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THE ROLE OF PERCEPTUAL FEEDBACK TRAINING ON SOUND LOCALIZATION ACCURACY IN AUDIO EXPERIMENTS

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Abstract: *The purpose of this paper is to present and compare the main techniques and methodological approaches aimed to improve audio discrimination in sound localization experiments. As reviewed from the literature, perceptual feedback training procedures provide listeners with the proper auditory/visual feedback concerning the correct sound source location. This type of feedback training can significantly improve localization accuracy, as well as the listener's ability to discern between the sound sources situated in the front and rear hemi-field, reducing the incidence of reversal errors (a very common situation in which the listener perceives a sound coming from the front as emerging from the back and vice versa).*
For instance, in a training session, the listener indicates the perceived location of the sound source and receives immediate visual and audio feedback consisting in the presentation of the correct direction of the audio signal and instant playback of continuous streams of the corresponding sound source location. These results are long-term, suggesting that even short periods of training can enhance audio localization performance under 3D sound conditions, using non-individualized Head Related Transfer Functions (in the case of virtual auditory displays).
In this paper we focus on the examination and investigation of the role of perceptual feedback training under controlled conditions in both free-field (using loudspeakers as the main audio rendering channel) and in virtual auditory displays that employ headphone-presented sound. The results obtained from this study will build the basis of a methodology aimed to improve 3D sound localization in the case of the visually impaired people.

Keywords: *Sound localization; 3D sound; virtual auditory display; training; perceptual learning.*

I. INTRODUCTION

In order to decode the direction of a sound source in space, the human auditory system uses a set of binaural cues (for localization in the horizontal plane) and monaural cues (for vertical localization and front-back disambiguation), the latter being generally referred to as the Head Related Transfer Function (HRTF). As the HRTFs depend on the anatomical features of the listener (pinna, head and torso), they are significantly individualized for each person apart. The processing method of a 3D sound consists of synthesizing an audio signal with the corresponding pair of HRTFs (for the left and for the right ear) of a given position in both the horizontal and the vertical planes and delivering it to the listener via stereophonic headphones. By employing binaural sound synthesis and other spatial effects, the user of a virtual auditory display is provided a high fidelity perception of the acoustic scene, similar to the free-field listening in real-world conditions. Nonetheless, due to the HRTF recording and processing techniques, to the impossibility of using the filtering properties of the pinna and to the unnaturalness of the virtual auditory environment [1], there is a certain degree of localization bias which is introduced especially in the vertical plane and in the front-back dimension. In order to reduce the incidence of these types of errors, a training-based approach has been devised, so that the listeners could familiarize with the task, the pointing method and with the acoustic perception that is acquired in a virtual auditory environment. This paper presents the main experimental approaches, learning procedures and provisional results aimed to help the listeners to adapt to localization cues that are different from their owns. Moreover, we intent to investigate the modality in which the human auditory system is capable to handle the acoustic sensory experience, to calibrate the sound localization characteristics (the temporal and spectral features of the sound) and to make cognitive adjustments in order to achieve a higher auditory localization accuracy.

II. EFFECTS OF TRAINING ON IMPROVING SOUND LOCALIZATION ACCURACY

As the HRTFs are significantly morphologically-dependent [2], the artificial sound rendered in a virtual auditory display via non-individualized or generic HRTFs introduces a series of artefacts, such as reversal errors (front-back and up-down confusions) and angular localization misjudgements, mainly in the vertical plane. Even though the virtualized sound offers a similar acoustic perception as in the real-world environment (especially in what concerns the sense of direction), it severely lacks externalization, spatiality, distance judgment and dynamic cues (the sound reaching the eardrums does not change automatically as a result of head movement).

In order to reduce the incidence of localization errors, it has been demonstrated that a period of adaptation to the distorted acoustic rendering conditions is required, so that listeners would get accustomed with the demands of the new hearing experience (different temporal and spectral sound characteristics from the ones expected by the listener's auditory system, in-the-head localization or inaccurate distance perception) [3] [4]. In addition to this, the majority of sound localization experiments take into account trial or training sessions (generically referred as the "learning effect"), aimed to familiarize the subjects with the perception of 3D sounds (especially in the case of inexperienced subjects), the requirements of the localization task and the pointing technique [5] [6] [7]. The particularity of this method lies in the fact that the listener learns how to adapt to non-individualized HRTFs, instead of modifying the HRTF to suit the auditory characteristics of each listener [2].

