

Effects of Abacus Training on Auditory Spatial Maturation in Children with Normal Hearing

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Abstract

Introduction The spatial auditory system, though developed at birth, attains functional maturity in the late childhood (12 years). Spatial changes during childhood affect navigation in the environment and source segregation. Accommodation of a new skill through learning, especially during childhood, can expedite this process.

Objective To explore the auditory spatial benefits of abacus training on psychoacoustic metrics in children. The study also aimed to identify the most sensitive metric to abacus training related changes in spatial processing, and utilize this metric for a detailed spatial error profiling.

Methods A standard group comparison analysis with 90 participants divided into three groups: I: children with abacus training (C-AT); II: children with no training (C-UT); III: adults with no training (A-UT). The groups underwent a series of psychoacoustic tests, such as interaural time difference (ITD), interaural level difference (ILD), and virtual auditory space identification (VASI), as well as perceptual tests such as the Kannada version of the speech, spatial, and quality questionnaire (K-SSQ).

Results Significant group differences were observed in the multivariate analysis of variance (MANOVA) and post-hoc tests, with the C-AT group showing significantly lower ILD scores ($p = 0.01$) and significantly higher VASI scores ($p < 0.001$) compared to the C-UT group, which is indicative of better spatial processing abilities in the former group. The discriminant function (DF) analyses showed that the VASI was the most sensitive metric for training-related changes, based on which elaborate error analyses were performed.

Conclusions Despite the physiological limits of the immature neural framework, the performance of the C-AT group was equivalent to that of untrained adults on psychoacoustic tests, which is reflective of the positive role of abacus training in expediting auditory spatial maturation.

Keywords

- ▶ spatial perception
- ▶ maturation
- ▶ psychoacoustics
- ▶ virtual
- ▶ discriminant analysis
- ▶ abacus training

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Introduction

The science of maturation and developmental plasticity advocates that the brain is maximally plastic during early childhood. Out of many auditory processes that mature with time, auditory spatial perception is of utmost importance. Spatial perception of sound encompasses the ability to perceive the stimulus in space at any given point.¹ This special ability involves the what (varying parameters of time, intensity, or frequency) and where (location of the sound in space, localization, movement tracking) pathways in brain,² which matures with time.³

The ventral and dorsal streams, also known as the “what” and “where” pathways respectively, involved in spatial perception, though completely developed at birth, are shaped by experiences throughout life and evolve into a matured system.⁴ The sound signal is initially processed by the outer-ear structures, which have a complex, convoluted shape. The interaction of outerear structures with incoming sound results in a complex pattern of sound resonance and diffractions. This is further compounded by the anatomic position of the pinnae. The physical distance between the two pinnae causes differences in the time of arrival and intensity of sound signal at rear ear (relative to the farther ear), resulting in an interaural time difference (ITD) and interaural level differences (ILD).⁵ The outer-ear structures, although present at birth, develop progressively with age, especially during early childhood, until 7 to 8 years.⁶

The development of auditory spatial perception, which is predominantly defined as the function of the outer-ear structures, parallels the development and functional maturation of ear structures. The basic internal representations of auditory spatial awareness emerge at approximately 6 months of age, and gets progressively refined until 7 to 8 years. The growth then becomes protracted due to the changes in head size. All these changes in outer-ear structures account for the peripheral developmental processes. Likewise, the development of the higher centers, including the brainstem and cortices, occur by late childhood, approximately at 11 years of age.⁷ The integrated development of these anatomical structures, in turn, contributes to developmental changes in spatial acuity, which continues to mature until 12 years of age.

