Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Issue: *The Neurosciences and Music V*

Moving with music for stroke rehabilitation: a sonification feasibility study

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Gross-motor impairments are common after stroke, but efficacious and motivating therapies for these impairments are scarce. We present a novel musical sonification therapy especially designed to retrain gross-motor functions. Four stroke patients were included in a clinical pre–post feasibility study and were trained with our sonification training. Patients' upper-extremity functions and their psychological states were assessed before and after training. The four patients were subdivided into two groups, with both groups receiving 9 days of musical sonification therapy (music group, MG) or a sham sonification training (control group, CG). The only difference between these training protocols was that, in the CG, no sound was played back. During the training the patients initially explored the acoustic effects of their arm movements, and at the end of the training the patients played simple melodies by moving their arms. The two patients in the MG improved in nearly all motor function tests after the training. They also reported in the stroke impact scale, which assesses well-being, memory, thinking, and social participation, to be less impaired by the stroke. The two patients in the CG did benefit less from the movement training. Taken together, musical sonification may be a promising therapy for impairments after stroke.

Keywords: sonification; stroke; neurorehabilitation; neuroplasticity, music-supported therapy

Introduction

The rehabilitation of stroke patients remains a challenge, although there are currently several new training programs that aim to improve efficiency and sustainability of stroke rehabilitation. Some rehabilitation programs lack general acceptance by patients, because of their rigor and high demands on the patients' cooperation, which sometimes is perceived as a frustrating experience.[1] Yet, even the well-established standard physiotherapies do not unambiguously provide evidence of efficacy in improving skilled motor behavior.[2–4] Therefore, there is an urgent need for innovative, motivating, and goal-directed training protocols in stroke rehabilitation.

This paper presents a novel approach to rehabilitation involving retraining the gross-motor functions of the affected upper limbs using musical sonification. Sonification is the use of non-speech sound representing otherwise inaudible information.[5] One of the first sonification apparatuses was the Geiger–Müller counter, which measures radiation and supplies the user with a beep pulse indicating the radiation dose or counts. In our study, arm movements were transferred into sound. We demonstrated in two earlier studies the efficacy of music-supported stroke rehabilitation training utilizing a musical instrument digital interface (MIDI) drum set and a MIDI piano.[6,7] Stroke patients with some residual ability to move the arm and fingers were instructed to play simple tunes on either instrument. We could convincingly show that auditory sensorimotor circuits, established via this form of music-supported therapy (MST), promote beneficial neuroplasticity in stroke patients.[8,9] The

doi: 10.1111/nyas.12691

only constraint of MST was that it was mainly designed to retrain fine-motor skills on MIDI instruments and did not provide continuous real-time feedback for the more frequently impaired proximal upper limb muscles. We think that a real-time movement feedback may be very beneficial because it informs the patients about the way they move, not just whether they hit the goal. With the musical sonification therapy introduced here, patients repeatedly train movements with their affected arm in a predefined space. They form associations of their relative arm position in space and the corresponding sound at this specific position. In the end, they even play well-known melodies with their arm movements. This musical sonification therapy therefore broadens the scope to train stroke patients from an earlier stage onwards, when still suffering from gross-motor dysfunction. Musical sonification will not only contribute to the motivation of the patients because of its playful and positive emotional character, it may also improve motor control, because potentially lost proprioception might be substituted by auditory real-time feedback of the patient's arm movements.

There are several preliminary studies with healthy participants applying nonmusical sonification in motor control and the perception of movements.[10,11] For example, Schmitz *et al.*[11] found that sonifying breaststroke swimming movements led to more precise perceptual judgments of movement velocity. They showed that sonification of movements amplifies the human action-observation system indicated by more pronounced functional magnetic resonance imaging (fMRI) connectivity patterns between the activation peaks of the left superior and medial posterior temporal regions with the basal ganglia, thalamus, and frontal regions, for movement-congruent sonification stimuli. Thus, sonification may be an important method to enhance training and therapy effects in neurological rehabilitation. Chen *et al.*[12] developed a real-time, multimodal feedback system for stroke rehabilitation; this sonification system was tested with stroke patients and showed promising results.[13] However, in this sonification design, music was only a passive byproduct of the arm movements of the participants, meaning that participants did not play with the sonification sound intentionally. Instead, they moved their arms, and harmonic music progressions were then played back to them. In contrast, we developed musical sonification therapy to train the stroke patients to explicitly and consciously play music through intended and voluntary movements of their affected upper extremities, in an effort to be able to use the beneficial effects of music on neuroplasticity to facilitate recovery after a stroke.[8] Because, in other studies, repetitive exercise was proven to be effective, our training is also of a repetitive nature.[4,14] We hypothesize that the auditory cues provided by the sonification may make multimodal associative learning possible where otherwise mere visual and motor learning would have taken place. We hope that patients will benefit in their rehabilitation process from the guided attention, the necessary concentration, and the long-term motivation to play music. After evaluating an optimal two-dimensional sonification mapping, we now introduce our three-dimensional (3D) musical sonification therapy.[15]

