The Journal of International Advanced Otology

J Int Adv Otol 2017; 13(1): 118-27 • DOI: 10.5152/iao.2017.3477

Original Article

Virtual Auditory Space Training-Induced Changes of Auditory Spatial Processing in Listeners with Normal Hearing

Kavassery Venkateswaran Nisha, Ajith Uppunda Kumar

All India Institute of Speech and Hearing, Audiology, Mysore, Karnataka, India

OBJECTIVE: Localization involves processing of subtle yet highly enriched monaural and binaural spatial cues. Remediation programs aimed at resolving spatial deficits are surprisingly scanty in literature. The present study is designed to explore the changes that occur in the spatial performance of normal-hearing listeners before and after subjecting them to virtual acoustic space (VAS) training paradigm using behavioral and electrophysiological measures.

MATERIALS and METHODS: Ten normal-hearing listeners participated in the study, which was conducted in three phases, including a pre-training, training, and post-training phase. At the pre- and post-training phases both behavioral measures of spatial acuity and electrophysiological P300 were administered. The spatial acuity of the participants in the free field and closed field were measured apart from quantifying their binaural processing abilities. The training phase consisted of 5–8 sessions (20 min each) carried out using a hierarchy of graded VAS stimuli.

RESULTS: The results obtained from descriptive statistics were indicative of an improvement in all the spatial acuity measures in the post-training phase. Statistically, significant changes were noted in interaural time difference (ITD) and virtual acoustic space identification scores measured in the post-training phase. Effect sizes (r) for all of these measures were substantially large, indicating the clinical relevance of these measures in documenting the impact of training. However, the same was not reflected in P300.

CONCLUSION: The training protocol used in the present study on a preliminary basis proves to be effective in normal-hearing listeners, and its implications can be extended to other clinical population as well.

KEYWORDS: Virtual acoustic space training, spatial acuity, RMS error, interaural threshold differences, spatial P300

INTRODUCTION

The human auditory system is a sophisticated spatial processor, which allows individuals to detect and monitor the positions of auditory objects in a three-dimensional space [1]. The auditory system depends on implicit acoustic cues to encode sound location. Spatial acuity in humans is strongly dependent on two types of cues, namely, the monaural and binaural spatial processing cues. Binaural disparity cues in terms of time (interaural time difference - ITD) and level (interaural level difference - ILD) aids in determining sound source in the horizontal plane. On the other hand, the spectral cues generated by the external ear provide the basis for localization in the front–back and vertical plane [2–4].

Errors in localization not only occur in individuals with hearing impairment but also in normal-hearing listeners as well. Most classically occurring errors in auditory space in normal-hearing listeners are those that arise due to the confusion of whether a source is ahead or behind [5]. Such errors in localization are termed as "front–back" errors and are defined as perceptual errors in location judgment, wherein the stimulus in front of the subject is localized to the rear or vice-versa [6]. When the confusions in front–back plane occur, the azimuth corresponding to the subjects' response will lie in a mirror symmetric plane opposite to the azimuth of the target source. The reason for this finding is commonly attributed to the symmetric shape of the human torso. Mathematically, the ITD value computed using Woodworth's formula [7] for a sound in the frontal plane in a certain left or right angle will be exactly the same if the sound source was behind.

Therefore, localization errors in the front–back plane though rare are not an indisputable phenomenon in normal-hearing individuals. The act of localization in normal-hearing listeners is often underpinned by some amount of inherent uncertainty and operational bias that results in source estimation errors [8]. Best et al. [9] showed that the normal-hearing listeners exhibited front-to-back errors in about 5% of the trials, whereas Makous and Middlebrooks [10] encountered about 2%–10% front-to-back confusions in broadband sound localization. Though front-to-back errors in the localization experiments are empirically proven, they are not so

Corresponding Address: Kavassery Venkateswaran Nisha E-mail: nishakv1989@gmail.com

Submitted: 28.12.2016 **Accepted:** 03.04.2017

predominantly experienced in real world situations, due to the role of the head movements in resolving such localization confusions [5]. However, such errors become more apparent in degraded acoustic environments and situations where visual cues of the sound source are not available. Though a review of the literature has ample of citations on the nature and consequences of spatial acuity deficits [11–14], the remediation programs initialized at ameliorating the spatial difficulties are scanty. Some of the notable strides in enhancing spatial acuity have used interaural difference training [15–21] in remediating errors due to poor spatial processing. However, these strides have limitations on the effect size and the generalization of the findings to other related tasks.

Need for the Study

In view of spatial acuity variations in normal-hearing listeners and abundance of literature in documenting the same, it is only apt if these strides are realized in the direction of ameliorating such spatial deficits. Hence, there is a strong need for implementation of an easy yet effective auditory spatial training regime aimed at fine-tuning the spatial acuity skills in normal-hearing listeners.

Aim of the Study

The present study is a preliminary research aimed at exploring the changes in the spatial performance of normal-hearing listeners using a training paradigm.

Objectives of the Study

The specific objectives of the study were to document and compare the pre- and post-training performance of the normal-hearing listeners on the following spatial acuity measures using behavioral spatial acuity measures such as root mean square (rms) error, virtual space identification scores & interaural difference thresholds and electrophysiological measure of P300 before and after subjecting them to virtual acoustic training regime.

MATERIALS and METHODS

Participants

Ten normal-hearing individuals (PTA<15 dBHL) without any otological, speech and language, and neurological and cognitive deficits participated in the study. All the participants of the study had "A" type tympanogram and acoustic reflexes from 500 Hz to 4000 Hz. The age range of the participants was 18–25 years with a mean age of 21.5 years.

Informed Consent and Ethical Guidelines

Written informed consent was taken from all the participants involved in the study. Ethical guidelines for Bio-behavioural research formulated by the institutional board of All India Institute of Speech and Hearing (AIISH), Mysore were followed.

Procedure

This study was conducted in three phases, i.e., pre-training, training, and post-training phase.

Phase I: Pre-training evaluation phase: To comprehensively evaluate spatial processing skills in the normal-hearing listeners, the behavioral spatial acuity measures in the free-field (localization test), closed-field (virtual acoustic space identification test - VASI), and binaural processing (interaural difference threshold: ITD & ILD) along with the electrophysiological P300 test were conducted prior to the initiation of training.