Even though the maturation of both the peripheral and higher centers involved in auditory spatial perception happens in late childhood, learning a new skill can expedite this process. Learning, unlike natural experiences, occurs continuously, and is not a process fixed in function or form. Learning is about the connections that build within the neural networks of the brain, which otherwise mature only with time. The long- or short-term learning of skills like music, chess, or abacus in childhood has been reported to strengthen the involved pathways.⁸

Knowing how to use an abacus is a skill, and abacus training enriches the co-activation of multiple brain regions responsible for cognition, visuospatial processing, auditory processing, mathematical skills, and other learning processes.⁹ Abacus-trained children have improved cognitive skills like working memory,^{10–12} storage,¹³ retrieval,^{14,15} fluid intelligence,¹⁶ and inductive reasoning.¹⁷ Notable evidence regarding the benefits

of abacus training on cognitive functioning across age groups has been documented in the review by Silva et al.¹⁸ Abacus training also induces improvements based on procedural learning that have been documented on visuospatial processing¹⁹ and visuospatial working memory.²⁰ The visuospatial memory and phonological loop form the vital processes of working memory.²¹ The phonological loop refers to temporary storage of phonological and auditory information. Hence, the benefits of abacus training on visuospatial memory can be postulated to exert a transfer effect to the auditory domain. Regarding the anatomical pathways, the visual magnocellular and parvocellular pathways function in parallel to the auditory pathways.² This anatomical and functional relationship that the visual spatial memory shares with the phonological loop can drive a possible improvement in the auditory spatial perception consequent to abacus training. However, to date, there is a scarcity of studies that have explored the effect of abacus training on spatial perception in children.

Despite a growing literature on spatial auditory perception in children,²² very little is known about the impact of training on auditory spatial maturation in children. Spatial changes during childhood invariably impact children's ability to navigate in their environment, to segregate sources, and to form auditory objects.²³ The present experiment aimed to examine the effect of abacus training on the spatial ability of schoolchildren, particularly to address its impact, if any, in the developmental period. In addition, the study also aimed to compare the spatial performance of abacus-trained children with untrained adults to understand the relationship between training and maturation processes.

Methods

Participants

The present study was conducted on three groups of participants: children who underwent abacus training (C-AT), children with no formal abacus training (C-UT), and adults with no formal abacus training (A-UT). All three groups consisted of 30 participants each. The target group was the C-AT (20 males; 10 females; mean age: 11.36 ± 1.21 years; age range: 9–14 years), who had received a minimum of 2 years of abacus training from Sharp Brains Abacus Coaching Center in Mysore, India. The C-AT group could perform abacus-based mental calculations to analyze arithmetic operations such as addition, subtraction, multiplication, division, square root etc. The children in the C-AT group were in different abacus levels, ranging from levels 5 to 8. The minimum level considered for inclusion was level 5, as certified by the Indian Abacus Standards. According to the syllabus of the training, individuals who are trained in level 5 and beyond shall be taught multiplication and division up to four digit numbers. The children in this group were first trained to use the 3 physical abaci with their hands, and later on, they practiced to stimulate abacus containing 4 digits in their minds, until they mastered the skill of manipulating numbers via an imagined Abacus in mind for 5 digit numerals without actual finger movements. The control group, the C-UT, was composed of 30 children (20 males; 10 females;

mean age: 10.56 ± 1.01 years; age range: 9–14 years) who did not receive any formal abacus training. And the A-UT group consisted of 30 untrained adults (13 males; 17 females; mean age: 27.73 ± 2.81 years; age range: 18–35 years), whose performance on spatial acuity tests were considered the reference values for a mature auditory system. Information on overall virtual acuity scores presented in the current study for the C-AT and C-UT groups has been briefly reported in a previous publication.²⁴

The sample size required for each group was statistically estimated in accordance with the study by Roy et al.,¹⁰ using G*Power. Düsseldorf, Northrhine-Westphalia, Germany), version 3.1.9.4.7.²⁵ The calculation yielded a sample size of 30 subjects in each group, for an effect size of ≥ 0.7 . Thus, the sample size ($N=90$) was verified to be appropriate for measuring psychoacoustical changes in auditory processing tests due to Abacus training.

