A mobile sonification system for stroke rehabilitation

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ABSTRACT

Growing evidence suggests that sonification supports movement perception as well as motor functions. It is hypothesized that real-time sonification supports movement control in patients with sensorimotor dysfunctions efficiently by intermodal substitution of sensory loss. The present article describes a sonification system for the upper extremities that might be used in neuromotor rehabilitation after stroke. A key-feature of the system is mobility: Arm movements are captured by intertial sensors that transmit their data wirelessly to a portable computer. Hand position is computed in an egocentric reference frame and mapped onto four acoustic parameters. A pilot feasibility study with acute stroke patients resulted in significant effects and is encouraging with respect to ambulatory use.

1. INTRODUCTION

Stroke is an emergency event that causes severe neurological impairments. Impairments are typically lateralized and may manifest as one-sided perceptual, representational or motor dysfunctions such as hemiparesis, hemineglect or hemiplegia. About 60% of the patients have somatosensory deficits [1] and extent of impairment is expected to be negatively related to recovery rate [2]. Most often arm functions are impaired [3]. When patients tend to use their unimpaired arm for compensation, they attain to a vicious circle, because the impaired arm receives less afferent and efferent stimulation. Accordingly rehabilitation methods focus on the sensory stimulation and activation of the impaired extremity.

In this paper we describe a sonification system for an auditory enhancement of sensory feedback by real-time capture and sonification of arm movements to support functional reorganization of arm representations within the CNS. The method was designed for ambulatory as well as home use in collaboration with the Institute of Microelectronic Systems of the LU Hannover and the Institute of Music Physiology and Musicians' Medicine of the HMTM Hannover. Here we present the concept of a movement-related sonification and data of a pilot feasibility study.

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2. IMPACT OF MOVEMENT SONIFICATION ON PERCEPTION AND ACTION

Artificial auditory feedback of human movement performance can substitute or augment naturally available feedback and might act on multiple physiological, psychological and cognitive levels. The following section focusses on general effects of auditory movement information on perception and action and then on specific findings on auditory feedback of goal-directed arm-movements.

2.1. Effects on movement perception, learning and motor control

A couple of movements are typically accompanied by sounds: When we are asked to think of a walking person, we inevitable imagine the sound of footsteps. Keeping such an example in mind, it is not surprising that sounds as footsteps can activate parts of the so-called action observation system [4]. This system processes biological motion information and enables us to identify human movement patterns. Artificial sounds might have similar effects: Young et al. [5] showed that sounds of walkers' ground reaction force have the same perceptual impact as natural sounds of footsteps. Furthermore, when subjects had synchronized their steps to the sound, they automatically changed their stride length in response to sound modification, which virtually reflected alteration of force.

An increasing number of studies shows that sonification can be used to enhance perceptual or motor performance when it amplifies movement features or provides additional movement information. For example, a sonification of ground reaction forces can improve perceptual performance during observation as well as motor control during reenactment [6], and a sonification of trunk acceleration can assist postural control [7]. These effects can be explained by concordance of visual and auditory movement information, which yield in superadditive activation of brain areas involved in multimodal motion perception [8]. Furthermore, sonification seems to be efficient during motor learning of gross motor skills [9, 10] and relearning of physiological movement patterns [11]. But the potential goes beyond purely perceptual stimulation: A recent study suggests that sonification of movement kinematics does not only activate the action observation system but also cortical/subcortical elements of the motor loop [12]. Latter is quite surprising, because subjects had not heard a sonification of their own movements before and therefore could not have developed specific perceptuo-motor expertise. But this finding is in line with current theories on embodiment, which describe action simulation in relation to the own motor repertoire. A kinematic sonification thus might address these mechanisms, as confirmed by discriminability of action-patterns without specific percepto-motor nor perceptual experience [13] and a particular sensitivity of the perceptual system to sonifications of own movement patterns [14].

Based on these results it can by hypothesized that movement sonification is beneficial in rehabilitation of arm-functions, as it might increase the understanding of actions with help of the action observation system or enhance the information processing of the impaired function by implicitly involving the motor system [12].

