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THE EXTERNALIZATION SENSATION IN BINAURAL LISTENING : A BEHAVIORAL AND ERP STUDY

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ABSTRACT

Binaural listening is an immersive audio technique that aims at recreating a realistic sound scene to the listener through headphones. The externalization sensation is the fact for the listener to feel like the sound sources come from outside his head and a good externalization sensation is paramount for the binaural listening to be convincing. An efficient way of improving externalization is to pair the binaural listening with a head tracking device, capable of modifying the audio content according to the head movements of the listener. The aim of this study was to find neurophysiological correlates of the externalization sensation by performing both an auditory evoked response potential (aERP) analysis and a behavioral analysis. The EEG of subjects listening to binaural stimuli was recorded, then, the subjects had to evaluate their externalization sensation. Depending on the conditions, the subjects were asked to perform head motion or to remain static and the head-tracking device was either active or inactive. In the condition with head movement and with head tracking active, the subjects reported a better externalization sensation than for other conditions. Performing a head movement, whether the head-tracking was active or not, enhanced the amplitude of ERP components after 100ms.

Keywords: *binaural, externalization, eeg, erp*

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1. INTRODUCTION

Before a natural sound reaches our eardrum, it is filtered by the listener's head, torso and pinna. This filtering is characterised by the head-related transfer function (HRTFs). Binaural listening is an immersive audio technique that aims at recreation a realistic sound scene to the listener through headphones. Synthetic binaural content is created by filtering an audio signal with a set of HRTFs. The externalization is the fact for the listener to feel like the sound sources come from outside his head and a good externalization is paramount for the binaural listening to be convincing [1, 2]. Under usual headphone listening (*i.e.* without head tracking), when the listener moves his/her head, the sound source moves accordingly to the head, which makes the listening experience unnatural and decreases the degree the sound is externalized [3, 4]. An efficient way of addressing this issue is to pair binaural synthesis with a head tracking system, thus enabling to take into account head movements to adapt the binaural synthesis so that the source remains fixed with respect to the external world, as in real life. Head-tracked movement (*i.e.* head movement paired with a head tracking system) can effectively increase externalization [5] and this increase remains even after the listeners stopped moving their heads [3, 4].

Objective markers (*i.e.* that do not require a response by a participant), based on brain activity such as event-related potentials (ERP), are often used to characterize brain activity evoked by sound stimulation. Previous ERP studies using electroencephalography (EEG) or magnetoencephalography (MEG) have compared different types of stimuli that are supposed to induce different externalization levels [6, 7]. In those studies, free

free-field listening was compared to individualized and non-individualized binaural listening and to stereophonic headphones listening. The results showed that the N1 and P2 components had a larger amplitude when elicited by stimuli that are supposed to be more externalized (free field, individualized and non-individualized binaural) than when elicited by spatially impoverished stimuli (stereophonic) and that that N1 and P2 latency were shorter for free-field and binaural stimuli than for stereophonic stimuli. However, in those studies, the internalized and externalized stimuli were different in term of listening device (free-field vs headphones) and spectral content. One could argue that the observed differences in resulting N1 and P2 are not due to differences of externalization, but rather to differences of spectral content [8–10] or listening device.

The present study aims to find a clear correlation between brain activity and externalization. In this purpose, two experiments - an EEG experiment and a behavioral experiment - were conducted by the same subjects in the same experimental conditions. To make sure that the only varying factor was externalization, stimuli were identical from one trial to another (identical location, identical spectral content and delivered by identical listening device) but they were preceded by either head-tracked movement or untracked head movement or no head movement. Stimuli preceded by head-tracked movements should be more externalized than stimuli preceded by both untracked head movements and no head movement.

2. MATERIALS AND METHODS

2.1 Participants

Twenty healthy subjects (eight men, 12 women ; mean age 25). All subjects had normal hearing by self report. The study conformed to the Code of Ethics of the World Medical Association (Declaration of Helsinki), printed in the British Medical Journal (18 July 1964) and was approved by the Institutional Review Board of IMT Atlantique (registered as IRB00013722 at the US Office for Human Research Protections). Furthermore, all subjects gave their written informed consent to participate in the study.

