Can simple error sonification in combination with music help improve accuracy in upper limb movements?

Anabel Immoos Dailly1, Roland Sigrist2, Yeongmi Kim1, Peter Wolf2, Hendrik Erckens, Joachim Cerny3, Andreas Luft3, Roger Gassert1, James Sulzer1

Abstract—While repetitive training is widely regarded to be a useful rehabilitation strategy, such training requires motivation that may be lacking. In order to improve motivation in a potentially inexpensive and simple manner, we introduce in this proof-of-concept study a combination of error sonification and music for upper limb training. Twelve healthy participants trained a figure tracing task for the upper limb, six receiving feedback in terms of error sonification and music and six without receiving feedback in the control group. The error-sonified feedback group decreased its amount of error significantly compared to the control group. Thus this particular paradigm can help teach planar reaching movements. Eventually this paradigm may become simple and useful enough to enhance existing therapeutic intervention in stroke rehabilitation.

I. INTRODUCTION

Stroke is one of the leading causes of long-term adult disability. Depending on the severity of the suffered stroke, only about 30% of the survivors regain normal neurological functions [11]. The majority of stroke patients remain partially disabled, greatly affecting their activities of daily living.

One of the most effective strategies to relearn these activities is repetitive practice [2]. However, endless repetition of the same or similar motor task may discourage patients. One way of maintaining motivation is playing background music during therapy, which has been shown to enhance cognitive recovery and motivation [7], [18], [19]. In addition, rhythmic music listening activates salient brain regions for motor learning [3]. Not surprisingly, music is often played in a clinical setting.

Aside from passive music, sound parameters can also be mapped to movement variables, which is generally known as movement sonification. In other rehabilitation fields auditory signals have been shown to be effective in cognitively healthy subjects, e.g., regaining physiological gait patterns after spinal cord injury, providing auditory feedback on applied forces or approaching threshold limits [1], [16], [17]. It has been shown that movement sonification can improve not only stride parameters in gait rehabilitation but also arm kinematics in a reaching task [14], [21], [22]. Also multimodal biofeedback systems have been successfully applied in reaching tasks to inform stroke patients about spatial and target position through vision and temporal and spatiotemporal feedback through audition [4], [10], [23].

However, these auditory signals do not inform about the extent of movement error, which could be sonified by some changes in sound parameters, such as pleasant harmony when approaching and reaching the target correctly [5]. The intensity of the signals can be directly related to the amount of error or even the direction in which to correct [8], [12], [15], [20].

While such elaborate systems may be useful in rehabilitation, they may also be overly complex. Therefore we hypothesize that simple error sonification combined with self-selected music can be a motivating and effective mode of therapy. As a first step towards this goal, we examined whether simple auditory feedback using position-error dependent music volume mixed with white noise could help train a planar reaching movement more effectively than no feedback at all. We expected that subjects receiving error-sonified feedback would reduce spatial error more than a control group listening to self-selected background music only.

II. METHODS

A. Subjects

Twelve healthy subjects (six men, six women) participated in this study. All subjects, aged between 24 and 27 years, were recruited within the ETH Zurich according to the protocol approved by the local ethics committee. An independent t-test was used to analyze the differences of the initial state of two groups based on the pretest results (t(10) = -0.015, p = 0.988). The initial level of performance of the groups did not differ significantly. All subjects were right-handed and had no medical disorders or deficits. All subjects had normal hearing abilities and no mobility limitations in the right shoulder or arm. None of the subjects had experience with the tested or a similar task. The twelve subjects were randomized into the error-sonified feedback group and the control group.
feedback group and the control group. All subjects gave written informed consent before their participation in the study.

