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RESEARCH ARTICLE

Vibrotactile Stimulation for Emotional Elicitation During Audiovisual Events

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ABSTRACT Audiovisual media are an essential source of information and leisure in our lives, but people with hearing disabilities lose the emotional content that is intended to be transmitted through this channel. Some previous studies have tried to find alternative ways to elicit these emotions using other sensory channels, and some attempts have been made with haptic systems synchronized with rhythms of music and action in movies, but they fail in studying deeply the provoked neural response. In this article, we propose the tactile channel as the alternative to the auditory channel to convey the emotions generated by audiovisual events, measuring the effect of a proprietary system in the emotions by monitoring neural response. We have developed a low-cost system consisting of an Arduino Uno, a pair of gloves with micromotors and a driver. Using EEG, we have measured brain activity generated during audiovisual stimulation of a short film with clearly negative emotional content, with and without synchronized tactile stimuli, in two groups of people, one without hearing impairment and the other with hearing impairment. We have used the Hotelling's T2 test as a multivariate statistical analysis of EEG measurements. Comparing the difference in brain activation generated in the conditions with and without vibration in both groups, we have found that multimodal stimulation by touch and associated with audiovisual stimuli enhances in a 30% the emotional, attentional, and auditory circuits activation, due to brain reorganization around frontal and parietal structures (all related to emotional responses) in the hearing-impaired group.

INDEX TERMS Accessibility, audiovisual, EEG, emotions, hearing impairment, multisensorial, parietal cortex, temporal cortex, vibrotactile.

I. INTRODUCTION

Since its inception, the purpose of cinema has been to move us, to make us laugh and cry and experience all the emotions in between. What we see on the screen helps us to imagine stories, what we hear not only helps us to understand the story, but the sound effects immerse us even more in it. In recent decades, watching audiovisual works has become an indispensable part of contemporary culture. Not only in the entertainment industry, but also in education, science, and art. However, hearing impaired; hard of hearing people miss out on a lot of information because they cannot hear voices, sounds or music.

This makes it difficult for hearing impaired people to enjoy the full experience. Article 30 of the United Nations Convention on the Rights of Persons with Disabilities establishes the

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right of persons with disabilities to participate in cultural life on an equal basis [1]. This includes access to everyday items such as television, as well as to cinemas, theatres, and all other performing arts. In the specific case of the audiovisual sector, the easiest way to make up for this lack of information is to use subtitles, with the transcription of the speakers, which appear at the bottom of the screen, or subtitles for sound effects and background music, which appear at the top right. The combined use of both subtitles helps to immerse the user to some extent but does not convey the emotional information contained in the auditory part, such as ambient music or the OST.

However, the auditory pathway is not the only way to activate emotional processing. Advances in tactile technology, with a focus on replacing the auditory pathway, are creating new opportunities for people who cannot hear music.

The sense of touch transforms vibrations into electrical signals, responding to the mechanical energy of these fluctuations, but also to chemical and thermal changes, having nociceptors or pain receptors, thermoreceptors, and mechanoreceptors. The 4 mechanoreceptors of the skin, located in the epidermis, directly convert the different vibrations into electrical signals. These signals are sent to the spinal cord by afferent neurons. These mechanoreceptors are divided into 2 groups, Slow Adaptation (SA) and Rapid Adaptation (RA): SA, slow adaptation, Merkel receptors, which detect edges and borders; Ruffini corpuscles, which detect static deformation. They respond to mechanical pressure, proportionally and for the duration of the stimulus. RA, rapid adaptation, Meissner's corpuscles, detect low frequencies, from 5 to 200 Hz; Pacini's corpuscles, detect high frequencies, from 40 to 1,000 Hz. Both respond to skin movement, and only during the change. These signals are subsequently processed in the somatosensory area of the brain parietal lobe [2], [3]. These frequencies and mechanical types of stimulation have to be taken into account whenever a stimulation system has to be designed.

There are many similarities in the psychophysical characteristics of the tactile and auditory senses, although the anatomy and physiology of the two modalities are quite different [4]. Both senses use their own systems to convert vibrations into electrical impulses. There are studies showing that audio-tactile integration occurs very close to the primary sensory areas, even before the pre-attentional mechanisms [5]. This transformation occurs, for auditory, in the cochlea and for tactile, through the different types of receptors located along the glabrous skin: Ruffini, Merkel, Meissner and Pacini, the last two being the most suitable for haptic stimulation due to their low activation threshold and frequency range as commented above [6], [7]. In addition, there is a strong physical relationship between the properties of sound and vibration, such as pressure and frequency [8], [9]. This relationship is so strong that asynchrony between auditory and tactile stimuli can be detected with delays as short as 7 ms [10]. It has also been suggested that there may be a tactile-auditory frequency matching mechanism [11], suggesting the existence of a joint action space involving vibro-tactile-auditory processing [5], [12]. This interrelationship is such that it is possible to modify the perception of frequencies by the counter-stimulus [13], [14].

Although the relationship between auditory and tactile stimuli is still in an immature stage, the existence of a brain area of coactivation for both senses close to the primary sensory areas has been suggested [15], even finding similarities between the cochlea and Pacini receptors in their way of encoding rhythm [13] and between auditory and tactile mechanisms that discriminate timbre [16]. Other studies support this idea, and it has been found that the application of low frequency vibrations not only activates the somatosensory area, but also activates the auditory system [17], and interactions between hearing and touch have been found in time and frequency perception [13], [14], [18]. In our study, we used a frequency of 1 kHz together with the intrinsic resonance frequency of the motors used. This frequency range is close to the peak sensitivity of Pacini's receptors and is therefore ideal for direct activation of the auditory system by tactile stimulation.