III. PERCEPTUAL FEEDBACK TRAINING FOR IMPROVING SOUND LOCALIZATION IN VIRTUAL AUDITORY DISPLAYS

This section presents some of the most significant sound localization experiments performed in the free-field and in virtual auditory displays that use a perceptual feedback training method (employing visual, proprioceptive or motor techniques) in order to improve sound localization performance under altered auditory cues conditions (Table 1).

Proprioceptive feedback based training for improving sound localization

The training-based sound localization procedure proposed by Honda et al [8] employs proprioceptive feedback cues for spatial acoustic localization under both head-movement-dependent and head-movement-free listening conditions. The subjects were divided into 2 groups: a group where the listeners have been given proprioceptive feedback and a control group with no type of response provided. The results demonstrated that the dynamic cues resulting from head movement, in combination with proprioceptive feedback, conduct to significant improvements in the sound localization accuracy, reducing the rate of angular errors in both the horizontal and the vertical planes.

Audiovisual training effect on monaural spatial hearing in the horizontal plane

It has been recently demonstrated that audiovisual training is able to improve perceptual performance due to the fact that multi-sensory information offers significant feedback about the position of a sound source in space, by enhancing the auditory decoding and by creating a cross-modal reference between the acoustic perception of sound and the visual stimuli. The experiment presented by Strelnikov

[9] aims to test this hypothesis by studying the degree of improvement of audiovisual training on monaural spatial hearing in the horizontal plane. The results showed that audio-visual feedback offers the highest rate of localization improvement, emphasizing the fact that cross-modal sensory interaction is essential for the development of enhanced spatial localization skills in the lack of binaural cues.

Adaptation effects on sound localization accuracy from playing a 3D audio game

In [10], the transfer effects of playing a virtual auditory game were analyzed in a sound localization experiment which involved the participation 40 subjects who used either their own HRTF sets or the HRTFs fitted from 16 listeners. After 2 weeks of training, the sound localization performance improved, reaching similar levels between both groups of subjects who used individualized and fitted HRTFs.

Perceptual plasticity in spatial auditory displays

The experiment presented in [11] investigates the rate of sound localization accuracy improvement when the subjects were exposed to linear transformations of the auditory space, i.e. simple associations between the sound cues and the corresponding directions from the exocentric space. As it has been previously demonstrated that long-term training conducts to significant sound detection enhancements even under difficult auditory conditions, this paper confirmed that short-term adaptation also ensures a notable degree of sound localization plasticity.

HRTF adaptation in a virtual auditory environment

The study of Parseihian at al [1] investigates the human ability to localize virtual sound sources when listening to generic HRTFs in a virtual auditory environment. The experimental procedure consisted of a pre-test, a training and a post-test session. In the post-test session, the results of the trained listeners were compared to the results of a control group of subjects who used individualized sets of HRTFs. The experiment concluded with significant improvements in the sound localization accuracy, especially in the vertical plane, where the trained subjects performed better than the listeners from the control group (with a rate of improvement of approximately 10 degrees).

Multi-modal training as a method for improving non-individualized HRTFs based sound localization

In the experiment presented in [2], a proprioceptive feedback method has been used to help the blindfolded subjects to manipulate the sound sources located at their hand position. The purpose of the experiment is to test whether auditory calibration can be developed by using additional sensory modalities, other than vision. This approach presents the advantage of offering natural interactivity by extending the spatial perception beyond the visual field and by strengthening the association between the sound stimuli and the ecological awareness of controlling the spatial position at the hand level.

