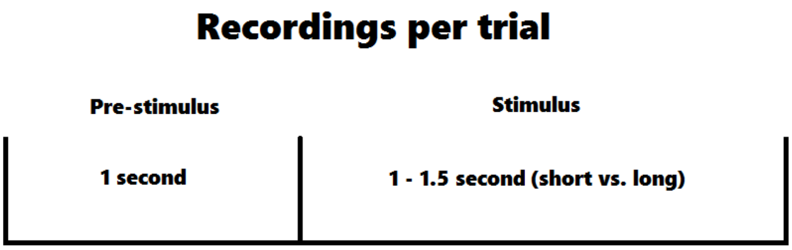

Figure 1: Spontaneous otoacoustic emissions were recorded 1 second before stimulus onset, as well as during the stimulus.

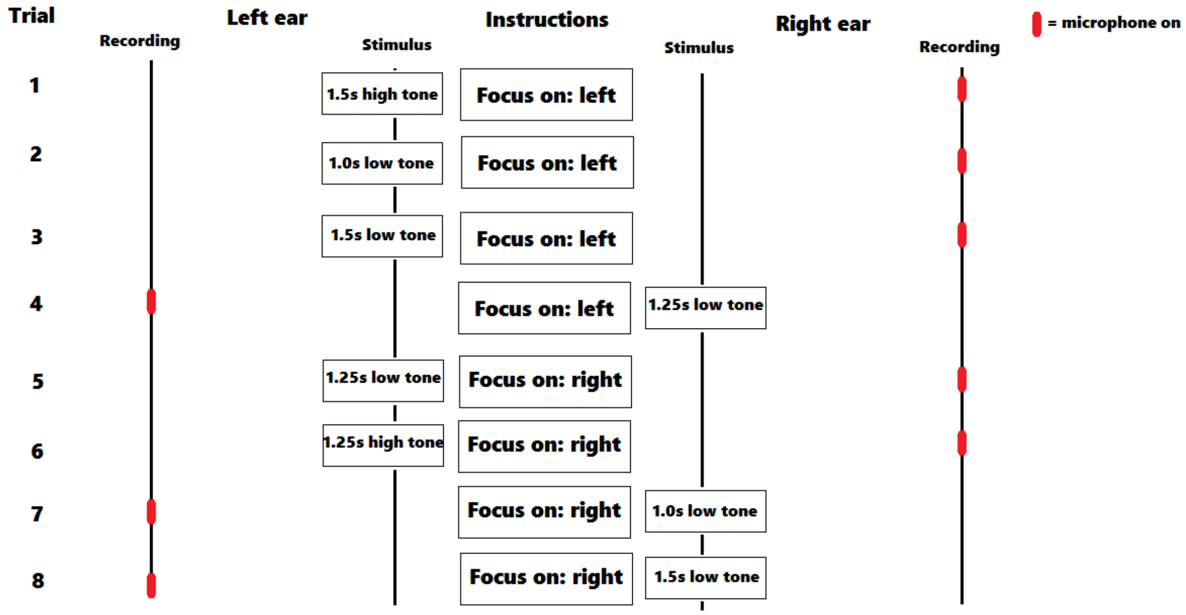

Figure 2: An example of the experiment paradigm. Illustrated above are the first 8 trials of the experiment. Participants were told to focus on a certain ear and press buttons corresponding to the tone while ignoring the tones in the other ear. SOAEs were simultaneously recorded in the contralateral ear (red line).