To check the activation of brain areas, a widely used technique is EEG, which allows measurement of electrical potential changes, in μV range, that occur between different points of the brain, detecting massive groups of neurons that are activated at the same time. This technique is often supported by AFC (Alternative Forced Choice) type questionnaires to improve feedback from volunteers. Among the areas that can be recorded with this technique are the areas of the auditory cortex, temporal cortex, parietal cortex, precentral and postcentral gyrus, and the cuneus and precuneus, located in the occipital lobe. The auditory cortex, together with superior temporal pole, Heschl's area, insula, and inferior frontal gyrus, are involved in musical affective processing [19]. The temporal lobe, to which the amygdala belongs, is involved in processes related to emotional prosody recognition, emotions through facial expressions and emotional processing [20]. The temporal cortex would be responsible for multimodal integration and emotional processes [21]. The detection of tactile stimuli is processed in the parietal lobe, also involved in emotional processes, sensory integration of multimodal stimulation, as well as the detection of rhythmic patterns [22], [23], [24], [25]. The precentral gyrus is activated with facial emotional recognition processes [26] and it has also been suggested that the postcentral gyrus would be related to implicit emotional processes without voluntary control of attention facing non-evocative stimuli of images [27], also involving the precuneus. The cuneus, however, would be linked to negative emotional recognition [28], [29].

The EEG technique has also been used to test brain activation during film viewing. Various tests have been carried out to induce positive and negative emotions [30], and a normalized database has been created according to their valence, linked to the intensity of the emotion, and arousal, linked to the sign of the emotion [31] or to study if reward and punishment modulated emotion [32]. Also, this theory has been used in Memristor-Based Circuit [33]. On the other hand, experiments have been carried out combining audiovisual stimulation with vibrotactile stimulation through different wearables such as jackets [34], haptic seats focused on 4D cinema [35], or accessibility improvements by adding vibrotactile stimulation to audio descriptions [36].

In terms of experimenting with acoustic and tactile stimulation, "haptic instruments" such as the one developed by Baijal et al. [37] or gloves that try to emulate the same emotions as audio [38] should be highlighted.

Users' opinions about the audiovisual experience through haptic devices have been measured, mainly based on self-reports. We present here an experimental work based on the following hypotheses:

- Touch can be an alternative channel for the transmission of emotions, offering augmented stimulation. New low-cost haptic devices can be developed, based on computational elements and micro-actuators that can evoke emotions in hearing impaired people.
- Haptic stimuli help to increase emotional arousal.

In our research, which extends the scope of previous studies, we have used EEG recording techniques to measure and compare the brain activity produced by multimodal stimulation consisting of audiovisual and vibrotactile stimuli in volunteers with hearing impairment, and we have compared it with the brain activity of volunteers with normal hearing, in both cases while watching videos.

The haptic stimulation used is a pattern that simulates a push and produces an unpleasant sensation.

In the following sections we will describe: the used materials and methods, with special emphasis in the selection of participants for the study and their characteristics, a detailed description of the physical stimuli generated by our system, and the procedure of the experiments: division of the Control and Target Group and the experiment schedule. After that, we will present the results of the EEG measurements performed while applying the different stimuli. Finally, we will discuss the differences between the control and target groups to raise our conclusions of the work, which will focus on the ability of our system to reinforce the intentionally synchronized emotional response of the brain in hearing disabled people when seeing a movie.

II. MATHERIALS AND METHODS

A. PARTICIPANTS

For this study we convened two different groups, a control group, and a target group.

The control group consisted of 34 people, 23 female and 11 males, with self-reported normal hearing, aged between 18 and 57 years (mean: 19.72, SD: 5.41). These subjects were recruited from the medical school where the study was conducted. Their level of education was as follows: 19 participants with a high school diploma, the vast majority of whom were medical students at the Complutense University of Madrid, 11 with a university degree and 4 with higher or postgraduate studies. This sample is consistent with other similar EEG studies [39], [40], [41].

The target group consisted of 8 people, 7 female and 1 male, with self-reported hearing loss, aged between 19 and 60 years (mean: 41.88, SD: 16.89). These target group volunteers were recruited through various foundations and associations of hearing impaired; hard of hearing people. Their educational level was 4 participants with a bachelor's degree, 3 with a university degree and 1 with a postgraduate degree. This sample is also in line with other similar EEG studies [42], [43].

Each subject self-reported their hearing loss according to the categories of the Audiometric Classification of Hearing Impairments of the International Bureau of Audiophonology (BIAP).

Self-reported hearing loss was classified according to the categories of the Audiometric Classification of Hearing Impairments of the International Bureau of Audiophonology [44]:

- Mild hearing loss, between 21 dB and 40 dB, at this stage speech is perceived when the voice is normal.
- Moderate hearing loss, between 41 dB and 70 dB, at this stage speech is only perceived when the voice is loud. The person understands better if they can see the person speaking. Everyday sounds are perceived.
- Severe hearing loss, from 71 dB to 90 dB, at this stage speech is only perceived when the voice is loud and close to the ear. Loud sounds are also perceived.
- Very severe hearing loss, from 91 dB to 119 dB, where speech is not perceived. Only very loud sounds are perceived.
- Total hearing loss, over 120 dB, at this stage nothing is perceived.

Five participants had very severe hearing loss over 91 dB and wore specific hearing aids (one of them using a cochlear implant in one ear), whereas 3 participants had total hearing loss over 120 dB (one of them had a cochlear implant). In order not to damage these devices, subjects were asked to remove them prior to testing, therefore their aids were not a parameter to include in the test.

All subjects were informed of the aims and general procedure of the study. Before the study, the subjects were asked about their clinical conditions: if they suffered from phobias, mental disorders, psychiatric or neurological pathologies and/or if they used psychotropic substances. None of the people who took part in this experiment were in any of the above situations.

