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COMPARISON OF DIFFERENT EXCITATIONS TO ASSESS THE OBJECTIVE OCCLUSION EFFECT MEASURED ON HUMAN SUBJECTS

Hugo Saint-Gaudens,
École de technologie supérieure, Montréal, Québec, Canada
email: hugo.saint-gaudens@etsmtl.ca

Hugues Nélisse and Franck Sgard
IRSST, Montréal, Québec, Canada
e-mail: hugues.nelisse@irsst.qc.ca, franck.sgard@irsst.qc.ca

Frédéric Laville, Olivier Doutres
École de technologie supérieure, Montréal, Québec, Canada
email: frederic.laville@etsmtl.ca, olivier.doutres@etsmtl.ca

Occlusion effect is a known phenomenon affecting in-ear device (e.g., hearing protection devices HPD, hearing aids) wearers. This psychoacoustical annoyance felt when the ears are occluded is perceived under various types of natural excitations such as physiological noises (chewing, breathing, heart beats) and one's own voice or under an artificial excitation such as a bone oscillator. A common objective measurement of this occlusion effect (denoted OE) is defined as the difference between sound pressure levels (SPL) measured inside the occluded ear and the unoccluded ear. Two factors may cause this indicator to be sensitive to the type of excitation: (i) the repeatability of the excitation, because occluded and unoccluded SPLs are commonly measured at two different moments and (ii) the contribution of airborne sound emitted during the excitation process and mainly captured during unoccluded ear measurements. To investigate the impact of these factors, SPLs are measured with miniature microphones placed in occluded and unoccluded ears of various participants subjected to 5 different excitations, namely chewing, bone oscillator and speech at three intensities. Measurements are done in three ear configurations: (i) both ears unoccluded, (ii) one ear occluded and contralateral ear unoccluded, (iii) both ears occluded. This allows for the calculation of the aforementioned OE, but also a much less common indicator called the Real-Time Occlusion Effect (RTOE). Results are presented and discussed to compare the occlusion effect induced by the three excitations and objectively measured using the OE and RTOE indicators.

Keywords: Occlusion effect, voice, bone oscillator

1. Introduction

In-ear devices are worn daily for many reasons, such as a worker wearing a hearing protection device (HPD) in a noisy workplace or a person with hearing losses assisted by a hearing aid. In both cases, even when the in-ear device is carefully selected, a person may remove it because of the induced discomforts. One source of discomfort is the occlusion effect which is often described as the psychoacoustical annoyances felt when the ears are occluded, e.g. one's own voice perceived as « hollow » or « muffled » [1,2] and increased perceived loudness of physiological noises such as breathing and chewing [3]. It can be objectively measured using a microphone in the earcanal as the difference of sound pressure level (SPL) in the occluded and unoccluded earcanal. It can also be subjectively measured as the difference of hearing thresholds between when the ear is occluded and unoccluded, when submitted to the vibrations generated by a bone oscillator.

This paper focuses on the objective measurement of the occlusion effect (OE) induced by hearing aids and HPD. Although numerous experimental investigations have been carried out on this measurement, the methodology has not yet been standardized and no consensus can be found on which excitation to use. Bone oscillators have been widely used, but have their limitations. To be effective, bone oscillators must be placed on a region where skin layers are thin and close to the skull, e.g. the forehead and the mastoid process. These two locations are often problematic when testing HPD since a mechanical interference can occur between the HPD and the bone oscillator [4]. They also require specialized equipment since they must be well controlled and calibrated. Although bone oscillators are clinical instruments with high repeatability, the generated excitations aren't as complex as other excitation types since it is applied on a single point on the skull and is entirely transmitted by bone conduction (BC) [5]. Speech, however, offers the advantage to be simple to use, e.g. the subject's own voice, and that it excites soft tissues and bones via the speech organ, e.g. larynx and oral cavities [5], generating an excitation with both an airborne conduction (AC) and BC component. However, high repeatability is more difficult to achieve and parameters such as speech content, speech duration and speech intensity vary from a study to another and their influence on the OE have not been thoroughly investigated. Finally, chewing is another excitation type used [2,5,6]. While simple, it has been reported that the type of food masticated, e.g. crunchy vs. soft, has an influence on the repeatability [6]. It is also suspected that the directives given to the subject might have an influence on the AC and BC components generated by the excitation, e.g. open vs. closed mouth, normal vs. exaggerated movement, thereby affecting the OE.