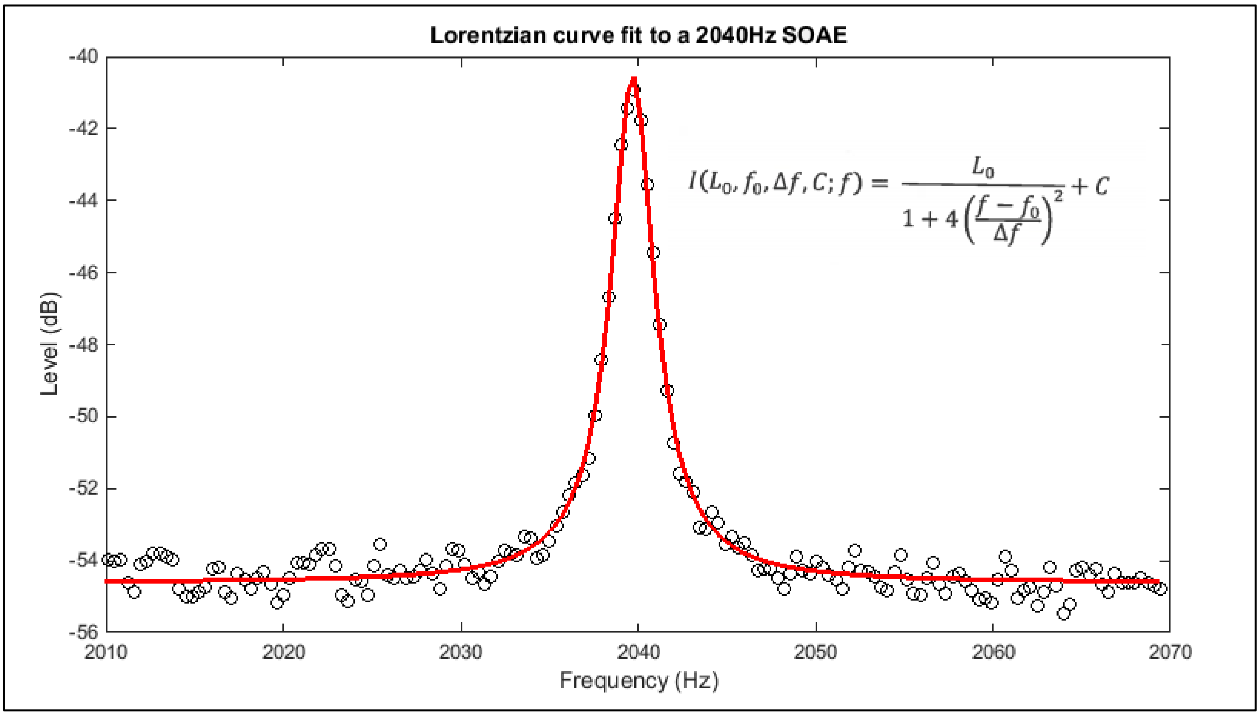

Figure 3: A Lorentzian curve [van Dijk & de Kleine, 2011] was fitted to the data points of the spectral analysis using the least square method. The f0 frequency of the SOAE was obtained by fitting curve for each trial separately.

Results

The results of one single trial analysis of one participant are demonstrated in figure 4 and 5. To illustrate, the f0 frequencies during all trials in the attending condition are summarized for one participant. The f0 is shown for each trial during the pre-stimulus (orange dots) and during the stimulus period (blue dots).

The MOC effect was then calculated by subtracting the acquired prestimulus f0 from the stimulus f0. Therefore, a positive value reflects an increase of frequency and therefore a suppression of the SOAE, whereas a negative value reflects a decrease of frequency and an enhancement of the SOAE (fig. 5).

A wide variance in SOAE frequencies was observed across all participants, even in the same condition. Values fluctuate 0-2 Hz around the expected SOAE frequency in rest (as found in the preliminary measurements). A simple linear regression fit demonstrates that overall, no SOAE suppression has occurred under these conditions (line at 0).

For a more in-depth analysis, the mean f0 frequencies and 95% confidence intervals were calculated for each trial across all participants in the corresponding condition (fig. 6). Significant activation of the MOCS was only observed in one participant in case of low tones. Following the experiment design, the tones in this condition were 1 octave below target emission (in this case a 2300Hz SOAE), which corresponds to a tone frequency of 1150Hz.

