Providing Augmented Feedback by Using a Bandwidth Method Affects Motor Automatisation

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***Summary*—The present study examines if feedback schedules with high error frequencies could negatively affect the automatisation of an arm-movement-sequence whereas feedback with reduced error frequencies or additional positive feedback may have a positive influence. The results show facilitated automatisation for groups with either feedback schedules with reduced error frequencies or reduced error frequencies and additional positive qualitative feedback. The group with a high error frequency feedback schedule and the control group did not show any changes in the automatisation level.**

INTRODUCTION

Feedback (FB) schedules with high error frequencies are supposed to induce cognitive control processes with the aim of correcting the movement as well as explicit learning [1]. However, the formation of a representation that is relatively awareness-independent in the sense of automatisation therefore may be limited, whereas FB with lower error frequency (e.g. bandwidth-feedback) could positively influence the automatisation process. This assumption, which has not been taken into account in earlier studies regarding bandwidth feedback [2], is tested in the current experiment.

METHODS

48 participants had to learn to hit 3 turning points as precisely as possible in an elbow-extension-flexion-sequence on a lever device. After an initial acquisition phase of 40 trials with 50% FB-frequency and a pre-test, the participants were divided into 3 interventional (IG) and 1 control group (CG) (factor GROUP) parallelised according to pre-test results. The groups IG-100 (100% quantitative FB), IG-BW (bandwidth: quantitative FB or positive qualitative FB on errors < 10°) and IG-Yoked (only quantitative FB on the same trials as the research-twin from IG-BW) practiced the movement with additional 720 trials distributed over 5 sessions. In a pre- and a retention-test (factor TIME), the movement and an n-Back-Task were conducted as a single- and a dual-task (factor STDT). As the movement task was prioritised, the dependent variable for testing the automaticity was the mean number of errors per trial for the cognitive task (n-Back-Error). For the movement task a mean absolute error for the 3 movement turning points was calculated.

RESULTS

The IG-BW, $p = .001$; $\eta^2_p = .66$, (TOM x STDT) and IG-Yoked, $p = .017$; $\eta^2_p = .42$, show a reduction of dual-task costs (DTC) for the n-Back-Error. The IG-100, $p = .793$; $\eta^2_p < .01$ and CG, $p > .999$; $\eta^2_p < .01$, do not show a reduction in DTC. The interaction (GROUP x STDT x TIME) for the IG-Yoked and the IG-BW is very close to being significant, $p = .056$; $\eta^2_p = .16$.

For the AE there is a significant main effect STDT at pre-test, $p = .013$; $\eta^2_p = .13$, but not at retention-test, $p = .816$; $\eta^2_p < .01$. There are no significant effects with factor GROUP for the AE.

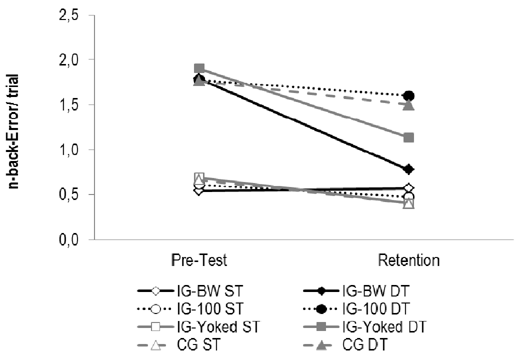

Figure 1 Pre-test and retention-test n-Back-Error per trial for single-task (ST) and dual-task (DT) conditions for each group.

DISCUSSION

Both, the IG-BW and the IG-Yoked show a reduction of DTC regarding the n-Back-Error, whereas the CG as well as the IG-100 are showing none. This is interpreted accordingly to an enhanced automatisation of the movement. Since the control group does not show any effects, one cannot act on the assumption of a DTC reduction caused by integrated task processing. Since the interaction (GROUP x STDT x TIME) between the IG-BW and the IG-Yoked is missed only just, it cannot be ruled out that the additional qualitative positive FB of the IG-BW has an effect on the processes of automatisation. But to a more important part the automatisation seems to be explained by a decreased error feedback frequency (here approx. 14%) in the IG-BW, opposite of the IG-100.