To demonstrate the feasibility of our approach, in this pilot study we present four cases—two patients using musical sonification and two control patients who received the same training but with no sound played back to them, in order to distinguish the outcome of our training and the role that music might play in it.

Methods

Patients

Four inpatients of the BDH-Clinic Hessisch Oldendorf participated after giving informed consent. They suffered from a moderate impairment of motor function of the upper extremity after stroke (Table 1 and Fig. 1). The inclusion criteria required patients to (A) have a residual function of the affected extremity (i.e., the ability to move the affected arm and the index finger without help from the healthy side); (B) have an overall Barthel Index higher than 50; (C) be right handed; (D) have had a stroke that affected the left brain hemisphere; and (E) not have other neurological or psychiatric disorders.

Patients were pseudo-randomly assigned to the experimental or to the control group by the study supervisor, who was not the experimenter. The experimental group (music group, MG) received conventional physiotherapy plus 9 days of musical sonification training. By chance, both patients assigned to the MG had subcortical lesions caused by an ischemic stroke (Table 1).

Table 1. Patient characteristics and stroke localization

Patient	Age	Sex	Ischemic stroke/bleeding	Localization	Symptoms
Patient A	59	F	Ischemic stroke	Left lentiform and head of caudate nucleus	Right hemiparesis, mild Broca's aphasia
Patient B	85	M	Ischemic stroke	Left putamen and cella media	Right hemiparesis
Patient C	59	M	Bleeding	Left frontal lobe, close to the anterior horn of the left lateral ventricle	Mild right hemiparesis, Broca's aphasia
Patient D	64	M	Bleeding	Left inferior frontal gyrus	Mild right hemiparesis, Broca's aphasia, speech apraxia

The CG also received conventional physiotherapy plus sham sonification training with exactly the same movements required as in the sonification study but with no sound played back. Both patients of the CG had frontal lesions caused by bleeding (Table 1). All of the patients were native German speakers. The study was approved by the Ethics Review Board of the Hannover Medical School (MHH).

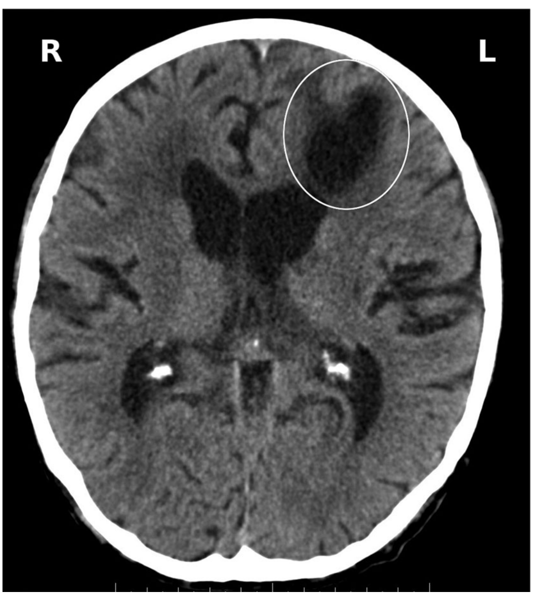

Figure 1. Computed tomography (CT) example of Patient C (male, 59 years old). There is a cystic lesion (white circle, top right) close to the anterior horn of the left lateral ventricle. This is a special case because the lesion is located very much in the front of the patient's brain.

Evaluation of motor functions and sonification training

Procedure. Patients were tested pre- and post-training with a battery of clinical motor function tests and neuropsychological questionnaires. The test battery consisted of the upper extremity part of the Fugl-Meyer Assessment (FMA), which is frequently considered the gold standard of motor recovery assessment after stroke;[16,17] the Action Research Arm Test (ARAT), which assesses upper limb functioning by using observational methods and collecting behavioral data;[18,19] the Box and Block Test (BBT) to assess unilateral gross manual dexterity;[20,21] the Nine-Hole Pegboard Test (9HPT), which measures finger dexterity;[22] and the Stroke Impact Scale (SIS 3.0) to assess health status after a stroke, including subscales for emotional well-being, memory, thinking, and social participation.[23,24] It took approximately 1 h to complete the test battery.

