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Research Article

Keywords: movement sonification, upper limb, hemiparesis, mixed methodology, rehabilitation

Posted Date: November 17th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2262801/v1

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Journal of NeuroEngineering and Rehabilitation on October 5th, 2023. See the published version at https://doi.org/10.1186/s12984-023-

01248-y.

Effect of sonification types in upper-limb movement: a quantitative and qualitative study in hemiparetic and healthy participants

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Abstract

Background: Movement sonification, the use of real-time auditory feedback linked to movement parameters, have been proposed to support rehabilitation. Nevertheless, if promising results have been reported, the effect of the type of sound used has not been studied systematically, and mechanisms involved during movement execution with sonification remain poorly understood. The aim of this study was to investigate in a single session the effect of different types of sonification both quantitatively and qualitatively on patients with acquired brain lesions and healthy participants. This experiment should be considered as a first step before establishing a longitudinal clinical rehabilitation study.

Methods: An experimental setup enabling arm sonification was developed using three different categories of sonification (direct sound modulation, musical interaction, and soundscape). Simple moving forward movements performed while sliding on a table with both arms were investigated with all participants. Quantitative analysis on the movement timing were performed, and different comparisons were processed (sound / no sound, affected arm / less affected arm, category and type of sonification). Qualitative analysis of semi-structured interviews were also conducted, as well as neuropsychological evaluation of music perception.

Results: For both the patient and healthy groups (15 participants each), average duration for performing the arm movement is significantly longer with sonification compared to the no-sound condition ($p<10^{-3}$). Differences were also observed between the sound categories in the case of the paretic arms of patients and the dominant arms of healthy participants ($p<0.05$). Qualitative analysis of semi-structured interviews revealed the motivational and affective aspects of each type of sonification. Most participants of both groups preferred to complete the task with sound, and more precisely with one that uses sound of nature environment (soundscape).

Conclusion: Overall, our results confirm that the sonification has an effect on the temporal execution of the movement during a single-session. This effect is variable among participants, which requires further studies to better understand. Globally, sonification is welcomed by the participants, and we found convergent and differentiated appreciations of the different sonification types. This enables us to provide researchers with recommendations for clinical studies for personalized music-guided rehabilitation.

Keywords: movement sonification; upper limb; hemiparesis; mixed methodology; rehabilitation

Background

Acquired brain lesions in adults, following stroke, head injury, or brain tumor, are major causes of acquired disability worldwide (Pollock, 2014 Chan, 2013). These lesions induce multiple sensory, motor, and cognitive disorders. Among these disorders, motor impairments could affect 40% of patients after stroke (Lecoffre, 2017). Upper limb hemiparesis, characterized by impaired motor control and muscle weakness, greatly reduces autonomy in daily living activities, and thus, the long-term quality of life of patients (Cerniauskaite, 2012).

In order to promote recovery, which is related to the substitution mechanism based on neuroplasticity, functional rehabilitation is essential (Yelnik, 2008). The effects of listening and playing music on brain plasticity have been highlighted in several publications (Münte, 2002 Gaser, 2003 Wan, 2010 Altenmüller, 2015), especially in patients with stroke induced (Altenmüller, 2009 Rojo, 2011 Amengual, 2013) and traumatic brain lesions (Siponkoski, 2020 Martinez-Molina, 2021). Also, the use of music is being studied in a wide range of rehabilitation settings (Sihvonen, 2017 Moumdjian, 2016), both for language, such as dyslexia (Flaugnacco, 2015), and aphasia (Raglio, 2016), as well as for motor skills in Parkinson's disease (De Dreu, 2012 Pereira, 2019), or acquired brain lesions (Zhang, 2016 Ghai, 2019). Among the various methodologies developed, it is necessary to distinguish audio-rhythmic stimulation (RAS), exercises with musical instruments (music-supported therapy), and movement sonification devices.

Movement sonification is based on the real-time translation of motion parameters into sound parameters (Effenberg, 2005 Hermann, 2011). Innovative devices have been developed in the last few years to meet the needs of different contexts. While several movement-sound interactive systems were initially designed and developed in the field of artistic creation, their potential interest on sensorimotor learning has been highlighted in several studies (Bevilacqua, 2016 Effenberg, 2016). In the context of rehabilitation, the motion capture systems on which they are based can notably be used as a measurement tool (Cho, 2018 Sethi, 2020 Berner, 2020).

Movement sonification devices have many advantages: access to a continuous 3D auditory information, fast adaptation of sound feedback to the movements performed, flexibility of use by participants with various profiles thanks to possible adaptation according to individual abilities. Thus, these devices present a real added value in comparison with other sound/musical methods and tools, and offer perspectives in adequacy with the needs described in the rehabilitation framework. Moreover, compared to other feedback modalities such as visual feedback, the use of the auditory modality does not constrain the user's posture. In this case, the dependence to the external feedback, called the guidance effect, might be less important with auditory compared to visual feedback since sonification could encourage to focus attention on intrinsic proprioceptive information (Dyer, 2015).

Their potential interest as a rehabilitation support tool is therefore currently under investigation (Schaffert, 2019 Mezzarobba, 2020 Veron-Delor, 2019 Ghai, 2018). Concerning more specifically rehabilitation after acquired brain lesions, in a pilot study with 7 patients with post-stroke motor sequelae (mild to moderate hemiparesis), Schmitz (Schmitz, 2014) had highlighted an encouraging evolution of the global dexterity scores (Box and Block Test) specifically for the 4 patients who benefited from the movement sonification system during the 20 minutes exercise sessions performed during 5 consecutive days. In a large-scale study of 65 sub-acute stroke patients, Raglio (Raglio, 2021) found similar benefits of two weeks of sonification-assisted rehabilitation on global dexterity scores (Box and Block Test, and Fugl Meyer Upper Extremity Scale) and pain scores (Numerical Pain Rating Scale). In both situations, standard motor rehabilitation exercises were sonified. In 2015, Scholz's team proposed an innovative device where users learn to move in a virtual space associated with a musical scale, with the aim of playing melodies (Scholz, 2015). In this case, a decrease in pain scores was reported, as well as a trend towards improvement in the Stroke Impact Scale functional hand assessment scores. Nevertheless, the comparative study of 25 patients with moderate upper limb motor deficits following stroke did not show any improvement in scores on the other functional assessments performed (Action Research Arm Test, Box and Block Test, Nine Hole Peg Test). In a pilot study, Robertson suggested that in the presence of audio feedback different results could be obtained depending on the hemispheric location of the brain lesion, and more precisely a deterioration in kinematic performances in the presence of audio feedback in the case of left hemispheric brain lesions) (Robertson, 2009).

Thus, although encouraging results have been obtained and repeated in different settings, contrasting effects have been demonstrated, sometimes with limited functional benefits (Nikmaram, 2019). One reason for these divergent effects could be related to the choice of sound design. Initially, the choice made was to sonify errors, for example, a sound emitted when the participant doesn't follow the predicted trajectory model (Maulucci, 2001). One trend in sound designs for motor learning or rehabilitation is to seek to avoid negative reinforcement (Bevilacqua, 2016). The quality of the sound rendering has not always been a central concern, yet the choices of sound design and mapping could be fundamental to ensure the adequacy between the sound and the gesture to be performed, and thus, the effect of sonification on the movement control and learning (Avanzini, 2013 Dyer, 2015). Questions about sound design and coupling modalities require further investigations (Kantan, 2021). In particular, these investigations must be considered with regard to the tasks to be performed, the user profiles they address, and individual singularities. The need to consider multiple sonification modalities and to evaluate their effects was notably highlighted in two recent literature reviews (Ghai, 2018 Nown, 2022). Indeed, if the issues of sound design of sonification devices have been exposed, more particularly in the context of motor learning, to date there are few specific recommendations to guide the choices to be made. Moreover, the mechanisms underlying the effects of sonification remain insufficiently documented.

Therefore, it appears important to closely examine the effects of different sound feedbacks and different coupling modalities, considering a given motor task and diversified participant profiles. In this perspective, the objectives of the present study were to evaluate different modalities of gesture-sound interactions, categories and types of sound feedback, with adult patients with hemiparesis following an acquired brain lesion and healthy participants.

In contrast to some sonification devices developed in the context of post-stroke rehabilitation that concern prehension (Raglio, 2021 Friedman, 2014), we focus here on a simple gross motor task. Precisely, this task consists in sliding the arm on a table. Such a forward arm extension corresponds to an earlier rehabilitation recovery stage, and concerns a larger number of patients.

Precisely, we aimed at jointly evaluating the sonification effect on performing movements analyzed quantitatively, and qualitatively considering the user experience. Importantly, our task was focused on the effects of the presence of sound feedback during a single session of movement sonification, and does not constitute in itself a rehabilitation protocol. On the contrary to typical rehabilitation assessments where the motor task must be performed as quickly as possible (i.e. scores in assessments typically indexed on the number of objects moved (Desrosiers, 1994 Croarkin, 2004), or the number of repetitions of a movement or targets reached), we rather chose to give no instruction concerning the speed of execution of the task. Our goal in this study was indeed to evaluate the spontaneous effects of the sound feedback on the temporality of execution of the movement.

Method

Participants

All participants met the following inclusion criteria (Table 1): age between 18-80 years old, ability to understand the consent form and simple instructions, ability to answer questions during semi-structured interviews, and consent to participate. Participants were included in the patients group if they were hospitalized in rehabilitation department of Pitie-Salpetriere Hospital and had upper-limb hemiparesis after acquired brain lesion with sufficient recovery to initiate an elbow extension and complete the motor task (stretch their elbow while sliding on a board), and if they did not have any other neurological disease. Participants were included in the healthy subjects group if they had no acquired brain lesions or other neurological pathology, and no upper-limb deficits of any origin. Participants of both groups were not included in case of musicogenic epilepsy, heart pacemaker, or hearing deficits requiring hearing aids.

Protocol

The experimental design consisted in three steps:

1. An interview of each participant was carried out to evaluate their musical experience (vocal and/or instrumental education and practice), listening habits and possible hearing deficits. Three levels of musical expertise were distinguished: no musical practice, amateur experience or practice corresponding to a minimum of two years of regular vocal/instrumental training, and professional experience or practice. After the interview, their musical perception was assessed with the Montreal Battery of Evaluation of Amusia (MBEA) (Peretz, 2003). The participants' scores were compared to the norm established during the validation of the tool (Peretz, 2003) in order to identify possible deviations from the norm in each group (Chi-square test). At last, their manual dominance was assessed with the Edinburgh Handedness Inventory (Oldfield, 1971).

2. The session of sonification of the elbow extension task was carried out. The participants were instructed to extend the arm repetitively (stopped by the experimenter after around ten repetitions), sliding on the table with a fabric to minimize friction, following a straight trajectory. The instruction did not impose any particular timing to perform the movement: the participants were explicitly asked to perform the movement at the speed of their choice. This allowed us to compare average movement durations according to the participant profiles, while keeping the sound conditions order identical for all participants. During the session, participants used each arm alternatively, less-affected then affected for patients, and dominant then non-dominant for healthy subjects, with three different categories of sonification (direct sound modulation, musical interaction, and soundscape, described in detail in section below:

Experimental Setup) and no-sound condition. The order of presentation of the sound conditions starting on purpose from simple sound modulations, shown in Figure 1, was identical for all participants, as we were aiming primarily to provide a comparable experience among participants. We included a no-sound condition at the beginning, the end, and between the three sonification categories, in order to assess the stability of the no sound-condition and any after-effect of each sound type on the no-sound conditions. This should allow us to ensure that the no-sound condition can be used as a participant-dependant control condition. In order for the system to adapt to the motor skills of each participant, a calibration was performed at the very beginning of the task (see section Experimental setup).