2.2. Auditory feedback of goal-directed arm movements

There is growing evidence that continuous auditory feedback can improve accuracy of hand and arm movements. Rosati et al. [15] investigated the effect of binaural spatialized task- and error-related sound feedback during a two-dimensional tracking task. Task-related feedback informed either about the velocity of the target (pink noise or sound of a rolling ball) or of a cursor (sound of DJ scratching), and error-related feedback (formant synthesis) about the spatial coordinates of the deviation between target and cursor. The cursor was controlled by a digitized pen on a tablet or a joystick. The authors reported that feedback about target velocity was beneficial, whereas feedback about cursor velocity had no significant effect and error-related feedback deteriorated performance. In another study subjects performed discrete pointing movements to artificial auditory targets while they received auditory feedback about the spatial distance between arm and target direction [16]. Again, auditory feedback about spatial deviations had no impact on pointing behavior, but a longer presentation time of a stationary target increased accuracy significantly. Thus it might be concluded that a sonification can address representations of movement goals and probably helps to specify feed-forward motor commands. Although effector-related feedback was not beneficial in these studies, it might not be concluded that a sonification of arm movements is not effective: Two recent studies on sensorimotor adaptation provide evidence that auditory feedback, which substitutes visual feedback of arm and hand movements by quantifying direction (pitch frequency) and magnitude (amplitude) of the target-related movement error, modifies performance and induces adaptation to a kinematic sensorimotor discordance within minutes [17, 18]. The persistence of adaptation after removal of feedback suggests a recalibration of sensorimotor transformation rules and results of at least one study [17] confirmed that continuous feedback modified the feed-forward component of movements.

Several studies investigated the effect of continuous auditory feedback in stroke rehabilitation. Wallis et al. [19] embedded real-time sonification into a multimodal feedback system for stroke patients and found indications for its efficacy on a descriptive level. Maulucci et al. [20] compared outcomes of two groups of chronic stroke patients that underwent a six-week training of reaching. Only one group received additional feedback about the magnitude of deviations from trajectories of healthy subjects by pitch frequency. This group showed larger training effects than the other group and significantly improved reaching paths. Robertson et al. [20] investigated the impact of two different types of auditory feedback on arm kinematics. One feedback-type informed about the distance between arm and target, the other additionally about the orientation of the hand with respect to the target through binaural spatial and spectral cues. Independently of feedback-type auditory feedback modified arm kinematics. Movements became straighter and more ballistic in patients with a right hemisphere lesion and less ballistic and more curved in patients with left hemisphere lesions. In contrast to the hypothesis, the more information-rich feedback was not better than the simple feedback.

Taken together, some few studies suggest that auditory feedback can improve accuracy of goal-directed arm movements and that it is effective in stroke rehabilitation. Other studies report a lack of effect or even a negative impact. Therefore the current state of knowledge does not allow to draw systematic conclusions about efficient factors with respect to feedback-nature.

Figure 1: Inertial sensors, attached to shoulder, impaired arm and trunk, were used to calculate spherical coordinates of the wrist during reaching and grasping.

3. DESIGNING A FEEDBACK SYSTEM FOR ARM MOVEMENTS

The goal of the project was to develop a wireless wearable system that provides a person with auditory feedback in real-time about the own arm-movements. A key-feature should be the applicability in multiple environments, independent from a stationary reference frame that ties a subject to a specific place. If such a system can be handled intuitively, it could not only be used during rehabilitation but as well during the daily routines and that way enhancing the daily duration of application considerably. Due to this reason, we decided to design a system which continuously feedbacks movement performance and does not need to take ideal paths or movement goals into account. To our knowledge, no study has reported a positive effect of such a kind of auditory feedback yet. Thus we intended to sonify parameters that can be easily controlled by human subjects, and that are supposed to be related to perceptuomotor representations in the brain.

3.1. Selection of movement parameters

Arm-movements have multiple degrees of freedom and a sonification of all of them might cause perceptual overload. Instead, sonification of a single set of parameters that are directly related to perceptuomotor control might be sufficient. It is widely accepted that programming and control of goal-directed movements depend on egocentric reference frames and that the brain contains multiple of them. It is further assumed that senses and effectors act in different reference frames. As a consequence sensory information has to be transformed into multiple reference frames [21] or into a common code that can be applied to different sensory and motor systems [22, 23]. Accordingly, artificial sensory information, as provided through movement sonification, might rather be introduced in an existing than in an artificial reference frame. The selection of an appropriate reference frame might be essential for the effectiveness of a method.

Graciano [21] reviewed single-cells studies of the so-called reach-neurons in monkeys and came to the conclusion that, at least near the motor output stage (premotor and primary motor cortex), hand-centered reference frames govern arm control. Nevertheless, spatial eye-centered and body-centered reference frames seem to be related to other stages of information processing located at the parietal cortex, premotor cortex and superior colliculus. Since at least parts of each area respond to sensory stimuli, it might be speculated whether different brain areas and functions (as for example movement control or monitoring) are activated by sonification of hand-centered, body-centered and eye-centered coordinates. It therefore might be valuable to implement multiple reference frames into a system for arm-sonification and to keep the possibility to switch between them depending on the context. Graziano further states that all reference frames refer to a movement vector with “a fixed spatial relationship to the end of the arm” [21, p. 178]. Thus it might be a good strategy to sonify spatial coordinates or the movement vector of the end-effector. This indeed was done in the study of Schmitz et al. [12] for the sonification of breast stroke movements and might explain its efficacy.