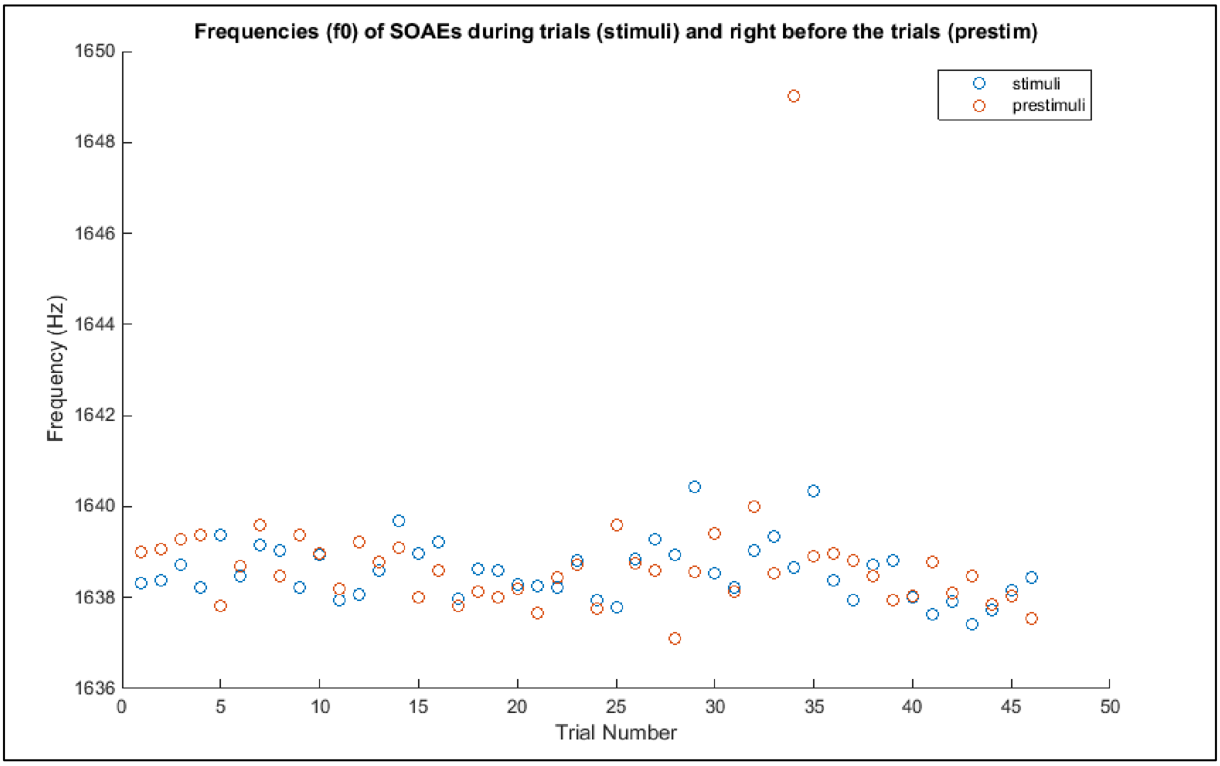

Figure 4: Spontaneous otoacoustic emission frequencies (f0) across all trials in the attending condition for participant 1.