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EEG-guided fMRI and functional connectivity analyses of audiovisual binding

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***Summary*— Correlates of audiovisual binding were analyzed in simultaneously recorded functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) with an EEG-guided fMRI analysis and a functional connectivity analysis. Participants observed series of visual stimuli being switched on and off either synchronously or asynchronously to auditory stimuli. They reported the temporal congruence and the location of the auditory stimuli. Behavioral results showed that auditory stimuli presented in temporal congruence to the visual stimuli were localized closer to the visual stimuli (ventriloquism effect). An indicator of binding was also detected in EEG time-frequency representations (in theta and alpha frequency range). This indicator correlated with brain activation in the right superior temporal sulcus (STS). The activation in the STS was functionally connected with the parieto-occipital sulcus and the intraparietal sulcus, supporting the role of the STS in crossmodal binding.**

INTRODUCTION

Crossmodal binding combines feature information caused by an external event or object and detected by different sensory modalities into a unified percept in the mind.

Methods: Simultaneously recorded functional magnetic resonance imaging (fMRI), electroencephalography (EEG); EEG-guided fMRI analysis, functional connectivity analysis.

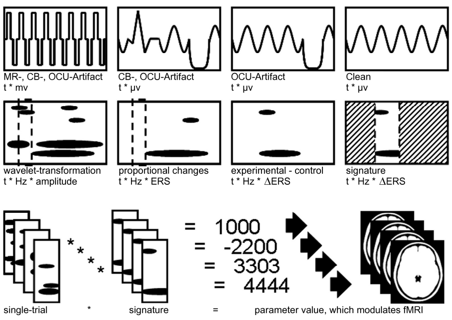

Figure 1 Schematic diagram of the EEG data analysis procedure. MR: Magnetresonance; CB: Cardioballistic; OCU: Ocular-movement; ERS: Event-related synchronization.

Time-frequency representations of segmented epochs across frequencies were acquired by continuous wavelet transformation. For each transform event-related de-/synchronization was computed. The amplitudes over time for all frequencies were summed up and this value was used as parametric modulator in the fMRI-GLM.

RESULTS AND DISCUSSION

The ventriloquism effect was utilized as an indicator of crossmodal integration. In the EEG, time-frequency representations of theta and alpha band activity at parietal electrodes discriminated temporal congruence and incongruence. In the EEG-guided fMRI analysis, hemodynamic changes in the right STS correlated with variations in EEG single-trial measures during binding.

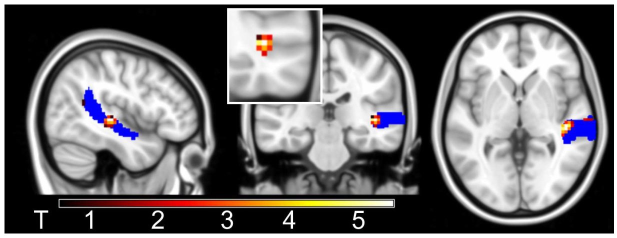

Figure 2 Effect of parametric BOLD modulation by binding. The statistical parametric map of the ROI-mask is projected on the standard MNI template (ICBM152). The STS is indicated in blue.

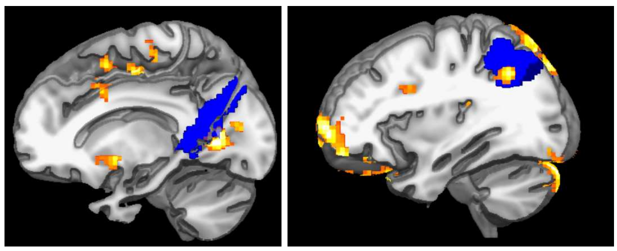

Figure 3 Analyses of connectivity with a seed-region approach revealed STS activation to be associated with the parieto-occipital sulcus (POS, left) and the intraparietal sulcus (IPS, right).

The correlation of low-frequency neuronal synchronization and hemodynamic response in the STS suggests that this region is significantly involved in processing the perceptual coherence during audiovisual binding. The connections revealed in the connectivity analyses further support this. Our results indicate that the STS is a central region for perceptual binding– the creation of a unified percept– in audiovisual integration and the IPS as well as the POS are involved in crossmodal binding.

Comparison of Hardware Platforms for Low-Power, Real-Time Interactive Movement Sonification

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***Summary*—The use of low power hardware platforms is a mandatory requirement in mobile sonification applications like assisted training in sports or home based medical rehabilitation. Emerging rehabilitation therapies like interactive auditory feedback assisted stroke rehabilitation demand high computational capabilities and a high flexibility, e.g. programmability. In the last years the number of hardware platforms and processor cores fulfilling the application requirements has grown enormously. Therefore, this paper provides a comprehensive comparison of hardware platforms for mobile, interactive movement sonification. The benchmarks focus on the major requirements of movement sonification: overall latency and power consumption. Additionally, the effect of customizing a processor template by adding instruction-set extensions is evaluated.**

INTRODUCTION

Wearable and mobile inertial measurement units (IMU) can be easily attached to the human limbs [1]. This is a requirement for human motion capturing in medical rehabilitation and sport training sessions. IMUs also overcome the spatial limitations of optical motion capturing systems due to the stationary camera setup.