Behavioral Measures

Test of spatial acuity in free field: Localization testing was conducted in a localization chamber free from visual distractors. The participants' head was always aligned to face the loudspeaker positioned at 0° azimuth at a 2 m distance as shown in Figure 1. They were asked to verbally respond with the digit corresponding to the loudspeaker which delivered the sound, whereas the tester manually entered the responses.

Test material: The stimulus used for localization in the free field consisted of a series of randomly sequenced white noise burst of 250 ms (including 5 ms rise & 5 ms fall time) generated using the AUX [22] software at 16 bit and 44100 Hz sampling frequency. The stimuli were loaded to a personal computer with Cubase software (Steinberg Media Technologies GmbH, Hamburg) and were assigned to different tracks based on the sequence assignment file. A total of 90 (18 speakers×5 repetitions) noise bursts were routed through Lynx Aurora (Lynx Studio Technology Inc.,) mixers to the array of 18 loudspeakers (Genelec 8020B BI amplified monitoring system, Finland) calibrated at 65 dB SPL (using SLM - B&K, 2270). Figure 1 depicts the schematic representation of the loudspeaker setup used in the study. The interstimulus interval was adaptively varied in accordance with the response of the client.

Analyses: RMS localization error [23] was calculated by running a program written in the Python script implemented in the paradigm experimenter builder software [24]. It represents the deviation for each participant of the differences between target locations and the localization response [23]. The overall rms error as well as the rms error for each individual speaker was calculated using the following formula:

rms error (°)= $\sqrt{\frac{\sum_{i=1}^{n}(\text{stimulus}-\text{response})^2}{n}}$, where n is the number of stimuli presented.

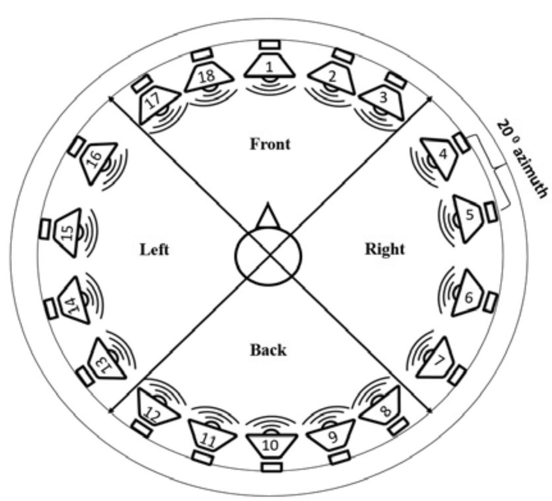

Figure 1. Schematic representation of loudspeakers setup for localization testing.

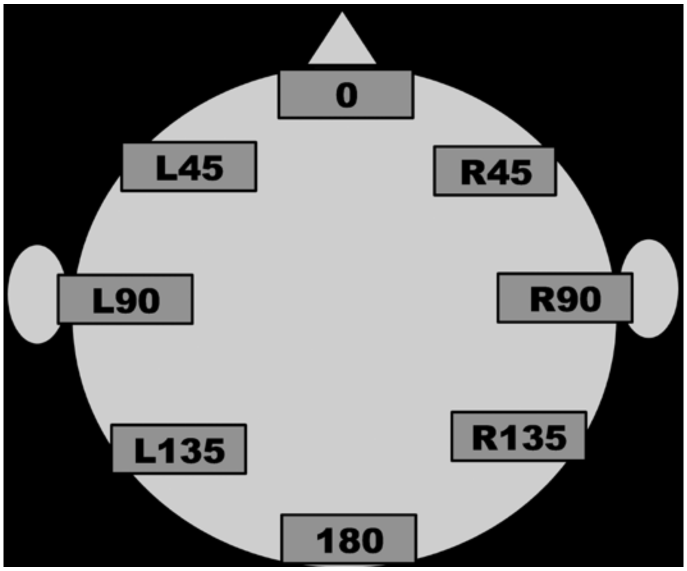

Figure 2. Pictographic representation of dummy head to be used for Phase I and Phase II of virtual auditory space identification (VASI) test. The alphanumerical code represents the location of stimulus lateralization. 0° - At the midline front, 180° - At the midline back, R45-45° azimuth toward the right ear; R90-90° azimuth toward the right ear, R135-135° azimuth toward the right ear; L45-45° azimuth toward the left ear, L90-90° azimuth toward the left ear and L135 -135° azimuth toward the left ear.

Test of spatial acuity in the closed field (VASI test): The VASI test commenced after familiarization of stimuli and task. The stimuli were presented using the paradigm [24] experimental builder software at 65 dB SPL (calibrated using SLM - B&K, 2270). In the VASI test, stimulus corresponding to each virtual location was played randomly (8 locations×10 repetitions=80 times). The subjects were asked to attend the stimuli and respond by clicking the arrow/mouse pointer on a dummy head location (Figure 2) which corresponds to the sound lateralized in the head. The test was terminated after the completion of 80 trails.

Test material: The stimuli for the illusionary effect of virtual auditory space was created by employing sound lab (Slab sound module of slab3d) [25]. These stimuli were formed by convoluting 250 ms white band noise with non-individualized slab3d's default HRTF database "jdm.slh." The stimulus generated using slab3d produced eight different spatial perceptions, i.e., mid-line front (0° azimuth), mid-line back (180° azimuth), 45° azimuth toward the right ear (R45), 90° azimuth toward the right ear (R90), 135° azimuth toward the right ear (R135), 45° azimuth toward the left ear (L45), 90° azimuth toward the left ear (L90), and 135° azimuth toward the left ear (L135). All the stimuli were routed through a professional soundcard MOTU MICROBOOK II (Cambridge, Massachusetts, USA) connected to a laptop and played through Sennheiser headphones HD 280 (Wedenmark, Germany).

Analyses: The accuracy scores of identification of each virtual space apart from the overall accuracy score were computed by adopting the Python script implemented in the paradigm [24] software. Further, a confusion matrix was also computed for each individual participant by adopting a modification of a confusion matrix for the syllable identification script [26] running on MATLAB version 7.10.0 (R2010a) (The Mathworks Inc., Natick) [22].

Test of interaural difference (ITD & ILD) thresholds: ITD and ILD were obtained by implementing the psychoacoustics toolbox [27] running in MATLAB version 7.10.0 (R2010a) (The Mathworks Inc., Natick) by employing the three-down one-up transformed up-down staircase procedure [28] in the three interval force choice converging at 75% of the psychometric function.