3. After the session of sonification a semi-structured interview of the subject experience was recorded with a dictaphone (Guide of semi-structured interview, on Supplementary Materials S1). We also asked participants to sort by order of preference the sound conditions, and to choose in order 5 qualifying terms to describe their feeling in a 18 qualifier list, based on a balanced valence/arousal diagram.

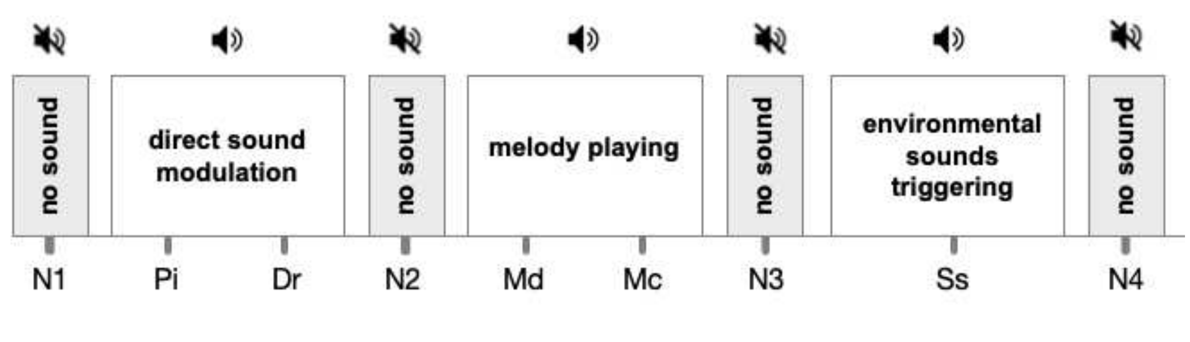

Figure 1 Order of the sound conditions with the “no sound” condition intertwined

Experimental setup

A specific system was built in order to provide sonification in response to the arm movement of the participant. Three wireless motion sensors, containing each an Inertial Measurement Units (IMU) were attached to both arms, as depicted in Figure 2. Each IMU embeds 3D accelerometers, 3D gyroscope and 3D magnetometers, and transmits the data sampled at 200 Hz in real-time through WiFi. Those data enable the computation of the orientation of the IMU units (i.e. the Euler angles). These angles are used to compute a normalized displacement parameter after performing a calibration consisting in recording the IMUs data at the start and stop positions (indicated in Figure 2 A). This displacement parameter is used as the input parameter in the sonification system (described in Section Sonification strategies). The calibration procedure was performed at the beginning of each participant's session, which allows adapting the sonification to each participant's motor capabilities, since the actual displacement can be different for each one.

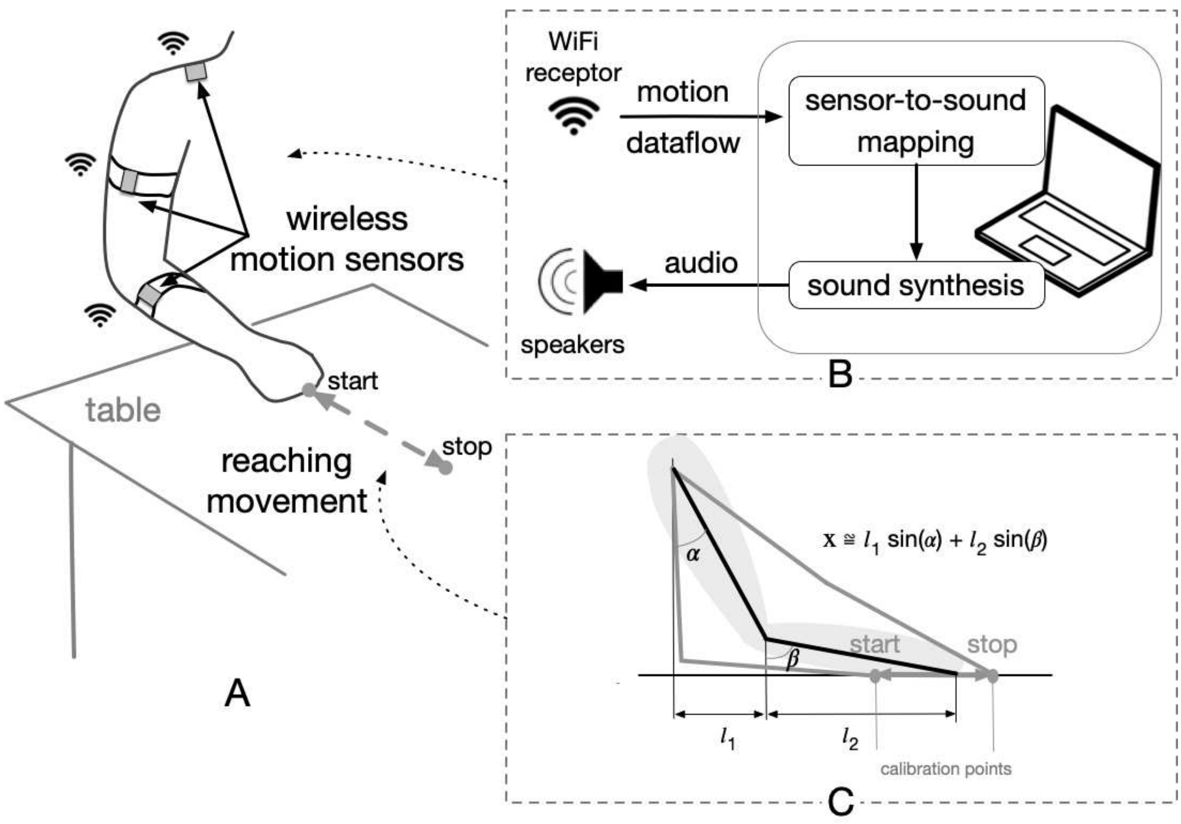

Figure 2 Experimental Setup. A placement of the motion sensors (IMU). B: Schematic of the dataflow process and auditory output. C: Basic description of the computation of the displacement using the two calibration points indicated as *start* and *stop* (median plane).

The laptop computer, connected to a soundcard and speakers, operates the sonification using a program written with Max7 (Cycling'74) and the extension MuBu for Max (Schnell, 2009). This library allows for performing data signal processing, and controlled sound synthesis. The software is also used to record all the IMUs data to the computer, along with the sounds. The audio rendering system was composed of one stereo speaker in front and two additional mono speakers in the back of the participant in order to create an immersive sound environment.

The displacement data, along with the raw IMUs data and audio output were recorded during all movement cycles, and saved in the computer. Video recordings were also performed during all the experiments, allowing the verification of the data collected with the IMUs.

A data analysis script (Matlab, R2018a, Mathworks USA) was developed allowing for data visualization, and semi-automatic segmentation of the displacement data in 4 different phases for each cycle (see Figure 3):

- the “elongation phase” of the upper-limb (extension of the elbow),
- the "plateau-1": phase of maintenance in a position of maximum upper-limb elongation,
- the “retraction phase”, return to the initial position,
- the "plateau-2" phase in the initial retracted position, elbow bent, before initiating a new extension-flexion cycle.

This led us to compute 5 different time duration: extension duration, plateau-1 duration, return duration, plateau-2 duration, and total duration time (sum of the 4 previous ones).

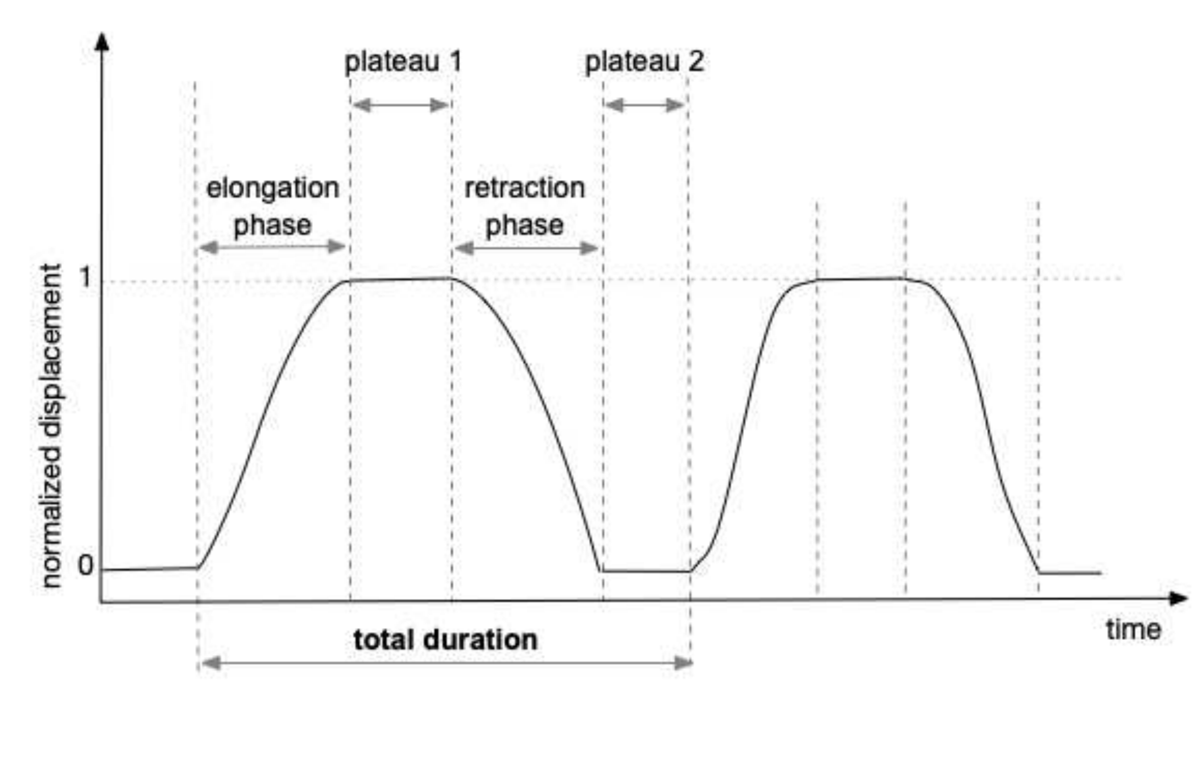

Figure 3 Normalized displacement over time with the different computed phases.

Sonification design

We decided to implement 5 different types of sound, classified in 3 different sonification categories, in order to evaluate how different sounds and musical interactions could influence the movement timing and how they were perceived by the users in this context.

Audios and sound spectrograms are presented in Supplementary Materials S2.

1. Direct sound modulation

This category of sonification has been largely implemented in sonification systems and reported in the literature (Dubus, 2013 Nown, 2022) .

Pitch (Pi): direct relationship between the reaching distance and the pitch. In order to avoid the annoyance of a pure tone, we use granular synthesis in order to vary the pitch of a sample sound that contains a rich spectrum (from 92-500 Hz). The farther the reaching point, the higher the pitch. The range of variation of the fundamental frequency is from 92 to 122 Hz, with a strong harmonic varying from 279 to 376 Hz.