Training. After the pretests, the patients received either 9 days of musical sonification training (MG) or 9 days of sham sonification training (CG), with each session lasting 30 min/day. The whole procedure followed a standardized protocol to train the gross-motor functions of the affected right

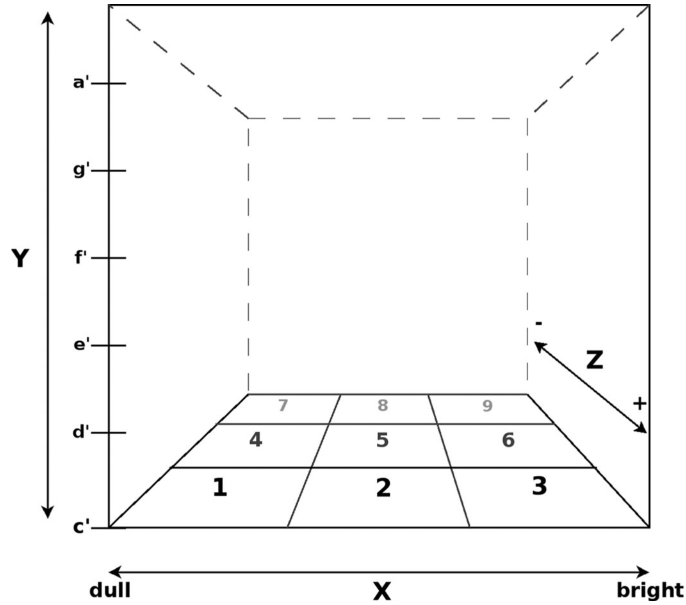

Figure 2. The defined 3D space that the patients moved their arm in. Pitch was mapped onto the *y*-axis ranging from c′ (256 Hz) at the bottom to a′ (440 Hz) at the top; brightness was mapped onto the *x*-axis from the left (dull) to the right (bright); and volume onto the *z*-axis was louder when closer to the patient and quieter when further away. Positions in the *x*–*z* plane were labeled with numbers 1–9 to instruct patients where to carry out the exercises.

upper extremity in a repetitive manner. Patients first had to move their arm in a 3D sonification space—a wooden cube-shaped frame of 51 cm edge length (Fig. 2)—to get acquainted with the sonification system and the acoustic effects produced by their own arm movements in this space. The sonification software was designed in a way that upward movements in the vertical axis resulted in an ascending C major scale from c′ (256 Hz) until the sixth interval a′ (440 Hz). Vertical movements in this space resulted in a change in brightness of sound (see legend of Fig. 1), and with movements along the *z*-axis, the volume level of the sonification output could be manipulated. After these simple exercises, which allowed subjects to implicitly learn the rules of the musical sonification in the predefined 51 × 51 × 51 cm large 3D sonification space (Fig. 2), more complex exercises followed, demanding incremental degrees of difficulty. At the beginning of each training session, patients had to play four times legato C major scales upward and downward at position 1 shown in Figure 2, and they then repeated the same exercise at positions 2, 3, 7, and 9. This exercise was followed by a more difficult task where patients had to play intervals four times by moving their arm faster but as precisely as possible from c′ to d′, then from c′ to e′, and so on at position 1. The same exercise was then repeated at positions 2, 3, 7, and 9. The final goal of the training was to teach the patients to play several simple folk song melodies only by moving their affected right arm in the 3D sonification space.

The experimenter gave the instructions for the training procedure verbally and also pointed at the visual cues written at the positions on the wooden frame of the 3D space (Fig. 2). When playing the melodies, patients could read the required coordinates from a paper sheet provided by the experimenter (Fig. S1). All melodies were played vertically (i.e., along the *y*-axis) at position 1 (Fig. 2). Tones could be repeated by dipping the hand horizontally in one direction while maintaining the hand position vertically. Patients always had to move their impaired arms by themselves. Their arm movements were never guided or physically supported by the experimenter.