Test material: Three 250 ms perceptually interaural-correlated white noise burst (stereo, 16 bit, 44100 sampling frequency) with 5 ms onset and offset ramps will be presented in each run. Interaural threshold difference tests (ITD & ILD) were conducted using the Sennheiser headphones HD 280 (Wedenmark, Germany) through a professional soundcard MOTU MICROBOOK II (Cambridge, Massachusetts, USA) connected to the laptop. The participants were instructed to indicate the interval in which the variant stimulus (interval in which the sound leads or is heard louder in the right ear) was presented by pressing the number corresponding to the same on the keyboard. The time or level of the variable tone was varied adaptively in accordance with the response of the participant. The testing was terminated at 10 reversals and the last four reversals were averaged to get the converged value of the interaural time and intensity difference thresholds.

Electrophysiological measure: Continuous EEG data was recorded using the scan module of the Neuroscan Compumedics system. Three non-inverting gold-plated scalp electrodes were placed at Fz, Cz, and Pz (10–20 system of classification) to record far-field EEG responses. The inverting electrode was pla ced at the nose tip, whereas the ground electrode was placed at the upper forehead. In addition, a bipolar channel was dedicated for recording vertical eye movements. The stimulus and recording parameters used in the study are shown in Table 1.

Offline processing and analyses of the evoked potentials*:* The recorded EEG was offline processed using a script incorporating the DC offset correction (3 order regression polynomial), ocular artifacts reduction, filtering (0.15–30 Hz, FIR 30 dB/octave zero phase shift), epoching (200 ms pre-stimulus to 800 ms post-stimulus), and baseline correction. The P300 peak amplitude and latency for the attended and unattended deviants in both the conditions (L45 & R45) were marked across all the 3 midline electrodes-Fz, Cz, and Pz. The peaked marked data were subjected to further statistical analyses.

Phase II: Training phase: The participants underwent training which lasted for 30 min/day for a minimum of 5–6 sessions, spanning over two weeks.

Training stimuli: The stimuli employed for training was similar to the one used in the VAS identification test except that they were graded in the hierarchy and were presented in a systematic and structured manner. Stimuli in the training phase varied adaptively in terms of their durations and number of locations based on the participants' performance. There were four stages graded in the hierarchy of most simple to most difficult based on the duration of stimuli and each stage consisted of three levels which varied in number of VAS locations presented. The stimulus hierarchy is depicted in Figure 3.

As depicted in Figure 3, the easiest level at which the training for each participant commenced was at 2000 ms of white noise burst with four VAS locations. Once the participant reached less than 70%

Table 1. Protocol for two-deviant P3a–P3b odd ball paradigm

Stimulus parameters		
	Standard/Frequent stimuli	**Deviant/Infrequent stimuli**
1. Stimuli		
A) R45 condition	Noise bursts producing center perception	Attended stimuli/Targets: White noise bursts producing a perception of approximately 45° azimuth to the right ear Unattended stimuli/Distractors: White noise bursts producing a per ception of approximately 45° azimuth to the left ear
B) L45 condition	Noise bursts producing center perception	Attended stimuli/Targets: White noise bursts producing a perception of approximately 45° azimuth to the left ear Unattended stimuli/Distractors: White noise bursts producing a perception of approximately 45° azimuth to the right ear
2. Duration of stimulus	250 ms	
3. Transducers	Insert earphones (Compumedics, El Paso, TX).	
4. Inter-trail interval	2 s interval (250 ms stimuli+200 ms pre-stimulus+800 ms post-stimulus+750 ms for response)	
5. Polarity	Alternating	
6. Number of sweeps	52 artifact-free sweeps for each infrequent stimulus and 296 frequents.	
7. Intensity	80 dB SPL.	
	Recording parameters	
1. Electrode montage	Inverting electrode–Test ear mastoid	
	Non-inverting electrode–all 64 cap electrodes	
	Ground–Non-test ear mastoid	
	2 bipolar electrode pairs for VEOG & HEOG	
2. Filter setting	0.1 Hz–30 Hz	
3. Recording Time window	1000 ms (including 200 ms pre-stimulus baseline)	
4. Notch filter	On	
5. Electrode impedance	<5k ohms	

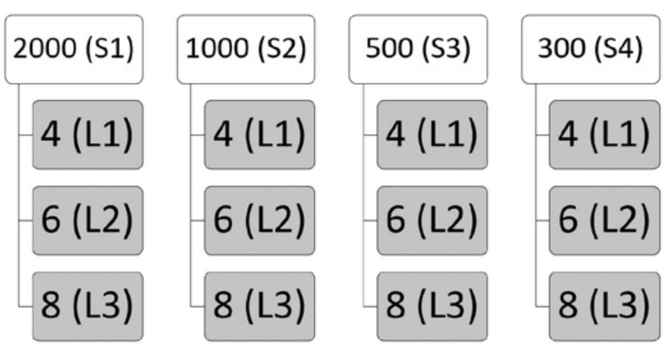

Figure 3. Hierarchy of stimulus (duration & attenuation parameters) presentation in the training phase of the study. Progression from left to right represents easy to difficult conditions.

of accuracy scores, the task was made more difficult in terms of increased locations from 4 to 6. Once the participant crossed this level with 70% VAS identification score, the next level comprising 8 stimuli was used for training. The most difficult level in the training was 300 ms duration with 8 VAS locations. The criterion employed to proceed from one stage to another is shown in Figure 4.

Phase III: Post-Training Evaluation phase: Phase III included the re-administration of all the spatial acuity measures (behavioral and electrophysiological) used in Phase I to quantify the changes (if any) due to VAS training.

Statistical Analyses

All behavioral and electrophysiological measures of spatial acuity and P300 were subjected to checks of normality in distribution using Shapiro-Wilk's test implemented in IBM SPSS version 20.0 (Statistical Package Social Sciences). Following this, parametric paired t-test (behavioral measures) and repeated measure ANOVA (P300) were conducted for the comparison of pre- and post-training scores for all normally distributed measures while non-parametric Wilcoxon signed-ranks test was employed for pre- and post-training data comparison of distributions which did not adhere to normality. Furthermore, post-hoc Bonferroni comparison was done for the statistically significant pairs. In addition, effect size values are also reported in the present study.