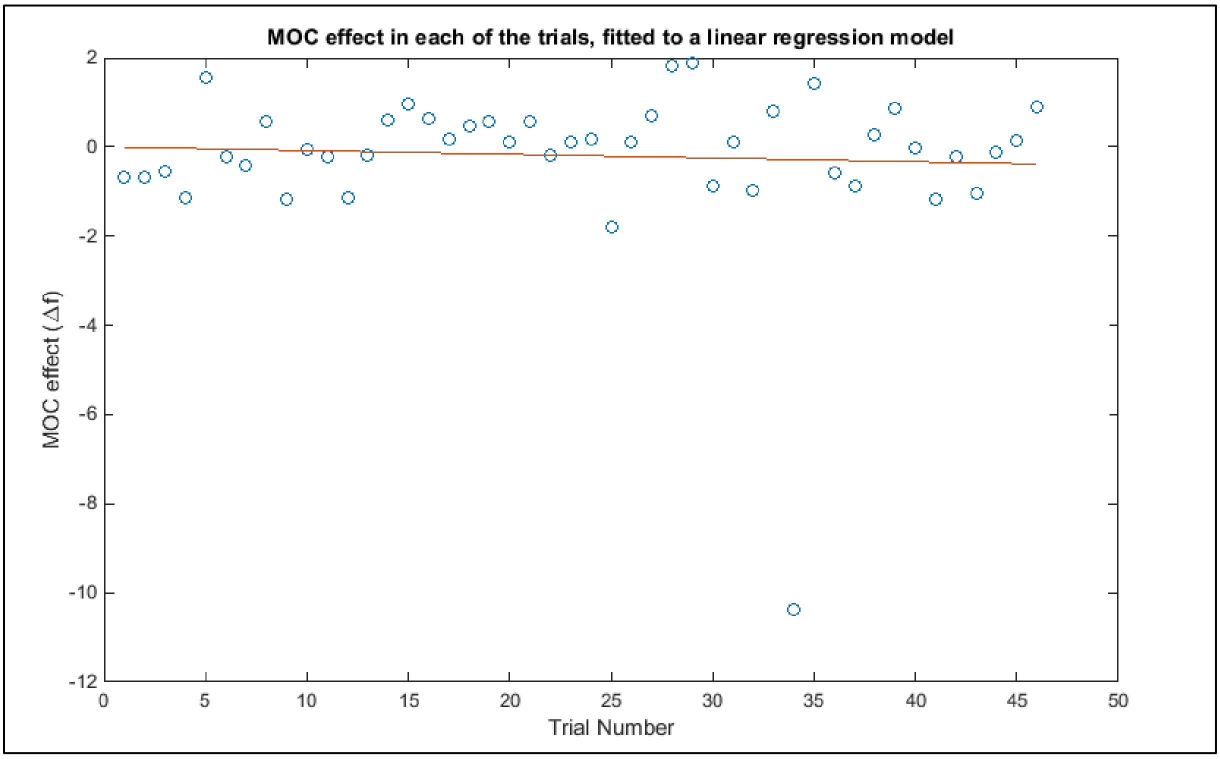

Figure 5: The observed MOC effect for participant 1 in the attending condition. Values vary about 0-2 Hz from the expected SOAE frequency in rest.

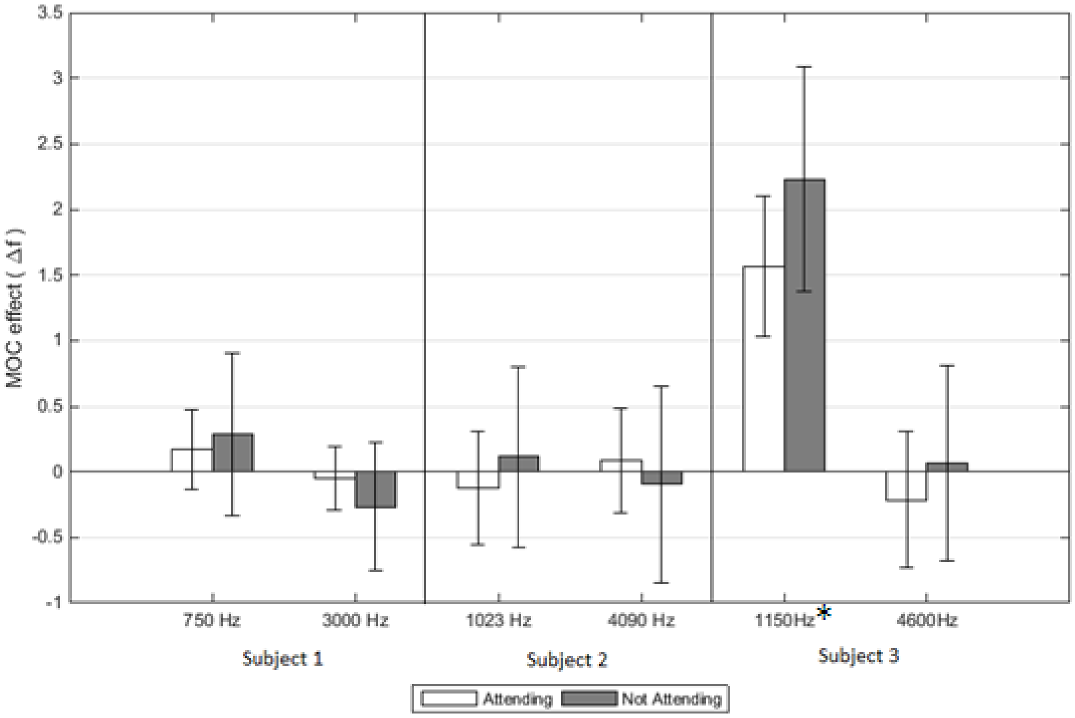

Figure 6: A summary of the experiment results across all participants (target SOAE subj1: 1500Hz, subj2: 2046Hz, subj3 2300Hz) showing the mean MOC effect in each condition along with their respective 95% confidence interval. Observed variance in frequency was larger than the mean MOC effect in all participants, with the exception of low frequency tones in subject 3 (in fig.).*