B. Experimental Setup

1) Movement tracking: We used an optical tracking system with active LED-clusters to monitor the movements (accuTrack 500, Atracsys LLC, Le Mont-sur-Lausanne, Switzerland). The tracking device used three linear infrared cameras to locate individual infrared LEDs within the cluster in the 3D workspace. One LED-cluster consisted of four LEDs. This enabled the system to calculate the LED-cluster’s position and orientation in space with respect to the tracker, which can be positioned anywhere in the room. However, for the current experiment, only the planar position of the LED-cluster on the table surface was needed. We calibrated the origin of the system based on a home position of a given location on a table. The program used for the tracking and error measurements was custom-developed in C++.

2) Hand Device: To mount the LED-cluster in a fixed position, we made a specially-designed wooden handle inserted into a platform (Figure 1). To reduce friction with the table surface, we attached Teflon pads to the bottom of the platform.

C. Study Design

1) Task: The subjects were comfortably seated on a height-adjustable chair in front of a table. The subjects were asked to trace a predefined trajectory virtually placed on a table surface within a given time. The target trajectory was designed like an asymmetrical lying eight (Figure 2). The width of the figure was defined to 400mm and its height at the maximum to 260mm. The figure was chosen due to its asymmetry, ability to cover most of the reaching workspace and its smooth contours. The time for each cycle was set to 4 seconds, indicated by an auditory metronome click. All auditory signals were supplied through headphones. The trajectory had to be traced in the counter-clockwise direction and all the tasks had to be completed with the right hand.

2) Conditions: This study comprised four consecutive conditions: familiarization, pretest, training and posttest. For the familiarization all subjects were asked to trace the trajectory ten times, displayed on a removable transparent acrylic plate. In the pretest, the visual trace was removed and subjects completed 40 cycles of the familiarized trajectory. The only visual cues provided were two points marking the horizontal width on each side of the trajectory. The training task included 150 cycles, either error sonification combined with music and white noise. In contrast, the control group just listened to background music alone, depending on the assignment of the subjects to the group. Subsequently, the posttest was the same as the pretest, consisting of 40 cycles without any feedback or music.

3) Training conditions: The training task differed based on the presence of feedback. The error-sonified feedback group received audio feedback during training, provided by music and white noise. In contrast, the control group just listened to background music during training and did not receive any feedback about its performance. The subjects were permitted to bring their own music.
4) Feedback: For the feedback provided, we used a linear mapping of the error of the current LED-cluster’s position. The music volume decreased while the noise volume concurrently increased, depending on the distance between target trajectory and current position of the hand device (Figure 3).

The 2 mm threshold allowed the subjects to deviate on each side of the target line without receiving feedback, this to allow room for sensorimotor noise.

D. Measurements

1) Error measurement: Using a sampling rate of 200 Hz, we calculated the error based on the minimum distance between the current position \( X_{hand} \) and the 4000-point resolution target trajectory \( X_{target} \) and then averaged over the entire cycle according to,

\[
\varepsilon = \frac{1}{T} \sum_{t=0}^{T} || X_{hand} - X_{target} ||_{min},
\]

where \( \varepsilon \) is the error, \( t \) is the current time and \( T \) is the period of the cycle.

E. Data Analysis

The primary outcome measures were the differences in mean error, \( \bar{T} \), between the pre- and posttests. We tested all the data used for analysis for normal distribution. To examine potential differences between groups in initial performance, we used a two sample t-test of the mean error in the pretests between the two groups. Within group, improvement from pre-to posttest was analyzed using a one sample t-test and between group comparisons were made using an independent samples’ t-test. The dependent variable was defined as the mean difference in spatial error between the pre- and posttest. For all the statistical data analysis we used the SPSS (IBM SPSS Statistics 19, Armonk, NY, USA).

III. RESULTS

A. Single Subject Results

Evidence of two representative subjects illustrates the effect of feedback. Figures 4 and 5 show the mean trajectory and standard deviation for the pretest and posttest of one representative subject from each group, respectively. In this case, the subject who receives no feedback maintains a similar posttest-trajectory to the pretest (subject 9-CG), while the subject in the error-sonified feedback group (12-FB) reaches a trajectory close to the target. Contrasting these subjects’ posttests the influence of the error-sonified feedback becomes visible.