This study is part of a line of research whose clinical trials were approved by the Clinical Research Ethics Committee (CEIC) of the San Carlos Clinical Hospital since April 4th 2019, Madrid (Spain).

B. MATHERIALS

1) STIMULI

For this study, we used synchronized multimodal stimulation by audiovisual and vibrotactile stimulation through a clip and its haptic specific stimuli.

The audiovisual stimulus was a short video of 2:20 minutes, following other studies using audiovisual stimulation and EEGs [45], [46], [47], and those of Pereira et al. [48], who demonstrated that the use of videos of more than one minute is convenient when trying to detect emotions through EEG.

This sequence was shot by the authors and validated by students. The short sequence shows a couple, a man, and a woman, arriving in a hotel room in a climate of increased tension, arguing and pushing each other, creating a tense atmosphere to show the existing discomfort between the partners, Figure 1 shows frames of the audiovisual stimulus used in this project.

FIGURE 1. **Images from audio visual stimuli showing partners in bad mood.**

The emotional content of the video was reviewed by 110 students from the Faculty of Computer Science at the Complutense University of Madrid. It was validated through a survey in which each student rated the type of emotion conveyed by each film. To develop the questionnaire, a discrete emotion model was used, which defines a space of limited, discrete, and basic emotions, as well as some complex emotions [49], [50]. When it comes to defining the basic emotions, there is great controversy in current studies, but there is a consensus that the following six emotions are basic ones: anger, fear, sadness, happiness, disgust, and surprise [51], [52], [53], [54].

However, if we rely on valence-based theories of emotional classification, there is greater consensus. This valence can be positive (pleasant) or negative (unpleasant), but is never neutral [55], [56], [57], and arousal ranges from low to high [49], [50].

In this study, students rated the short film. The students rated the negative video with an intensity of 4.3 out of 5. They also identified the following negative feelings in the video: anxiety, 17%; fear, 37%; sadness, 34%; anger, 12%, as shown in Figure 2.

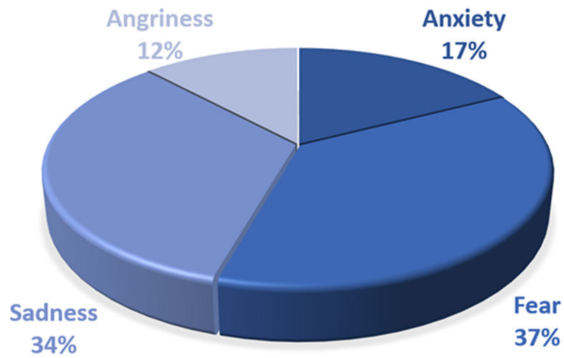

FIGURE 2. **Negative feelings survey as reported by the students who watched the video used in this research classified based in valence.**

The vibrotactile stimuli were a sequence of haptic stimuli. A pair of gloves designed for this experiment provides this haptic stimulation. The haptic stimulation associated with the negative emotion mimics a push, providing a strong and fast vibration through the six vibration points simultaneously. The hardware is explained in more detail in the Hardware section. The negative haptic stimulation takes 250 ms. This stimulus waveform is shown in Figure 3. The haptic stimuli are modulated in a PWM signal with variable duty cycle due to intensity control, in bursts of 1 kHz.

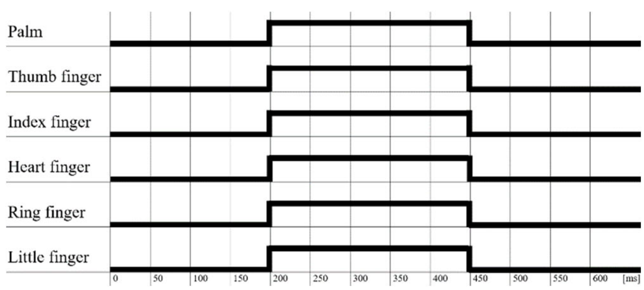

FIGURE 3. **Negative haptic pattern simulating a push showing that all the motors are activated synchronously.**

The vibration pattern is generated in both hands, as it is imperative that it is precisely timed to coincide with the emotional peaks in the film, simulating a sudden push or impact. These negative emotional peaks were chosen by the director and co-writer of this research and always coincided with moments when the two actors touched each other with their hands or other parts of their bodies. The gloves were fitted tightly to the user's hands to ensure the correct haptic stimulation from the motors.