The target application of the evaluated hardware platforms is motion capturing in stroke rehabilitation sessions, where the captured movement data is used to generate an auditory feedback [2]. Recent research showed that patients in stroke rehabilitation remarkably benefit from interactive movement sonification [3].

Figure 1 highlights the system architecture incorporating IMUs attached to the limbs, a processing platform, and auditory feedback via headphones, hearing aids or speakers. Based on a connected rigid chain body model, movement parameters like relative positions and angles between body segments can be computed. Additional force sensors enable the assessment of performed grasping tasks.

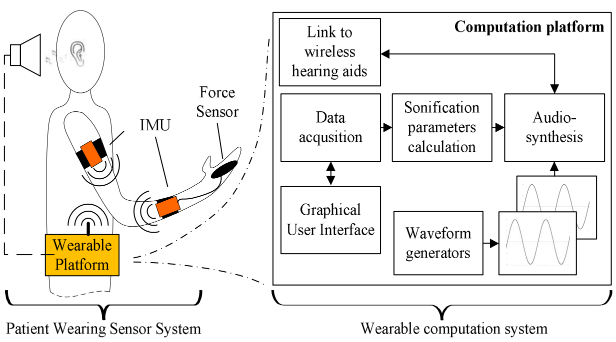

Figure 1 System architecture

HARDWARE PLATFORM EVALUATION

Three different kinds of processor cores are evaluated. The Intel Core2Duo processor is a general purpose processor. Such processors are characterized by high power consumption and are commonly used in stationary desktop computers. A significant latency is caused by operation system (OS) calls. The heterogeneous TI Integra RISC / DSP processor comprises an ARM Cortex A8 and a floating-point DSP core. This type of processors is used in mobile consumer devices. In [4] a sonification demonstrator based on this processor is evaluated. Features of this processor cores are a reduced power consumption and low latency due to optimized access to the hardware. The Tensilica Xtensa LX4 processor is a customizable processor core. Non OS based operation achieves very low latencies. Due to the customized instruction set a high energy efficiency and low power consumption is achieved.

Table 1 compares the performance of the processors. The evaluation bases on inertial sensor data of two IMUs at 50 Hz, a 44.1 kHz audio stream and the use of the sound synthesis toolkit bowed instrument for sonification.

Table 1 Hardware platform comparison

Hardware platform	Overall latency	Power consumption
Intel Core2Duo	16.22 ms	≈ 65 W (TDP)
TI Integra	8.07 ms	6.5 W
Xtensa LX4	6.02 ms	0.05 W

CONCLUSIONS

The use of customized processor cores achieves highest energy efficiency and low latency by moving the execution of most frequent and time consuming functions from the normal ALU to customized instructions.

In general, the use of low power Integra core enables low latency, real-time sonification and a short development time. Due to the time intensive design of customized ASIP architectures, these processors are a solution for extra low-power or extra low latency applications.

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Intermodal Action Identification

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***Summary*—It is already known that humans are capable to indentify human movement from point-light displays. With movement sonification it is possible to create an acoustical counterpart. Here we show that also acoustical movement information can be sufficient for action identification. Knowledge about the exact course of the movement increases identification performance.**

INTRODUCTION

Humans are able to visually identify human actions solely on the basis of the kinematic and dynamic movement pattern [1]. Biological motion stimuli of different modalities are processed closely linked, for example in posterior superior temporal sulcus (STSp) [2]. The aim of the present study was to explore if humans are also capable to identify human actions on the basis of an auditory kinematic movement pattern. Special attention has been paid on the impact of prior information about the course of the movement on identification performance.

METHODS

40 right-handed males and females (mean age 24,2 ± 3,5) participated in the study. They were asked to identify six instrumental everyday actions by means of sonification. Participants were naive concerning the systematic of sonification. Height and velocity of metacarpophalangeal joints of an acting model's right hand were computed from spatial orientation data of six 5 MTx-sensors (Xsens) and subsequently sonified (see Fig. 1). Two experimental groups contained different information before being familiarized with the stimuli: for group "Own motor imagery" (group I) actions were only named, videos of the actions were presented only to visual instructed group (group V). Testing phase consisted of 24 trials of sonifications of the six actions directly followed by the participants' responses.