Effects of training and pointing method on 3D localization of virtual sound sources

The sound localization accuracy of several trained listeners has been tested using both head and hand pointing methods in a virtual auditory environment [12]. The results of the performed experiments demonstrated that the auditory localization errors decreased after the training session, with the large improvements taking place during the first 400 trials and with slight consequential enhancements beyond the initial 400 training rounds. Moreover, there is no significant effect of the pointing method, proving that this aspect is irrelevant in respect with spatial auditory perception and sound localization performance.

Generalization and long-term effects of auditory training

The experiment presented in [13] confirms that sound localization can be improved as a result of training in the horizontal and vertical plane. The benefits of the training tasks were still persistent one month after, suggesting that the human auditory system possesses the ability to consistently adapt to altered acoustic cues and that the learning effect is available even for the untrained positions and sound types.

Table 1. Comparative analysis between the most relevant perceptual feedback training solutions for sound localization

Experiment	Sound localization procedure	Results
Proprioceptive feedback based training for improving sound localization [8] **Free-field**	**Participants:** 32 blindfolded subjects (16 male, 16 female) **Sound stimuli:** Triangle waves (200 Hz), modulated with a 25-Hz sinusoidal envelope, 70 dB SPL, 1 second in duration. **Sound localization approach:** 36 loudspeakers, located at 30 degree intervals in the horizontal plane and at -30/+30 degrees in the vertical plane. The listeners from the restricted head movement group were allowed to move their heads, while the others were not. **Experimental scheme:** Pre-test (72 trials), 5 training sessions and a post-test phase (10 days later, consisting of 72 trials). **Training:** The feedback group performed the sound localization tasks with proprioceptive feedback, while the control group did not benefit from feedback. The training phase consisted of 36 sound localization trials, extended over a period of 5 days. **Test:** The post-test session was carried out in order to assess the post-training localization performance and to compare the two groups of subjects.	The training phase conducted to significant sound localization improvements, especially for the proprioceptive feedback group. The feedback group obtained a smaller rate of localization errors in the vertical plane. Both unrestricted head movements and proprioceptive feedback led to a decrease in the rate of sound localization errors in both the horizontal and the vertical planes. Head movements during the training phase are important for ensuring long-lasting improvement effects on the sound localization accuracy. Head movements are especially related with localization improvements in the horizontal plane, while proprioceptive feedback is responsible for increasing the sound localization accuracy in the vertical plane. Proprioceptive feedback is beneficial for improving spatial localization accuracy, regardless if the head movements are restricted or not.
Audiovisual training effect on monaural spatial hearing in the horizontal plane [9] **Free-field**	**Participants:** 18 subjects, divided into 3 groups. **Sound stimuli:** Rectangular white noise, 50 ms in duration, 60 dB SPL. **Sound localization approach:** 15 loudspeakers arranged in the horizontal plane. Monaural conditions: one ear of the listener was plugged with an ear plug. The listener indicated the perceived direction using a laser beam. **Experimental scheme:** A pre-test (under normal hearing conditions), a training and a post-test session (with one ear plugged). **Training:** 3 training groups. Group A: auditory-only conditions, group AV: the auditory stimuli were accompanied by visual cues and in the group FB, the listeners were given feedback about the correct response (also auditory-only condition). 5 days training practice, 20 trials per loudspeaker, resulting in 300 training trials. **Test:** Post-test phase, after 5 consecutive days of training.	In the pre-test phase, the subjects obtained a significantly lower localization performance for elevation discrimination than for horizontal localization. In the monaural condition (with one ear plugged), the listeners obtained a lower localization accuracy in the horizontal plane. There was recorded a certain degree of reduction in the spatial error rate in the post-test phase of the experiment, demonstrating the beneficial influence of bimodal visual-auditory training. The rate of improvement is the smallest for the auditory training group, followed by the group which received feedback about the correct response and finally, the highest for the audiovisual training group. Despite the intensive training, the localization accuracy never reached the values recorded in the pre-test binaural conditions.
Adaptation effects on sound localization accuracy from playing a 3D audio game [10]	**Participants:** 40 subjects (20 women, 20 men), divided into 3 groups: a group who used individualized HRTFs (10 subjects), a group who used HRTFs fitted from 16 listeners (10 subjects) and a control group of 20 subjects. **Sound stimuli:** A triangle wave (200 Hz), modulated with a 25-Hz sinusoidal envelope (for the training game).	The number of hits increased and the number of misses decreased with training, independent of the type of HRTFs used: individualized or fitted from the 16 subjects. The sound localization performance was better in the post-test than in the pre-test session. The sound localization accuracy of the trained group (using both individualized and