2.2 Stimulus

Each trial consisted of a 5.5 s excerpt from the French poem “l’Albatros” by Charles Baudelaire followed by a train of 10 repetitions of a 1 s non semantic bi-syllabic pseudo-word “boru”. A 200 ms - long silence was inserted between the sentence and the first “boru”, as well as between each “boru”. The total trial length was 17.5 s. The sound chosen to induce ERP was the pseudo-word “boru”. The litterature sugests that such a word should generate ERP (*e.g.* [11–13]).

The audio was recorded by a female speaker in a small anechoic chamber with a Neumann U87 microphone and a RME babyface audio interface, connected to a Windows computer using Protools recording software. The word “boru” was composed of 400 ms of direct sound followed by 600 ms of reverberation. While the direct sound was directly binauralized, the reverberation was generated using the 4th-order ambisonic impulse response of the small concert hall “Ubu” (Rennes, France) [14].

The stimuli were generated using 3 randomized non-individualized HRTFs because individualized HRTFs measurement is a long and complicated process [15] and the great majority of binaural content is thus produced using non individualized HRTFs.

2.3 Apparatus and reproduction setup

Experiments were conducted in a dimly illuminated, double-walled sound-proof room. A dimmed screen was used to display the visual information required for the subject. Stimuli were presented over headphones (Sennheiser HD650). The subjects were not allowed to remove the headphones at any point in the experiment. The sound pressure was adjusted to 65 dBA. Playback, interface and data capture were controlled using a software implemented in Max/MSP on a Windows computer connected to a RME Babyface soundcard.

Head-tracked movements were taken into account by a rotation of the sound source (for the direct sound) and a rotation of the Ambisonic matrix (for the reverberation) causing the position of direct sound and directional reverberation to rotate in the opposite direction than that of the head, thus keeping the whole sound scene fixed with respect to the external world. A head-tracker T3 by *Feichter Audio* was placed on top of the headphones and sent the head position to the binauralization software. Those information were recorded to control that the subjects performed the head movements correctly.

2.4 EEG recording

To record the EEG signal, a light setup with few electrodes was designed so that subjects could perform head movements with ease while minimizing the movements on electrical wires. A Bluetooth Cyton board from *Open BCI* on which was connected six goldcup electrodes was used. Three of those were placed on C3, Cz and C4 according to the international 10-20 system, where the N1 ERP usually has the largest amplitude [16]. An electrode was placed at Fp2 to control ocular activity and two were placed on mastoids to be used as references. Synchronisation between audio stimuli and the EEG was achieved using a short pulse generated by the sound card and connected to the Cyton board with a bipolar montage. Importantly, the board was placed on the subject to minimize cable movements. All signals were sent through Bluetooth to a Linux computer and recorded with the OpenBCI software. All channels were recorded with a sampling rate of 250 Hz.

2.5 Procedure

To make sure that the only varying factor was externalization, each trial was divided into two phases: 1) subjects listened to binaural stimuli either with head-tracked movements or with untracked head movement or without head movement, then 2) they listened to binaural stimuli while keeping their heads still. Behavioral and EEG measurements were conducted during this second phase. This protocol ensured that the signal presented at the ears of the listener was identical during measurements (identical location, spectral content and listening device), yet with varying degrees of perceived externalization depending on whether or not the measurement had been preceded by head-tracked movements during the first phase. Indeed, as previous studies have shown that externalization persist once the subject has stopped moving his/her head [3, 4], stimuli preceded by head-tracked movements should be more externalized than stimuli not preceded by head-tracked movements.

For each trial, the subjects were instructed to either make a horizontal head movement or to stay still. During head movements, the head tracking device was either active or inactive. As a consequence, our experimental procedure consisted in three different motion conditions:

- **SF** : “Static” (head tracking inactive), “Fixed” (no head movement)
- **SM** : “Static” (head tracking inactive), “Movement” (with head movement)
- **DM** : “Dynamic” (head tracking active), “Movement” (with head movement)

Subjects were requested to hold their heads in a natural upright position when listening to the stimuli. For condition SM and DM, during the 5.5s sentence, they had to execute a 60° head rotation of one side then 60° to the other side before returning to forward-facing. During the train of “boru” repetitions, they had to remain stationary.