Lacquaniti et al. [24] investigated neuronal activity in the superior parietal cortex before and during arm movements. They found that distinct neuronal populations code direction, elevation and the amplitude of a movement, and argue that those dimensions are programmed in parallel and independent from each other. Evidence for the existence of similar mechanisms in humans comes from studies that experimentally investigate sensorimotor transformations by adaptation of movements to two-dimensional discordances. This is a special form of motor learning: Previously veridical feedback about hand or arm movements is altered with respect to direction or amplitude of a movement. A prolonged exposure to such a discordance results in a modification of sensorimotor transformation rules (recalibration), which can be measured as implicit change of movement direction or amplitude from pre-exposure to post-exposure. Several authors have shown that adaptation of movements executed to single directions generalizes poorly to untrained directions [25, 26]. These and further results suggests that adaptation is directionally tuned, effector-independent and quite similar to directional tuning curves of neurons in different brain areas [27, 28, 29]. Furthermore adaptation of movement amplitudes and directions reveal different generalization schemes [25, 30], suggesting that those parameters are controlled independently from each other.

Taken together those results suggest that arm movements are governed by reference frames, which have non-orthogonal axes and differ with respect to their anchor point. It is not clear, which reference frame is the most appropriate for feedback about arm movements, but this question might not be too critical, since learning within one reference frame can generalize to other reference frames [31, 32]. Despite this ambiguity, it might be a good strategy to consider the key-features of vector-coding and independent display of direction, elevation and radial amplitude.

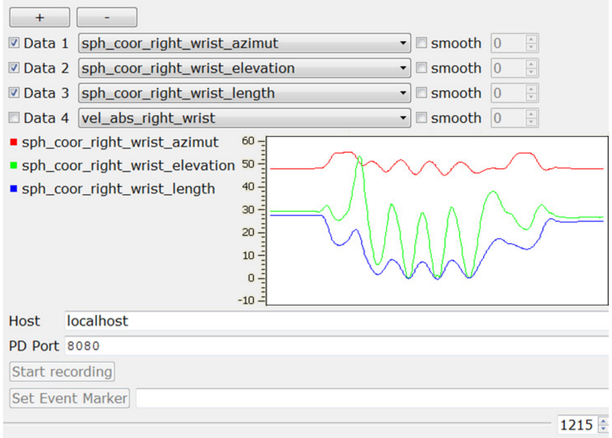

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Figure 2: Interactive software tool for sensor data fusion. Multiple movement parameters can be selected, monitored and exported to other software applications as, for example, PureData or CSound.

3.2. System specifications

Detailed technical features of the system are published in Brock et al. [33] and just will be summarized here. Up to eleven intertial sensor units (MTx miniature inertial 3DOF orientation tracker; Xsens Technologies BV, Enschede, The Netherlands) can be attached to the back of the fingers, back of the hands, upper and lower arms, shoulders and the trunk. They transmit their orientation and acceleration data via cable to the Xbus Master attached to the belt, which sends the synchronized data set via Bluetooth to a portable computer. Sensor data (50 Hz) of all sensors are fused by an interactive software (Figure 2) that calculates positions, velocities and accelerations of limb segments in relation to individual anthropometry by using a forward kinematic model. Spatial parameters can be calculated in Cartesian and spherical coordinates of trunk-, shoulder-, elbow- or wrist-centered reference frames. Up to sixteen parameters can be exported to other software applications, in that case to Pure Data and CSound for sonification.

4. EMPIRICAL PILOT STUDY

The perceptual impact of our sonification was proven by Vinken et al. [13]. Subjects were able to discriminate six similarly sonified upper-limb actions of another person, although they had not been informed about the nature of the sonification before. Discrimination was already above chance level during the first trials and further improved, indicating immediate auditory pattern discrimination and perceptual learning. Nevertheless, it remained unclear whether the method is effective for motor control and can be applied in stroke rehabilitation. Therefore, feasibility was scrutinized in a small clinical study. Assessment of motor functions prior and after a standardized movement intervention served to prove the efficacy of movement sonification.