Inclusion Criteria

All participants met the following criteria: a) normal bilateral hearing sensitivity with pure-tone air and bone-conduction thresholds ≤ 15 dBHL at octave frequencies of 250–8,000 Hz;²⁶ b) no complaints of speech, language, hearing, or learning problems; c) no known history of attention and neurological deficits; d) no musical training; e) no previous experience in psychoacoustic testing; and f) normal intellectual ability according to the Binet-Kamat scale. The first criterion was checked using the android hearing assessment application,²⁷ while criteria “b” to “e” were based on what was reported by the parents or guardians on a questionnaire administered before the beginning of the testing. The intellectual ability of all children enrolled in the study was tested using the Binet-Kamat scale,²⁸ and only children with age appropriate IQs were included. The high quality of the Binet-Kamat test in assessing the intellectual abilities in Indian children is documented in the literature.²⁹ The overall duration of the spatial tests was of approximately 45 minutes, with the order of testing counterbalanced among the participants.

Informed Consent and Ethical Guidelines

Written informed consent was taken from all the adult participants and parents or guardians of the children who were involved in the study. The ethical recommendations for bio-behavioral studies³⁰ formulated by the institutional board were followed, and approval (AIISH/RP_24_2021-2022) was obtained before the start of the study.

Procedure

All study participants completed a series of psychoacoustic tests that assessed different aspects of spatial acuity. The temporal and intensity correlations of spatial acuity were assessed using binaural processing tests of ITD and ILD thresholds respectively, while the composite score of spatial acuity—temporal, intensity, and spectral—was obtained using the virtual acoustic space identification (VASI) test.³¹ In addition to the aforementioned psychoacoustic tests, perceptual correlations of spatial acuity were obtained using

the spatial subsection of the Kannada Speech Spatial and Quality Questionnaire (K-SSQ).³²

Stimuli and Test Environment

All the spatial acuity tests (except the K-SSQ) were performed using a 250-ms white band noise (recorded in stereo, 16 bit, 44,100 sampling frequency). The stimuli were presented at an overall intensity of 60 dB SPL, calibrated using a B&K 2270 (Hottinger Brüel & Kjær A/S. Nærum, Denmark) sound level meter. The test stimuli were routed through Sennheiser HD 200 headphones (Sennheiser GmbH & Co. Wedenmark, Germany) connected to a laptop. The spatial acuity tests were carried out in a quiet room, with no additional visual or auditory distractors. The noise level in the room was measured before the test using the Sound Meter (Smart Tools co. Daegu, Republic of Korea)³³ application for Android. We ensured that the noise levels did not exceed 30 dB SPL.

Binaural Resolution Tests

Temporal Correlate of Spatial Resolution – ITD Threshold

This test was conducted using the MATLAB (MathWorks Inc., Natick, MA, USA) software, version 2019b, with 250-ms stimuli presented in the three-interval forced-choice method. A three down, one up rule in the staircase procedure running in the psychoacoustic toolbox³⁴ was adopted to obtain the ITD thresholds. The signals (250-ms noise bursts, 10-ms ramp) were routed to both ears in three consecutive trials for each run. In each run, one stimulus served as a variable, while the other two were standards. The variable stimulus differed acoustically from the standards as it produced lateralization to the right ear, achieved by the introduction of a time delay in the left channel. The preference for the right over the left ear is based on the rationale of the right ear's advantage in processing spatially-loaded acoustic stimuli.³⁵

The starting level of the time delay introduced in variable stimulus was of 3 ms, and the changes in time varied adaptively with a factor size of 2 based on the response of the participant. The participant verbally uttered the number corresponding to the interval of variable stimulus, while the experimenter entered the response using a keyboard. Finally, the test was terminated after ten reversals, and the last four of them were averaged to determine the ITD threshold. The obtained thresholds were equivalent to 79.4% of the psychometric function. ► **Figure 1** shows the schematic representation of the stimulus used in the ITD test.