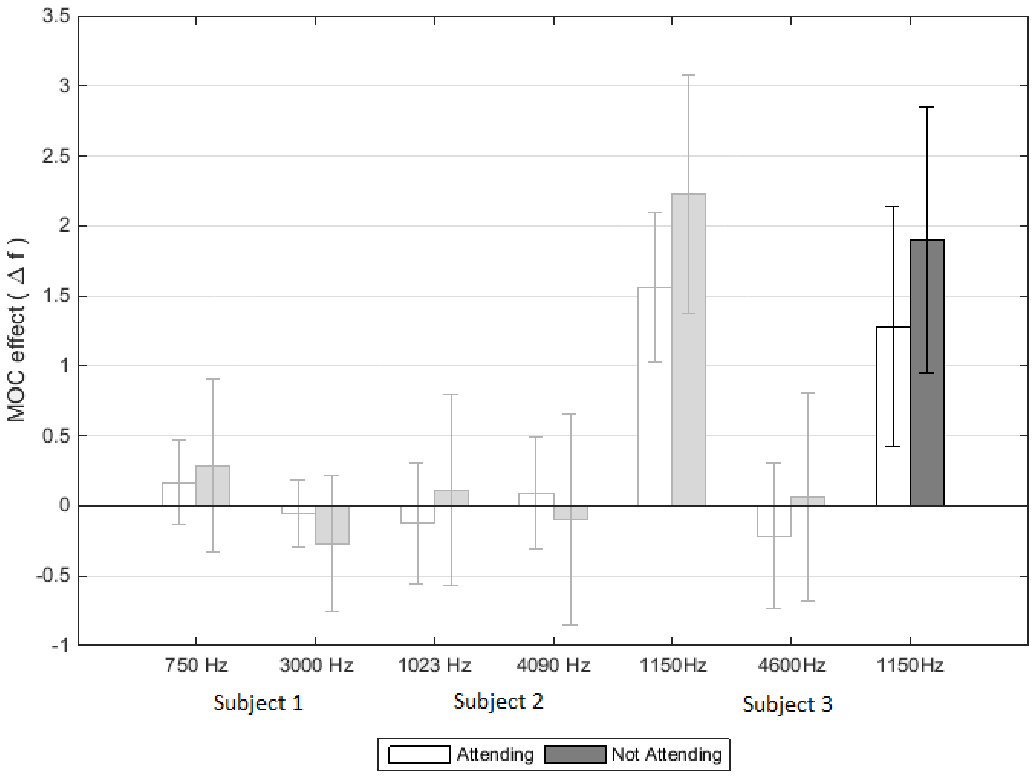

Figure 7: Follow up experiment with subject 3 (preliminary results), visualised alongside the results of the original experiment.

Discussion

The goal of this pilot study was to investigate the activity of the MOCS during auditory attention tasks. It was expected that the SOAEs would be less suppressed when the participants were attending to the auditory stimulus and would be more suppressed when they were ignoring the auditory stimulus. We aimed to activate the MOCS through contralateral stimulation with pure sinusoidal tones, and to investigate MOC effects in attending conditions versus non-attending conditions. However, several complications with the experiment design and the analysis of data have made it impossible to come to a definitive conclusion on the attentional effects of the MOCS.