In order to reduce the variability due to an excitation repeatability, simplify the procedure and obtain a robust measurement of the objective occlusion effect, a much less common indicator is investigated: the real-time occlusion effect (RTOE). Instead of measuring the occluded and unoccluded SPL in a single ear successively, the RTOE uses both ears simultaneously. As mentioned by Hansen [5], the RTOE is expected to provide advantages over the OE since excitations are only generated once. First, the time required to measure the occlusion effect is halved. Second, variability due to the poor repeatability of some excitation types, e.g. speech amplitude shifts when the ears become occluded [6], which affects the OE, is decreased when using the RTOE.

The goal of this paper is to determine if the RTOE could be substituted for the OE while also investigating the influence of the excitation type on the occlusion effect. First, the experimental protocol is presented. More specifically, the participant's selection, the necessary equipment and the calibration procedure, the definition of the indicators and the experimental procedure are explained. Then, OE and RTOE results for different excitation types are compared and discussed. Finally, a conclusion recalls the significant elements of this study and presents the next steps of the investigation of the RTOE.

1.1 Participants selection

15 male participants between the age of 22 and 33 (average = 25.1; standard deviation = 2.9) volunteered to participate in the study. All participants met the following inclusion criteria: (i) no wax plug or

injuries detected during an otoscopy, (ii) normal tympanogram measures (static compliance = 0.3-2.5 mL; pressure = -100 - +50 daPa), (iii) airborne hearing thresholds ≤ 20 dB HL in both ears with an interaural difference ≤ 10 dB HL (from 125 Hz to 8000 Hz), (iv) bone conduction hearing thresholds ≤ 20 dB HL with a masked/non-masked difference ≤ 10 dB HL (from 250 Hz to 8000 Hz). A Shoebox Pro audiometer (Clearwater, Canada) was used with 3M™ E-A-RTone™ insert earphones (3M™, USA) for measuring airborne thresholds and a RadioEar B-81 bone oscillator (RadioEar, USA) for measuring bone conduction thresholds. Prior to taking part in the study, participants were required to read the project general information and sign a consent form, as approved by the IRSST and ÉTS Research Ethics Committee (Certificate #H20180402)

1.2 Equipment and calibration

Measurements were done in a 20 m³ audiometric booth (Industrial Acoustics Company Inc., USA) equipped with four speakers and a computer screen as shown in Fig. 1. Two microphones were placed 125 cm above the floor and approximately 60 cm from the participants' mouth: a 1" G.R.A.S type 26HF with a type 12HF amplifier (G.R.A.S, Denmark) and a ½" B&K type 2669 with a type 2829 amplifier (Brüel & Kjaer, Denmark). Both were used as reference microphones: the 1" microphone was connected to a real-time sound level meter in a LabVIEW interface (National Instruments, USA) for the participant and experimenter to monitor the A-weighted equivalent continuous sound level, denoted as Leq(A), with integration time of 500 milliseconds (Leq(A)$_{500ms}$). The ½" microphone was connected to a NI PXI 1033 chassis mounted with NI PXI 4461 & 4462 acquisition cards (National Instruments, USA) controlled with an in-house Matlab program (MathWorks, USA) for the data acquisition.

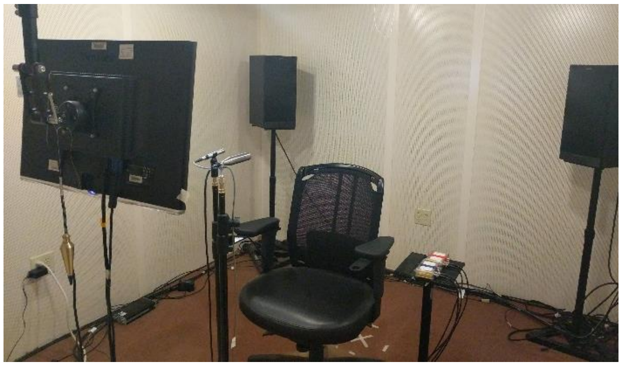

Figure 1 - Measurement setup in the 20 m² audiometric booth with the participant's chair in the middle, four speakers and computer screen for real-time feedback system.