Training game- Virtual Auditory Display **Localization experiment- free-field**	The target stimuli consisted of a 1 s honeybee sound, 70 dB SPL (for the free-field sound localization experiment). **Sound localization approach:** A speaker array of 36 loudspeakers arranged in the horizontal plane and at -30/+30 degrees elevation. The listeners were required to indicate the perceived direction using a 100 cm long rod**.** **Experimental scheme:** The pre-test and the post-test free-field sound localization experiments consisted of 3 sessions of 108 trials each. **Training:** A virtual auditory display based game, called Bee Bee Beat, in which the sound of a honeybee appeared at an arbitrary direction on a sphere and the listener was required to use a plastic hammer to hit the honeybee and to detect its position in space. The virtual auditory display allowed head movements. The first 2 groups of subjects (who were blindfolded) played the game 30 min/day for a period of 2 weeks. **Test:** A pre-test and a post-test sound localization session in the free-field.	fitted HRTFs) increased by approximately 20% as a result of playing the virtual auditory display game. The localization performance of the listeners who used fitted HRTFs was similar with that of the subjects who used individualized HRTFs in both free-field and virtual listening conditions. The control group localization performance did not change from the pre-test to the post-test session. 7 subjects from the trained group have undergone the localization test one month after the post-test session. Their results remained unchanged in comparison with the results of the post-test session, demonstrating that the transfer effects still persisted after 1 month. The long-term sound localization adaptation and transfer effects are based on perceptual motor learning as a result of playing the training game, proving their effectiveness and high degree of persistency after a period of 1 month in which the listeners hadn't played the game at all.
Perceptual plasticity in spatial auditory displays [11] **Virtual Auditory Display**	**Participants:** 7 subjects. **Sound stimuli:** Short, broadband noises, convolved with the personalized HRTFs of the listeners. **Sound localization approach:** 10 adaptation sessions (of 42 runs each). The middle 28 runs used a 2x-linear transformation (this means that to each location corresponded the doubled angle sound cue), while the first and the last runs were based on normal spatial conditions. Each run consisted of 14 trials, in which the listener was required to identify the perceived source location via a handheld device with visual feedback concerning the correct response.	Even if the linear remapping produces a high degree of initial bias, after short-term training, the listeners became able to adapt to the new spatial acoustic conditions, recording little residual errors. Localization acuity increased, as the listeners expected larger-than-normal alterations in the relationship between the perceived sound stimuli and the actual location of the sound source. The auditory system responded better to linear transformations of the auditory cues than to unnatural or distorted combinations of spatial-acoustic cues that provide a confusing sound image.
HRTF adaptation in a virtual auditory environment [1] **Virtual Auditory Display**	**Participants:** 24 subjects (5 women, 9 men). **Sound stimuli:** 40 ms Gaussian broadband noise. **Sound localization approach:** In the post-test session, the listener was required to identify the location of the 3D sound by pointing with his hand towards the perceived direction. **Experimental scheme:** An adaptation session, where the listeners moved a ball around their body (consequently followed by the perception of the corresponding spatialized sound) and a test session**.** **Training:** The adaptation task (3 sessions of training had been performed) was designed as a game-like scenario, where the listener was required to search for animal sounds hidden around him, using a hand-held position trackball.	At least 2 adaptation sessions were sufficient to improve sound localization under the non-individualized HRTFs conditions. By the end of the training sessions, the localization acuity of the listeners who used non-individualized HRTFs equalized the initial performance of the subjects who used individualized HRTFs. For the non-individualized HRTF group, the polar angle error reduced with 23 degrees. The front-back confusion rate reduced to 25% and the up-down confusion rate decreased to 11%. Sound localization performance under non-individualized HRTF conditions got nearer to the accuracy obtained when using personalized HRTFs.