Most subjects exhibited some change before and after training. Table I lists five out of six subjects in the error-sonified feedback group with a significant improvement from pre- to posttest. In the control group however, the subjects were less consistent, with three improving error, and two worsening.

B. Pre- and Posttest Comparison

While the error-sonified feedback group improved performance significantly \((t(5) = 3.429, p<0.05)\), the no feedback group did not \((t(5) = 0.729, p>0.05)\). The error-sonified feedback group improved significantly in performance compared to the no-feedback group \((t(10) = -3.063, p<0.05)\).

<table>
<thead>
<tr>
<th>Subject-group</th>
<th>Mean error pretest [mm]</th>
<th>Mean error posttest [mm]</th>
<th>Mean error difference [mm]</th>
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<tr>
<td>01-FB</td>
<td>27 (17)</td>
<td>15 (11)</td>
<td>-12</td>
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<tr>
<td>04-FB</td>
<td>21 (17)</td>
<td>20 (14)</td>
<td>-1</td>
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<tr>
<td>06-FB</td>
<td>15 (13)</td>
<td>14 (9)</td>
<td>-1</td>
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<tr>
<td>08-FB</td>
<td>19 (12)</td>
<td>10 (7)</td>
<td>-9</td>
</tr>
<tr>
<td>10-FB</td>
<td>22 (17)</td>
<td>14 (10)</td>
<td>-8</td>
</tr>
<tr>
<td>12-FB</td>
<td>19 (14)</td>
<td>12 (9)</td>
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<tr>
<td>02-CG</td>
<td>27 (16)</td>
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<tr>
<td>11-CG</td>
<td>15 (12)</td>
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Error-sonified feedback group (FB), control group (CG)
Auditory perception is very important in life; many daily tasks and also sports are managed with the help of auditory information, often unconsciously [6], [9]. To avoid strong reliance on visual or multimodal information it could be beneficial to focus on giving feedback almost exclusively through the auditory system.

The purpose of this study was whether simple error sonification combined with music can help learn a planar reaching movement more effectively than no feedback. As expected, subjects who received error-sonified feedback improved their performance better than subjects passively listening to background music.

We conclude that auditory feedback, as introduced, helps improve movement accuracy and may maintain motivation during repetitive practice. While all error-sonified feedback subjects improved, only some of the control subjects increased performance, while some decreased. We attribute the variance in improvement of the no feedback group to random chance, although some of the improvement is likely to be due to repetitive practice alone.

With our approach of giving feedback through auditory channels, we aim to find a simple and realizable paradigm. Such a simple training method is intended for eventual clinical rehabilitation implementation.

Although, we can see the potential of our training method, there will be some challenges to solve before finally implementing it in stroke rehabilitation. As our method does not use any robots to assist or guide the movements, the stroke patients will already require some free range of motion in the paretic arm to fulfill at least parts of the requested movement by themselves. The complexity of the target trajectory will have to be adapted in shape and size, e.g. a circle would likely be more easily completed than the pattern in this experiment [13], adaptations could even be made for each patient individually. Further, the time for completion of one trial will have to be appropriately modified or even not limited for the beginning of the therapy.

V. CONCLUSION

This study shows that a very simple concurrent error sonification can assist unimpaired subjects in learning new movements better than repetitive practice. The conclusions drawn of this study are limited due to the relatively small number of tested subjects and only one single training session.

However, we intend to expand on this pilot study to examine the mechanisms of motor learning and eventually apply this paradigm to stroke rehabilitation. Our vision is to exploit existing background music in order to improve attention and engagement in therapy and to develop a therapeutic method without relying extensively on vision.

VI. ACKNOWLEDGMENTS

This work is supported by the National Centre for Competence in Research in Neural Plasticity and Repair of the Swiss National Science Foundation. The authors are members of the Neuroscience Center Zurich (ZNZ) and the Rehabilitation Initiative and Technology Platform Zurich (RITZ).

REFERENCES