Figure 1 Screenshot of the video of action "drinking".

RESULTS

Ratio of correct responses varied from 3/24 to 17/24. Participants identified actions more often than expected at random judgment (see Fig. 2). Group V (50.2% ± 12.5% correct responses) showed a better identification performance than group I (40.2% ± 15.2% correct responses). T-test for independent samples reveals a significant difference between the two experimental groups with $p<0.05$ ($t=2.217$).

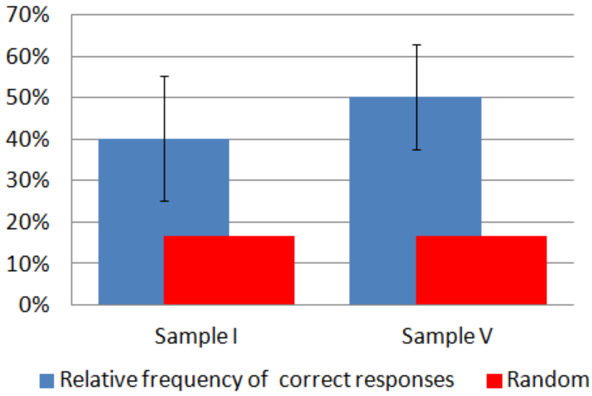

Figure 2 Mean of correct responses (blue) with standard deviations in groups I and V and the values expected at random judgment (red).

DISCUSSION

The acoustically coded trajectory of the end effector enables identification of instrumental everyday actions above chance. Even if the exact course of the movement is not known, more than twice as many correct responses as expected at random judgment were reached. Sonification enables action identification because it can reflect the structure of the action in a characteristic way. Apparently, not only visual but also auditory movement information can be compared with already acquired action representations in brain.

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Auditory Contributions to the Representation of Space

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***Summary*—We investigate the influence of auditory stimuli on the spatial representation in humans using an ‘impossible worlds paradigm.’ Our results indicate that auditory stimuli affect the internal representation of space.**

INTRODUCTION

The relation between the physical world and its mental representation has been extensively investigated during the last decades. It is unquestionable that visual input is a fundamental element and motor output may also play an important role for the representation of space [1]. But it still remains unclear whether auditory spatial information is also included in this cognitive ‘image’ of space. To address this question we conducted behavioral experiments in virtual environments (VE) taking care of ecological realism by covering visual, auditory, and motor/proprioceptive aspects.

The experiments were run featuring an ‘impossible-worlds paradigm,’ i.e. subjects were presented with VEs including severe violations of Euclidean geometry. In previous experiments we have shown that subjects are able to navigate inside these impossible VEs [2], despite the fact that there is no single, physically plausible interpretation accounting for all sensory perceptions. In the present study we added auditory landmarks to these impossible VEs and assessed how these manipulations affected the subjects' internal representation of space.

METHOD

The experiments were run in a ‘Virtusphere,’ a rotatable hollow sphere that allows a subject inside to walk, while immersed in a virtual environment. Both the rotation of the sphere and subject's head movement were tracked to process the view within the virtual environment presented on a head-mounted display. Auditory features were dynamically processed in order to exactly align sound sources and visual objects.

The subjects’ task was first to explore and learn a VE and afterwards to reproduce the walked path outside of the learning VE: they were presented with an ‘empty’ VE and had to reproduce the learning VE’s layout by walking its path from memory. The subjects were randomly assigned to either an audio condition or a no-audio condition. After a training phase they were presented with seven trials consisting of possible and impossible VRs of different complexities and they had to ‘blindly’ reproduce the path after each trial. The routes of these ‘blind-walking’ trials were recorded as indicator of the underlying spatial representation.

RESULTS

Preliminary results show that (1) subjects are able to ‘blindly’ reproduce the layout of possible VEs with an acceptable deviation of reproduced angles and distances. These data provide a robust baseline of the subjects’ individual performance in geometrically possible VEs. (2) Path reproduction data of geometrically impossible VEs show characteristic distortions of different spatial features (such as angles, etc.). (3) The results moreover indicate an effect of auditory landmarks on spatial memory and thus path reproduction. Interestingly, a greater effect was assessed on the distortion of angles or changes of layouts, whereas distances were less systematically affected. It should be noted that most participants did not notice geometric violations in impossible VEs.