RESULTS

This study aimed to explore the changes in the spatial performance of normal-hearing listeners using a VAS training paradigm on behavioral and electrophysiological measures of auditory spatial processing. The results will be discussed under the following headings:

(i) Effect of VAS training on behavioral spatial acuity measures
(ii) Effect of VAS training on electrophysiological acuity P300 measures

Effect of VAS Training on Behavioral Spatial Acuity Measures

Shapiro-Wilk's test revealed that all behavioural measures except ITD were normally distributed. Hence, paired t-test was conducted for the comparison of pre- and post-training scores for all normally distributed measures, whereas non-parametric Wilcoxon signed-ranks test was employed for pre- and post-training comparison of ITD thresholds. The results of these analyses will be discussed as follows.

a) Effect of VAS training on spatial acuity in free field
b) Effect of spatial acuity in closed field
c) Effect of spatial acuity on binaural processing

a) Effect of VAS training on spatial acuity in free field: The rms error measure obtained in pre- and post-training phases of the study were

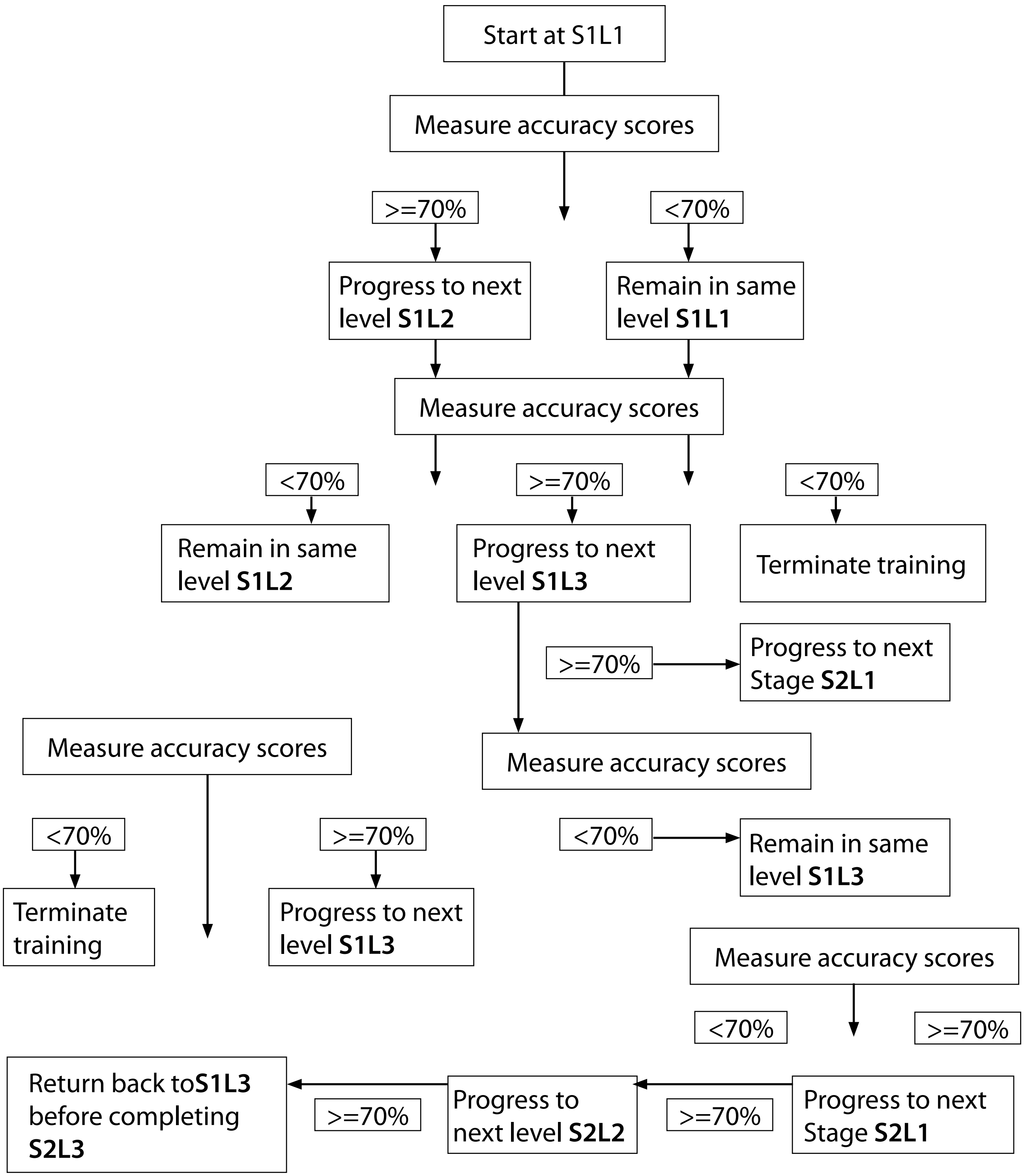

Figure 4. Hierarchy criteria for different levels in training S1 indicates the 2000 ms stimulus duration; S2-1000 ms stimulus duration; S3-500 ms stimulus duration, and S4-300 ms stimulus duration, whereas L1 indicates the 4 VAS locations; L2-6 VAS locations, and L3-8 VAS locations.