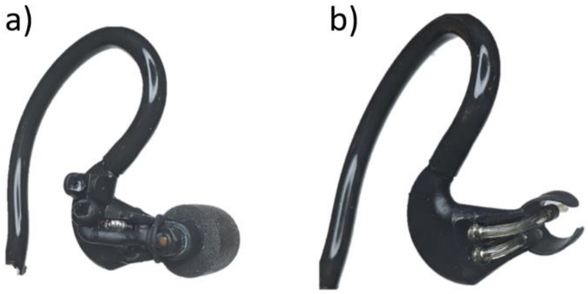

Figure 2 - Pictures of the custom microphonic earpieces. a) Occluded configuration (with the Comply ear tip). b) Unoccluded configuration.

SPLs in earcanals were measured using two pairs of different custom-made earpieces [7,8] as shown in Fig. 2. A first pair, a protecting earpiece (Fig. 2a), was used for occluded ear measurements. It was designed so that various sizes (small, medium, large) of Comply T-400 Isolation ear tips could be installed (Comply, USA) to ensure some noise attenuation. A second pair (Fig. 2b) was used for unoccluded ear measurements. This earpiece was designed to be almost acoustically transparent, thus causing no or minimal occlusion effect. Both pairs of earpieces were equipped with two microphones: a first microphone connected to a probe tube to measure SPL approximately 15 mm into the earcanal from the tragus; a second microphone to measure the SPL at the entrance of the earcanal. Probe tube microphones were calibrated by placing the probe tubes opening next to the calibrated reference microphone inside the audiometric booth and by generating a 90 dB(A) uncorrelated white noise using four speakers. A frequency-dependent correction factor was then calculated for each microphone of each earpiece. Custom-made electronic switch boxes allowed the connection between the earpieces and the NI PXI cards.

1.3 Occlusion effect indicators and methodologies

Two objective occlusion effect indicators with their respective method were investigated. First, the standard occlusion effect indicator, denoted as OE, is calculated as the difference between occluded and unoccluded ear SPLs, respectively referred to as Lp_{OCC} and Lp_{UNOCC}, in a single ear. The excitation signal was produced successively in the occluded and unoccluded ear to measure Lp_{OCC} and Lp_{UNOCC} separately. OE is given by Eq (1).

$$OE = Lp_{OCC\,(ear\,1)} - Lp_{UNOCC\,(ear\,1)} \tag{1}$$

Second, the real-time occlusion effect indicator, referred to as RTOE, is calculated as the difference between occluded and unoccluded SPLs, but using both ears simultaneously. One ear is occluded with the protecting earpiece (see Fig. 2a) while the other one is instrumented with the “transparent” earpiece (see Fig. 2b). With a single excitation, Lp_{OCC} and Lp_{UNOCC} are measured simultaneously in their respective ear. RTOE is given by Eq (2).

$$RTOE = Lp_{OCC\,(ear\,1)} - Lp_{UNOCC\,(ear\,2)} \tag{2}$$

Although measurement durations are expected to be reduced by half and the indicator not to be influenced by an excitation repeatability, hypotheses have to be made to allow measurement of the RTOE. First, the excitation type and location must induce a similar excitation in both ears. Second, the left and right earcanals should be sufficiently anatomically symmetrical to use the RTOE [5]. Assuming these hypotheses are met, equal Lp_{UNOCC} should be measured in both earcanals.

1.4 Experimental procedure

Each participant was first met for an admissibility session. The eligibility criteria presented in section 1.1 were evaluated under the supervision of a Canadian-registered audiologist. The ear with the lowest airborne and bone conduction thresholds was identified as the ipsilateral ear (IE) and the other ear as the contralateral ear (CE). For subsequent bone oscillator measurements, the IE mastoid process was used for bone oscillator placement. Each participant was then met in a second session for the objective measurement, during which SPLs were measured with six microphones (two reference microphones and two microphones in each of the two earpieces), allowing for calculation of the various occlusion effect indicators (OE, RTOE) and earplug sound attenuation (NR).