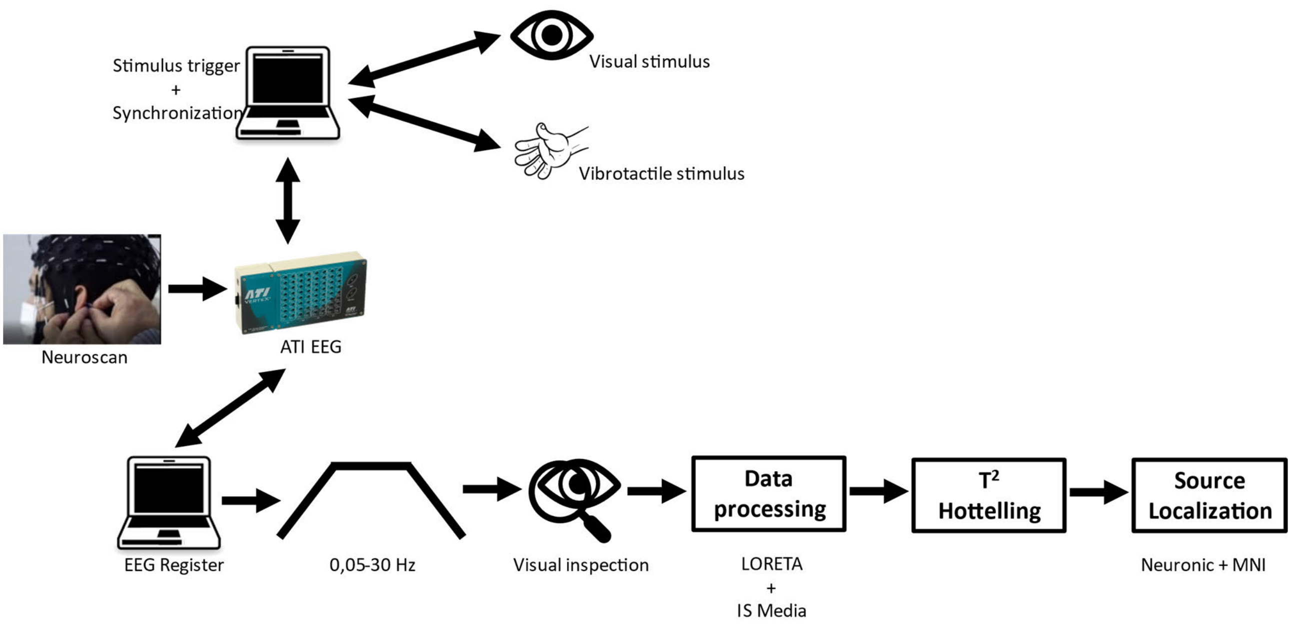

FIGURE 4. System architecture diagram of EEG signal analysis.

2) HARDWARE

The hardware used for these experiments is divided into two parts, one relating to the EEG signal recording system and the other relating to the vibrotactile stimulation system.

The first one, used for recording EEG signals, consists of two identical laptops HP ProBook 450 G8 Intel Core i5-1135G7/16GB/512GB SSD/15.6", a custom-designed Neuroscan electrode cap with 64 sensors, 2 references and ground, an EEG signal amplifier, and a custom-designed soundproof, faradized room with a comfortable chair in which the subjects sat down during the tests.

The function of second laptop was to trigger the video, send time marks to the EEG amplifier and synchronize each of the three stimuli. The second function of the laptop was to register and collect the EEG data from the cap.

The EEG signal was recorded using a custom-made cap and an ATI EEG system provided by Advantek SRL, with 64 channels, including additional channels to monitor eye movement placed in the right and left lateral canthi and superior and inferior orbits of the left eye. All scalp electrode placements were based on the international 10-10 system and consisted of Ag/Ag-Cl. The reference electrodes were placed on the mastoids. The ground electrode was placed on the forehead. Impedances were kept below 5 kΩ. The EEG signals were processed to a mean reference after acquisition and filtered with a bandpass filter between 0.05 Hz and 30 Hz with a sampling rate of 1 kHz. The time base and sensitivity of the recording device used to record the EEG were maintained at 30 μV/s and 100 μV/cm, respectively.

A 1 s window was used to segment EEG marks for each subject in each condition. All EEG recordings were visually inspected off-line to ensure clean data from the trial and to identify eye and muscle movement artefacts. Trials that contained artefacts such as eye movements or blinks, or that were noisy, were discarded. Noisy channels were replaced by linear interpolation of adjacent channels. From the cleaned bank of EEG recordings, mean values were calculated, with IS Media software, separately for each participant and condition. Only grand averages were used to estimate differentially activated regions, regardless of the frequency bands involved.

Each of the individual averaged recordings identified each of the sources of brain activity, sources of neuronal current, of the different scalp potentials through a process known as low-resolution electromagnetic tomography (LORETA) [58], which calculates the three-dimensional distribution of neuronal generators in the brain as a current density value (A/m^2) for a total of 2,394 voxels through an inverse solution method. In this work, we considered the same 90-part segmentation from different anatomical constraints of the Montreal Neurological Institute (MNI) average brain atlas [59]. In Figure 4, it is show the system architecture.

Finally, the mean map of statistically significant brain activation was obtained for each of the participants group in each of the conditions. Next, the map of differences in brain activity was obtained for the same condition in the different groups.

The hardware used to show the different visual stimuli was a LG 24M38A-B 23.5" full HD 1920 × 1080 resolution monitor embedded in a wall at a distance of 1.5 m in direct line of sight, which displays the visual stimulation; Presonus Eris E3.5 loudspeakers were in charge of auditory stimulation; and a custom pair of gloves, control electronics to drive the micromotors and an Arduino UNO are used for haptic stimulation.

This bespoke pair of gloves is integrated with 2 professional golf gloves, one for each hand, model Inesis Golf Glove 100, on which a total of 12 Uxcell 1030 micro-motors have been placed on the fingertips and palms of each hand, 6 on each hand, as shown in Figure 5.