	Test: 25 positions (5 repetitions each), full azimuth range of 360 degrees, elevation from -40 to 90 degrees.	The auditory system is able to undergo plastic changes through audio proprioceptive and kinesthetic feedback.
Multi-modal training as a method for improving non-individualized HRTFs based sound localization [2] **Virtual Auditory Display**	**Participants:** 10 subjects (3 women, 7 men), divided into 2 groups: a test group that used non-individualized HRTFs and a control group who used their own HRTFs. **Sound stimuli:** Pink noise bursts, 200 ms duration. **Sound localization approach:** The subjects were required to indicate the perceived sound source location in a virtual auditory display. **Experimental scheme:** A pre-test, an adaptation and a post-test session. There were 25 positions equally distributed in the horizontal field, 5 repetitions each, resulting in 125 stimuli. **Training**: In the training session (designed as a game-like scenario), the subjects were required to search for animal sounds hidden around them. Using a positional hand tracked ball, the listeners indicated the perceived direction of the sound. When the listener identified the correct location, the pink noise was replaced by a sound that was similar to that produced by an animal and the next direction was generated having as reference point the previous sound source location. In this way, the subject was provided continuous proprioceptive and auditory feedback and could explore the entire spatial field around him. **Test:** In the pre-test and the post-test sessions, the blindfolded subjects were asked to indicate the perceived sound location using the hand pointing technique.	The test group recorded a slight improvement in the sound localization performance (azimuth and elevation errors and front-back confusion rate) after the adaptation session, converging to the performance level of the control group. The angular error reduced with 6.1 degrees between the pre-test and the post-test sessions. The rate of front-back confusions decreased by 9.3% between the pre-test and the post-test sessions. There can be concluded that the sound localization improvements are the result of human auditory system adaptation to non-individualized HRTFs and not the training after effects of the sound localization tasks imposed by the game scenario. Auditory-kinesthetic training is an efficient modality for spatial map recalibration in the presence of altered auditory cues. As a result, visual information as a means of perceptual feedback can be effectively replaced by other multimodal associations in order to recalibrate spatial hearing.
Effects of training and pointing method on 3D localization of virtual sound sources [12] **Virtual Auditory Display**	**Participants:** 10 subjects (4 female, 6 males), divided into two training groups: a group which has been trained with the head-pointing method and another group which has been trained using the hand-pointing technique. **Sound stimuli:** Gaussian white noise bursts with a duration of 500 ms. **Sound localization approach:** The listeners were required to look at the reference position during acoustic stimuli presentation. After the sound presentation, they were asked to point to the perceived direction with the head or with the manual pointer. **Experimental scheme:** 4 blocks of 100 trials were tested for each subject in all the experimental conditions (HMD/darkness and head/hand pointing). **Training:** The subjects played a simple game in a virtual auditory environment. Via HMD, a visual target in the form of a rotating cube was presented to the listener and he was required to point at it within four seconds. Auditory information about the direction of the target was also provided. Then the	The spatial auditory localization error was smaller for the hand-pointing method. After training, the listeners showed a considerable improvement in the sound localization accuracy, especially for the eye-level targets. The angular localization error decreased from 23 degrees during the pre-test session to 19 degrees in the post-test trials. The most significant improvements had been recorded during the first 400 training trials. This leads to the conclusion that 400 trials are sufficient to acquire a considerable improvement for spatial auditory localization. The number of front-back confusions reduced between the two localization tests. Proprioceptive and visual feedback offered an efficient means for improving sound localization, due to the perceptual association between the two sensory modalities. As the listeners improved their localization performance quite rapidly, it can be