DISCUSSION

Path reproduction results of impossible VEs show characteristic distortions: These may not necessarily provide an insight on the underlying mental image, which enables subjects to navigate in VEs that include geometric violations, since it has been shown that navigation does not necessarily rely on a map-like representation but rather on a sensorimotor or graph-like one. Thus, these distortions may rather be the result of a mandatory cognitive process, in the sense of ‘making-geometry-possible’, which takes place when the subjects reflect on their route memory. There is also an effect of auditory stimuli that applies particularly to VEs that bear a distinct ambiguous nature: These environments may be considered bistable, e.g. one feature supports the interpretation of a rectangle-like layout whereas another feature supports the interpretation of a triangle layout. The support of one of these interpretations by auditory landmarks causes a change of the representation to this particular interpretation of the layout. VEs without bistable characteristics are less affected, which is reflected in a smaller influence of auditory stimuli on distances.

The results indicate that spatial memory does not completely rely on visual and motor information. Auditory landmarks also shape the internal representation of space.

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Pointing task to sonified targets

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***Summary* – Pointing task to sonified targets.**
There is some evidence that arm movements can be controlled not only by visual but also auditory information. However, it still remains unclear how instruction and feedback information have to be designed to show most effective and efficient performances using the method of movement sonification.

INTRODUCTION

In reaching and pointing tasks the main focus often is on vision. Lately there is some research focusing on the role of audition, e.g. localization tasks [1] or auditory substitution [2], in goal-directed arm movements.

With this exploratory study we want to look at different characteristics, such as kinematic/sound parameters and role of vision, while posing the question: How precisely can pointing movements be conducted solely relying on movement-related auditory information?

METHODS

24 right-handed males and females (mean age 22.21 ± 2.96) conducted 108 pointing movements towards 27 acoustically presented target points which were equally positioned in the frontal, transversal, and sagittal plane (see figure 1a).

Inertial sensors were used to track the effector-endpoint trajectory of the dominant arm. The kinematics were then sonified in such a way that arm movements in different axes lead to specified sound-changes. Participants were naive concerning the systematic of sonification.

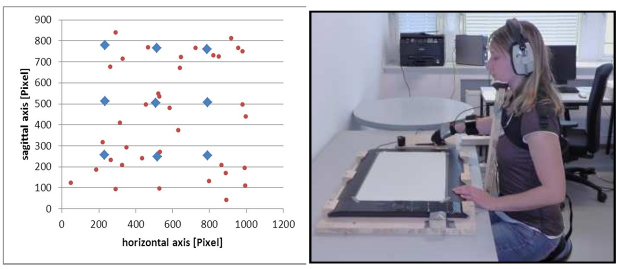

Figure 1 **a)** Grid pattern of the 9 target points in the transversal plane. **b)** Experimental apparatus in the transversal plane.

A univariate ANOVA with repeated measures for the factor S*ound parameter* with distance to the target point as dependent variable was computed.

RESULTS

The mean absolute distance to the given target points was 11.12 cm over all subjects and conditions. A closer look at the conditions revealed differences in the pointing accuracy. Data of the inferential statistics are shown in table 1.

Figure 1a) exemplary shows the pointing performance (red dots) of one blindfolded subject in the transversal plane.

Table 1 Inferential statistics.

Factors	F-value	p-value
Group: blindfolded/vision	*F(1,22) = .017*	*p = .897*
Presentation: discrete/continuous	*F(1,22) = 4.459*	*p =* ***.046***
Range of sound changes	*F(1,22) = 90.974*	*p <* ***0,001***
Sound parameter	*F*(2,44) = 5.766	*p =* ***.006***

DISCUSSION

The precision of the pointing tasks was similar with and without vision. It is concluded that acoustic space information provide an orientation framework and that movement sonification can be applied as an additional sensory source not getting influenced by vision.

As the pointing precision varied dependent on the different information about the arm movement (kinematic parameters, discrete or continuous instruction and feedback presentation, differentiation/range of sound changes) it becomes evident that a closer look at the sonification process is of huge importance to provide an efficient method for motor learning.

This exploratory study supports the view that movement sonification is a subsidiary method in the process of motor learning, but clarifies the need for situational/further specifications.