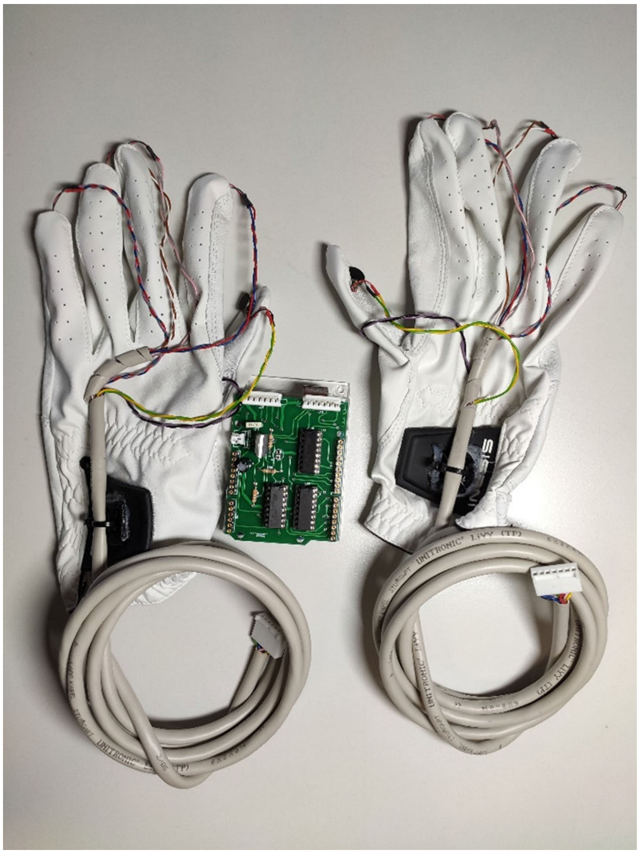

FIGURE 5. Custom haptic gloves designed for this research formed by Inesis Golf Glove 100, Uxcel 1030 micromotors and Arduino UNO control.

These professional gloves ensure perfect fit, comfort for the user, and allow easy implementation of micromotors. We chose the position of the micromotors based on the Penfield homunculus, where the hands are shown to be a very sensitive tissue [60], due to the higher concentration of fast adapting receptors such as the Meissner and Pacini receptors, which are responsible for the uptake of vibrational stimuli as stated above [61], [62], [63], [64]. Haptic stimuli are electronically triggered by the same microprocessor unit that activates temporal EEG markers. We have used this advantage to automatically synchronize the emotional response to be measured, which is ensured by triggering both EEG marks and stimuli at the same time. Moreover, the amplitude and motors' natural frequency of vibration (12.500 $\pm$ 2.500 rpm, 208 $\pm$ 41 Hz) are aligned with the necessary ones to activate the response of Pacini corpuscles, as stated in the Introduction section. Finally, as the intention is to reproduce a push or impact (see Stimuli subsection), all of the motors are simultaneously activated.

In order to be able to control the motors independently and to supply them with the necessary current, which exceeds the maximum one provided by the Arduino UNO board, a controller was designed based on the L293D, powered by an external 5V, 5000mAh battery, more than enough capacity for the duration of each full individual test.

3) PROCEDURE

All participants were invited to attend an individual COVID-19-free session. During the trial, hygiene and disinfection measures were prioritized. All participants, researchers and assistants wore face masks throughout the study, and the room was well ventilated. All materials used were disinfected with hydroalcoholic gel between each session.

Each participant first completed a questionnaire providing information on age, sex, level of education, type and degree of hearing loss and hearing aids. No information about the dominant hand was requested for this test, as the haptic stimuli were applied to both hands at the same time through the pair of gloves.

Participants were then asked to sit down on an armchair facing a screen in the soundproofed, faradized room. Only one other person was allowed to enter the room to minimize the risk of contamination, just to place the EEG cap on the subject's head, to check the fit of the two gloves, and to check the correct operation of the system. It was necessary to ensure that the glove fitted perfectly to the hand by positioning each of the 12 micro-motors in its appropriate position, either on the palm or the fingertips.

Sound was provided through stereo speakers attached to the screen for hearing volunteers only. Volunteers with hearing loss were asked to remove their hearing aids, but not their visual aids such as glasses, if necessary.

Participants were told that they would first take a vibration test to ensure that the haptic stimuli themselves did not produce any brain activity beyond the expected tactile detection. Then they were going to watch the film, so they were instructed to sit comfortably and relax during the video projection. The room lights were turned off and the corresponding video was played.

The stimuli were presented in a first vibration test, condition 0, and then random sequences of both emotional videos with different multimodal stimuli, conditions 1 to 3, to avoid learning one of the videos, and according to the following conditions:

- Condition 0: 3 minutes of constant vibration at a frequency of 2 Hz. The signal consisted of a PWM signal with a 10% duty cycle, turning all motors on for 50 ms and off for 450 ms.
- Condition 1: control group watched the video, neither auditory nor vibrotactile stimuli.
- Condition 2: target group watched the video, neither auditory nor vibrotactile stimuli.
- Condition 3: both groups watched the video with vibrotactile stimuli.