Drum (Dr): direct relationship between the reaching distance and the tempo of a regular beat pulsation. We used a drum sound, with a regular rhythmic pattern (such as 4 eighth notes). The farther the reaching point, the faster the tempo. The range of variation is from 3.2 to 16 Hz beats. At the fast tempo, the drum sounds like a drum roll.

2. Melody Playing

Sonification implying music can potentially be motivating for the participant as shown previously (Ghai, 2018). In this paradigm, the user can play a melody by moving the arm. All the notes are programmed, so the task consists in activating the progression of the melody. Two distinct cases were implemented:

Music / Discrete (Md): a full forward arm movement triggers a “discrete melody”, following a tonal harmonic progression (based on Concerto No. 5 in F Minor, BWV 1056). The movement triggers a different part of the melody at each outward and backward movements (four notes per outward or backward). This sonification was previously used in a music education scenario (Guédy, 2013).

Music / Continuous (Mc): a full arm movement enables one to continuously “play” a complete musical phrase, using the so-called gesture follower technique, which has been used in music pedagogy (Bevilacqua, 2007 and Bevilacqua, 2010). In this system, a time progression index of the gesture is estimated by comparing the performed gesture with a displacement profile recorded previously. Then, this estimated time progression index is used to trigger notes of the melody. The piece was a record of the Prelude in C Major by J.S. Bach interpreted by Glenn Gould.

3. **Environmental sounds Triggering**

This sonification category is based on everyday listening, invoking recognizable sound environment (Lemaitre, 2018). In this paradigm, the reaching movement is divided in three different zones, each one being associated with a specific environmental sound, called 'soundscapes'.

Soundscape (Ss): The reaching movement is divided in three equal parts. Each one triggers, respectively, sounds of wind, river and birds.

Data Analysis

Movement Analysis

The statistical analyses were performed with JMP software® (SAS Inc., Cary, NC, USA). All tests were 2-sided. A p-value ≤ 0.05 was considered statistically significant.

A first step consisted in testing the homogeneity of the "no sound" conditions using analysis of variance (ANOVA) on repeated measures (or Friedman non parametric test on ranks when underlying assumptions were not verified), to evaluate any order effect in the no-sound sequences. Differences between these sequences being non significant, data were normalized by dividing duration values by the average of the no sound values in order to take into account inter-individual variability.

Then, for each participant (patient or healthy participants) and arm considered, Student paired t test (or Wilcoxon signed-rank test) and Anova on repeated measures (or Friedman test) were performed on normalized data taking into account sound context. This was followed, when needed, by post-hoc Tukey HSD analysis (or Durbin-Conover test). When parametric tests were applied we made sure that the underlying assumptions (normality, homoscedasticity or sphericity for repeated measures) were valid.

Participant's experience Analysis

In order to obtain the average preference of sound and qualifying terms used by the participants, we associated 1 to 5 points (5 being the preferred) to each sound or qualifying term for each individual ranking order. We then calculated the average points for each sound or terms.

The audio recording of each semi-structured interview has been transcribed verbatim. Three experimenters (IP, BC, FB) carried out the thematic analysis of the transcribed interviews (Braun, 2006). Each experimenter read the transcription and generated individual codings from the participant's interviews. The experimenters then gathered the codes and kept the common codes or the ones that may not be common to the three experimenters, but that reached a consensus after discussions. From the selected codes, we defined thematic axes, and we kept a list of illustrative quotations for each axis. For each result we distinguish particularities of each group of participants (designed as "P" concerning patients, and "H" concerning healthy participants).

Results

Participants Description

Two groups of subjects participated and followed the protocol entirely: 15 patients with motor deficit (hemiparesia) resulting from acquired brain lesions, and 15 healthy participants were included.

Descriptive information about gender, age, musical background, MBEA scores, and side of hemiparesia are reported in Table 1. More details about each participant are reported on Supplementary Materials S3 (Descriptive data of participant's profiles).

Statuts	**Patients**	**Healthy**
Gender (M/F)	6M/9F	6M/9F
Age (mean; range)	45 years; 20-70	42 years; 21-71
Musical Background (None/Amateur/Pro)	8N/6A/1P	7N/6A/2P
MBEA (norms/falls)	10N/5F	15N/0F
Dominant Side (R/L)	15R/0L	15R/0L
Hemiparesis (R/L)	6R/9L	/

Table 1 Description of the groups of participants

All participants were right-handed, and gender repartition, age and musical background are similar between groups. Comparative analysis of MBEA scores revealed lower scores in patient groups than in healthy ones (Supplementary Materials S4). This difference is at the limit of significance (test Chi^2 $p=0.05$).

Movement data results

Individual data

Data without normalization of the averages of the total durations performed by each individual with no sound (N1, N2, N3 and N4) and with sonification (Pi, Dr, Md, Mc, Ss), are presented in Figure 4, considering the subject group (patient and healthy participants) and the arm (paretic side vs. less affected, and dominant vs. non-dominant).

In Figure 4, it appears that the average duration of a complete cycle varies across participants. This result must be considered in regards to the fact that we did not give any timing constraint on the movement performance. We also observe that there are more variations in the sound condition compared to the no sound conditions. More precisely, as shown in Figure 5, the four “no sound” conditions were compared for all participants, and no significant difference was found. Therefore, this stability confirmed that the “no sound” condition can be used for normalizing each participant's sound conditions measurement. The results are described in the next section.

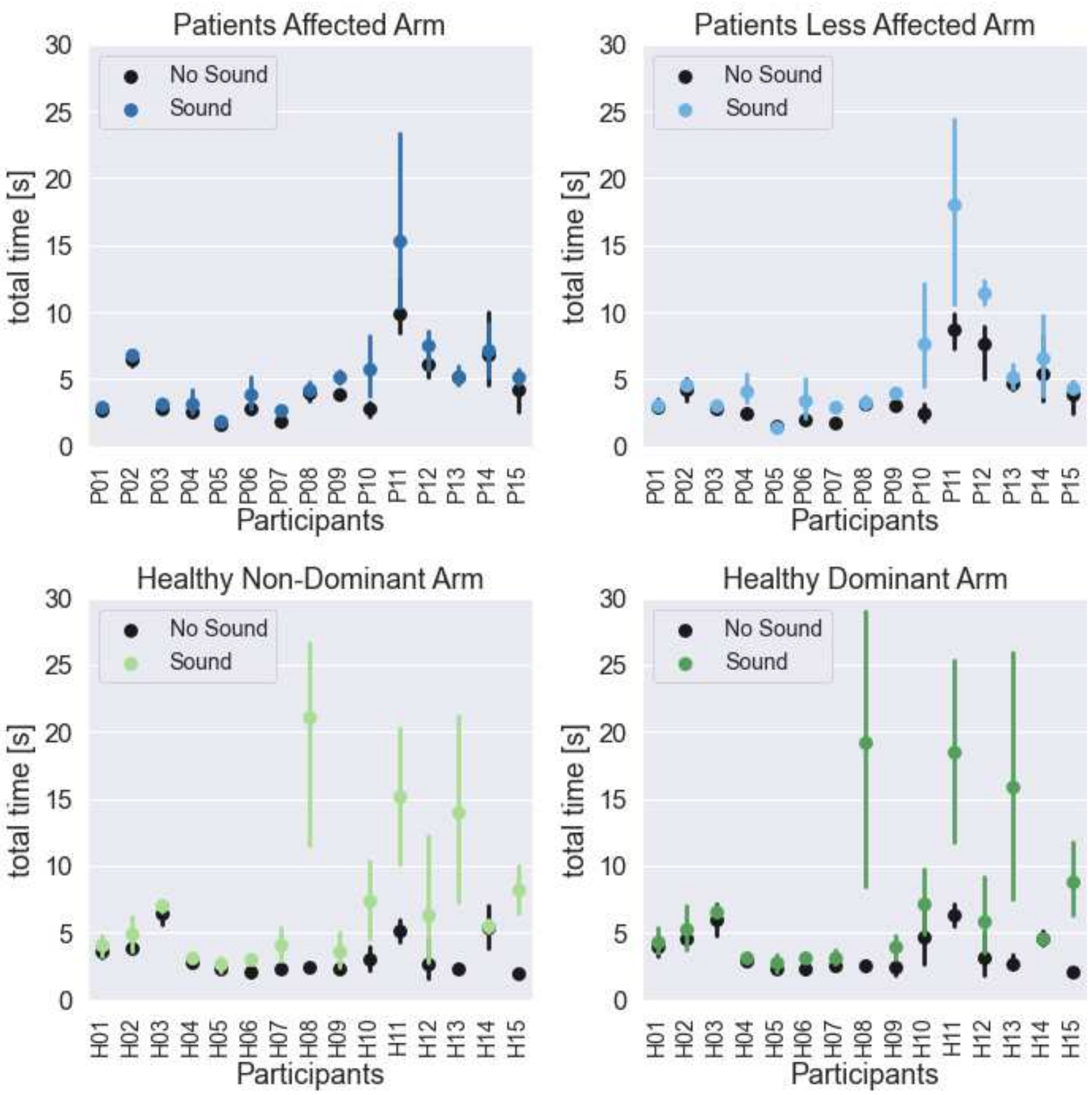

Figure 4 No sound vs sound condition, for patients and healthy participants. The error bars correspond to the 95% confidence intervals.