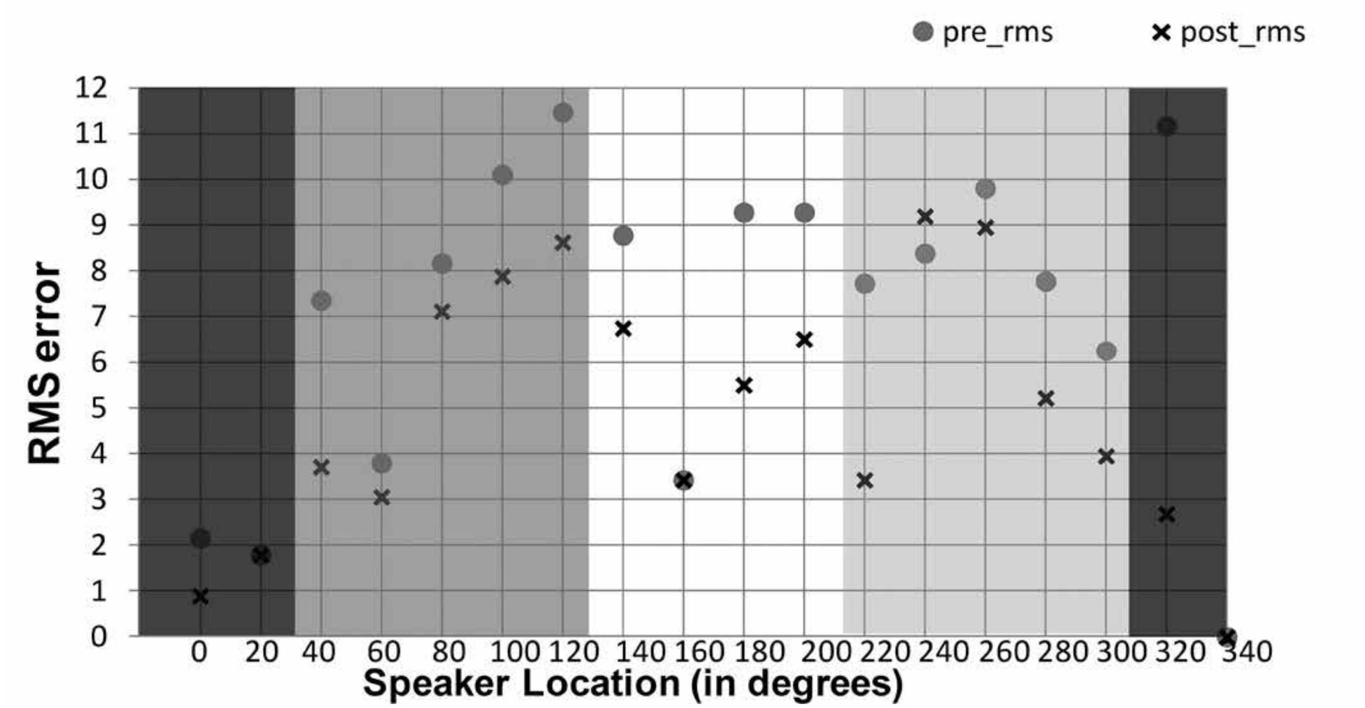

Figure 5. Comparison of mean rms error scores in pre- vs. post-training conditions across 18 loud speaker locations. The color shading represents different planes in the spatial field. Black-shaded region depicts anterior/front plane, dark gray-shaded region denotes right horizontal plane, white region codes for posterior/back plane, whereas light gray-shaded region codes for the left plane.

subjected to descriptive statistics, including the mean and standard deviation (SD), which indicated that mean rms error measured at the post-training phase (7.862) reduced from that observed in the pre-training phase (9.483). This is further complimented by the decrease in SD in the post-training phase. Paired t-test was conducted to statistically ascertain the impact of VAS training on localization performance. The results of the t-test showed that rms error score obtained at the post-training phase was not significantly different ($t(9)=2.136$, $p=0.061$) from that obtained in the pre-training phase. However, the p value was nearing the significance range. An attempt was made to understand the impact of VAS training in different planes (front, back, right, and left) of localization; the rms error obtained for each loudspeaker measured at pre- and post-training phases were compared; and the same is depicted in Figure 5.

Two main inferences can be drawn from Figure 5. First, on visual inspection of the figure, it is clear that rms mean values at the post-training phase are lower than the pre-training condition. This trend is more clearly visible in the front and back planes as shown in black- and white-shaded areas in Figure 5.

b) Effect of VAS training on spatial acuity in closed field: VASI scores measured under closed field is the direct measure of lateralization abilities of the participants. Descriptive statistics showed an increase of 14.3 in mean identification scores in the post-training phase (63.3) from 49 in the pre-training phase. The results of the paired t-test showed that VASI scores in the post-training phase were significantly better ($t(9)=-4.934$, $p<0.01$) than the pre-training phase. Furthermore, to check for the efficacy of the training and its clinical applicability, the effect size was calculated using the equation effect (r) = $\sqrt{\frac{t^2}{t^2+df}}$ [29]. The effect size was found to be substantially large (0.85). With a view to understand the conflicts arising in the correct recognition of the target VAS location, confusion matrices were created separately for each individual by denoting the stimulus–response relationship in the form of a 8×8 grid. Confusion matrix provides opportunity to study the perceptual confusions arising from limitations in perception of the target VAS location. The results of the confusion matrix across the 8 VAS locations in the pre- and post-training conditions are represented in Table 2.

It can be inferred from Table 2 that the mean correct identification rates improved for each VAS target location in the post-training phase as compared to those in the pre-training phase of the study. This is further complimented by declined confusion rates after training.

c) Effect of VAS training on binaural processing (ILD & ITD): ITD and ILD thresholds represent minimum perceptible differences in terms of time and intensity between two ears. Paired t-test was conducted to find the statistical difference (if any) in ILD thresholds between pre- vs. post-training phases. On the other hand, as the ITD data was not normally distributed, non-parametric Wilcoxon signed-ranks test was employed for comparison of ITD thresholds in pre- vs. post-training thresholds. The results are shown in Table 3.

It can be concluded from Table 3 that ILD thresholds in the post-training phase were not significantly different ($p>0.05$) from the pre-training phase. In contrast to ILD, post-ITD thresholds were significantly better ($Z=-2.524$, $p<0.05$) than ITD thresholds measured in the pre-training phase. Furthermore, the effect size (r) calculated by the equation $r=Z/\sqrt{N}$ [29], where Z is the Z-score and N is sample size, was large (−0.798).

Effect of VAS Training on Electrophysiological Acuity Measure

The grand average waveforms obtained by averaging the individu-

Table 2. Confusion matrix denoting the mean response option provided for each VAS location in pre (top grey panels)- and post-training (bottom white panels) phases. The diagonal (pink) represents accurate VASI scores in each panel

	Target VAS locations							
Response option	**R45**	**R90**	**R135**	**180**	**L135**	**L90**	**L45**	**0**
R45	4	1.9	1.4	0.3	0.1	0	0	0.7
	6.8	0.6	1.4	0.1	0	0	0	0.3
R90	2.6	6.5	1.3	0	0	0	0	0.3
	1.3	8.4	2.2	0	0	0	0	0
R135	3.8	2	6.5	0.7	0	0	0	0.7
	1.6	1.2	6.2	0	0	0	0.1	0
180	0.1	0	0.5	8.1	0.9	0	0	2.2
	0	0	0.1	9.7	0.1	0	0	1
L135	0	0	0.1	0.4	4.1	1	2	0.7
	0	0	0	0	8.1	0.4	0.6	0
L90	0	0	0	0.1	3.6	7.9	2.1	0
	0	0	0	0	1.1	7.8	1	0
L45	0	0	0.2	0.1	1.6	1.5	6.3	0.3
	0	0	0	0	0.7	1.8	8	0.3
0	0	0.1	0.5	0.8	0.2	0.1	0.1	5.6
	0.1	0	0	0.3	0.1	0	0.2	8.3