Before each experiment (EEG and behavioral), the subject had to perform a training phase to learn how to correctly execute the head movements. Before each trial, visual indications were displayed on the screen to tell the subjects to execute the head movement (tracking conditions SM or DM) or to remain static (SF). During the EEG experiment, when one trial was over, the next one started automatically after a 1200 ms pause. Each “boru” repetition generated an ERP and is considered as an independent stimulus. During the behavioral experiment, after each trial, subjects had to move a slider on the computer interface to evaluate externalization during the second part of the trial (*i.e.* the train of repeated “boru”). The slider scale ranged from 0 (sound perceived inside the head, in the center) to 100 (sound perceived outside the head, completely externalized).

2.6 EEG preprocessing and analysis

EEG preprocessing and analysis was done using MNE Python, version 1.0.3 [17]. Raw signal was re-referenced on the mean of the mastoids and line noise was removed using a notch filter at frequencies 50 Hz, 100 Hz and 150 Hz. Slow drifts in the EEG were removed by applying a high-pass filter with a cut-off frequency of 0.1 Hz, Segments containing eyes blinks were identified on the raw signal using the module *find-eog-event* from MNE and removed when creating the epochs. Data was epoched from -200 to 500 ms around stimuli onset (each repetition of “boru”). To remove bad epochs, the module *autoreject* [18] from MNE was used. 5 subjects were rejected because their rejection rates were too high ($\geq 20\%$). For the other subjects, the mean rejection rate was 11% of epochs. Finally, a low-pass filter with a cut-off frequency of 40 Hz was applied to maximize signal to noise ratio for ERP analysis, and a baseline correction and a z-scoring was applied on the final preprocessed epochs [19].

For each subject, different epochs averages were performed in order to explore statistical differences between conditions while keeping a sufficient number of epochs. Early analysis suggested that the position of the “boru” in the train of repeated “boru” had an impact on the ERP. To explore the differences between motion conditions while controlling the effect of the “boru” position in the train, epochs were averaged among HRTFs for each motion condition and each repetition group (the 3 first "boru" of each train were averaged together as *"repetition group 1"*, the 3 next as *"repetition group 2"* and the 3 last as *"repetition group 3"*. To keep an equal number of "boru" repetitions per condition, we did not include the 10th "boru" of each train). To explore the effect of the HRTF, epochs were averaged among the 10 "boru" repetitions for each motion condition and each HRTF.

Three time windows were defined around the components of interest: 70-100 ms (corresponding to N1), 90-160 ms (corresponding to P2) and 170-230 ms. This last time window corresponds to a positive peak being part of the auditory change complex (ACC). The ACC typically appears after the N1-P2 complex for complex stimuli such as speech syllables [20–22], which is the case of our stimulus. The values of latency and amplitude of those components peak were extracted on Cz electrode and for each set of values (latency or amplitude) of each component (N1, P2, ACC), two repeated-mesures ANOVA were performed: 1) Listening conditions [SF, SM, DM] $\times$ repetition groups [repetition group 1, repetition group 2, repetition group 3]. 2) Listening condition [SF, SM, DM] $\times$ HRTF [HRTF 1, HRTF 2, HRTF 3]. Then, Holm Bonferroni post-hoc tests were performed on significant results.

3. RESULTS

3.1 Behavioral results

Analysis of the head movement data showed that the subjects were on average very compliant to the given instructions and performed the head movements correctly.

Since the scale used for the subjects answers was continuous, a z-transform was performed and the data were submitted to a repeated-measures ANOVA : motion condition [SF, SM, DM] $\times$ HRTF $\times$ trial repetition. There was a main effect of the motion condition ($F[2,\ 38] = 17.8;\ p < 0.001$). A post-hoc Holm Bonferroni test indicated externalization was higher under condition DM compared to conditions SF ($p < 0.001$) and SM ($p < 0.001$). There was no significant difference between conditions SF and SM (see Fig. 1). There was no main effect of neither the HRTF nor the trial repetition and the interaction was not significant.