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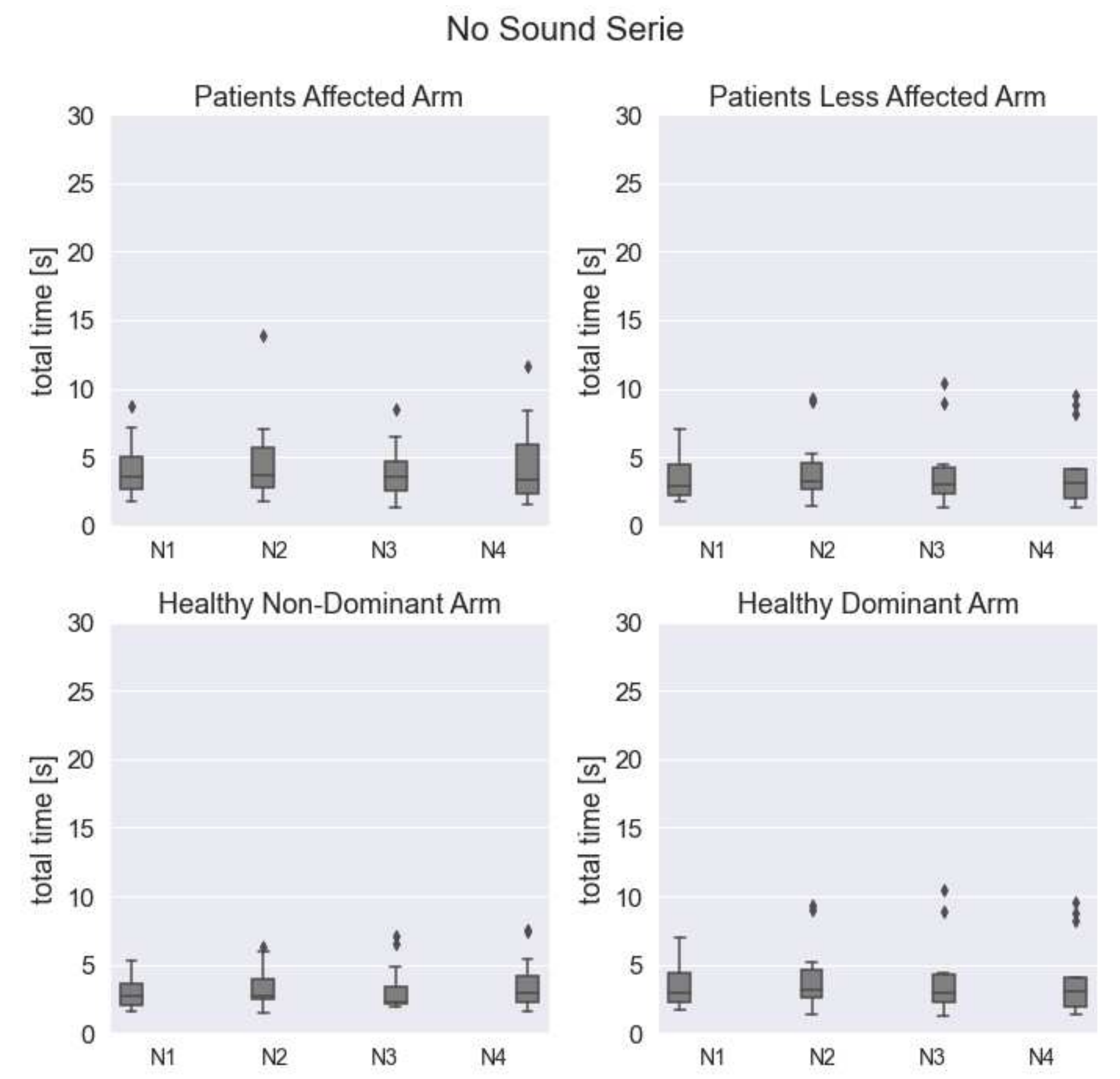

Figure 5 “No sound” series for patients and healthy subjects. The y-axis range [0-30] has been chosen to be identical to figure 4 to facilitate the comparison. The box of the boxplots represents the limit of the 25th percentile and 75th percentile, the median being indicated inside.

Comparison between the sound and no sound conditions

The comparative analysis of the average of total cycle durations with no sound compared to sonification shows a significant difference for each situation considered ($p<10^{-3}$ for both arms in patients and healthy participants) (Figure 6). Specifically, the total average duration increased with sonification compared to cases without sound feedback.

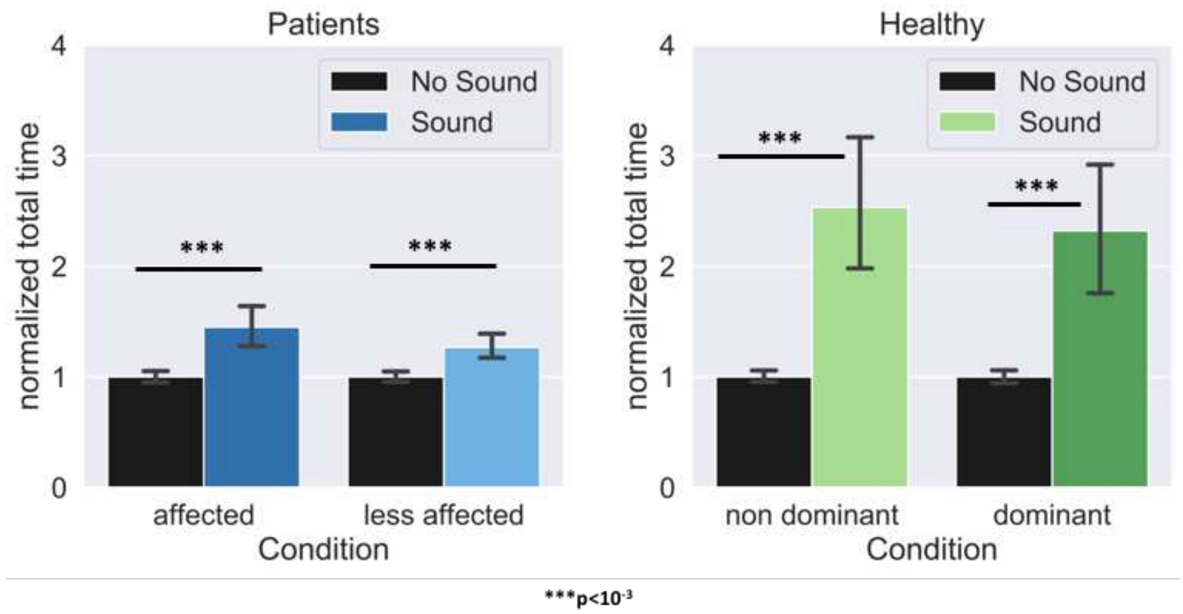

Figure 6 Mean for the patients (left) and healthy participants (right), for all the sound and no sound conditions, considering the different arms (affected / less affected for the patients, and non-dominant / dominant for the healthy participants). The error bars correspond to the 95% confidence intervals.

If we consider in more details the duration of the different phases constituting the extension-flexion cycles of the elbow, we observe significant differences in the average duration of plateau-1 (phase of maximum elongation), retraction phase, and plateau-2 (phase of minimum elongation between two extension phases), when comparing sonification to no sound conditions for both groups. Plateau-1 and the return phase were longer whatever the arm considered both in patients and healthy participants ($p<10^{-3}$). Thus, participants remained in maximal extension for a longer time with sonification compared to no sound condition and returned to the starting point slower in the presence of sonification compared to the no sound condition. The average duration of plateau-2 were also longer both in patients for paretic and less-affected arm ($p<0.03$ and $p<10^{-3}$, respectively) and in healthy participants for non-dominant and dominant arm ($p<0.005$ and $p<0.02$, respectively).

Concerning the extension phase, significant differences between the sonification and no sound conditions were observed in the healthy participants for both arms and in patients for the less affected arm ($p<10^{-3}$).

Comparison between each sound condition

The comparative analysis of the average of total cycle durations according to the sound feedback categories (Anova on repeated measures) shows significant differences between sonifications categories, in the case of the paretic arms of patients and the dominant arms of healthy participants ($p<0.05$) (Figure 7). These significant differences are not found in the other situations (less affected arms of patients and non-dominant arms of controls).

The comparative analysis of each type of sound (Friedman's test) revealed no significant differences. However, there are interestingly several tendencies worth noting on descriptive analysis of repeated measures for each sound condition (Supplementary Materials S5) in regards to the qualitative analysis presented in the next section. Similar profiles seem to appear regarding the two groups, whatever the arm considered (S5, Fig. C2). The median durations with discrete melodies are always lower. We could also notice that there is a comparable inversion between Pitch and Drum between arms inside a group. Otherwise, results concerning Soundscape are different regarding the subject group.

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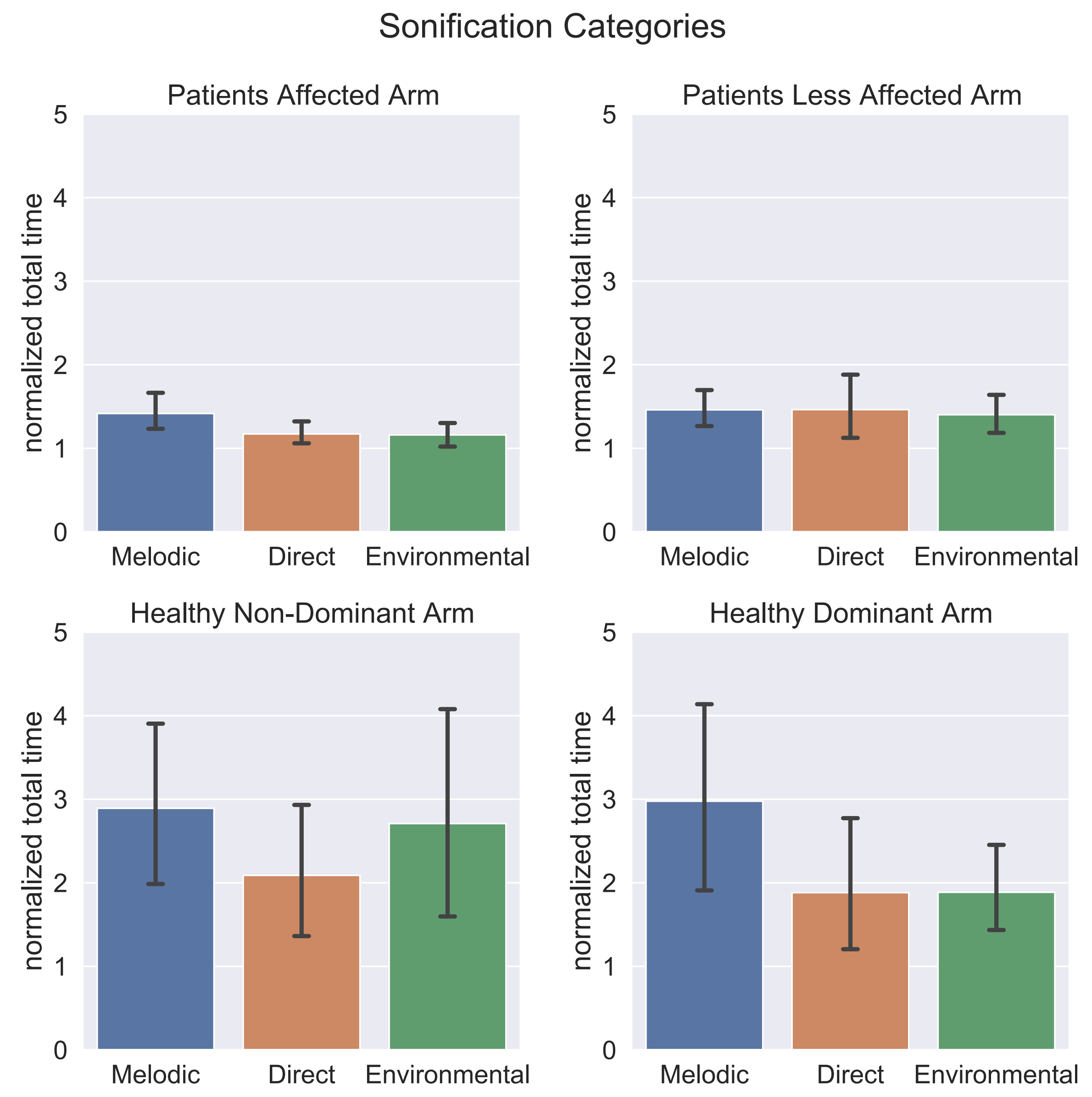

Figure 7 Mean for the patients and healthy participants, for the categories of sound conditions, considering the different arms (affected / less affected for the patients, and non-dominant / dominant for the healthy participants). The error bars correspond to the 95% confidence intervals.

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Results concerning the participant's experience

Sound preferences and Experience qualifiers

We report the individual rankings, rated from 1 to 5 points, according to the hierarchical preference of the sound feedback and the qualifying terms respectively.

We found that the most appreciated sound feedback by both groups of participants is the soundscape, followed by the continuous music. The order of preferences for the others' sound feedback is different regarding the participants' group, as summarized in Table 2.