4.1. Methods

4.1.1. Subjects

Seven patients from a rehabilitation clinic, two to four weeks post-stroke, participated in the study. They all suffered a hemiparesis with low to moderate motor impairments. Thus they were able to move the impaired arm and the finger of their impaired hand without help of the unimpaired arm. Individual patient data are listed in table 1. Participants were randomly assigned to the sonification group (HH, MA, AC, MS) or a control group (SG, BB, HS).

Table 1: Patient data.

patient	**sex**	**age [years]**	**affected hemisphere**	**hand dominance**
SG	female	55	right	right
BB	female	58	right	right
HS	female	82	right	right
HH	male	63	left	right
MA	female	53	right	right
AC	male	51	left	right
MS	male	57	left	right (retrained)

4.1.2. Assessment of motor functions

Motor and movement functions of both arms was assessed twice during the experiment. The Action Research Arm Test (ARAT) was applied to evaluate the initial status and change of general arm and hand functions, whereas the Nine Hole Peg Test (NHPT) and the Box and Block Test (BBT) provided distinct measures for fine (NHPT) and gross motor skills (BBT). Due to patients' heterogeneity with respect to age, data of the latter two tests were normalized to aged-matched means and standard deviations taken from Mathiowetz et al. [34, 35].

4.1.3. Intervention

Subjects sat in front of a table and performed arm movements of varying complexity. They were allowed to use their impaired arm within a defined *task-space* while the unimpaired arm rested on the tabletop. Three-dimensional *task-space* had a side length of 51 cm and was subdivided into nine quadrants of 17 cm side length. Subjects were instructed to direct their movements at a self-chosen speed towards the center of a quadrant and then back to the starting position near the edge of the table, or towards one or more other quadrants, thus performing pointing movements with increasing number of sequences. In a second task, subjects grasped a soft ball located within the task-space on a wooden block of 17 * 17 cm side length and height of 8.5 cm, 25.5 cm or 42.5 cm. They were either instructed to grasp and release the ball or to lay it onto another wooden block of the same or a different height at a different spatial position and move their hand back to the starting position (Figure 1). Number and complexity of the tasks were standardized. All sessions had a net-training-time of 20 minutes. Each subject participated in five interventions on consecutive days.

4.1.4. Alignment of sensor orientation, kinematic-acoustic mapping

Before and between tasks sensor orientations were (re-)aligned with a defined arm position. For this purpose the experimenter hold a subject's arm in an outstretched position in line with the shoulder axis. Based on this calibration-procedure the origin of a trunk-centered reference frame was defined at the intersection between shoulder axis and spine. Hand-positions were calculated in spherical coordinates. Trunk-centered reference frame and spherical coordinates were chosen in consideration of Graziano [21] and Lacquaniti et al. [24] (see section 3.1).

Data were sonified with CSound. Sound synthesis was based on frequency modulation with a carrier and modulator frequency of 133.3 Hz (saw tooth waveform). Arm velocity was linearly mapped onto amplitude, elevation angle linearly onto frequencies between 133.3 Hz and 266.6 Hz. Radial arm amplitude modified logarithmically the frequency modulation index from 0 to 0.15 yielding the impression of brightness changes. Azimuth angle defined the panning (equal power panning). Mappings were individually adjusted to subject's self-preferred movement speed at a familiarization phase at the beginning of the first intervention.

4.2. Results

All patients except two yielded the highest ARAT-score during the pre-test already. This ceiling effect precluded measurability of improvements during the post-test. Patients SG (control group) reached a score of 48 in the pre- and 47 in the post-test, and patient HH (sonification group) improved his performance from a score of 36 in the pre- to 42 in the post-test.

NHPT-scores were very heterogeneous across the patients (table 2) and two patients were not able to perform the pre-test with their impaired hand. Thus neither in the control-group nor the sonification group pre-post-changes became significant (one-sided Wilcoxon-tests; control group, impaired hand: Z=-1.34, n.s., unimpaired hand: Z=-0.54, n.s.; sonification group, impaired hand: Z>-0.01, n.s.; unimpaired hand; Z=-0.37, n.s.).

Table 2: Results of the Nine Hole Peg Test. Completion times were z-standardized with respect to means and standard-deviations of aged-matched healthy persons reported in Mathiowetz et al. [35].

	impaired hand		**unimpaired hand**	
patient	**pre**	**post**	**pre**	**post**
SG	-	67,65	0,85	0,08
BB	21,57	34,17	6,62	7,38
HS	2,88	6,37	0,52	2,93
HH	-	-	3,60	2,00
MA	3,63	3,30	0,80	1,60
AC	2,11	1,00	-1,17	-0,30
MS	7,23	9,15	-1,25	0

In contrast to the ARAT and the NHPT, results of the BBT were encouraging. As illustrated in Figure 3, scores of both hands were below the mean of aged-matched, healthy people (represented as z=0), but all subjects were able to perform the test.