Patients arm movements were sonified in real-time with the use of two small inertial sensors (Xsens, X-MB-XB3) placed at the wrist and the upper arm of the affected arm. These sensors sent a continuous data stream of acceleration, rotation, and gravity via Bluetooth to a laptop. Data were recorded and the spatial information of the arm movements in the 3D space were mapped and sonified at the same time. The parameters of this 3D sonification mapping varied on the y-axis in pitch (ranging from $c^1 = 226.6$ Hz at the bottom to $a^1 = 440$ Hz at the top, in Helmholtz pitch notation), on the x-axis in brightness via a variation in the sound synthesis (SynthesisToolKit, STK)[31] with three different timbres (from dull = clarinet sound at the very left, to saxophone in the middle, and at the very right a bowed instrument = bright), and on the z-axis in volume (the sound was louder if the patient's arm was closer to the body and quieter if further away). The only difference in the training procedure for the sham sonification group (CG) was that there was no sound played back to the patients. Otherwise, exactly the same movements were carried out during the training sessions.

Results

Figure 3 shows the results for the upper extremity part of the FMA, the motor function tests (ARAT, BBT, NHPT), and the SIS 3.0 of the four patients included in the study. Both patients (Fig. 3, Patients A and B) of the musical sonification group (MG) showed improvement in the FMA, most of the motor function tests, and the SIS 3.0 from pre- to post-training. Patient A did improve in the upper-extremity part of the FMA, the ARAT, and the BBT (Fig. 3, top left), but did not improve in the NHPT, which mainly assesses fine-motor control. However, he improved considerably in the SIS 3.0, which involves motor and psychological domains, such as strength, hand function, mobility, activities of daily living, emotion, memory, communication, social participation, and stroke recovery. Patient B (Fig. 3, top right) improved in all of the motor measures (FMA, ARAT, BBT, and NHPT) and reported

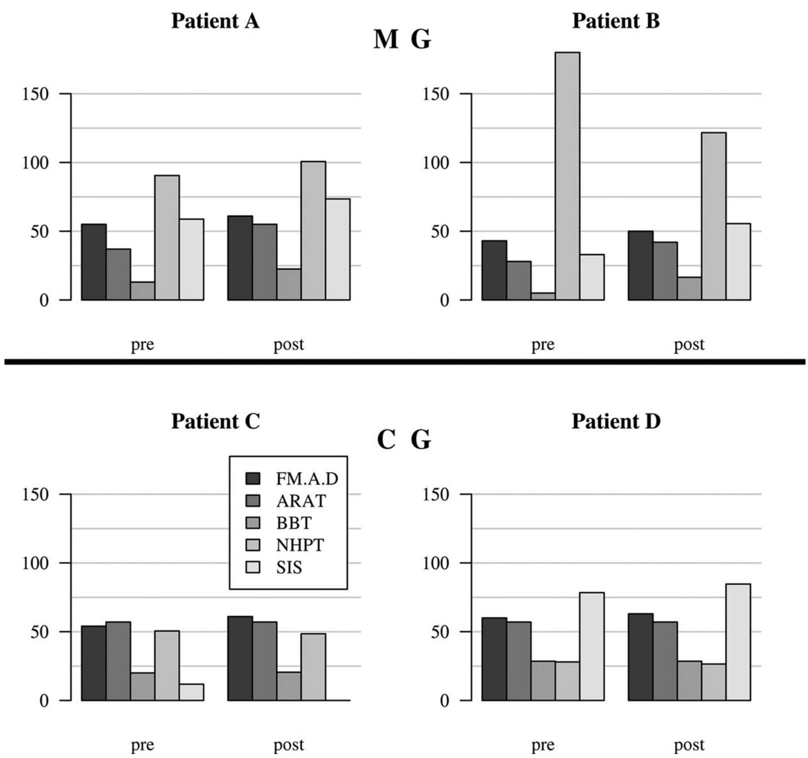

Figure 3. Pre- and post-test battery scores of the four patients separately. Shown are scores for the Fugl-Meyer Assessment (FM.A.D), the Action Research Arm test (ARAT), the Box and Block test (BBT), the Nine-Hole Pegboard test (NHPT; time in seconds required to complete the test), and the Stroke Impact Scale 3.0 (SIS 3.0). The upper row shows the pre–post results of the motor function tests and the SIS 3.0 of the two patients of the musical sonification group (MG). Improvements can be seen for Patient A in the FM.A.D, the ARAT, the BBT, and in the SIS 3.0. For Patient B, improvements are visible in the same tests plus the NHPT. The lower row shows the results of the two patients of the control group (CG). Here, no improvements are seen, except for Patient C in the FM.A.D and for Patient D in the SIS 3.0.

generally less stroke impact after the intervention on the SIS 3.0.