Five distinct excitations were produced to induce the occlusion effect, divided into three categories: chewing, bone oscillator and speech. Chewing consisted of masticating a chewing gum on the IE side, mouth closed. This directive was given to ensure a similar mastication for each participant. Bone conducted sounds were generated by a RadioEar B-81 bone oscillator driven at 25 dB HL with a pure tone signal for the fixed frequencies of 0.25, 0.5, 0.75, 1.0, 1.5 and 2.0 kHz. Speech was produced by the participants pronouncing random numbers. Three $Leq(A)_{500ms}$ were to be achieved: 60, 70 and 80 dB(A). A LabVIEW sound level meter was displayed on the screen in front of the participants to allow reaching and maintaining the targeted $Leq(A)_{500ms}$ during the 20 seconds recording for each excitation type.

The five excitations were repeated for three ears configurations: A. Transparent earpieces in both ears; B. Protecting earpiece in the IE and transparent earpiece in the CE; C. Protecting earpieces in both ears. Following the positioning of the protecting earpiece inside the earcanal for the configurations B and C, a 90 dB(A) white noise was generated to measure the NR provided by the protecting earpiece. If the sound attenuation (NR) was too low, the earpiece was repositioned into the earcanal and the measurement was repeated until sufficient attenuation was obtained. For each recording, temporal data were recorded and then used to calculate the SPL in third octave bands with in-house Matlab scripts. SPLs were then used to calculate the OE, RTOE and NR. Occlusion effect measurements with the five excitations were randomized from one subject to the other to prevent an order effect.

1.5 Statistical tools

Student T-test and ANOVA were used to analyze the data. Following the ANOVA, a multiple comparison test was used to determine if means could be grouped. Frequency bands were not considered as a factor in the analyses since it is expected that the acoustic phenomena of interest are frequency dependent. Therefore, statistical analyses were always carried out per each frequency bands. For all statistical tests, two statistical significance levels were used: weak (p-value < 0.05) and strong (p-value < 0.01).

2. Results and discussion

2.1 Excitation type influence on the ipsilateral ear occlusion effect

First, OE results for the IE only are shown in Fig. 3 for each excitation type namely chewing (n = 15), speech (n = 15) at 60, 70 and 80 dB(A) (noted V_{60}, V_{70} and V_{80}) and bone oscillator (n = 14). The frequency range of interest is 160 Hz to 2000 Hz except for the bone oscillator which starts at 250 Hz.