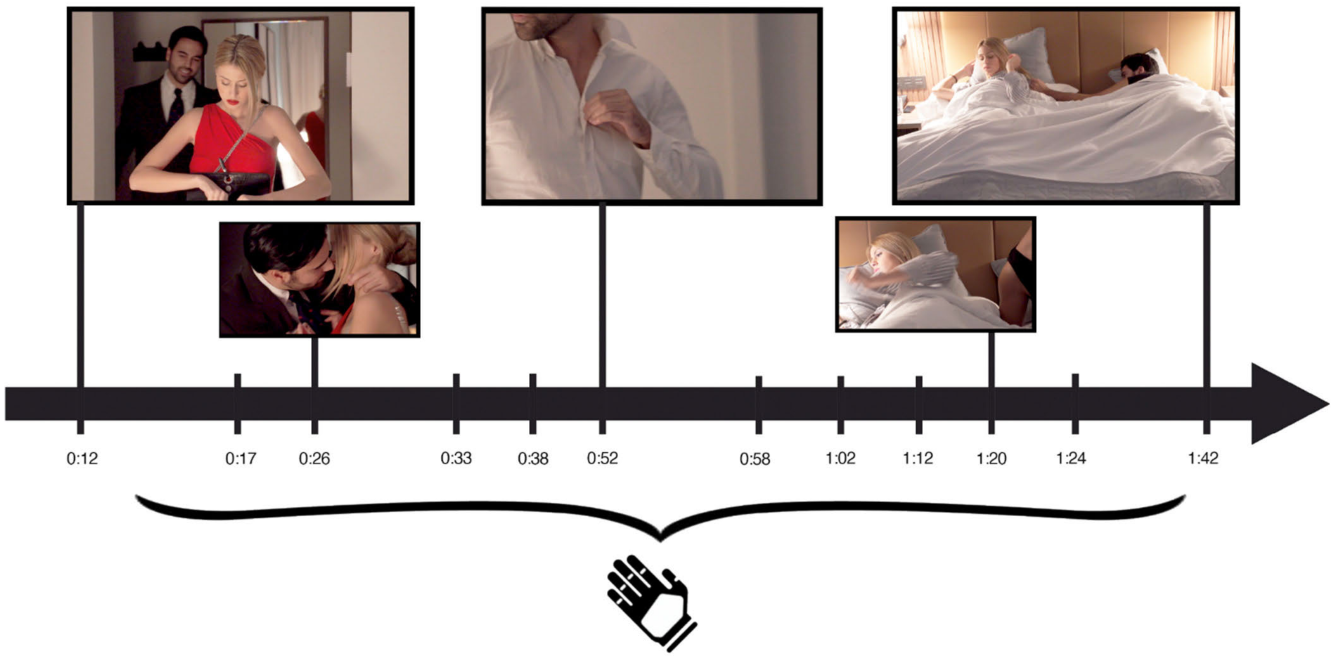

FIGURE 6. Time marks and photograms of points of highest emotional content in the fil. At these points the haptic stimulus is activated, and the EEG recording is triggered.

In Condition 3, the director decided on the 12 points of highest emotional content in the negative valence video, all of which are shown in Figure 6 with their time marks and some selected photograms. At each of these moments, an EEG tag was generated to analyze the 100 ms following each oscillation. All stimuli were tracked in this way to assess differences in brain activity between viewers. To ensure the correct processing of each emotional stimulus, special care was taken to ensure that there was a minimum of 4 s between each stimulus, so that there was sufficient reaction time between the marks.

Upon completion of the EEG test and recording, each participant was given a Self-Assessment Manikin (SAM) questionnaire to assess emotional experience as a function of valence, arousal, and intensity of emotion [53], [65]. This information added up each subject's subjective emotional experience for each of the conditions of the same video on a 5-point Likert scale.

The total duration of each session was 60 minutes. None of the participants received financial compensation.

III. RESULTS

Statistically significant differences between conditions were located by calculating the SPM for Hotelling's T2 test on a voxel-by-voxel basis for independent groups [66]. The resulting probability maps were obtained and displayed as 3D activation images overlaid on the MNI brain model.

These maps were obtained by considering the peaks of maximum significant activation in each group with Hotelling's T2 test, which is a multivariate statistical analysis applied to the values recorded by the EEG on the electrodes, detecting the brain areas with statistically significant activation compared to the average condition [66], using a covariance matrix.

Once the probability maps were obtained, anatomical structures were identified using the Automated Anatomical Labelling (AAL) atlas. Local maxima were then identified by locating them according to the MNI coordinate system.

For this study, the differences in the same condition between the target group and the control group were evaluated. For this comparison, we considered up to 8 statistically significant maximum activation peaks in each test, obtained with Hotelling's T^2 test against zero. The following tables show in the first column: AAL atlas, corresponding to the location of the activated zone; X, Y, Z: corresponding to the coordinates of the activated zone according to the Montreal Neurological Institute (MNI) average atlas; Act. [$\mu A/m^2$], corresponding to the numerical value of the zone activation.

The results obtained in Condition 3 in the control group show that the statistically significant differences between the target group and the control group are found in the bilateral frontal and cingulum areas. Figure 7 above shows the brain activation map and Table 1 shows the numerical values of these areas.

The results obtained in condition 3 in the target group show that the statistically significant differences between the target group and the control group are found bilaterally in the frontal and cingulum areas, Figure 7 below shows the brain activation map, and Table 2 shows the numerical values of these areas. It has been studied that no significant differences arose when it came to the analysis of data within the target group