Among the 18 qualifiers list, *playful* is the first shared term for both groups of participants to qualify their experience. Three qualifiers are common for both groups: *amusing*, *stimulating* and *intuitive*. On the patient group the qualifier *surprising* is present in the top 5, while the qualifier *captivating* is more frequently on the healthy group of participants.

Patients	**Healthy**
Soundscape	Soundscape
Continuous Music	Continuous Music
Discrete Music	Pitch
Pitch / Drum	Discrete Music
	Drum

Table 2 Sound Feedback Rankings

Patients	**Healthy**
Playful	Playful
Surprising	Amusing
Stimulating	Captivating
Intuitive	Stimulating / Intuitive
Amusing	

Table 3 Experience's Qualifiers Rankings

Thematic analysis based on semi-directive interviews

The thematic analysis revealed common themes across subject groups, as well as specific themes to each subject group. First, two common themes were identified: 1) the perception of the gesture-sound interaction, and 2) the role of emotions, mental imagery and attentional processes. Secondly, we found that a specific theme for the healthy group was related to an analytical approach of the sonification system and of the gesture-sound interaction which do not appear for the patient group. Thirdly, for the patient group, we identified a specific theme related to the applicability of the sonification system in the context of rehabilitation and its potential future uses.

1. Common theme to the patient and healthy group: the perception of the gesture-sound interaction

As part of this first theme about the perception of gesture-sound interaction, we identified three sub-themes which correspond to participant’s feelings using the system, the identification of cueing role, and the assignment of roles during the interaction as leader or follower.

Reported feelings using the system:

First, the majority of participants reported feeling a difference in the sound context when performing the task (24/30; 14 Patients - 10 Healthy), and they prefered performing the gestures in the presence of sonification (29/30; 14P-15H). Some participants spontaneously stated that the task was more enjoyable, funnier, more engaging, and more interesting with any type of sonification. Among the six participants who did not report perceiving any difference related to sound context, two indicated that they consciously tried not paying attention to the sound interaction, in order to move their arm independently of the sound context. These two cases represent idiosyncratic appropriation of the instruction compared to the other participants. A third participant mentioned a notable distinction between perception and volition (P04): "The impressions were not different but the intentions could be". This participant reported a deeper involvement in the task performance in the presence of the sonification: "[...] The movement is more voluntary when it produces a sound".

Second, the task performance was not considered to be more difficult with sonification than without in the majority of cases (22/30; 11P-11H). Thirteen participants (7P-6H) even reported that it was easier to perform the forearm extension task with sonification. Nevertheless, six participants (2P-4H) reported the experience being occasionally more difficult with some specific couplings, which they justify with two different reasons: a mismatch between the sound type and the gesture to be performed (Md), and when a specific movement quality was required for the sound production (Mc). Concerning the first aspect, several participants underlined that the jerky sound of the discontinuous melody was not matching with the representation of a regular gesture to be carried out. That induced a desire to adapt the gesture in relation to the produced sound, which implied then to perform it in a jerky way. Concerning the second aspect, the participants specified that Mc generates an expectation for the quality of the music produced. In turn, this would require a finer motor control (H01): "Since it's music, I want it to sound like something fluid that one could listen to".

These remarks highlight on the one hand that the sounds convey a representation of the gesture to be carried out, which can trigger a motor mental imagery associated with the perception of certain sounds, and on the other hand the need of an adequacy between the gesture and the sound. Therefore, this implies that 1) the interaction design should ensure fluidity in the gesture-sound coupling, 2) the choice of the type of sound feedback can therefore either favorably reinforce the feeling of interaction or conversely create a feeling of inadequacy.

<u>The notion of cues:</u>

Looking more specifically at the interaction between movement parameters and sound coupling, the participants spontaneously mentioned a notion of “cues”, as guides for the movement. This appeared recurrently while mentioning various movement characteristics: amplitude, fluidity, regularity and reproducibility. For example, about amplitude, an healthy participant said: "The sound helped me to know that I had arrived at the end of the movement" (H03), and concerning fluidity a patient commented: "If I had a fluid movement the sound was fluid, if I had a defect in my movement I heard it immediately, not only I felt it, or perhaps I did not feel it too much, but I heard it in any case " (P03).

Among the characteristics mentioned above, temporal aspects were very predominant. Several types of the sonifications effects were mentioned with respect to the temporal characteristics of movement and sound, such as a modulation of the feeling of time (P07): "I had the impression that when I perform a movement with the sound I took more time, I went less quickly to do it", the temporal reference mark (P09): "With music we have a reference point, we keep the same cruising pace", or the more conscious search for an adaptation to the representation conveyed by the sound, in order to obtain a certain sound quality (H08): "When there was no sound I always performed at the same speed, when there was sound I varied the speeds a little because I wanted it to fit with the sound". H04: "In general, if you want the sound to be harmonious, you have to make a special rhythm".

Modalities of interaction:

The participants reported different perceived interaction modalities. For a minority of participants, the interaction modality was unidirectional: four of them felt that the sounds led the movement (4 participants, 3P-1H), and four other participants felt that the gesture controlled the sounds (or vice versa that the sounds followed the gestures 3P-1H). Other participants (4 patients) expressed having experienced a feedback loop. According to them, the gestures triggered the sounds which in turn provided them with feedback on the gestures, allowing them to adapt to the perceived sound/music. Finally, for the majority of the participants, the experience of the interaction varied and evolved during the experiment (18 participants; 5P-13H) according to 3 main parameters: the type of sound feedback (1P-6H), the arm performing the task (3P), and the evolution of their understanding of the functioning of the system during the experiment (3H).

Regarding the categories, types of sound feedback, and the proposed couplings, participants unanimously expressed that the gestures controlled the sounds for the simple couplings (Pitch and Drum) while the gestures adapted to the sounds for the musical couplings, especially the continuous melody (Mc).

Regarding the way the arm performing the task affects the experience of the interaction, patients specified that, for the paretic arm, the gesture controlled the sound, whereas, with the less affected arm, the sound controlled the gesture, or that the gesture adapted to the sounds.

Finally, regarding the evolution during the experiment of the interaction understanding, participants expressed that they followed the sound at first, and that later they voluntarily controlled their gesture in order to modulate the sound. H13: "At the beginning I had the impression that I was trying to follow the sound...well to make a gesture following the rhythm, and then I understood that I could control the sound myself with the gesture". H07: "At first I didn't realize that the way I was moving my arm was influencing the sound [...] by the time I realized that the movement could influence the sound, then it started to become a lot of fun".

All of these findings suggest that the nature of the sound feedback and the coupling modalities had an influence on the perception of the interaction and on the participants' experience. H06: "The coupling between the sound and the movement changes the experience of the movement, and so even if you're trying to do the same movement, even if it's exactly the same movement, the way you experience it is different, the involvement of the person in the task is really changed."

2. Common to the patient and healthy group: Emotional mobilization, mental imagery and attentional process

This second theme was commonly found by both the patient and healthy groups, and we identified three sub-themes which correspond to participant's emotional mobilization, mental imagery and attentional process.

Emotions

Generally, experiencing the sonification device aroused many emotions. For each participant, these emotions could be contrasted, depending on the protocol stages and the sound couplings. Globally, we can highlight four main affective states expressed by the participants: playfulness, curiosity, frustration and relaxation. The notion of playfulness is predominant in the spontaneous comments of the participants (8P-9H), who repeatedly mentioned the playful dimension of the study and the use of the device. Many also mentioned curiosity and the notion of discovery linked to the exploratory dimension, and their surprise concerning the device. This surprise was often at the origin of the playfulness mentioned above. P07: "I was surprised by the sounds I was making when I was doing the acceleration and deceleration movements. It surprised me, and I liked it, I found it very playful". In other cases, the curiosity was formalized by expecting something from the device. Frustration could also emerge in reaction to the restrictive framework of the instruction: H08: "The fact that I could only do one movement of extension of the arm is a little frustrating because I would have done other movements [...] me in any case I wanted to adapt my movements to the sounds". Finally, the notion of relaxation was expressed many times by the participants, more particularly regarding two couplings: the 'continuous melody' and the 'soundscape', implying in some cases body feeling and the task performance. P09: "With the music it softens, it soothes, it's like we were being massaged, as if we were being put in a second state to be willing. At one point there was music with the sea, the wind, it relaxes you, when you are obliged to make a movement and you can't do it, it relaxes you".

Mental imagery

In addition to the motor imagery mentioned previously (section 1. Perception of the gesture-sound interaction), suggesting that a sound can induce a gesture representation to be associated with (case of the discontinuous melody inducing the desire to perform a jerky movement), the sound couplings used in the device also allowed the participants to recall and evoke certain autobiographical memories, withdrawing them from reality.

Thus, many participants associated the gesture-sound couplings with different mental imagery. The 'pitch' was associated with images of a vinyl record, a soft car engine, an ocean or even described as celestial. The 'drum' has been associated with muffled hammering or African drums. The 'discontinuous melody' has been the object of less and contrasted associations (mandolin, stalactic in a cave), although images of bouncing movements have been widely mentioned. The 'continuous melody', which original musical piece was sometimes recognized and named, was associated with the idea of spring, and 'dream-space'. This sonic coupling, in some cases, created the illusion of being a musician (H13): 'I caught myself for thirty seconds as if I were Mozart, so I was very pleased with myself'. Finally, the 'soundscape', a metaphorical space by design, was the most prolific in terms of images, very often associated with the idea of escaping. H09: "There were images that appeared, [...] I imagined a kind of walk in a forest, we walk next to the river, then we arrive in a meadow, where there were birds… we imagine the scenery that goes with it".

The stimulation of mental imagery is linked to the participants' preferences: the more the person appreciates the coupling, the more his or her mental imagery is triggered and stimulated. P08: "Every time there was music, I imagined a scene or a moment that I experienced. Especially on the music that I liked in fact ".

These data support the hypothesis that the choice of sound feedback used for sonification is not neutral: in addition to its adequacy with a gesture, its emotional connotation is crucial. Thus, a further study addressing the mechanism of synchronization of the sonification emotional aspects with the user emotional state seems essential for future development of sonification devices.

Attentional modulation

Evocating the feeling of escape, as well as various emotions, led several participants to report having felt a modulation of their attention during the task, and this depending on the sound context. However, differences across groups should be highlighted.

In the control group, the majority of participants mentioned that their attention was mainly focused on the sounds (10H) H01: "When there was a sound I was thinking less about the movement, I was thinking less about reaching out, I was focusing on the sound". For the other five participants in this group, they could either focus their attention simultaneously or alternately on the sound and the gestures. One participant specified the effects of the feedback loop on their attention and evoked the notion of embodiment: "The attention is not on the movement itself, but on the movement in the context of the effects it has on the music, so I think it changes a lot our way of thinking about the body during the movement".

Within the group of patients, the comments were more contrasted: 4 expressed that their attention was rather focused on the sounds, 4 rather on the gestures, while the others mentioned that the focus of the attention varied, either according to their appreciation of the coupling, or according to the arm performing the task. Indeed, as the gesture could be difficult to perform with their paretic arm, the attention could then shift to the gesture, while being supported by the sound: P06: "[affected side] we are very preoccupied by the very basic movement we have to do. The extension is difficult so we focus on the movement. When I liked the sounds, the attention was directed to the sounds".