Firstly, the stimuli used in this study were pure sinusoidal tones as opposed to the broadband noise stimuli that were used in a previous study on the fast and slow effects of the MOCS. In this study, SOAE suppression was found only when presenting low frequency tones to the third participant. No significant activation was found across all other participants, in any of the conditions. In order to confirm this finding, a short repeat experiment was done with this particular participant, using only stimuli 1 octave below target SOAE frequency (fig. 7). Similar results were achieved: a large frequency shift was observed and the shift was higher in the non-attending condition versus the attending condition. Due to a lack of time however, it has not yet been possible to perform a follow up experiment on the other participants yet. This finding is an indication that the contralateral activation of the MOCS might be more frequency dependent than previously thought and may even differ across individual participants. We recommend using stimuli with a lower frequency than the target SOAE, rather than using higher frequency stimuli. More investigation on this matter is necessary in order to rule out frequency dependency in any follow up experiments.

Secondly, a problem that further complicated the analysis was the frequency instability of SOAEs. Over time, SOAEs often show a clear and steady increase in frequency when recording for a sufficiently long period of time. The experiment typically lasted around 45 minutes. Silent, more reliable SOAE measurements were performed before and after the experiment. These measurements showed in most cases that over time, a much larger frequency shift would occur than the expected frequency shift due to suppression of SOAEs. Therefore, it was necessary to study each of these trials individually (previously mentioned as *single trial analysis*), further complicating analysis.

Lastly, we found that overall the current analysis technique was not sufficiently accurate for detecting small MOC effects in the range of 1-2 Hz. Large effects such as the one found in the third participant can be observed, but accuracy is still not sufficient when looking at differences between the attending and non-attending conditions, the most important aim of this pilot study.

This inaccuracy is most likely a result from the analysis technique that was used as well as from the method in which the SOAEs were recorded. SOAEs were recorded in a relatively short time period (see fig. 1) and this complicates the frequency analysis that is needed for investigating SOAEs. More specifically, the Welch windowing FFT algorithm that is used to calculate the power spectral density (PSD) estimates in this study gets more accurate as recordings get longer. Generally, SOAE recordings are 120-180s as opposed to the 1-1.5s recordings in this study. This resulted in PSD estimates that included a relatively high noise floor, and were inaccurate overall. Therefore, any follow up studies should place particular emphasis on developing an experimental design that allows for both longer uninterrupted recordings as well as optimizing the frequency analysis method.

Even though the results of this experiment have not shown any significantly large differences between the auditory attending and non-attending conditions due to complications in analysis, there are still indications that the effect of the MOCS may be present. In the case of participant three in the low tone condition, we do observe a small difference in the suppression of SOAE. More suppression of the SOAE seems to occur during non-attending tasks, and less suppression of SOAEs during attending auditory tasks, which is consistent with the hypothesis that attentional effects can influence the MOCS.

Conclusion

The goal of this pilot study was to provide more insight into how the medial olivocochlear system (MOCS) influences the gain of the cochlea during auditory attention. We have possibly observed an effect, measured only in one out of three participants using contralateral stimulation with a pure tone, 1 octave below target spontaneous otoacoustic emission (SOAE) frequency. When the participant was attending to the auditory stimulus, less suppression was observed than when the participant was not attending to the stimulus. Similar results were however not achieved across all participants due to unsuccessful activation of the MOCS. It was found that MOC activation is more frequency dependent than previously anticipated. Not enough data was acquired along the duration of this study to provide conclusive evidence and statistical significance.

Current techniques to measure SOAEs, using a similar setup to the one used in this experiment, are most likely accurate enough and well suited to solve this problem given the proper circumstances. Future research should therefore firstly focus on improving the experiment protocol to allow for longer SOAE recordings. More MOCS activation was observed in case of stimuli that were 1 octave below target SOAE, so improvements may also be made by investigating at which frequencies maximal MOCS activation occurs (i.e. -0.9/-0.3 oct. stimuli). Secondly, more accuracy in the measurements can be acquired by further optimizing the analysis of the recordings and the parameters of the Welch algorithm. Finally, statistical significance may be acquired by testing a large amount of participants with the revised experiment.

Although this pilot study has been unsuccessful in demonstrating conclusive evidence of an attentional effect on the MOCS, subtle differences have been observed between the attending and non-attending conditions in one participant. This indicates the possibility of a real, but small influence of attention during these auditory attentional tasks. However, as of yet, there is insufficient data for a truly meaningful answer to these questions.

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