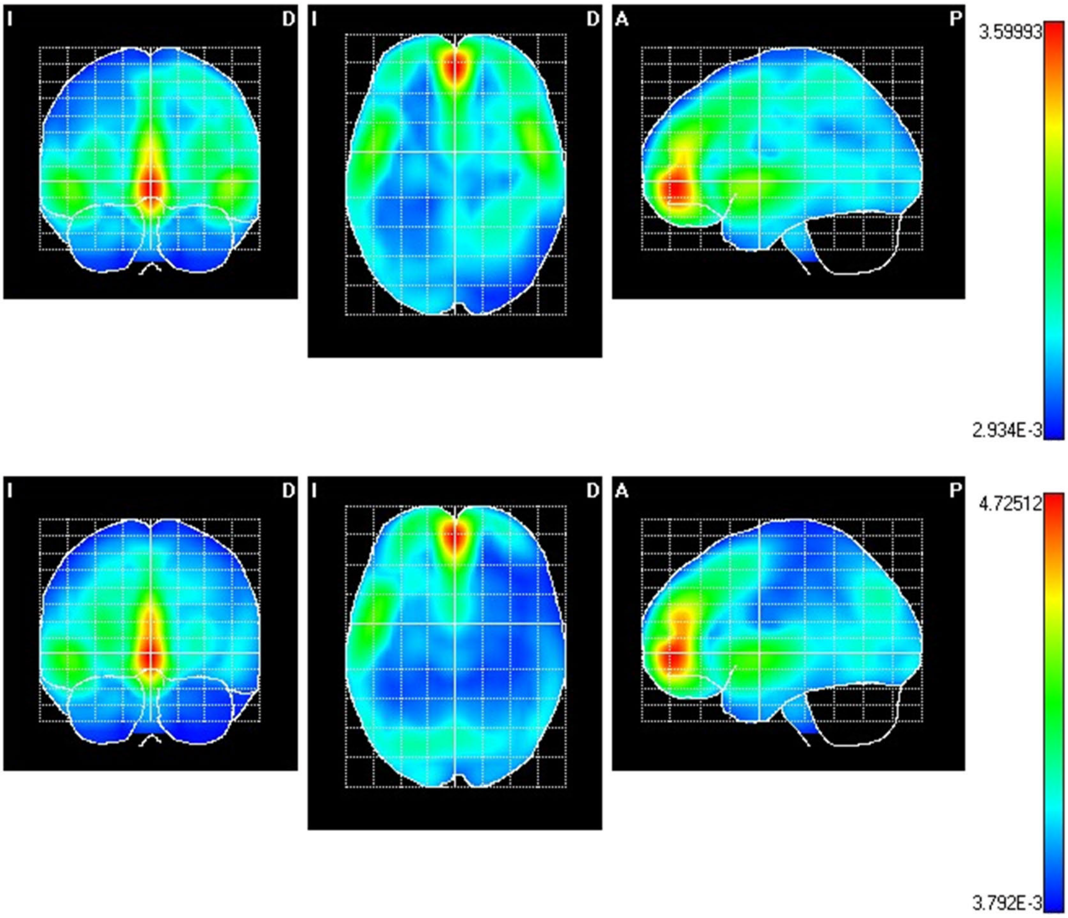

FIGURE 7. Map of activation of frontal areas in Condition 3. In red the statistically significant brain areas (T2 Hotelling - 0.001). Map above, in control group; Map below, in target group. Both maps show similar activation in frontal mid and superior lobe and cingulum areas, with high activity in target group. All bars show $\mu A/m^2$ MKS units.

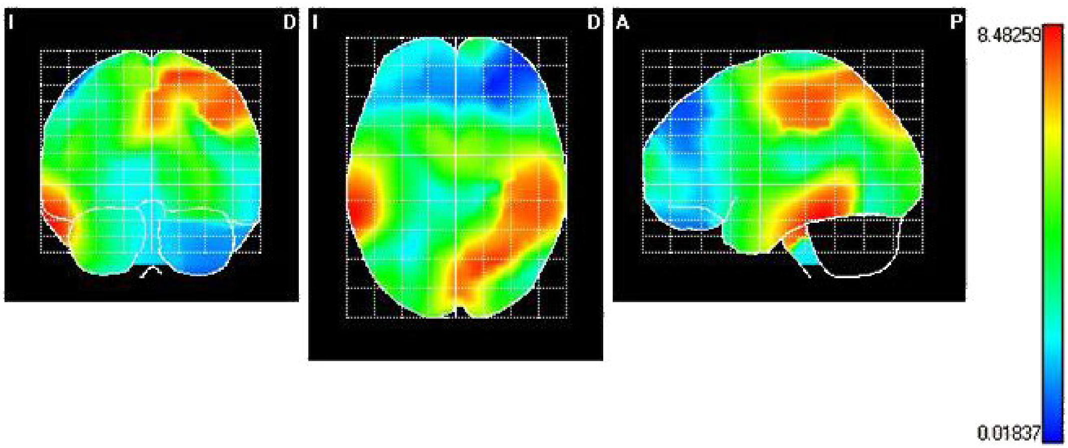

FIGURE 8. Maps of differences in activation of temporal and parietal areas in Condition 3. In red the statistically significant brain areas (T2 Hotelling - 0.001), showing activation in frontal mid and superior lobe and cingulum area. All bars show $\mu A/m^2$ MKS units.

between individuals with severe hearing loss and total hearing loss.

When watching the emotionally negative video with vibrotactile stimulation, Condition 3, we can see that the statistically significant differences between the target group and the control group are found in the right superior parietal, right inferior parietal, left inferior temporal, left middle temporal, right postcentral, right supramarginal, right postcentral

TABLE 1. Condition 3 in control group.

AAL	X	Y	Z	Act. [μA/m²]
Frontal_Mid_Orb_R	2	54	-4	3,600
Frontal_Mid_Orb_L	-2	54	-4	3,591
Frontal_Sup_Medial_R	2	50	0	3,494
Cingulum_Ant_L	-2	50	0	3,486
Frontal_Sup_Medial_L	-2	54	0	3,464

TABLE 2. Condition 3 in target group.

AAL	X	Y	Z	Act. [μA/m²]
Frontal_Mid_Orb_L	-2	54	-4	4,725
Frontal_Sup_Medial_L	-2	54	0	4,700
Frontal_Mid_Orb_R	2	54	-4	4,667
Cingulum_Ant_L	-2	50	0	4,598
Frontal_Sup_Medial_R	2	50	0	4,547

and right precuneus areas, Fig. 8 shows the brain activation map differences and Table 3 shows the numerical values of these areas.

TABLE 3. Differences between groups in condition 3.

AAL	X	Y	Z	Act. [μA/m²]
Temporal_Inf_L	-66	-38	-20	8,401
Temporal_Mid_L	-70	-38	-16	8,297
Parietal_Sup_R	14	-70	68	8,115
Precuneus_R	10	-74	64	7,901
Parietal_Inf_R	50	-34	52	7,806
Postcentral_R	50	-30	52	7,769
SupraMarginal_R	42	-34	44	7,744

IV. DISCUSSION

Some attempts had been made to elicit or pump up an emotional response synchronized with the music of an audiovisual effect, like those in [37] and [38], but they lack on the specific measurement of such a response by means of EEG data, which can demonstrate the corresponding activation of brain areas related with the intended emotional or attentional burst. Our results reinforce these kinds of attempts by using a synchronized specific EEG measurement while using our proprietary stimulation system.