Table 3. Mean amplitude of interaural time difference (ITD) and interaural level difference (ILD) along with two standard deviation (in parentheses) measured at pre- and post-training phases

	Measurement phase		
Spatial acuity measure	**Pre-training**	**Post-training**	**Statistic**
ITD	0.16 (0.13)	0.13 (0.13)	Z= −1.85 (p<0.05)
ILD	2.4 (0.67)	2.15 (0.54)	t(9)=1.225 (p>0.05)

al waveforms of 10 participants for each of the deviant stimuli (L45 and R45) in both attended (target) and unattended (distractor) states were compared with the standards (center). The results of this analysis revealed a positive peak around 250-400 ms in the deviant waveforms irrespective of the attentive state. Following this, to account for neural changes induced by VAS training, the grand average waveforms of deviants (target and distractor) in the pre- and post-training phases were compared and the same is depicted in Figure 6 for all three Fz, Cz, and Pz electrode sites.

On visual inspection of Figure 6, it is clear that there were slight changes in the mean amplitude and latency between the deviant waveforms evoked in pre- vs. post-training measurement phases irrespective of the attention deployed during the task. To quantify these subtle changes in the post-training phase, descriptive statistics were conducted separately for peak latency and amplitude.

P300 amplitude analyses: Table 4 shows the mean amplitude of P300 obtained for R45 and L45 conditions measured at all three electrodes (Fz, Cz, and Pz).

It can be noted from Table 4 that the mean P300 amplitude at the post-training condition was lesser than the one measured at the pre-training condition for both targets and distractors in R45 and L45 conditions. To statistically ascertain these differences, a four-way repeated measure ANOVA was carried out with electrode sites (Fz, Cz, Pz), attention state (target vs distractor), the phase of measurement (pre vs. post), and stimulus condition (L45 vs. R45) as independent variables and P300 amplitude as the dependent variable. The results of this analysis showed that there was no significant effect of training/measurement phase ($F(1,9)=1.97$, $p>0.05$) on the P300 amplitude. However, a main effect of attention ($F(1,9)=6.74$, $p<0.05$) on P300 amplitude was seen. Post-hoc Bonferroni test revealed that amplitude of P3a was significantly lesser ($p<0.05$) than P3b. Significant two-way (attention*electrode site) and three-way (attention state*-stimulus condition*electrode site) interactions were observed. None of the other interactions were significant.

P300 latency analyses: The descriptive analyses of P300 latency for deviants in R45 and L45 conditions at the pre- and post-training phases across the 3 electrodes is depicted in Table 5.

As shown in Table 5, no noticeable change in mean latency was observed between the pre- and post-training phases for targets across electrodes. However, the mean latency of P3a elicited for distractors in the post-training phase occurred slightly earlier than the one elicited in the pre-training phase. Four-way repeated measure ANOVA similar to the one conducted for amplitude was repeated for P300 latency as well. Similar to amplitude analyses, the main effect of training/measurement phase ($F(1,9)=0.35$, $p>0.05$) on P300 latency was not seen. However, the main effect of attention ($F(1,9)=7.555$, $p<0.05$) and electrode site ($F(2,18)=10.29$, $p<0.001$) was seen for P300 latency. Post-hoc test of Bonferroni pairwise comparison for the attention state revealed that the latency of unattended distractors was significantly earlier ($p<0.05$) than the attended targets. Post-hoc test for the electrode site revealed that P300 measured at Pz occurred significantly earlier ($p<0.05$) than that at Fz. However, P300 latency at Pz was not statistically different ($p>0.05$) from Cz.

Table 4. Mean amplitude of P300 for the two deviants (targets and distractors) along with two standard deviation (in parentheses) measured at the pre- and post-training phases for R45 and L45 conditions

		Measurement phase			
		R45		L45	
Electrode site	State of Attention	Pre-training	Post-training	Pre-training	Post-training
Fz	Target	5.34 (3.04)	4.68 (2.19)	6.21 (2.55)	4.84 (2.1)
	Distractor	5.69 (1.87)	4.26 (2.69)	5.73 (3.07)	4.28 (2.25)
Cz	Target	6.69 (3.21)	6.31 (3.31)	7.48 (3.24)	6.24 (1.87)
	Distractor	6.64 (2.56)	4.69 (3.55)	5.65 (2.34)	4.76 (3.14)
Pz	Target	7.93 (4.26)	7.34 (3.38)	6.714 (3.33)	7.50 (3.24)
	Distractor	6.05 (3.05)	3.99 (3.74)	4.86 (2.36)	4.96 (2.12)

Table 5. Mean latency of P300 for the two deviants (targets and distractors) along with two standard deviation (in parentheses) measured at the pre- and post-training phases for R45 and L45 conditions

		Measurement phase			
		R45		L45	
Electrode site	State of Attention	Pre-training	Post-training	Pre-training	Post-training
Fz	Target	394.6 (45.55)	408.5 (54.08)	373.7 (38.61)	375.5 (39.51)
	Distractor	361 (36.77)	347.9 (46.74)	345.3 (34.86)	349 (44.4)
Cz	Target	391.5 (43.99)	401.2 (46.84)	372.2 (42.04)	374.6 (41.86)
	Distractor	356.8 (32.19)	333.6 (28.94)	347.8 (32.79)	345.2 (44.76)
Pz	Target	414.3 (41.77)	404.9 (44.09)	358.5 (52.56)	392 (34.66)
	Distractor	380.8 (48.31)	332.6 (32.88)	369.9 (59.58)	346 (43.67)