Intensity Correlate of Spatial Resolution – ILD Threshold

This test follows a protocol similar to that of the ITD implemented on the MATLAB, version 2019b platform, except that the variable stimulus lateralized to the right ear due to its higher intensity in that ear. The starting level of the variable stimulus was of 5 dB SPL. The level of the variable stimulus was adaptively manipulated based on the response of the participant. A step size of 1 dB was used to track the threshold. The test was terminated after ten reversals, and

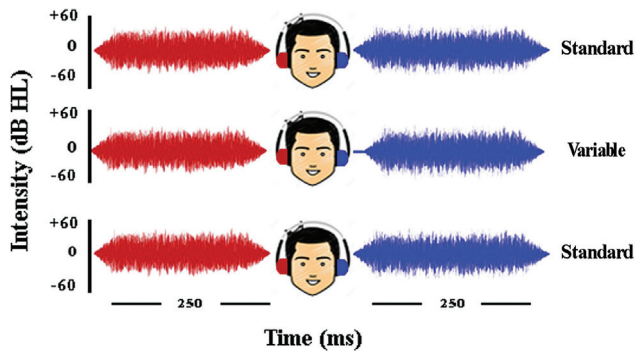


Fig. 1 Schematic representation of the stimulus used in the ITD test. The top and bottom panels correspond to the standard stimuli, while the central panel denotes variable stimuli with a time lag in the left channel and corresponding lateralization to the right ear.

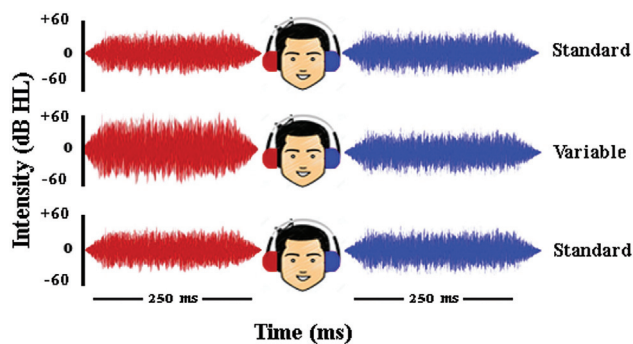


Fig. 2 Schematic representation of the stimulus used in the ILD test. The top and bottom panels correspond to the standard stimuli, while the central panel denotes variable stimuli with higher intensity in the right channel.

the last four were averaged to determine the ILD threshold. The thresholds obtained thus were equivalent to 79.4% of the psychometric function. **Figure 2** shows the schematic representation of the stimulus used in the ILD test.

Composite Test of Spatial Acuity: VASI

The VASI test used in the current study is similar to one developed by Nisha and Kumar,³¹ which contained all three cues (time, intensity, and spectrum) of spatial perception. The stimuli in the VASI test comprised spatial percepts created within the head and called virtual acoustic space (VAS) stimuli. The VAS stimuli (250 ms) were generated by convolving the white band noise (WBN) with the default head-related transfer function (HRTF) of the Sound Lab (SLAB 3D) software (Ames Research Center, Moffett Field, California, USA), version 6.7.3.³⁶ The HRTF model used in SLAB 3D is comparable to the head models provided in the Center for Image Processing and Integrated Computing (CIPIC) HRTF database, and is shown to produce reliable lateralization responses.³⁷ A total of 8 auditory locations within the head were simulated: 0° azimuth at the midline front; 180° azimuth at the midline back; 45° azimuth towards the right (R45) and left ears (L45); 90° azimuth towards the right (R90) and left ears (L90); and 135° azimuth towards the right (R135) and left ears (L135).