The results of the statistical analysis and the differences between the brain activity of hearing impaired; hard of hearing and hearing-impaired people shows that the brain activation was much higher in the hearing-impaired group than in the control group. Furthermore, the most significant differences between the two groups were found in the superior and inferior parietal lobe and precuneus in the right hemisphere and the inferior and medial temporal lobe in the left hemisphere. In the light of these results, we can deduce the existence of a differential brain reorganization in hearing impaired; hard of hearing subjects, associated with a greater sensory, attentional, and emotional capacity.

In fact, thanks to the plasticity of the brain, hearing impaired; hard of hearing people reorganize the neural network of the frontoparietal nodes in order to compensate for their auditory deficit. This reorganization leads to a strengthening of their neural connections, generating greater activity [67]. On the other hand, this lobe is associated with decision-making processes and attention to basic and routine actions, as well as monitoring the environment [68], [69]. To compensate for the lack of information provided by the sense of hearing, hearing impaired; hard of hearing people have improved their visual capacity, showing a larger lateral field of vision and a greater speed of dynamic identification [70], thus showing a greater presence of cognitive processes related to attentional processes.

The area of the brain associated with attentional processes is the frontal lobe. Looking at the map of differences, we can see a high activation in the frontal lobe, with a significant increase in brain activity in the hearing-impaired group compared to the activity produced by the control group. This area is also associated with audiovisual integration processes, although this could be induced by McGurk's illusion [71], as all members of the target group are postlingually hearing impaired; hard of hearing.

Several studies argue that when auditory stimuli are presented to people with an apparent lack of auditory response, there appears to be increased frontal activity in the brain associated with a greater effort to process auditory activity [72], [73]. Our processing capacity is not infinite, in fact it is quite limited, so our brain must be able to prioritize and select which information to attend to. When one sense fails, cross-modal reorganization is regulated by selective attention or attentional shift from private modality to conserved modalities via descending modulation of the prefrontal cortex [74]. This is consistent with our results above, so we can conclude that the high attentional activation is due to a reorganization of neural connections.

Another important part of our study is whether emotional processes can be induced or at least enhanced. Basic studies relate activation in temporal brain areas to emotional processes [41], [75], [76], [77], [78], [79], specific to film environments [18]. In particular, they are associated with sad emotional processing [80], [81]. In addition, other studies [24], [25] identify activation of parietal areas related to sensory processes as an integration of multimodal stimulation and as a result of the detection of rhythmic patterns. In this study, the hearing-impaired participants focused on the negative content of the perceived emotions rather than on the rhythmic patterns. Our results are also consistent with other recent studies that have used tactile stimulation in hearing impaired individuals to enhance audiovisual experiences. As mentioned in the Materials section, the emotional content of the used video was validated by 110 people, resulting in the identification of emotions with a clear negative valence. Moreover, those volunteers filled an emotion questionnaire to assess their emotional experience as a function of valence, arousal, and intensity of emotion. Although the EEG results cannot provide an authoritative classification for the elicited emotions, we can assume that they are aligned with those extracted from the previous validation. Consequently, the relationship of the activation of the temporal lobe found in the EEGs with the processing of sad or negative valence emotions is reinforced [80], [81]. In addition, right hemisphere brain activation is associated with greater intensity in the perception of an audiovisual work, whereas left hemisphere activation is associated with the valence of the emotion [82], [83]. Both of those activations have been enhanced in the target group, but it has a higher effect on the left one (see Figure 8).

Other significant differences between the experimental and control groups may be due to the tactile stimulation associated with the film images. These differences reflect the activation of the postcentral gyrus, which, interestingly, is the location of the primary somatosensory cortex, the main receptive area for the sense of touch. In particular, the postcentral gyrus is involved in the localization of touch and vibration, anticipation of touch and motor learning [84]. This is not unexpected as the stimulus is a vibration. On the other hand, precuneus activation is associated with the ability to successfully implement attentional deployment and the predisposition to use adaptive emotion regulation strategies when viewing unpleasant images [85]. It is worth noting that a strong activation of the precuneus has been demonstrated in hearing impaired; hard of hearing people when confronted with dynamic and static visual stimuli [86]. Therefore, we can conclude that we have observed an increased brain activity strongly related to emotions, driven by the vibratory stimuli (as activity appears in sensory post-Rolandic areas).

V. CONCLUSION

Based on the obtained results, we conclude that the addition of a tactile stimulus to the viewing of a film triggers a greater emotional and sensory response in people with deafness than the traditional viewing of the same film without such a stimulus, and even greater than in non-disabled viewers, as can be seen in the map of differences in the activation zones of the target group vs. the control group. It is needed to be stressed that temporally EEG marks for the analysis of results were electronically triggered by the microprocessor unit that controls the stimuli activation, which automatically correlates tactile stimuli with EEG results.

This main result could be a product of the fact that people who have a lower information input channel during film viewing, such as people with deafness, increase their emotional response when a new information channel, such as tactile stimulation, is available. Although this channel is not a substitute for the auditory channel, we have demonstrated in this experiment that these people reorganize their brain areas to produce a greater emotional and sensory response than when watching the video without tactile stimulation, and that the emotional response is also greater than that of the normal-hearing viewers in the control group.

However, we would like to point out the limitations and the preliminary nature of such a study, which we would like to extend in future work to focus on the influence of tactile specific stimulation on hearing impaired people during film viewing.

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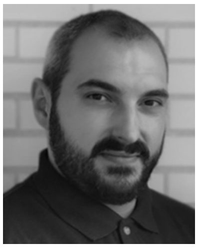

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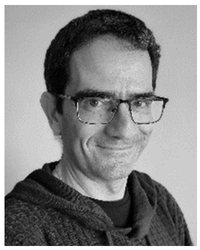

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