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QUANTIFICATION OF THE ENVELOPMENT SENSATION BY SOUND DURING UNDERWATER LISTENING EXPERIENCE: THE WORK OF A BIMODAL PERCEPTION?

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ABSTRACT

Investigating human hearing underwater through auditory thresholds have been of interest for nearly a century. The qualitative perception of sound underwater is however underexplored despite a growing quest by humans to enchant their senses in the water. We conducted two observational experiments involving underwater listening (ears underwater) and showed that Envelopment Sensation by Sound (ESS) was highly frequent (40 people out of 49) in both live aerial and underwater loudspeaker broadcasting (speech and music). This sensation involved the whole body, with a predilection for the head region (77.5%) followed by the trunk (55%). Our study, supported by an extensive bibliography, shows that the ESS is probably a bimodal perception; auditory and vibro-tactile. Our results corroborate the hypothesis that bone/soft tissue conduction mechanisms predominate in the stimulation of human hearing underwater, presumably reinforced by the vibrotactile stimulation of skin mechanoreceptors in the presence of low frequency acoustic stimuli (<1kHz). This bimodal synergy would be the source of the enveloping and penetrating sensation of sound described by the participants. Careful recommendations for the level and frequency content of underwater sound broadcasting will thus allow for an optimal musical experience underwater, particularly via low frequencies.

Keywords: underwater hearing, acoustic stimulation, auditory perception, touch perception, envelopment sensation, real world research.

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1. INTRODUCTION

Mankind gives particular attention to the wonderment of his senses while exploring the aquatic world, whether it is for enjoyment, athletic or therapeutic purpose. Our senses of sight and touch are often exalted in the aquatic environment, our human ability to hear though seems to be impaired. Several studies revealed that Humans have higher hearing thresholds and poorer capacity to localize sound underwater in comparison to their performance in the air. Moreover, very few studies have addressed the qualitative perception of an underwater hearing experience, and even fewer were conducted in a real world environment. The aim of this study was to:

1. Present the main findings on human auditory perception underwater,
2. Assess the Envelopment Sensation by Sound (ESS) in a real-world acoustic experiment with ears underwater.

2. UNDERWATER ACOUSTIC PERCEPTION IN THE LITERATURE

2.1 Higher hearing thresholds for humans underwater

In airborne environments, the human auditory system is particularly sensitive to the frequency range of 1.5 - 6 kHz [1]. In the aquatic environment, the sensitivity of the human ear decreases considerably underwater regardless of the frequency (a difference that varies from 24 dB SPL for 25 Hz to 72 dB SPL for 4 kHz) [2–5]. For frequencies below 1 kHz the range of bone conduction intensity is consistent with the underwater hearing curves. This suggests that bone conduction plays an important role in our underwater hearing, especially

since the curves of underwater auditory thresholds are much closer to those of bone conduction than to those of air transmission for the frequencies studied [250, 8000 Hz]. We note the presence of a shift from the frequency range to which the human ear is more sensitive, i.e. 1.5 to 6 kHz in the air, to the 0.25 to 2 kHz range in the water. Also, human underwater hearing has a greater affinity for low frequencies than for high frequencies, whereas the latter are the frequencies of choice in the air.

2.2 Auditory stimulation underwater: three mechanisms instead of two?

Hearing is the act of perceiving sound in response to acoustic waves or mechanical vibrations acting on the body [1]. Airborne acoustic stimulation is mainly done by two transmission mechanisms: air conduction (AC) and bone conduction (BC). Being a terrestrial mammal, the AC is the primary mode of transmission for humans. It requires the participation of the external and middle ears in the excitation of the internal ear.
The BC is the transmission of vibrations to the cochlea through the bone cavities housing the ear [6]. Stimulation can be direct (contact with a vibrating object on the mastoid region or skull) or indirect, by picking up vibrations from the environment, which usually have to be of high intensity [1, 7].

Soft tissue conduction (STC) is a third mode of auditory stimulation that has recently been explored and which complements the two other types of conduction [6]. STC is defined as hearing induced by vibrational stimuli that reach the skin and soft tissues which do not directly overlie the skull bone, such as the neck, chest and body. Vibrations induced in soft tissues propagate along those tissues until they reach and excite the ear [6].

The literature is divided on the parts that each of these three types of stimulation plays in human underwater listening. Some authors support the idea that BC predominates over AC [4], whereas others argue against this hypothesis [5], in addition to some researchers who imply the involvement of STC in the process [6].

2.3 Envelopment sensation by sound underwater

The difference in impedance between the human body and air results in increased reflection at the skin-air interface compared to the skin-water interface, where the latter favors sound transmission due to comparable impedances of human body and water [8].