3.2 EEG results

3.2.1 Motion condition

A main effect of the motion condition was found for the N1 amplitude ($F[2,\ 28] = 5.01;\ p = 0.014$): a post-hoc test indicated that SM had a more negative amplitude than SF and DM (see Fig. 2A). The interaction repetition group $\times$ motion condition was significant for the ACC amplitude ($F[2,\ 28] = 16.73;\ p < 0.001$): a post-hoc test indicated that, for the repetition group 1, SF had a less negative amplitude than SM and DM (see Fig. 2B).

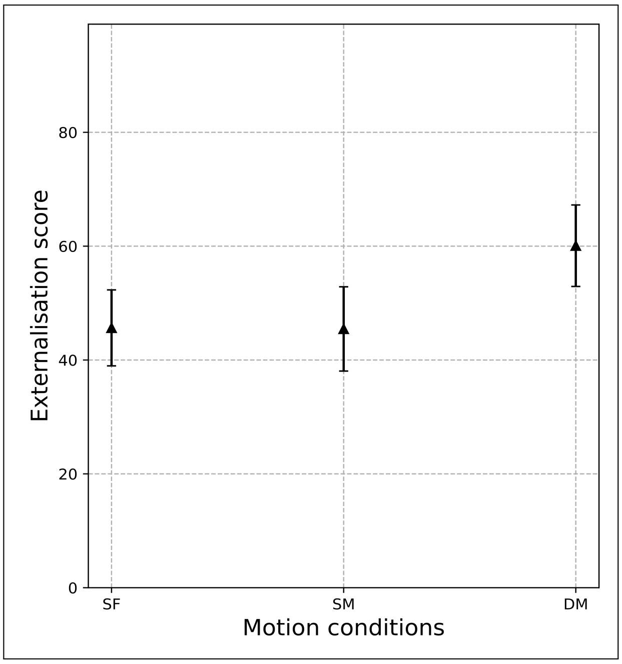

Figure 1. Mean of normalized externalization score across subjects for each motion conditions (SF: no head movement, head tracking inactive, SM: head movement, head tracking inactive, DM: head movement head tracking active), error bars show 95% confidence interval.

To verify the absence of effect, additional Bayesian repeated measure ANOVAs were performed on latencies and amplitudes [23]. The results provided moderate to strong evidence for the absence of differences between DM and the two other listening conditions.

3.2.2 Repetition groups

Effects found for the repetition groups were the following: On the P2 latency ($F[2,\ 28] = 8.30;\ p = 0.001$): a post-hoc test indicated that repetition group 1 had a shorter latency than repetition groups 2 and 3. On the P2 amplitude ($F[2,\ 28] = 8.67;\ p = 0.001$): a post-hoc test indicated that repetition group 1 had a more negative amplitude than repetition groups 2 and 3 (see Fig. 2C). The interaction repetition groups × motion condition was significant for the ACC amplitude ($F[2,\ 28] = 16.73$; $p < 0.001$): a post-hoc test indicated that, for SM and DM, repetition group 1 had a more negative amplitude than repetition groups 2 and 3. (see Fig. 2B).

4. DISCUSSION

In this study, we conducted both a behavioral experiment and an EEG experiment in order to find electrophysiological correlates of the perceptual externalization. We expected the stimuli under the motion condition DM (head movement, head tracking active) to be more externalized than stimuli under other motion conditions [3–5]. The literature also suggested that the N1 and P2 ERP components generated by stimuli under the condition DM would have a larger amplitude and a shorter latency than those generated under other motion conditions [6, 7]. For the behavioral experiment, the condition with head movement and head tracking active (DM) induced a better externalization than the conditions without head tracking (SF and SM) while the condition with head movement and head tracking inactive (SM) as well as the condition with no head movement (SF) provided similar externalization. For the EEG experiment, the condition with head movement and head tracking inactive (SM) induced a more negative amplitude of the N1 component and both conditions with head movement (SM and DM) induced a more negative amplitude on components after 100 ms. Finally, stimuli presented latter in the repetition train had a reduced amplitude of all components compared to stimuli presented at the beginning of the train.