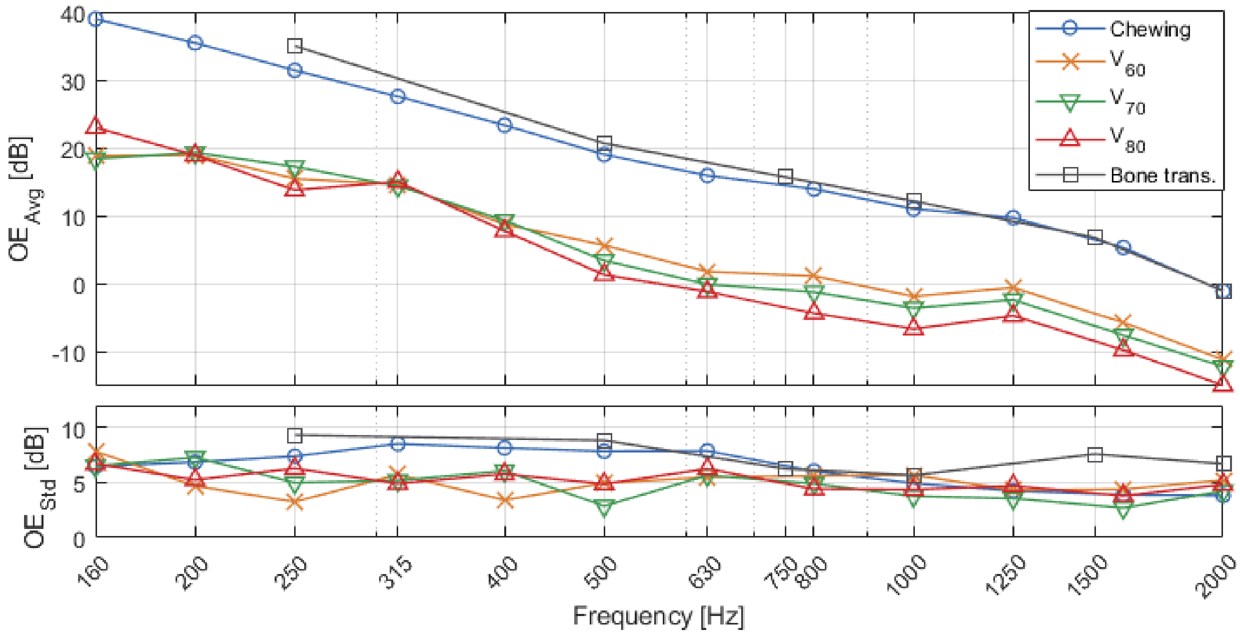

Figure 3 – Mean OE (top) with standard deviation (bottom) for the ipsilateral (IE) ear obtained with chewing (--o--), speech at 60 dB(A) (--x--), 70 dB(A) (--▼--), 80 dB(A) (--▲--) and bone oscillator (--■--) .

Highest OE values are obtained with chewing and bone oscillator over the observed frequency spectrum. Chewing induces OE close to 39 dB at 160 Hz, down to -1 dB at 2000 Hz. Similar behaviour is observed with the bone oscillator, with 35 dB at 250 Hz and down to -1 dB at 2000 Hz. In both cases, mean OEs decrease with a slope of approximately -30 dB/decade between 250 Hz and 1000 Hz, close to the values and slope predicted by Stenfelt's lumped electro-acoustical model for an earplug inserted 10 mm into the earcanal [9]. Mean OE values obtained with chewing and bone oscillator are compared using a Student t-test. The statistical analysis indicates no significant statistical differences for frequencies of 0.25, 0.5, 1.0 and 2.0 kHz. Therefore, it suggests that chewing could be used to estimate bone oscillator

OE for the IE ear. When comparing the variability, both excitation sources yield a standard deviation variation between 4 dB and 10 dB between 250 Hz and 2000 Hz. Replacing the bone oscillator by mastication could make the BC occlusion effect measurement much faster and simpler. The obtained results seem to suggest similarity between both excitation sources, but further investigations are required to confirm whether chewing can be used as a substitute for bone oscillator measurements.

Although three different speech intensities were to be achieved by the participants, mean OEs are similar. OEs range from 18 dB and 23 dB at 160 Hz and are all equal to 15 dB at 315 Hz. From 315 Hz and beyond, OE decreases differently for each speech intensity. V_{80} induces the least OE, reaching 0 dB between 500 Hz and 630 Hz, down to -15 dB at 2000 Hz. On the other hand, V_{60} causes the largest OE, reaching 0 dB between 800 Hz and 1000 Hz, down to -11 dB at 2000 Hz. Standard deviations range from 3 dB to 8 dB for all three speech intensities. An ANOVA analysis followed by a multiple comparison test were conducted to determine if differences were statistically significant between all three speech intensities.

At lower frequencies, between 160 Hz and 400 Hz and at 630 Hz, all three means are statistically equal. At 500, 1000 and 1250 Hz, there is a statistically weak difference between the means of V_{60} and V_{80}. At 800 Hz and 1600 Hz, strong statistical differences are observed between the means of V_{60} and V_{80}. Although there are statistical differences between V_{60} and V_{80} at multiple frequencies, these differences are less than 6 dB. On the other hand, no statistical differences were found when comparing together V_{60} against V_{70} and V_{70} against V_{80}. These results show that vocal intensities have very little influence up to 630 Hz. At 800 Hz and above, OE is influenced by how loud the participant talks, though these differences are statistically significant when varying speech intensity (low voice vs. shouting). Additional tests would be necessary to conclude if a real-time feedback system is necessary for a participant to adjust its voice to obtain a specified speech intensity for OE measurement. Since the OE phenomenon is more important in the low frequencies, the present results suggest that such system wouldn’t be required.