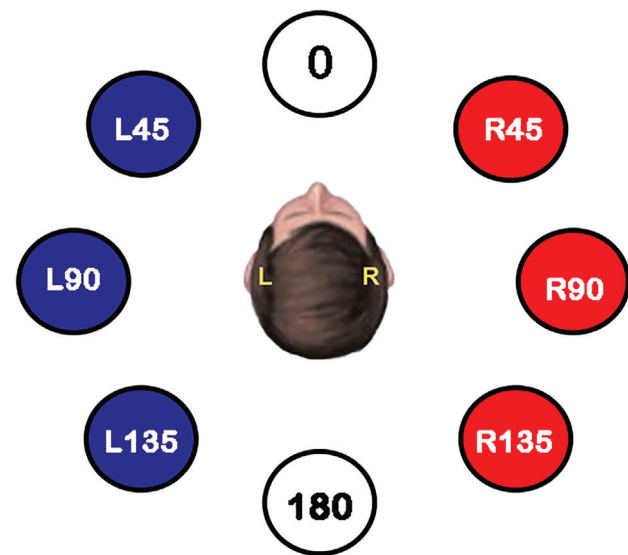


Fig. 3 Pictorial representation of the dummy head interface used for stimulus-response acquisition in the VASI test. The alphanumeric code corresponds the virtual location to which the stimulus is lateralized. (eg: R45–45° to right).

These virtual stimuli were played randomly using a paradigm player software (Perception Research Systems, 2007),³⁸ not exceeding 10 times at each location (total = 80: 8 locations*10 repetitions). The intensity was maintained at 60 dB SPL. The participants' task was to click on the locations which emitted the sound. A dummy head display on the user interface, as shown in **Figure 3**, was used to obtain responses. The test was terminated after 80 trials, and the output stored in an Excel (Microsoft Corp. Redmond, WA, US) file was evaluated to obtain acuity (VASI) scores. The scores were also subjected to spatial error analyses within and across, using a confusion matrix³⁹ for each participant.

Perceptual Correlation of Spatial Processing – K-SSQ

The perceptual difficulties in daily listening situations were assessed using the spatial subsection of the K-SSQ.³² This rating scale comprises 14 questions which are marked on a scale from 0 to 10, in which 0 represents the minimal spatial ability, and 10 represents the maximum spatial ability.

Statistical Analyses

The raw scores of the collected data were subjected to statistical analysis using the Statistical Package for the Social Sciences (IBM SPSS Statistics for Windows, IBM Corp., Armonk, NY, US), version 20.0. Descriptive statistics (mean and standard deviation) were calculated for all of the measurements. Following this, the Shapiro-Wilk test of normality was administered. The group differences in the psychoacoustic tests were statistically verified using multivariate analysis of variance (MANOVA) for the parametric data, and the Kruskal-Wallis test for the non-parametric data. Whenever significant differences were found between the groups, the measured effect size of partial Eta-squared (η^2) was reported, and corresponding post-hoc tests were carried out. In addition to this, correlation analyses were carried