Theme specific to the healthy participants group: Analysis of the sonification system

The wording used by the participants of the healthy group during the interview, concerning reasoning and understanding, reveals an analytic approach of the device. This is to be put in regards with its discovery and first use. H15: "With music I was trying to understand the relationship between my movement and the music".

This analytical step could relate to the device itself, but also to perception or behavioral levels: H02: "Each time I asked myself what part of the movement triggered or had an influence. Do we aim for regularity or do we analyze irregularity? Do we follow the movement or do we provoke it? [...] The questions I asked myself the most were what actually affects what? At times I tried to let myself be carried along... Where do I stand between the gesture and the sound? It's hard to be right in the middle actually, there's always a moment where the willingness is exercised, either the willingness to follow or the willingness to move."

Furthermore, several participants mentioned that the search for understanding of the gesture-sound interaction, aroused their curiosity and was a driving force behind their interest in it: H11: “I had a certain feeling when I found it logical. From the moment I couldn't find the logic, it was more complicated for me."

Thus, part of the interest shown by these participants towards the device is attributable to the search for understanding how it functions. This suggests that, in order to maintain an appeal for the device, particularly by generating sustained curiosity, evolving modalities should be necessary to maintain a continuous high interest.

Theme specific to the group of patient participants: Applicability of the sonification system

In the patient group, the device generated a lot of enthusiasm about its potential use as a complementary rehabilitation tool. Fourteen patients stated that they thought it could be interesting to use it in occupational therapy sessions during hospitalization and to develop an easy-to-use device for self-rehabilitation when returning home.

The only participant who expressed limitations about the device's use specified that music listening was a special time for him. He did not necessarily wish to associate it with his rehabilitation exercises. Moreover, two participants mentioned that the benefit of using the device had to be demonstrated beforehand.

Two other participants also specified that its use should be dedicated for specific time periods, guaranteeing a minimal prior recovery in order to be of interest. Thus, without being necessarily of an immediate benefit, the patients seem to enthusiastically embrace it as an accompanying tool for exercises repetition during the forearm extension recovery. Both uses in rehabilitation sessions at the hospitals and in the context of self-rehabilitation at home were considered.

Discussion

Temporality: with sound versus without sound feedback

In the present study, our objective was not to obtain a velocity gain or an improvement in the trajectory during the execution of the gesture, as usually expected in rehabilitation evaluations. Our goal was to evaluate the spontaneous effect of sonification on temporal parameters and sensation, without giving any temporal constraints to the participants, as stated in the instruction that we provided where the gesture timing was left free. Thus, whatever the sound condition (with or without sound), the participants were not asked to move as fast as possible, as there was no imposed tempo to follow. However, in the presence of sound feedback, an implicit timing could be suggested in some cases by the sound feedback. For example, in the case of the continuous musical sound feedback (Mc), although the speed remained free, the implicit tempo of the piece could suggest a movement speed.

The results we obtained suggest that, whatever the status of the participants (patients with sequelae of an acquired brain injury, or healthy participants) and the arm considered (paretic vs. less affected or dominant vs. non-dominant), the presence of a sound feedback has an effect on the participant’s feeling during the experience and on the gesture performance timing of the extension-retraction of the elbow on a table. It appears that the significant fall in average amusia scores in patients does not prevent the sonification effects on the gesture timing, as also found in the healthy participants.

For all the situations considered, the quantitative results highlight a significant global slowing down of the movement in the presence of sound feedback, with in particular a longer duration of maintenance in maximum extension and minimal extension, and a slowing down of the return phase in all the situations considered. The observation of a longer duration of maximum extension in the presence of sound feedback is encouraging as to the possibility of using it in a rehabilitative context, in order to prolong the duration of a posture maintenance during stretching exercises, with the aim of promoting a progressive gain in the amplitude of movement.

Moreover, a significant increase in the duration of phase 1 (elbow extension), was also observed for the healthy participants, for both arms, and for the less affected arm of patients. Different mechanisms that could shed light on the reasons for the differences in temporality of movement in the presence of sound feedback can be considered, regarding the participants' comments and the literature.

A first hypothesis would be that the induced attentional load may have contributed to the slowing down of the movement in the presence of sound feedback. However, this hypothesis does not seem to be in agreement with the analysis of the qualitative results and the literature. Indeed, the participants indicated that the sound feedback worked as cues, allowing them to pace the movement, and this even when no tempo or intrinsic rhythmic element was present in the sound feedback (cases of the pitch and the soundscape). In this regard, Sihvonen (Sihvonen, 2017) suggests that in the presence of sound feedback participants make inferences about the timing of sound events, consequently influencing the temporality of movement completion. The repetition of a movement at a regular and constant tempo with audio feedback would thus be likely to induce its automation, and the attentional system could be less solicited thanks to this temporal cueing function. Further, research on attentional processes mobilized during motor learning has shown that external focus induces a more automatic control, less costly, and therefore beneficial for the realization of the movement (Ferrel-Chapus, 2010). From this perspective, assuming that sound feedback are sources of external focus and implicit learning, their use should therefore allow to limit attentional load, provided that the design is adapted (Dyer, 2015). Also, the observed slowing of movement would therefore not be attributable to an attentional overhead. Nevertheless, in the case of our experiment, as this was the first use of a motion sonification device for all participants (both healthy and patients), it cannot be totally excluded that other processes were involved. In particular, it is more usual for novices to adopt a strategy of attentional focus on internal parameters and explicit learning (Ferrel-Chapus, 2010). Although the intrinsic principle of sonification devices is conducive to external focus and implicit learning (Dyer, 2015), the attentional processes mobilized during the use of sonification devices remain insufficiently known to date. In particular, it would be necessary to study the strategies used according to the users' experience in order to determine in which cases sound feedback can be considered as distractors (Parmentier, 2014 Liu, 2022), sources of external focus, or even sources of internal focus if we consider that an optimized mapping could be likely to favor attention to proprioception. In the case of rehabilitation, it is commonly accepted that it is important to limit attentional distractors and that dual-task situations can be too costly and diminish motor performance in the case of gait (Montero-Odasso, 2012). However, decentering participants' attention during the execution of a motor task can, under certain conditions, also improve its completion (Kim, 2019). In this perspective, investigations centered on the mobilization of the attention aroused by sonification in the case of rehabilitation should be carried out. On this topic, the comments of the participants in our study suggest differences in strategies between individuals. Some participants mentioned focusing on the sound source, others focusing on the movement, or an oscillation in the source of attentional focus, navigating between internal (movement) and external focus (sound), depending in particular on the sound feedback used, or even in some cases a joint attention to the different sources.

A complementary approach corresponds to considering sound feedback as information contributing to internal models of movement control. Based on work on motor control and learning, Effenberg (Effenberg, 2005 and Effenberg, 2011) proposed to consider motion sonification from the perspective of multisensory integration theory. Under a reserve of few conditions (design adequacy and sound mapping) the effects of motion sonification would not be solely related to rhythmic adaptation. Building on the work of Rauschecker (Rauschecker, 2011) Effenberg (Effenberg, 2016) and Schmitz (Schmitz, 2018) clarified that, in a manner comparable to the processing of visual information, two dissociated pathways for the processing of auditory perceptual information should be considered: the conscious ventral pathway ("what") and the unconscious dorsal pathway ("where"). According to these authors, the dorsal pathway, which is unconscious and particularly important for motor control, could be brought into play during the sonification of the movement according to the design and the sound mapping. Thus, the auditory information related to the movement transmitted during the sonification would contribute to the improvement of the sensorimotor representations, and to the internal models, by being processed at a non-conscious level.

In the case of our study, the participants reported that, beyond an impression of modulation of the movement speed, the sound feedback exerted a more global influence on their volition, their intention and their implication in the movement. We could therefore suppose that a conscious processing also took place during the task performance, along with a modulation of the sense of agency. Beyond an effect on the physiological parameters of the movement, the movement sonification was shown to possibly modify the participants' body perception and representation (Tajadura-Jimenez, 2016). By extension, movement sonification could therefore modify their relationship to their movement by diverting them from a functional goal to an aesthetic one (Vickers, 2017). In our study, the task at hand does not involve a functional goal as in the case of pointing or grasping an object. The presence of a sound feedback thus provides the participant with a goal for the task, allowing the transition from a simple repetition task to a goal-oriented task, we can refer to a "sound-oriented" goal (Bevilacqua, 2016). The presence of a sound feedback thus modifies the intentionality of the gesture. Moreover, the interactive process influences the participants' perception of their movement control, and allows them to playfully experiment situations, alternating between sensations of producing or following sounds. In this perspective, this modulation of the sense of agency in the presence of sound feedback, especially reinforced during the first use of a sonification device, could also explain the global slowing down of the movement.

In order to shed light on the processes (neurophysiological, perceptual, attentional and cognitive) involved in the execution of simple gestures with a movement sonification device, further studies are necessary.

Specificity of the sound feedback

The comparative analysis of the temporal movement data reveals significant differences according to the category of sound considered in the cases of paretic arms of patients and dominant arms of healthy participants. No significant differences were found in the other cases, and concerning comparative analysis of each type of sound condition. However, similarities of distribution profiles encourage deepening investigations, considering our small sample size (15 participants in each group) induced a low statistical power. Also, it would be necessary to randomize the order of presentation of sound feedback to further describe a possible differentiating effect of each sound. In addition, very contrasting feelings according to the types of sound feedback were expressed in the participants' interviews and also support the interest to investigate further the effect of each sound feedback on movement timing.

The temporal dimension of a sound feedback could indeed influence the movement performance differently. In this study, Drum displays explicit timing information (direct variation of a pulse according to the extension of the elbow) while discrete and continuous music (Md, Mc) displays implicit timing information. By implicit timing information, we refer to cases where the participants try to adapt their movement to render the musical extract as they anticipate, using prior knowledge. The intrinsic temporal and aesthetic sonification characteristics seems to influence the movement performance timing and feeling, which was previously reported in the literature (Dyer, 2015).

In the case of the continuous melody, some participants indicated they found the task more difficult considering it seems to call for a higher sound quality (as if they were playing an instrument), thus pushing towards finer motor control. However, this involvement of finer motor control did not induce any specific movement slowing down. Moreover, in spite of this greater apparent difficulty, this sound feedback was particularly appreciated by the participants. Thus, it seems that a higher musical quality was perceived as a motivational added value, even if it imposes larger constraints on the movement performance.

These observations furthermore support the hypothesis that the movement slowing down observed beforehand in the presence of sound feedback cannot be explained only by greater mobilization of attention, or a greater complexity of the gesture with certain sound feedbacks. The characteristics of the sound feedback also carry on certain specific information or agency, and they are likely to mobilize different processes from implicit to conscious control of the movement. The participants' statements about the transient illusion of being a musician with continuous melody feedback support the hypothesis of a modulation of the sense of agency during the sonification tasks, depending on the nature and characteristics of the sound feedback.

Furthermore, the participants' interviews also pointed towards the notion of affordance. In the case of sounds, affordance can be defined as the opportunities for actions elicited by a sound (Dyer, 2017), in other words, the sound characteristics eliciting a representation of an associated movement (Caramiaux, 2014). In our case, the discontinuous sound feedback (Md) was indeed associated with the desire to perform bouncing motions, rather than a continuous sliding motion. These remarks underline the intrinsic link between representations of movements associated with sound feedback and the necessity to take them into consideration during the sound design for a correct adequacy between the characteristics of the proposed sound and the motor task to be performed. It is very interesting to note that, beyond the category of sound feedback, the specific characteristics of each sound feedback are likely to influence the participants' feelings and emotional states. Precisely, within the "musical" class, the specificities of each sound feedback induce different feelings and a notable preference.