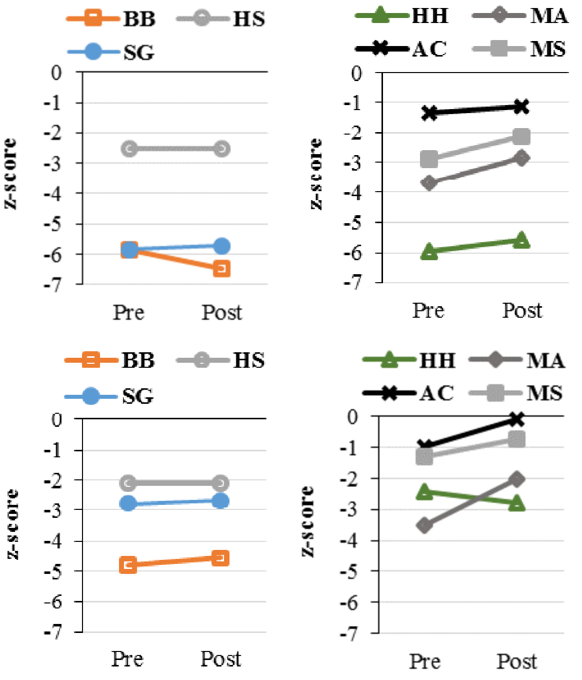

Figure 3: Results of the Box and Block Test in patients SG, BB and HS from the control group as well as patients HH, MA, AC and MS who heard a sonification of their impaired arm during the intervention. Upper graphs illustrate pre- and post-measures of the impaired, lower graphs measures of the unimpaired arm. Raw values were z-standardized on aged-matched means and standard deviations as reported in Mathiowetz et al. [34].

In the control group neither the impaired (Z=-0.45, n.s.) nor the unimpaired arm (Z=-1.34, n.s.) showed meaningful improvements, whereas the subjects from the sonification group yielded a significant pre-post-change with their impaired arm (Z=-1,826, p=0.034). Changes in the unimpaired arm were not significant (Z=-1.46, n.s.).

4.3. Discussion

This pilot study was performed to test the applicability of the sonification system for motor rehabilitation after stroke. Patients felt not affected by the inertial sensors attached to their trunk, shoulder and arm. Although the sonification was rather functional than aesthetical, patients reported that they liked the sound of their arm movements.

The sonification had been designed to address gross motor skills and provided four-dimensional information about arm positions and trajectories. Standardized and established clinical tests, commonly utilized for the assessment of stroke rehabilitation, were used for pre-post-testing. Nevertheless two of three tests might not have been adequate for the study:

1. The ARAT resulted in a ceiling effect, probably because it tests too many different arm functions. 2. The nine hole peg test requires fine motor skills. These were neither specifically trained nor sonified during the intervention and intact fine motor skills had not been inclusion criterion. Thus subjects SG, BB and HH, who were strongly impaired in that domain, were not excluded from the study.

A significant result was achieved with the BBT, which assesses gross motor skills. The results are plausible and encouraging. Nevertheless, sample size was very low and patient-groups were heterogeneous with respect to age, handedness and locus of damage in the brain. Thus the presented data have to be interpreted very cautiously.

Improvements of the unimpaired arm were not significant, but it should not be concluded yet that our sonification addresses arm specific representations: Three of four subjects enhanced their performances in the post-test. Soechting and Flanders [23] argue that kinematic information are coded effector-independently in the central nervous system. Indeed, a recent study on adaptation of arm movements suggests that audiomotor adaptation modifies effector-independent representations, because it transfers from the adapted to the un-adapted arm [17]. The two-dimensional reference-frame used in [17] was part of the three-dimensional, body-centered reference frame used in the present study. It might be possible that our real-time sonification addresses these effector-independent representations, too.

5. CONCLUDING REMARKS

The present paper describes a system for real-time sonification of upper-limb movements. Individual movement parameters are calculated on the basis of acceleration and orientation data from inertial sensors. Wireless data transmission ensures utilization independent from stationary reference frames and allows the user to move around freely. Results from a pilot study provide initial indications on the efficacy of the system in motor rehabilitation and seem to support our concept of real-time auditory feedback. The key-feature of mobility opens the opportunity to wear the device during activities of daily living, enhancing the duration of additional sensory stimulation. Furthermore, large accelerometer ranges (18G) suggest applications at highest movement speeds as for example in the field of Sport.

6. ACKNOWLEDGMENT

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