As observed by Sgard et al. [4], the OE obtained with the bone oscillator is much larger than with speech. It is suspected that this difference is related to the relative contribution of the AC and the BC component. With the bone oscillator and chewing, most of the energy is transmitted via BC, hence measuring a low Lp_{UNOCC} when the ear is unoccluded. On the other hand, higher Lp_{UNOCC} are measured when using speech since both AC and BC components are present. Since OE is based on the difference between Lp_{OCC} and Lp_{UNOCC}, measured OE is larger with the bone oscillator and chewing although the SPLs measured with speech are much higher (not shown here).

2.2 Occlusion effect (OE) and real-time occlusion effect (RTOE) comparison

Before analyzing RTOE against OE, unoccluded SPLs in the IE and CE for speech and chewing are first compared, but are not shown here. This made it possible to verify that the hypothesis stated in section 1.3, namely that Lp_{UNOCC} should be equal in the IE and CE for RTOE, is valid for all four excitations. Using a Student t-test, mean Lp_{UNOCC} are typically statistically equal in both ears for the three speech intensities and only different between 400 Hz and 630 Hz for chewing ($p\text{-value} < 0.01$). Even though statistical differences are found with chewing, this excitation is kept for the OE and RTOE comparison.

The OE and RTOE obtained with chewing and speech are shown in Fig. 4. Mean RTOE obtained with chewing ranges from 36 dB at 160 Hz down to -5 dB at 2000 Hz. Typically, the RTOE is 3.5 dB lower than the OE. The OE and RTOE slopes are also different: while the OE decreases approximately -30 dB/decade between 160 Hz and 2000 Hz, the RTOE slope almost becomes null between 630 Hz and 1000 Hz. Standard deviations obtained with the RTOE are typically lower than with the OE and more consistent over the entire frequency range. For speech, OE and RTOE yield almost identical mean values and differences between the two are typically lower than 3 dB. Mean speech-induced RTOE ranges from 18 dB to 22 dB at 160 Hz and all means are equal between 200 Hz to 315 Hz. Beyond 315 Hz, the influence of speech intensity is the same as with OE: V_{80} induces the least RTOE and V_{60} creates the greatest RTOE. As with the RTOE, the differences between V_{60} and V_{80} are typically lower than 5 dB. Standard deviations are similar for both indicators with differences < 1 dB. However, the RTOE standard deviation is more consistent over the entire frequency range. To determine if both indicators are equal, a Student t-test was carried out between OE and RTOE for each excitation and each frequency band.

For chewing, weak statistical differences ($p\text{-value} < 0.05$) are found between 400 Hz and 800 Hz. Below and above these frequencies, the RTOE and the OE are found to be statistically equal ($p\text{-value} > 0.05$). For speech, both indicators measure a similar occlusion effect since only weak statistical differences ($p\text{-value} < 0.05$) are found in isolated frequency bands for V_{60} and V_{80}.