The term of envelopment sensation by sound during an underwater listening experience has been initially introduced by the French composer M. Redolfi, specialized in underwater concerts. He describes "*the space of the underwater listening to be a space perceived as mat and enveloping*" [9]. His words were corroborated in [8] which simulated the experience of drowning using in-lab sound installation. The author found that envelopment /immersion was the most reported feeling by the participants using open-ended questions. This sensation was also found in preliminary trials we conducted with a group of participants accustomed to water aerobics, where a ESS was spontaneously reported by most of them while listening to the Qanûn with ears underwater. They reported the music to be *positively enveloping, penetrating or piercing sensation, like an aura or a halo*. These terms may indeed differ semantically, but we have considered them as synonyms in the present work to illustrate this singular underexplored sensation that sound can trigger during an underwater listening experience.

3. UNDERWATER LISTENING EXPERIMENT

3.1 Material and methods

3.1.1 Study design & setting

We conducted a cross-sectional study using a questionnaire to explore human auditory perception during an underwater listening experience. We focused on studying the ESS as an expression of this perception during water recreational activities in 2 swimming pools: Experiment 1 (Zmorda space Tunis, Tunisia, april 2022) and Experiment 2 (Couloisy, France, june 2022). Experiment 1 (Exp1) focused on underwater listening with live aerial broadcasting (speech of coach and music of Qanûn[2], sound level 30 - 95 dB SPL A airborne), floating on their backs (ears underwater versus in the air) whereas Experiment 2 (Exp2) involved a concomitant sound diffusion via aerial and underwater speakers' sound level (85-90) dB SPL A, various positions (ears underwater versus in the air). We used the patented underwater speaker of Ocean'sArise which allows a wide band diffusion in the water (40 Hz - 12 kHz). Pre and

[2] The Qanûn is a musical string instrument, a type of Psaltery (for more details, consult this link https://mimo-international.com/mimo/detailstatic.aspx?RSC_BASE=IFD&RSC_DOCID=OAI_CIMU_ALOES_0867262&TITLE=/psalterion-qanun)

post-survey discussions were held with the participants about the experiment's execution and purpose.

3.1.2 Variables of interest

Envelopment sensation by sound (ESS): we inquired about the presence of penetrating/enveloping sensation by sound when listening underwater using a Yes/No question. We insisted in the briefing that aquatic envelopment (being surrounded by water) was not the outcome of interest.

Body areas involved with ES: participants were asked to specify using an open-ended question where in their body they felt ESS (if any). We used the Body Map package (Talevich, 2021) to illustrate the frequencies of the reported anatomical regions .

3.2 Results

Participants: We included 49 healthy volunteers (good apparent health, with no contraindications to practice sports nor known hearing problems) who were divided between Exp1 and Exp2. In Exp1 we included only adults (>18 years) while in Exp2 children (~10 years) were included in the swimming session. All individuals in Exp1 participated in water aerobics, whereas participants of Exp2 took part in various water activities (training, concert, sophrology).

Our listening protocols were approved by the Biomedical Ethics Committee of the Pasteur Institute of Tunis (CEBM) and the National Instance of Personal Data Protection (INPDP) of Tunisia.

Data collection: Data were collected using a self-administered questionnaire, in paper format, written in French. The confidentiality of personal data was duly respected during the collection and entry of Exp1 using pseudonymization. The second experiment's questionnaire was anonymous. Both questionnaires included general questions (socio-demographic) and perception-related questions; the latter included ordinal questions (5-point likert scale), categorical scale (yes/no questions) and open-ended questions.

3.2.1 Prevalence of envelopment sensation

The majority of participants (40 over 49) reported feeling an envelopment by the sound (voice and/or music) during the different underwater activities (figure 2).

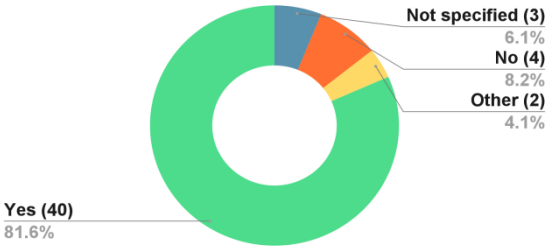

Figure 2. Distribution of responses on envelopment sensation (ESS) Yes/No: presence/absence of ESS

whether it was live aerial listening (Exp.1) or sound diffusion by underwater loudspeaker (Exp.2),

3.2.2 Body regions involved in envelopment sensation

For the 40 persons who reported ESS, the most frequently mentioned areas of the body were the head (77.5%), followed by the chest (57.5%) and abdomen (42.5%) as detailed in table 2 and figure 3.

Table 2. Frequency of body regions reported as involved with envelopment sensation.

Body region	Retained responses	Freq. of responses
Head	head, back of the head, brain, skull, whole body, upper body.	31
Neck	neck, nape, whole body, upper body.	13
Thorax	chest, torso, thorax, whole body, upper body	23
Abdomen	belly, whole body	17
Back	back, backbone, marrow, upper body, whole body	13
Limbs	legs, arms, shoulders, whole body	10

We hypothesize that the ESS induced by acoustic waves is a bimodal perception, involving both hearing and the vibrotactile sense. The human skin is endowed with mechanoreceptors (Meissner's and Pacini's corpuscles) that capture the surrounding vibrations whose frequency is up to 1 kHz [10-11]. This is particularly interesting given that low frequency waves are less attenuated when

traveling through water and the human body compared to the higher ones. Moreover, several studies confirm that auditory and tactile perceptions are coupled, where the two senses influence each other by altering the perceived amplitude level [10-14]. This suggests the existence of bimodal processing and integration of this acoustic signal [13-14], likely resulting in ESS.