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Extensive use of hands facilitates tactile learning

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***Summary*—Tactile perception and underlying cortical mechanisms can be substantially changed by interventions. We investigated weather baseline performance levels and expertise acquired through extensive, dexterous use of hands at work facilitates tactile learning and corresponding neurophysiological changes. EEG was measured while experts and non-experts performed tactile discrimination tasks before and after a tactile stimulation, known to improve tactile perception. We found experts to learn more than non-experts and to have a stronger facilitating effect of the stimulation on the amplitudes of the P300 differences wave. Within the group of experts baseline performance determined learning effects. We conclude that expertise increases meta-plasticity in a way that it allows for more improvement.**

INTRODUCTION

Older adults with lower baseline performance benefit more from a tactile intervention than young adults, a finding interpreted as ceiling effect [1]. On the contrary, experts in fine motor control, e.g. pianists, not only have improved tactile acuity in comparison to non-musicians, they also have a higher potential for further improvement [2].

This study addressed the questions whether adults who use their hands frequently in dexterous way at work, similar to musicians, have higher learning gains after a tactile short-term intervention and whether baseline performance determines the amount of learning. Using electroencephalography (EEG) we aimed to reveal learning related changes in behavior as well as on the somatosensory and the cognitive processing level.

METHODS

Healthy, right-handed experts (precision mechanics, n=22, 11 females; mean age=53.5, SD=9.0) and non-experts (service employees, n=23, 13 females; mean age=53.5, SD=9.2) took part voluntarily in the experiment. They performed a tactile two-choice pattern discrimination task (PDT) and a frequency discrimination (FDT) task in a pre- and posttest design with 30 minutes tactile high frequency stimulation before the posttest [3]. During the tasks EEG was recorded. Acuity in PDT and FDT, defined as d', and event-related brain potentials (ERP) P50, N70 (peak amplitudes and latencies at C4), and the P300 (mean activity of difference waves in 50ms intervals at Fz, Cz, and Pz) were analyzed. Learning gain scores were calculated by subtracting pretest- from posttest performance.

RESULTS

In the PDT, performance improved after the intervention, $F(1,31)=26.17$, $p<.01$, $\eta_p^2=.45$. Experts tended to perform better, $F(1,31)=2.98$, $p=.09$, $\eta_p^2=.09$, and were shown to learn more than non-experts (Expertise × Intervention: $F(1,31)=5.38$, $p=.03$, $\eta_p^2=.15$). No significant effects were found for the behavioral performance in the FDT.

Linear regression analysis with age and baseline performance as predictors for learning gain revealed that lower baseline performance allowed for larger learning gain: PDT in experts: $sr^2=.32$; FDT in experts: $sr^2=.36$; PDT in novices: n.s.; FDT in novices: $sr^2=.22$ (m.s.).

ERP components, P50 and N70, were not affected by training. In the FDT, P300 difference wave amplitudes peaked earlier (Intervention × Latency: $F(7,217)=4.29$, $p=.01$, $\eta_p^2=.12$) and, at PZ, were higher in the post- as compared to the pretest (Intervention × Electrode: $F(2,62)=5.61$, $p=.02$, $\eta_p^2=.15$). An Expertise × Intervention × Electrode interaction, $F(7,217) = 4.41$, $p = .01$, $\eta p^2=.13$, further revealed that parietal to frontal gradients were steeper in the posttests, especially in experts. For the PDT a marginally significant Expertise × Intervention × Latency interaction, $F(7,210)=2.43$, $p= .08$, $\eta_p^2 = .08$, was found.

DISCUSSION

We showed that expertise allowed for a higher learning potential in terms of increasing discrimination performance and facilitation of cognitive processing of tactile stimuli. We interpret our findings in a way that experts have higher plasticity (meta-plasticity) and therefore have more room for improvement than novices. One might assume that this meta-plasticity of experts might also be found in experts of other perceptual or motor modalities.

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Sonification of paretic arm-movements for Stroke-rehabilitation: A Sonification-based clinical trial

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Summary **- Stroke is one of the leading causes of disability worldwide and the consequences such as motor impairment and loss of proprioception are still difficult to treat. Recently attempts are being made to use sonification for rehabilitation purposes. This pilot study investigates a first movement-sonification-therapy to find out how it could enable stroke patients to recover from motor impairment and how to substitute lost proprioception.**

INTRODUCTION

In a joint research project together with the Institute of Sport Science and the Institute of Microelectronic Systems both of the Leibniz University Hanover we developed a portable sonification device suitable for real-time sonification in a stroke rehabilitation setting [1]. Our part of the research project was to develop a music oriented sonification. Another aspect was to develop a manual for a music based sonification therapy we could then test in a clinical trial. We therefore enhanced a music supported stroke rehabilitation therapy (MuT) introduced by Schneider, Altenmüller et al. [2]. This music supported therapy is mainly designed to retrain the fine-motor skills of stroke patients. We now developed a music therapy which is capable of retraining gross-motor movements which are the main issue in the early rehabilitation of stroke. Since a stroke is often accompanied by a loss of proprioception in the most affected limbs [3] sonification might help to substitute the lost proprioception by a 3D sound mapping. This associative 3D mapping could be established by multi-modal learning of visual and auditory input at a time.