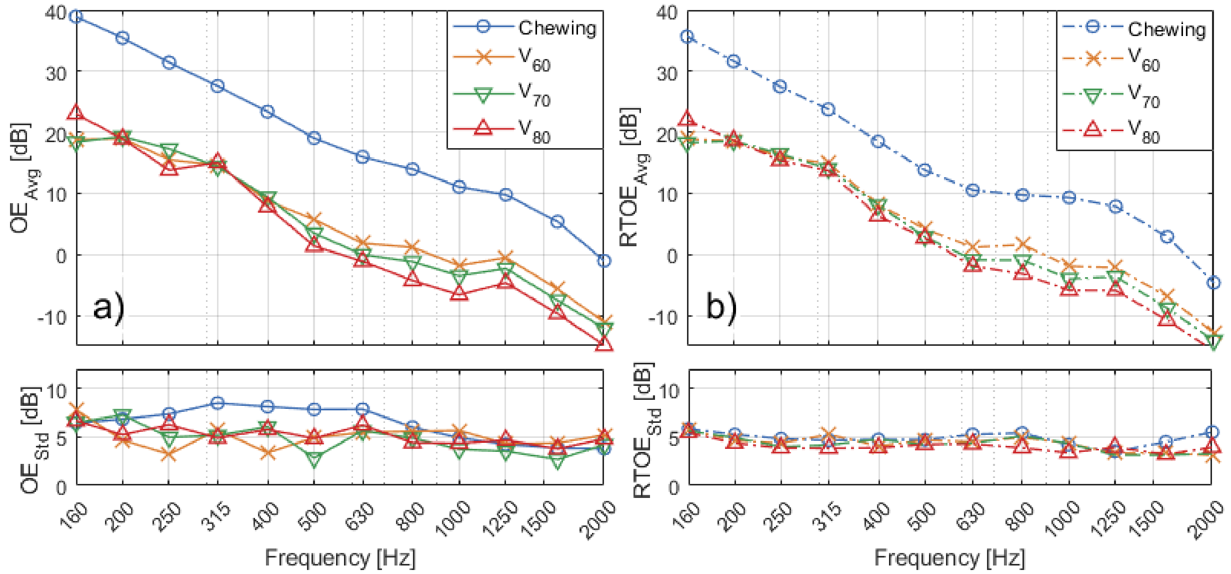

Figure 4 - a) Mean OE with standard deviation (top) with standard deviation (bottom), b) mean RTOE (top) with standard deviation (bottom). For both OE and RTOE, excitations are chewing (--o--) and speech at 60 dBA (--x--), 70 dBA (--▼--), 80 dBA (--▲--).

While more measurements and analyses are required to further validate the RTOE, some factors may explain the differences between OE and RTOE in the case of the chewing excitation: excitation source location, earpiece movements and excitation type. Firstly, chewing was realized on the IE side of the mouth to homogenize the mastication process across all participants, which made the excitation source closer to the IE than the CE. Further measurements will be performed to verify how the chewing movements and location affect the OE and RTOE. Secondly, transparent earpiece movements were reported by some participants due to the earcanal deformation by the contraction of jaw muscles while chewing, which might have affected the measured SPLs. Finally, since OE and RTOE are different indicators with their respective measurement procedures (two consecutive measurements steps in one ear vs. one measurement step in both ears), each might be adequate for different excitation types. Repeatable excitation types such as the bone oscillator might be more adapted for OE while less repeatable ones such as speech and chewing more adapted for RTOE. Although the present work shows encouraging results on the use of the RTOE as a substitute for the OE, parameters affecting RTOE need to be further investigated.

3. Conclusion

The measurement of the objective occlusion effect induced by earplug or hearing aids was investigated using the OE indicator based on a single ear-two steps measurement, and a much less common indicator, the RTOE, based on both ears-single measurement step. Both indicators were analyzed for fifteen human subjects using chewing, speech at three vocal intensities (60, 70 and 80 dB(A)) and a bone oscillator placed on the mastoid process. Results showed that for the OE, chewing and the bone oscillator yielded similar results when measured on the IE. Speech produced a much lower occlusion effect than with the bone oscillator or chewing. It does not come as a surprise as a more important AC is present with speech compared to the bone oscillator or chewing. It was also found that speech intensity only slightly influenced the OE and RTOE. The differences were more pronounced when comparing two very different speech intensities, for example, low voice and shouting. The RTOE was then compared to the OE for chewing and speech. RTOE yielded occlusion effect values very similar to the OE for speech, but statistical differences were found for the mastication. The excitation source location, earpiece movements and excitation types are parameters that are suspected to explain the differences between OE and RTOE and will be investigated in the future. All results presented in this paper are preliminary because data were collected on fifteen participants only. It is intended to gather data for a total of forty participants. Future analyses will continue to assess the influence of excitation sources and measurement methodology on the occlusion effect, with the objective of developing a new robust and simple method to measure the occlusion effect in order to improve hearing protection devices and hearing aids research and development.

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