	subjects returned to the reference position and listened to the same sound again. While the target could be still visualized, they had to point to it once more. There had been performed 6 blocks per session (50 trials per block), with one or two sessions per day. **Test:** 2 different environmental conditions (HMD and darkness) and 2 pointing methods (head and hand pointing) were tested.	suggested that the subjects had learned to discern between the spectral differences of the sounds, thus enhancing their selective attention. The localization improvement is the result of the recalibration of the initial audio-visual spatial map due to sensorial plasticity and enriched association between the visual and the auditory system.
Generalization and long-term effects of auditory training [13] **Virtual Auditory Display**	**Participants:** 10 subjects participated in the main condition experiments and 9 listeners in the control group for the experiments which were conducted one month later in order to evaluate the long-term adaptation effects. The control condition was identical with the main condition, except for the post-test session procedure which had 2 sessions (one immediately after training and the other one either one day, one week or one month later). **Sound stimuli:** Anechoic recordings of speech and white noise with the duration of 3 s, convoluted with non-individualized HRTFs. **Sound localization approach:** The azimuthal locations were 0, 10, 20, 30, 40, 50, 60, 70, 80, 90 degrees to the right, with the same elevation positions in the median plane. The listeners were required to indicate the apparent source position on a touch screen, together with the level of sound externalization outside the head. **Experimental scheme:** A pre-test session (where the speech and noise sounds were repeated 10 times), a training session and 5 pre-test sessions. **Training:** During the training session, the angular locations were restricted to 4 directions. The training stage continued until the subjects were able to locate 80% of the azimuth positions and 70% of the elevation directions for two consecutive trials. **Test:** There had been 5 post-test sessions: immediately after training, one hour, one day, one week and one mother later.	**Azimuth experiment** All the listeners improved their sound localization performance after the training session. The spatial localization error decreased from 21 to 15 degrees in the post-test phase. The white noise is more effective for localization than speech (in the post-test session, the listeners who trained with white noise obtained an angular error of 13.8 degrees, while the subjects who trained using the speech sound obtained an average localization error of approximately 18 degrees). The effects of improvement were persistent even after one month after training. The best localization accuracy had been recorded for the frontal and lateral stimuli, while the largest errors were observed in the range 10-40 degrees. The positions which improved most were 0, 10 and 20 degrees, while the positions which improved least were 50, 60 and 90 degrees. The effect of training was significant even for the untrained positions. What is more, several untrained positions recorded higher improvements than the trained ones. The externalization level increased after one week. This fact involves that there is a tendency for sound externalization to improve as the listeners get familiarized with the altered cues and that the rate of improvement evolves slower than in the case of sound localization acuity.

IV. DISCUSSION

The results of the previously presented experiments demonstrate that training plays a fundamental role for auditory adaptation to altered hearing conditions. A rapid adaptation of the auditory system to non-individualized HRTFs is possible through a spatial map recalibration with multimodal sensory associations [2]. The visual, proprioceptive and kinesthetic feedback methods were highly efficient for improving localization performance in the horizontal and in the vertical planes and for reducing the incidence of reversal errors and ambiguous localization judgments. It can be argued that auditory adaptation is not necessarily dependent on the presence of visual stimuli, as higher levels of sound localization performance were achieved as a result of training other sensory modalities and by offering proprioceptive, vestibular or motor feedback. Thus, non-visual adaptation procedures can be successfully applied to the visually impaired people in order to train them to use virtual auditory display systems based on non-individualized HRTFs [1]. The majority of the subjects who performed a training session reached the same level of localization performance as their counterparts from the control group. In addition to this, the training procedure proved to have long-term effects, as the listeners recorded similar levels of performance even one month after the experiment had taken place [10]. Moreover, the game-based training provided an efficient solution for learning and adaptation to altered acoustic cues. The ludic-based approach for learning to localize sounds in unknown environments helped the players to easily manipulate the location, to recalibrate the spatial representation of the virtual setting and to concentrate their attention on the direction and on the spectral and temporal cues of the incoming sounds [14] [15].

V. CONCLUSIONS

In conclusion, training significantly enhances procedural learning, adaptation, plasticity and the setting of transfer effects for the sighted listeners under altered acoustic conditions in a virtual auditory display. Future plans include the development of a perceptual training strategy aimed to help the blind or blindfolded subjects to adapt to non-individualized HRTFs in order to improve their navigation and orientation abilities in unfamiliar acoustic virtual environments, navigational audio games or 3D sound based electronic travel systems.

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