METHODS

Seven mildly impaired stroke patients were recruited from a rehabilitation clinic near Hanover. They were randomly assigned to experimental ("Music Group") and control group. The movement abilities of their affected arms were assessed with a battery of several motor function tests, followed by a two weeks lasting sonification training. Training sessions lasted thirty minutes per day on five days a week. The participants' affected arm-movements were sonified and recorded in real-time while they performed several motor and musical tasks. The 3-dimensional sound mapping used for sonification varied in pitch, timbre and volume. The training of the arm was applied in a predefined 3-dimensional space. Outcome measures of the training were the established Action Research Arm Test (ARAT), the Nine-Hole Pegboard Test (NHPT), the Box and Block Test (BBT) as well as a novel, self-developed test putatively sensitive to gross motor function abilities in a pre-defined 3D space (Scholz-Test).
Furthermore we acquired the Stroke Impact Scale (SIS-16) and the upper extremity part of the Fugl and Meyer assessment. A repeated measures ANCOVA was used to statistically evaluate the data.

RESULTS

We did not find any significant difference between experimental and control group from pre to post-measurements.

DISCUSSION

In future clinical studies we want to implement the knowledge we gained from this pilot-study. The sample-size of the here presented dataset is very small. To yield statistically interpretable effects we will increase the number of participants. Music based 3D movement-sonification will be evaluated further as a therapeutic training method to enhance stroke patients arm movements rehabilitation through massed practice and substituted proprioception.

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Information-Driven Audio-Visual Source Localization on a Mobile Robot

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***Summary*— We designed a system for active audio-visual source localization for use on a mobile robot. An information gain mechanism is used for the selection of the most informative action at each step.**

INTRODUCTION

Multisensory source localization systems can be useful for many areas of application. For example, the detection and localization of a speaker in a noisy environment is an essential feature for automatic camera control for video conferences. This is a very difficult problem to solve with computational vision alone, because classification of gestures and lip movements is very unreliable. In contrast, systems based solely on auditory information are prone to reverberation and noise. While there are auditory, visual and audio-visual tracking systems based on Kalman- or Particle-Filters (e.g., [1]), to our knowledge, our approach is the first to use bio-inspired sensors and an information-driven action-selection strategy. Because of the robot's mobility, the system is suitable for use in complex and cluttered environments, which require movement to detect and disambiguate all possible sources.

METHODS

The system was implemented and tested on a mobile robot of the type Pioneer P3-DX, which we equipped with a rotatable head with realistic human-like pinnae. We use in-ear stereo microphones, which are inserted directly into the ears, mimicking the human outer ear system (pinna, auditory canal and eardrum) (see Fig. 1, left), and a stereo camera.

An overview of the system's components is shown in Fig. 1. Sound is recorded by the stereo microphones and transformed into a biologically plausible time-frequency representation (cochleagram) by a gammatone filterbank. We use a classic binaural auditory source localization approach based on interaural time differences (ITDs), which are calculated by normalized cross correlation of the filter bank outputs of the left and right channels. To map the ITDs to their corresponding angles, we measured ITDs for the robot in ~5 degree intervals. The visual estimation of source position is calculated by a template matcher based on cross-correlation, utilizing templates for multiple orientations. The resulting images are combined by identifying the maximum correlation for each pixel. We utilize an particle filter with importance resampling for the temporal integration of consecutive measurements and for the combination of auditory and visual information. In order to reduce the number of movements required to achieve accurate position estimates, actions are selected by an information gain mechanism: in each step the system chooses the action, which minimizes the expected entropy of posterior probability density function (PDF), thereby minimizing the resulting uncertainty.

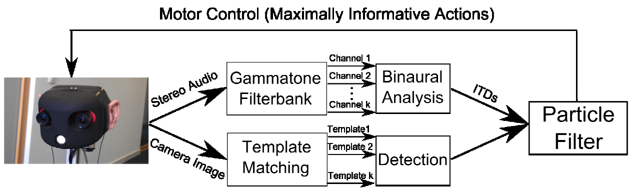

Figure 1 System Overview.