Both CG patients (Fig. 3, lower row) did not benefit noticeably from the sham sonification movement training added to their standard physiotherapy in the FMA and the motor function tests. Only Patient D (Fig. 3, bottom right) reported being less impaired after the intervention on the SIS 3.0.

Discussion

The results of the current feasibility study show that musical sonification therapy may be a promising new way of treating motor impairments after stroke. Musical sonification therapy may even improve psychological well-being after stroke. Both patients of the musical sonification group improved in nearly all motor function tests and in the SIS 3.0, which assesses, in addition to motor domains, the emotional state of the patient, memory, and social participation. In contrast, the two CG patients receiving only sham movement training without producing musical sounds improved only very little in some of the tests. Thus, we assume that the musical aspect plays an important role in the sonification therapy, but we did not control whether it is the musical aspect of our sonification that is important or just any sound information being provided by the sonification. Of course, as we currently only present case studies, we are not able to conduct quantitative statistics, and results have to be verified in a large group of patients. Furthermore, because of the random assignment of the patients to the different groups we had two patients in the experimental group with subcortical lesions induced by an ischemic stroke and two patients with frontal lesions caused by bleeding in the control group. The severity and the location of the impairments after the stroke may have played an important role for the responsiveness to our training and the achieved improvements after it. However, the main aim here was to test in a small pilot study the feasibility of the musical sonification training.

The novel aspect of our approach is that we encouraged the patients in the musical sonification group to actively play and create music by their arm movements. This way, music was not only a byproduct of, for example, a grasping motion. Instead, movements resembled more a novel musical instrument that patients were starting to play. Hence, our sonification training was designed to resemble a music lesson rather than shaping a movement during sound playback. Furthermore, we used a novel approach by introducing musical stimuli such as a musical major scale with discrete intervals and timbre parameters derived from the sound characteristics of acoustical musical instruments.

One of the ideas was that participants could improve control of arm positions in space via associative learning, leading to associating a given relative arm position with a specific musical sound. This sound–location association may then substitute the frequently declined or even lost proprioception. In addition, the trajectories while moving their arms to the target point were audible as well. Thus, multimodal learning could take place because patients received sound as an additional parameter supplying information. One could speculate that this multimodal learning could help to close the sensorimotor loop, which may be affected by the stroke.

In view of the clinical application, reduced gross-motor functions of the arm and reduced proprioception are common disabilities in stroke patients.[25] Hence, the advantages of continuous real-time musical feedback are obvious: the therapy therefore aims at retraining gross-motor movements of the arm, which are the most disabling challenges in early rehabilitation of stroke. Second, real-time sonification may substitute deficits in proprioception of the arm, which frequently are a consequence of stroke.

Finally, this form of therapy is highly motivating to transform movements into sound and could thus enhance motor functions and the emotional well-being in two patients, maybe through the creative, playful character of this musical sonification device.[26–30] Taken together, we have developed and tested a novel musical sonification therapy supporting learning effects in auditory sensory–motor integration. Multimodal learning of spatial, motor, auditory, and proprioceptive information in the rehabilitation of arm motor control in stroke patients should next be evaluated in a larger representative randomized controlled clinical trial.

Acknowledgments

This work was supported by the European Regional Development Fund (ERDF) and the Hertie Foundation for Neurosciences. This work is part of a Ph.D. of D.S. at the Center for Systems Neurosciences (ZSN), Hanover. The authors thank Prof. Alfred Effenberg and Dr. Gerd Schmitz (both at Leibniz University Hanover, Institute of Sport

Science) and Prof. Holger Blume (Leibniz University Hanover, Institute of Microelectronic Systems) for important insights while working on the joint ERDF project on movement sonification. We also thank Hans-Peter Brückner and Benjamin Krüger for implementing the real-time 3D sonification for the clinical study. Finally, we would like to thank the patients and the staff of the BDH-Clinic Hessisch Oldendorf for their ongoing support and patience.

Conflicts of interest

The authors declare no conflicts of interest.

Supporting Information

Additional supporting information may be found in the online version of this article.

Figure S1. An example sheet of the melody "Freude schöner Götterfunken" ("Ode to joy") from Beethoven's Symphony No. 9, provided to the patients to train them to play melodies by moving their affected arm in the 3D space at the end of the training sessions.

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