These observations are in line with the literature (Dyer, 2015 Roddy, 2020) and therefore support the hypothesis that the nature of the sound feedback used, its characteristics, the sound design, and the coupling modalities, influence the movement timing and participant’s experiencing. Moreover, we can hypothesize that the temporal modulations of the elbow extension gesture, found in the participants' experience, could be put into perspective with the intentionality mentioned by the participants, suggesting the interest that experimentation with the agency induced by sonification could have for engagement in the task to be performed. Finally, the trends we observed on the temporal execution of movements and differences in feeling’s participants in this study centered on spontaneous effects of the sonification during a single session, suggest that, in the case of a long-term use, the impact on participant’s motivation would be important to consider, particularly in a rehabilitation perspective.

Conclusion, limitations and perspectives

In conclusion, the sonification has a significant effect on the temporal execution of the movement during a single-session, even if individual temporal variations were found. This effect was established for all participants, both healthy participants and patients with upper-limb hemiparesia after acquired brain lesion, despite diminished amusia average scores. Moreover, qualitative analysis pointed out that performing the task with sonification changes participants' feelings, notably concerning intentionality, volition and motivation during movement.

Specificities and intrinsic characteristics of each type of sound feedback and gesture-sound coupling could be likely to influence the effect of sonification on the temporality of the gesture and its experience. The majority of participants have a preference for the soundscape and musical feedback, under reserve of congruence with the gesture to perform. Special attention must be paid to the potential difficulty induced and the emotions likely to be felt.

Beyond the limits present in this study (limited sample, single session without follow-up over several sessions, no randomization of the order of presentation of sound feedback, focus on the temporal criterion in the analysis of movement data) methodological questions arise concerning the evaluation of the effects of movement sonification in the context of rehabilitation.

Our qualitative results suggest that it would be interesting to investigate attentional processes mobilized according to sonification modalities with multiple motor tasks and various participants profiles, and the possible evolution of the attentional cost according to the training.

This study calls for further investigations. A first question concerns the most efficient use of sonification, whether an immediate and spontaneous effect on movement performance with sound is finally preferable to the results of progressive learning with long-term training. Second, it remains to better establish relevant parameters or criteria (physiological, functional, attentional, motivational) for the evaluation of the effectiveness of a movement sonification system. Third, it seems important to evaluate any potential unconscious effect of the sonification of movement on voluntary motor skills.

Abbreviations

MBEA: Montreal Battery of Evaluation of Amusia; IMU: Inertial Measurement Unit; N: No Sound; Pi: Pitch; Dr: Drum; Md: Music discrete ; Mc: Music continuous; Ss: Soundscape; P: Patients; H: Healthy participants; ANOVA: Analysis of Variance

Declarations

Ethics approval and consent to participate

Ethical approval for the study was obtained from the appropriate ethic committee prior to the beginning of the study (CERES: 2016-55, University of Paris-Descartes IRB: 20165500001072). All participants signed an informed consent.

Consent for publication :

All the authors approved the publication of the article.

Availability of data and materials

The data sets and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

This study was supported by Institut Universitaire d’Ingénierie en Santé (I. Peyre’s PhD scholarship from IUIS, Sorbonne Université), the Labex-SMART (ANR-11-IDEX-0004-02) and from the Element project (ANR-18-CE33-0002).

Authors' contributions

IP, ARB, MS, VMP and FB conceptualized the study and developed the protocol. IP and PP-D have selected the patients and healthy participants, and performed the experiments. IP, ARB, FB, BC and AG analyzed the data and wrote the draft of the manuscript. AG performed the statistics. All authors participated in finalizing the manuscript.

Acknowledgments

The authors wish to express their gratitude to all the participants and to the staff of the department of rehabilitation of the Pitié-Salpêtrière Hospital, especially to the occupational therapist team.

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Supplementary Materials

S1: Guide of semi-structured interview

1. Could you summarize the study (steps, elements you noticed, those you appreciated and didn't like)?
2. Could you describe your impressions, physical feelings, and the thoughts that crossed your mind when you carried out the different stages of the experience?
3. Did you notice any differences according to the sound context when you were doing the movement? Which differences? In which cases?
4. During gesture-sound coupling, on which elements did you focus your attention?
5. a. What sound contexts did you appreciate? For what reasons?
   b. What sound contexts did you not appreciate? For what reasons?
   c. Could you rank the sound contexts in order of your preference?
6. Answer only for patients: Would you use this type of device to continue your rehabilitation at home?
7. In this list, choose the terms that correspond to your feelings during the experience. Then, rank them from 1 to 5.

Unpleasant	Tiring	Stressful
Uncomfortable	Playful	Stimulating
Intuitive	Captivating	Annoying
Surprising	Relaxing	Frustrating
Irritating	Easy	Pleasant
Difficult	Embarrassing	Amusing

S2: Sound Spectrogram

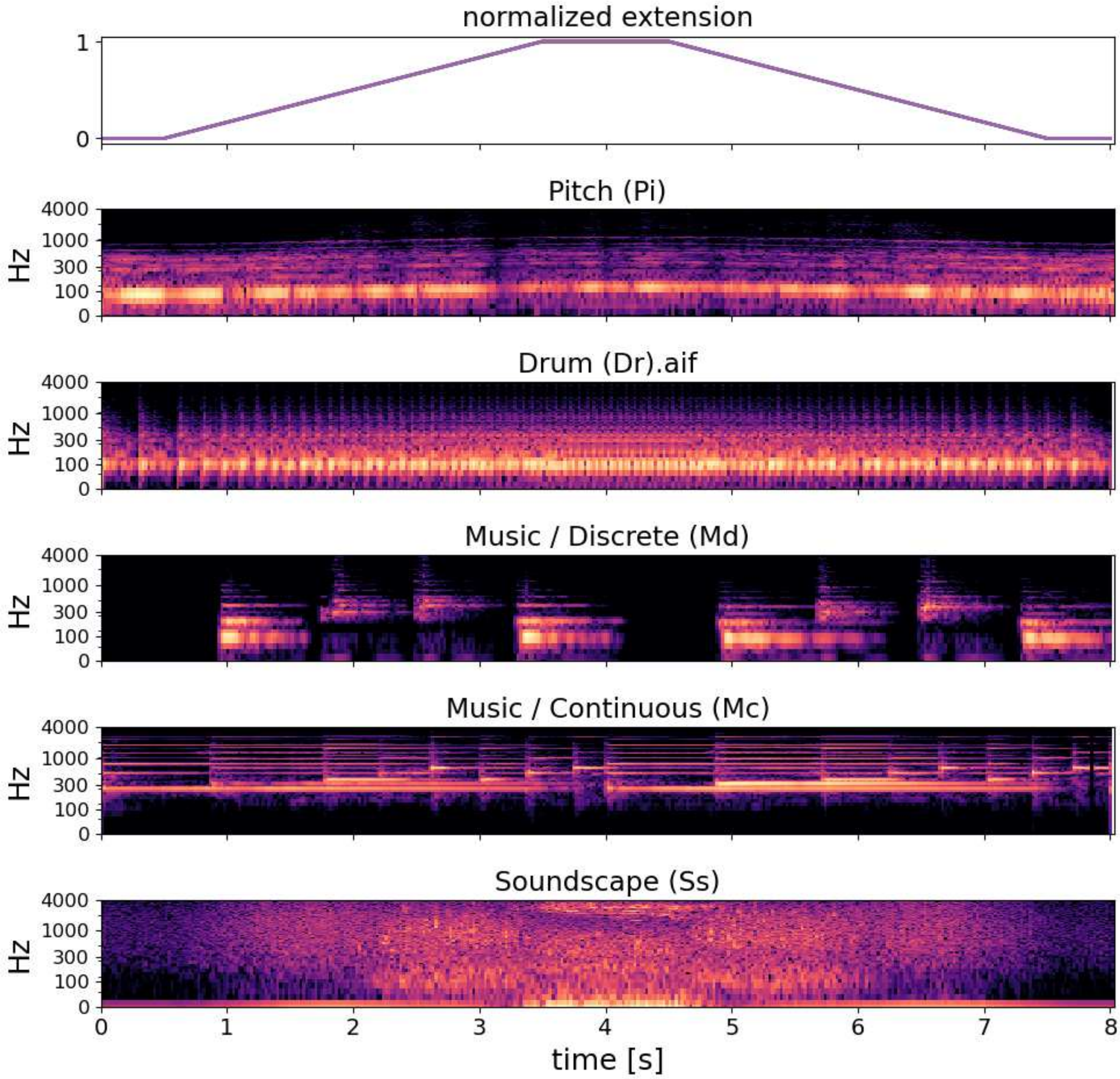

Figure A: Sound spectrogram for each sound condition. This was measured using the same simulated extension for each sound condition to enable the comparison. This was performed using the librosa library using a FFT window of 2048 pts and a hope length of = 1024 pts, at sampling frequency of 44.1 KHz).

S3: Descriptive Data of Participant's Profiles

Patient	Age	Sex	Type	Site	Paretic Arm	Time between lesion and sonif session (months)	Musical Background	MBEA Average	Hearing troubles / Exploration
P1	34	F	Hemorrhagic Stroke	Right Frontal Lobe	Left	2	Amateur	25,8	None
P2	42	F	Ischemic Stroke	Pons-Midbrain	Right	4	None	23,4	Tinnitus
P3	49	M	Ischemic Stroke	Territory of Left Middle Cerebral Artery	Right	1	None	27,0	None
P4	27	M	TBI with post-TBI hematoma	Right Fronto-Parietal Lobe	Left	9	Amateur	19,2	Tinnitus
P5	40	F	Ischemic Stroke	Territory of Right Middle Cerebral Artery	Left	4	None	17,2	None
P6	59	F	Ischemic Stroke	Territory of Left Middle Cerebral Artery	Right	1	Amateur	22,4	None
P7	45	F	Ischemic Stroke	Territory of Left Middle Cerebral Artery	Right	7	None	23,6	Audio test OK
P8	28	F	Ischemic Stroke	Territory of Right Middle Cerebral Artery	Left	10	Amateur	24,2	Audio test OK
P9	47	M	Ischemic Stroke	Territory of Left Middle Cerebral Artery	Right	16	None	21,2	Audio test OK
P10	55	F	Hemorrhagic Stroke	Pons	Left	13	None	21,4	Audio test OK
P11	70	F	Hemorrhagic Stroke	Right Capsulo-thalamus	Left	3	Amateur	26,0	None
P12	64	M	Ischemic Stroke	Right Paramedian Pons	Left	1	Professional	26,6	Transient Tinnitus Audio test OK
P13	20	F	Ischemic Stroke	Right Anterior Cerebral artery	Left	2	None	26,4	Transient Tinnitus Audio test OK
P14	42	M	Ischemic Stroke	Left Posterior cerebral artery	Right	11	None	25,4	Transient Tinnitus Audio test OK
P15	48	M	Ischemic Stroke	Territory of Left Middle Cerebral Artery	Right	4	Amateur	26,6	Audio Test OK