RESULTS

We show that the system is able to accurately estimate the position of the source (azimuth and distance). The fact that the robot is able to estimate the distance of a source without explicitly measuring it, can be explained by the application of the particle filter, which combines multiple measurements of angles from different positions into a distance estimate. As expected, the entropy of the estimated PDF decreases with each performed action and the number of actions needed to achieve an accurate estimate is minimized. We present preliminary results for the application of audio-visual speaker detection and show that the combination of auditory and visual data helps to disambiguate the estimate of a speaker's position.

DISCUSSION

The approach presented here shows promising results and we are planning to improve it for use in more complex and realistic situations. While we are currently assuming a single, static source, the system is easily extendable to handle multiple dynamic sources by including an arbitrary source separation mechanism for the audio data. The template matching algorithm only serves as proof of concept and will be replaced by a more robust algorithm based on local color descriptors [2]. With these changes, our approach might become an alternative to expensive microphone arrays for mobile robots equipped with cost-efficient standard sensors.

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Learning effect of visual feedback boosted by movement sonification

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***Summary*—In a rowing simulator, non-rowers were asked to train a complex oar movement. A segregation of augmented feedback about spatial and temporal aspects to the specialized senses, the visual and auditory sense, respectively, was hypothesized to be effective. Indeed, the combination of visual feedback and a sonification of the oar movement was more effective than visual feedback only. In conclusion, audiovisual feedback allows learning of spatiotemporal aspects of a complex movement in parallel without overloading the learner.**

INTRODUCTION

Visual augmented feedback is commonly provided to enhance motor learning. However, a segregation of spatial and temporal information to the specialized senses, i.e. the visual and auditory sense, respectively, may be more effective [1]. We hypothesized that non-rowers who train with visual feedback only learn the spatial aspects of the complex oar movement. Compared to them, non-rowers who receive a combination of visual feedback and sonified oar movement learn both, spatial and temporal aspects.

METHOD

Sixteen non-rowers (aged between 18-30 years) participated in the study in the sweep rowing simulator (Fig. 1). To instruct the task (body-arm rowing), the oar was moved by the rope-robot through the reference trajectory with a complex velocity profile for 180 s while the subjects were holding the oar with both hands (one cycle lasted 2.5 s; 24 strokes/min). In the subsequent pre-test, the subjects were asked to perform the same movement on their own for 180 s. Thereafter, five training sessions of 180 s with either visual feedback only (group V) or visual feedback combined with movement sonification (group V+S) followed. Between training sessions and also after the last training (post-test), non-feedback trials of 60 s were performed.

The visual feedback consisted of a blue virtual reference oar moving along the reference trajectory and the superimposed virtual blade controlled by the subject drawing a trace as soon as the deviation to the reference path exceeded 1°. The tail of the trace disappeared after 8 s (Fig. 1). For the movement sonification, the horizontal oar angle was mapped to a change of pitch when the oar was outside the water. As in all conditions, a purling sound was played when the blade was in the water. Subjects were asked to synchronize the own movement displayed on the right headphone to the sonified reference oar movement displayed on the left headphone.

Figure 1 Applied augmented visual feedback.

For the pre-test and the post-test, a spatial error and a velocity error was calculated based on dynamic time warping. A repeated-measures ANOVA was performed to assess significant differences between the developments of the groups from pre-test to post-test ($p < .05$).

RESULTS

From pre- to post-test, V+S reduced the spatial error and both groups the velocity error significantly ($p < .05$) (Fig. 2). No significant differences between the groups in the development from pre-test to post-test were found for the spatial error, but for the velocity error ($F_{(1,14)} = 6.28$, $p = .025$).

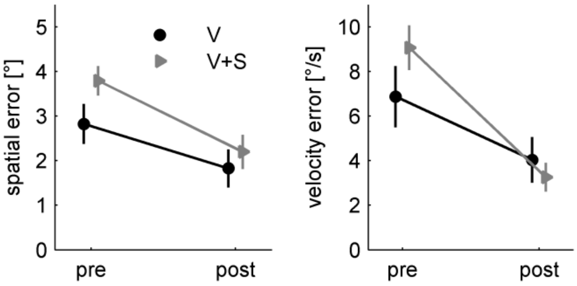

Figure 2 Improvement from pre- to post-test (Visual group V; visual+sonification group V+S)

DISCUSSION & CONCLUSION

Learning of temporal aspects from purely visual feedback was not optimal, probably due to perceptive limitations. The addition of the movement sonificiation fostered learning of temporal aspect, i.e. the velocity profile. Free capacities of the auditory sense should be exploited to improve learning of complex, dynamic movements.

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