4.1 Behavioral findings

The stimuli were more externalized in the condition with head movement and head tracking active (DM), which replicates previous findings with a similar paradigm [3,4]. However, the improvement in externalization induced by head movement reported in the present study was less substantial than what could have been expected from previous studies [3,4]. Moreover, no difference could be found between the condition with no head movement (SF) and the condition with head movement and head-tracking inactive (SM), whereas Hendrickx *et al.* [3, 4] found less externalization for condition with head movement and head-tracking inactive (SM) than for condition without head movement (SF). This poorer externalization found in the present study could be explained by the nature of the stimulus used. The stimulus was not natural speech but an unnatural repeated word designed to evoke ERP, which may have broken the logical continuity (consistency) of the sound. Indeed, several subjects reported that, even if they experienced a good externalization during the head movement (hence, during the natural sentence), the externalization dropped significantly when the train of repeated word started. Few studies have studied the influence of the nature of the sound on externalization [5, 24], and further studies would therefore be needed to estimate the influence on externalization of such discontinuous and non-semantic speech stimuli.

4.2 EEG findings

The fact that the first group of repetitions has, after 100 ms, a more negative amplitude than the second and third group probably comes from an effect of suppression due to the repetition of the "boru" word as previously documented (*e.g.* [9, 25, 26]).

In both studies of Getzmann and Lewald and Palomaki *et al.*, differences between stimuli types (free field vs individualized binaural vs non-individualized binaural vs stereophonic) were found on N1, N1m and P2 amplitude and latency. In the present study, externalized stimuli (DM) were compared to less externalized stimuli (SF and SM). No effect of motion condition where DM was different from both SF and SM could be found. Hence, the differences that Getzmann and Lewald and Palomaki *et al.* found on N1 or P2 latency and amplitude might not have been caused by differences of externalization induced by the different stimuli types but could have been caused by differences of frequency content or listening device. Indeed, they compared individualized vs non individualized binaural stimuli, which means different HRTF sets so different frequency contents between stimuli. Also, they compared free field vs binaural thought headphones, which implies differences of visual and kinestesic (headphones on the head) information that could have had an influence on the ERPs.

Since the results of the present study could not highlight neural correlates of externalization, externalization could be investigated using different paradigms. Auditory ERP generated by stimuli location change are known to be sensitive to the subject's attention [27, 28]. Thus, if one considers that externalization can be intermixed with distance perception (it is however unclear whether externalization and distance perception are distinct or whether