Table A: Descriptive information of each patient

Healthy	Age	Sex	Musical Background	MBEA Average	Hearing troubles / Exploration
H1	24	H	Amateur	27,5	Tinnitus
H2	37	H	Professional	30	Transient tinnitus
H3	21	F	None	28	None
H4	23	H	None	27,2	Tinnitus Audio test OK
H5	30	F	Amateur	27,5	None
H6	34	H	Amateur	25,7	Tinnitus Audio test OK
H7	61	F	Amateur	28,7	None
H8	32	F	Amateur	28,8	None
H9	29	H	Professional	29,3	Tinnitus
H10	46	F	None	25,3	None
H11	42	F	None	24,2	Audio test OK
H12	58	F	None	26,7	Audio test OK
H13	52	H	None	23,3	None
H14	71	F	None	26	None
H15	68	F	Amateur	24	Audio test OK

Table B: Descriptive information of each healthy participants

S4: Amusia Scores

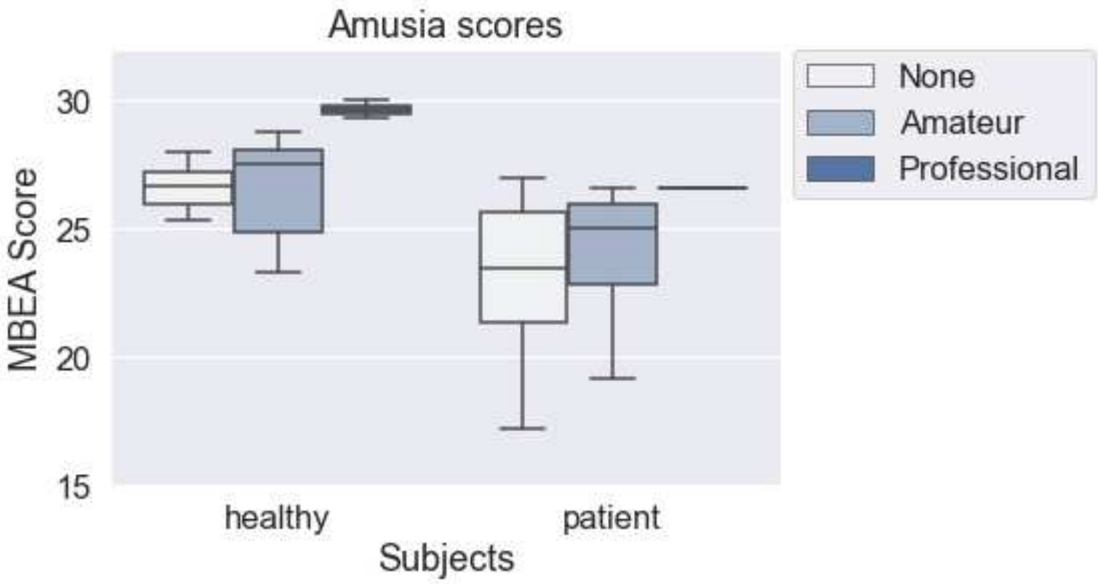

Figure B: Plot of the amusia score for the healthy and patient participants, considering different levels of music practice: non-musician ("None"), Amateur and Professional. The box of the boxplots represents the limit of the 25th percentile and 75th percentile, the median being indicated inside.

S5: Sound condition results

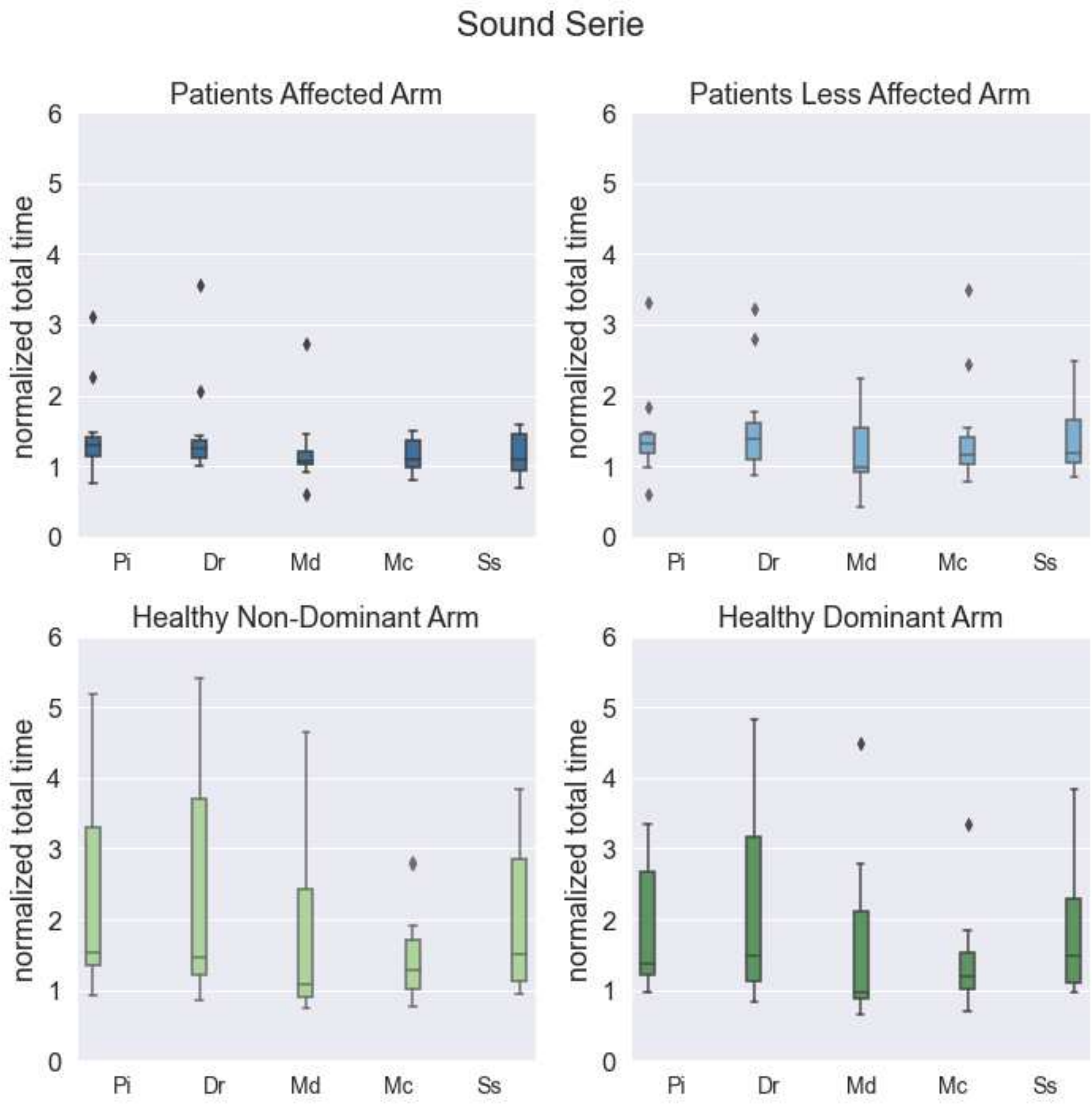

Figure C1: Boxplots of the normalized total time for each sound condition, reported for the Patients and Healthy participants, considering each arm. The box of the boxplots represents the limit of the 25th percentile and 75th percentile, the median being indicated inside.

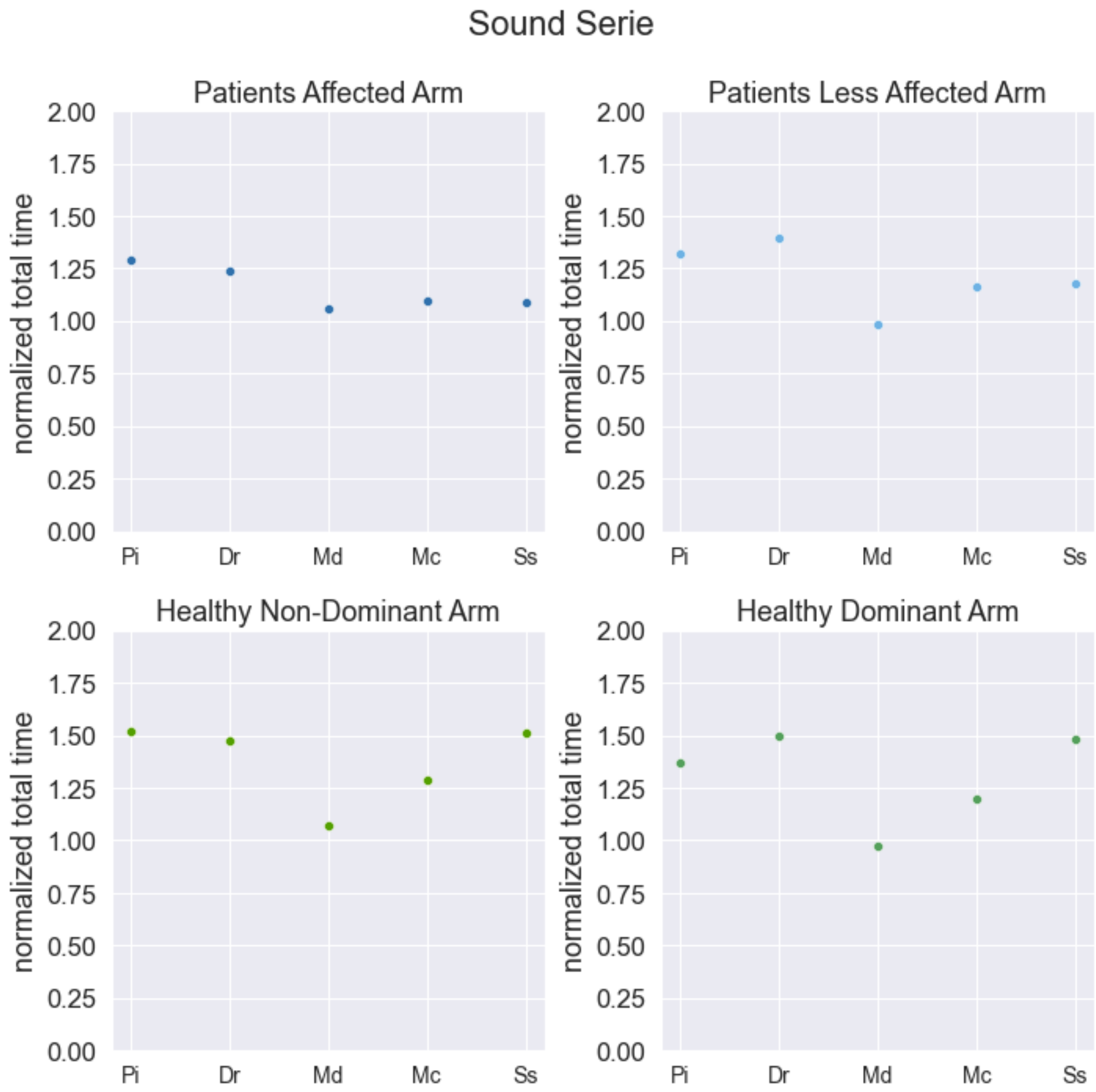

Figure C2: Median of the normalized total time for each sound condition, reported for the Patients and Healthy participants, considering each arm