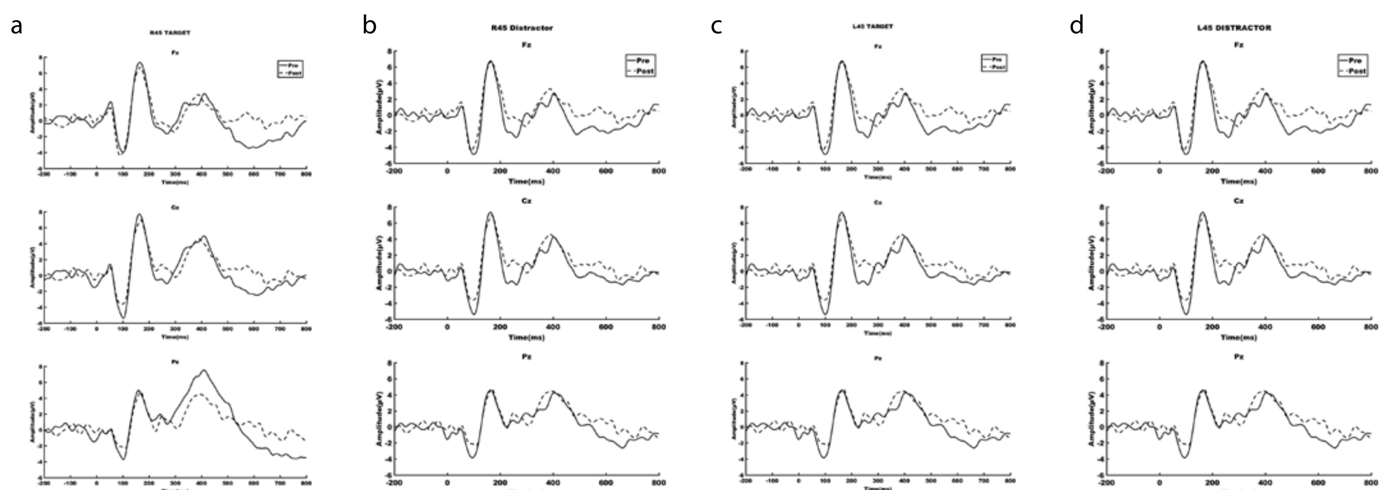

Figure 6. a-d. Grand average deviant (target and distractor) waveform in pre- vs. post-training phases measured at Fz, Cz, and Pz electrode sites for (a) R45 attended target, (b) R45 unattended distractor, (c) L45 attended target, and (d) L45 unattended distractor. Time is plotted along the x-axis, and amplitude (μv) along the y-axis.

DISCUSSION

The study aimed at documenting the effect of VAS training on the spatial abilities of normal-hearing listeners. Decrease in the mean rms error score and standard deviation (SD) in the post-training phase of the localization test is indicative of the benefit derived as a consequence of training. However, paired t-test results showed a lack of statistically significant change in the post-training t-test. This finding can be attributed to two reasons. First, the localization performance of the participants in the study reflected the ceiling effect in the pre-training condition itself, which was an expected finding as all the participants of the study are normal-hearing listeners. Second, the sample size considered in the study was considerably small to demonstrate any effect of training. The hemifield/quadrant-wise analysis in the free field showed that the training paradigm used in the current study resolved the front–back confusions which are the most prevalent of the spatial errors demonstrated by normal listeners [9]. Similar findings were also reported by Kuk et al. [30] in adults with hearing impairment who were trained using the free-field-based localization regime. This finding shows that VAS training used in the current study can be effectively generalized to other tasks (localization) indicative of not only task learning (learning the intricacies of the same task used in training regime) but also procedural learning (learning the intricacies of other tasks related to the one used in training). This study is thus in support with the study of Ortiz and Wright [15] who found that ITD/ILD training implied in their study improved not only binaural processing abilities but also generalized to temporal acuity (GAP detection) of the participants.

Results of closed-field VASI showed that VAS training induces plausible changes in the VASI scores in the post-training phase suggestive of learning the skill in which the participant is trained for task learning. Ample task learning reports [15, 17, 19, 21] using other training paradigms such as ITD/ILD training are well documented in the literature. The confusion matrix (stimulus response) showed that there was a decline of perceptual confusions in the post-training phase. This finding further confirms the positive outcome of VAS training in normal-hearing listeners.

On binaural processing skills, the mean ITD at the post-training phase showed an improvement relative to one recorded in the pre-training phase. However, no statistically significant difference was seen. In contrast, ITD measured at the post-training phase improved significantly ($p<0.05$) than the one observed in the pre-training measurement. This finding showed that ITD is more rampant to improve when subjected to training as compared to ILDs. The reason can be because ITDs code the low-frequency information and humans are prone to listen to more of low-frequency sounds in their day-to-day conversations (speech frequency being more predominant from 300 to 2 kHz). Thus, human listeners tend to get more ITD cues in their daily listening situations which could have been further refined by VAS training and resulted in a better ITD threshold in the post-training evaluation phase. Furthermore, the effect size was high (0.86 for VASI; −0.79 for ITD), indicating the clinical relevance and efficacy of this measure in documenting the effect of training.

In the electrophysiological measure, the mean P300 amplitude and latency at the post-training phase were not statistically different when compared with P300 measured at the pre-training phase. This finding shows that the conventional latency and amplitude measure failed to tap subtle changes in neural intricacies involved in auditory spatial coding. High-density multi-channel recording can act as a vital tool for encoding subtle changes reflected due to training as it facilitates additional analyses such as scalp topography and source estimation [31]. However, the mean reduction in amplitude at the post-training phase is attributed to the attention-driven mechanisms in coding P300. In adults, perceptual learning is mediated by top-down influences such as attention and task relevance [32, 33]. Prior to the onset of training due to the novelty of the task and stimuli, the participants had to employ more attention for the active identification of the target and distractor from standards resulting in larger amplitudes of both P3a and P3b. However, after training as the task becomes easier, they had to deploy less attention as the deviants were readily distinguishable from standards resulting in a lower P300 amplitude. However, no such trend was seen in the latency analyses.

CONCLUSION

The findings of this study show that spatial auditory system in normal listeners can be refined further when subjected to training. The VAS training protocol used in the present study on a preliminary basis proves to be effective as documented by statistically significant changes in performance of participants on behavioral spatial acuity measures. The findings of the study substantiates the scope of adopting the same training regime in the clinical population such as individuals with sensorineural hearing loss, central auditory processing disorder, and auditory neuropathy spectrum disorder who are bound to have spatial difficulties.

Ethics Committee Approval: Ethics committee approval was received for this study from the ethics committee for Bio-behavioural research in All India Institute of Speech and Hearing (AIISH), Mysore.

Informed Consent: Written informed consent was obtained from patients who participated in this study.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept - K.V.N., A.U.K.; Design - K.V.N., A.U.K.; Supervision - A.U.K.; Resources - A.U.K.; Materials - K.V.N., A.U.K.; Data Collection and/or Processing - K.V.N.; Analysis and/or Interpretation - K.V.N., A.U.K.; Literature Search - K.V.N.; Writing Manuscript - K.V.N., A.U.K.