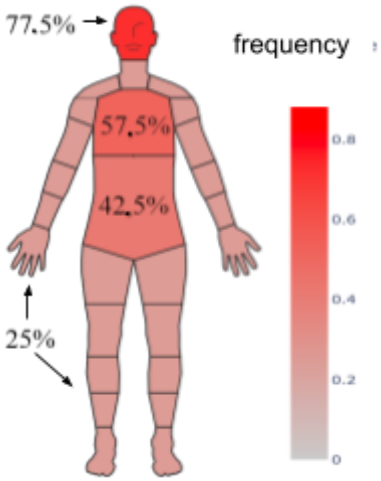

Figure 3. Heatmap of the anatomical regions concerned by the sensation of envelopment and their frequency.

This study has indeed brought new insights into human acoustic perception underwater, but it still has some limitations. Firstly, this study was observational with no possible inference to make. Secondly, the perception of ESS has not yet been well defined, hence leading to possible measurement or acquiescence biases. Although the recall bias has been limited by getting all questionnaires immediately filled after the experiment. Further studies should be conducted to address these biases and eventually involve patients with conductive hearing impairment or cutaneous hypoesthesia in order to better understand the roles played by vibrotactile perception, BC and STC in the genesis of ESS.

4. CONCLUSION

The present work was an attempt to uncover some aspects of human acoustic perception underwater. We focused on the envelopment sensation by sound while listening underwater, which was notably prevailing in our study sample (82%) independently of the aquatic activity undertaken. In order to achieve an optimal auditory experience underwater, especially with the advent of innovative aquatic speakers, we recommend careful adjustment of sound levels and equalization of its frequency content, with special attention to the low frequencies.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] A.A. Scharine, K.D. Cave, and T.R. Letowski: “Auditory perception and cognitive performance.” 2009.
[2] D. Fothergill, J. Sims, and M. Curley: “Neoprene Wet-Suit Hood Affects Low-Frequency Underwater Hearing Thresholds.” Aviat. Space Environ. Med. vol. 75, pp. 397–404, 2004.
[3] P.M. Hamilton: “Underwater Hearing Thresholds.” J. Acoust. Soc. Am. vol. 29, no. 7, pp. 792–794, 1957.
[4] H. Hollien and S. Feinstein: “Contribution of the external auditory meatus to auditory sensitivity underwater.” J. Acoust. Soc. Am. vol. 57, no. 6, pp. 1488–1492, 1975.
[5] K. Sørensen, J. Christensen-Dalsgaard, and M. Wahlberg: “Is human underwater hearing mediated by bone conduction?” Hear. Res. vol. 420, pp.108484, 2022.
[6] H. Sohmer: “Soft Tissue Conduction: Review, Mechanisms, and Implications.” Trends Hear. vol. 21, pp. 425–429, 2017.
[7] P. Henry, T. Letowski: “Bone conduction: Anatomy, physiology, and communication.” pp. 192, 2007.
[8] L. Lamy: “Submersion. Explorer l’expérience de la noyade par l’installation sonore”. Master’s thesis. Uni. Paris Lumières. https://www.ens-louis-lumiere.fr/submersion-explorer-lexperience-de-la-noyade-par-linstallation-sonore, 2020.
[9] M. Redolfi: “Ecouter sous l’eau”. Alliage : Culture - Science - Technique, 10, pp.47-54,1991.
[10] S. Merchel, M.E. Altinsoy: “Psychophysical comparison of the auditory and tactile perception: a survey.” J.Multimodal User Interfaces. vol. 14, no.3 , pp. pages 271–283, 2020.
[11] R.T. Verrillo, A.J. Fraioli, and R.L. Smith: “Sensation magnitude of vibrotactile stimuli.” Percept. Psychophys. vol. 6, no. 6, pp. 366–372, 1969.
[12] S. Merchel and M.E. Altinsoy: “Auditory-tactile music perception.” J. Acoust. Soc. Am. vol. 133, no. 5, pp. 3256–3256, 2013.
[13] T. Ro, J. Hsu, N.E. Yasar, L. Caitlin Elmore, and M.S. Beauchamp: “Sound enhances touch perception.” Exp. Brain Res. vol. 195, no. 1, pp. 135–143, 2009.
[14] H.-I. Won and M.E. Altinsoy: “Effect of Auditory Feedback on Tactile Intensity Perception in a Touchscreen Application.” IEEE Trans. Haptics. vol. 13, no. 2, pp. 343–353, 2020.