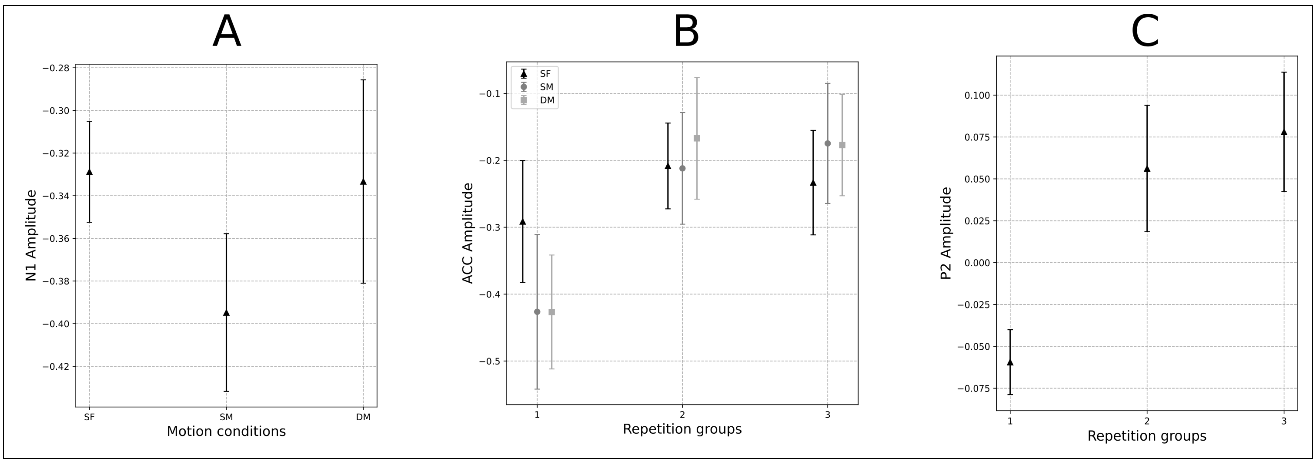

Figure 2. (A) Mean of normalized peak amplitude for the N1 component, on Cz, motion conditions grouped, per repetition groups. Error bars show 95% confidence interval. Arbitrary amplitude units. (B) Mean of normalized amplitude over the ACC time window, on Cz, for each repetition groups, per motion conditions. Error bars show 95% confidence interval. Arbitrary amplitude units. (C) Mean of normalized peak amplitude for the P2 component, on Cz, repetition groups grouped, per motion condition. Error bars show 95% confidence interval. Arbitrary amplitude units.

they form part of the same continuum [29]), one could expect significant differences between more or less externalized stimuli to emerge in ERP from a paradigm involving subject's attention. Indeed, a previous fMRI study found neural differences between binaural stimuli and stereophonic stimuli using a localization task [30].

For components after N1, the fact that the first repetition group for motion conditions SM and DM had a more negative amplitude than SF could be a processing effect related to the temporal proximity of the head movement. More precisely, the fact that subjects had just stopped moving the head might have altered the processing of the sound that came after the motion. Considering further this possibility, this altered processing may not be attributed to a change in externalization since, in the behavioral experiment, the motion condition DM induced a difference in externalization compared to SF, but SM did not. A possibility is that such an effect could be linked with activity of the vestibular system, which can be induced by head movement and continues even after the movement has stopped [31, 32].

The fact that, on N1, SM had a more negative amplitude than SF and DM may come from a difference of spatial frame of reference. In both the conditions SF and DM, the sound remained consistent in regard to the world throughout the playback, as it would in natural listening condition. Indeed, in SF, there was no head movement and the sound remained in front of the subjects. In DM, the subjects executed a head movement but the head-tracking allowed the sound to remain fixed with respect to the external world, *i.e.* the sound was consistent in an "terrestrial" frame of reference as would a real sound source in natural listening condition. However, in SM, when the subject executed the head movement, the sound moved with the headphones and became inconsistent with the world, while being then consistent in a "listener's head" frame of reference (the sound is no longer realistic as would a real sound source). This difference of frame of reference between SM and the two other conditions could have induced differences of neural processing and perception of the "boru" stimuli, as have been reported in previous studies [16, 33]. Those studies obtained different ERP while comparing sound stimuli that were consistent in either a "terrestrial" frame of references or a "listener's head" frame of reference.

5. CONCLUSION

In this study, a behavioral experiment and an EEG experiment were conducted to study neural correlates of externalization using ERPs. To make sure that the only varying factor was externalization, similar procedures, stimuli and sound reproduction setup were used for both experiments. Different degrees of perceived externalization were achieved by preceding EEG and behavioral measurements with 1) head-tracked movements, 2) untracked head movements, and 3) no head movement. While we asked for a subjective rating of externalization in the behavioral task, the EEG task was a simple passive listening task. Performing a head movement, whether the head tracking was active of not, enhanced the amplitude of ERP components after 100ms, which could be a processing effect related to the temporal proximity of the head movement, possibly attributed to the vestibular system. Moreover, moving the head with head tracking inactive increased the amplitude of the N1 component, which could be a marker of a coherence break in the sound. The behavioral experiment revealed that head-tracked movements did enhance externalization, as observed in previous studies. On the other hand, no specific neural correlates of externalization were found in the ERP, which suggests that differences observed on ERP components between more or less externalized stimuli in previous studies might not have been caused by externalization but rather by differences of spectral content or listening device.

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