Acknowledgements: The authors thank the Director, All India Institute of Speech and Hearing, Mysore, HOD, Department of Audiology and participants of the study.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study has received no financial support.

REFERENCES

1. Grantham DW. Spatial Hearing and Related Phenomena. In: Moore BCJ, editor. Hearing, Academic Press; 1995. [CrossRef]
2. Blauert J. Spatial Hearing: The Psychophysics of Human Sound Localization. MIT Press; 1997. doi:10.1037/025238. [CrossRef]
3. King AJ, Schnupp JWH, Doubell TP. The shape of ears to come: Dynamic coding of auditory space. Trends Cogn Sci (Regul Ed) 2001; 5: 261-70. [CrossRef]
4. Van Wanrooij MM, Van Opstal AJ. Contribution of Head Shadow and Pinna Cues to Chronic Monaural Sound Localization. J Neurosci 2004; 24: 4163-71. [CrossRef]
5. Brimijoin WO, Akeroyd MA. The role of head movements and signal spectrum in an auditory front/back illusion. Iperception 2012; 3: 179-81. [CrossRef]
6. Middlebrooks JC, Green DM. Sound localization by human listeners. Annu Rev Psychol 1991; 42: 135-59. [CrossRef]
7. Woodworth RS (1938). Experimental Psychology. Holt, New York.
8. Letowski T, Letowski S. Localization Error: Accuracy and Precision of Auditory Localization. In: Strumillo P, editor. Adv. Sound Localization, InTech; 2011, p. 55-78. [CrossRef]
9. Best V, Kalluri S, McLachlan S, Valentine S, Edwards B, Carlile S. A comparison of CIC and BTE hearing aids for three-dimensional localization of speech. Int J Audiol 2010; 49: 723-32. [CrossRef]
10. Makous JC, Middlebrooks JC. Two-dimensional sound localization by human listeners. J Acoust Soc Am 1990; 87: 2188-200. [CrossRef]
11. Hawkins DB, Wightman FL. Interaural time discrimination ability of listeners with sensorineural hearing loss. Audiology 1980; 19: 495-507. [CrossRef]
12. Koehnke J, Culotta CP, Hawley ML, Colburn HS. Effects of reference Interaural time and intensity differences on binaural performance in listeners with normal and impaired hearing. Ear Hear 1995; 16: 331-53. [CrossRef]
13. Noble W, Byrne D, Lepage B. Effects on sound localization of configuration and type of hearing impairment. J Acoust Soc Am 1994; 95: 992-1005. [CrossRef]

14. Rakerd B, Velde TJ, Hartmann WM. Sound localisation in the medial sagittal plan by listeners with presbyacusis. J Am Acad Audiol 1998; 9: 466-79.
15. Ortiz JA, Wright BA. Contributions of procedure and stimulus learning to early, rapid perceptual improvements. J Exp Psychol Hum Percept Perform 2009; 35: 188-94. [CrossRef]
16. Rowan D, Lutman ME. Learning to discriminate interaural time differences: An exploratory study with amplitude-modulated stimuli: Aprendiendo a discriminar diferencias inter-auriculares de tiempo: Un estudio exploratorio con estímulos de amplitud modulada. Int J Audiol 2006; 45: 513-20. [CrossRef]
17. Wright BA, Fitzgerald MB. Different patterns of human discrimination learning for two interaural cues to sound-source location. Proc Natl Acad Sci 2001; 98: 12307-12. [CrossRef]
18. Wright, Zhang Y. A review of learning with normal and altered sound-localization cues in human adults: Revisión del aprendizaje en adultos con claves de localización sonora normales o alteradas. Int J Audiol 2006; 45: 92-8. [CrossRef]
19. Zhang Y, Wright BA. Similar patterns of learning and performance variability for human discrimination of interaural time differences at high and low frequencies. J Acoust Soc Am 2007; 121: 2207-16. [CrossRef]
20. Noble, Byrne D, Ter-Horst K. Auditory localization, detection of spatial separateness, and speech hearing in noise by hearing impaired listeners. J Acoust Soc Am 1997; 102: 2343-52. [CrossRef]
21. Spierer L, Tardif E, Sperdin H, Murray MM, Clarke S. Learning-Induced Plasticity in Auditory Spatial Representations Revealed by Electrical Neuroimaging. J Neurosci 2007; 27: 5474-83. [CrossRef]
22. Kwon BJ. AUX : A scripting language for auditory signal processing and software packages for psychoacoustic experiments and education. Behav Res Methods 2012; 44: 361-73. [CrossRef]
23. Rakerd, Hartmann. Localization of sound in rooms. III: Onset and duration effects. J Acoust Soc Am 1986; 80: 1695-706. [CrossRef]
24. Perception Research Systems. Paradigm Stimulus Presentation 2007.
25. Sound lab (SLAB 3d) 2012. http://slab3d.sonisphere.com/, http://human-systems.arc.nasa.gov/SLAB/
26. Gnanateja N. consonant confusion matrix 2014. https://in.mathworks.com/matlabcentral/fileexchange/46461-consonant-confusion-matrix.
27. Soranzo A, Grassi M. PSYCHOACOUSTICS: a comprehensive MATLAB toolbox for auditory testing. Front Psychol 2014; 5: 712. [CrossRef]
28. Levitt H. Transformed up-down methods in psychoacoustics. J Acoust Soc Am 1971; 49 (Suppl 2): 467+. [CrossRef]
29. Field A. Discovering Statistics Using SPSS. Second. London: Sage Publications Ltd.; 2005.
30. Kuk F, Keenan DM, Lau C, Crose B, Schumacher J. Evaluation of a Localization Training Program for Hearing Impaired Listeners. Ear Hear 2014; 35: 652-66. [CrossRef]
31. Murray MM, Brunet D, Michel CM. Topographic ERP analyses: A step-by-step tutorial review. Brain Topogr 2008; 20: 249-64. [CrossRef]
32. Gilbert CD, Sigman M. Brain states: top-down influences in sensory processing. Neuron 2007; 54: 677-96. [CrossRef]
33. Keuroghlian AS, Knudsen EI. Adaptive auditory plasticity in developing and adult animals. Prog Neurobiol 2007; 82: 109-21. [CrossRef]