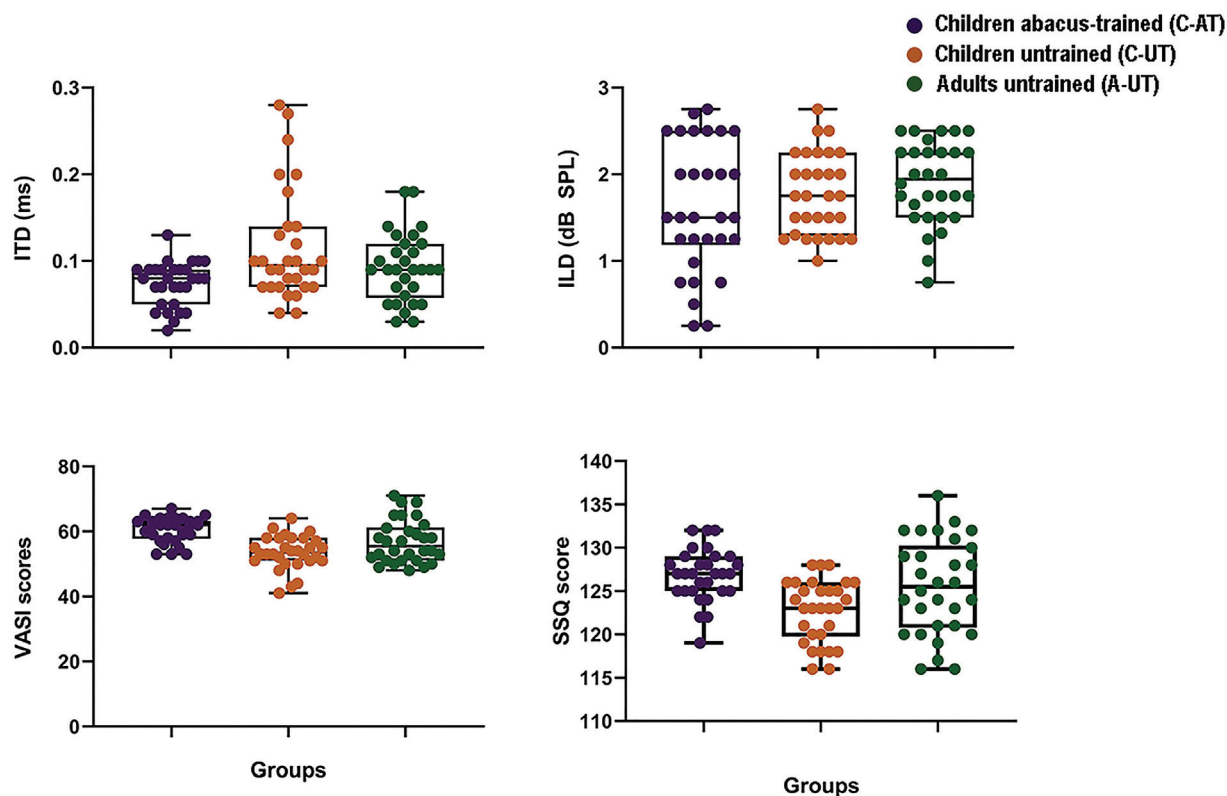


Fig. 4 The central tendencies and the individual data of the three groups of participants in the study regarding the spatial perception tests.

out to determine the relationship of various psychoacoustic tests with the perceptual K-SSQ measure, with the Pearson test being chosen for parametric data, and the Spearman test for non-parametric data. The Fisher linear discriminant function analysis (FDA) was performed for group classification based on the test scores of all the participants. The FDA is a multivariate analysis technique that attempts to categorize groups based on measurements obtained from the same set of variables,⁴⁰ by generating a mathematical operation ($D_i = a + b_1x_1 + b_2x_2 + \dots + b_nx_n$; D_i = predicted discriminant score; a = constant; x = predictor; and b = discriminant coefficient) that maximizes the differences in performance for each group, based on weights generated for each test variable. The weights obtained in the FDA were used to determine the robust metric with the greatest predictive power to segregate the C-AT and A-UT groups from the C-UT group. Based on this metric, a detailed analysis of spatial errors was performed. In addition, the FDA-derived group assignment of the participants was compared with the otherwise original allocation to determine the overall error rate for group segregation.

Results

The present study analyzed the effects of abacus training on spatial performance of schoolchildren and compared it to their age-matched untrained peers, and to untrained adults using a battery of psychoacoustic and perceptual tests. The Shapiro-Wilk test showed that the ILD, VASI, and K-SSQ adhered to normality ($p > 0.05$). In contrast, the ITD did

not follow normality ($p < 0.05$). The mean and variability (one standard deviation) of central tendency, along with the individual score of each participant is shown in **Figure 4**.

The MANOVA for the tests which followed normality—ILD, VASI, and K-SSQ—revealed the main group effect for all the tests: ILD: $F(2, 87) = 4.58, p = 0.01, \eta_p^2 = 0.09$; VASI: $F(2, 87) = 14.57, p < 0.001, \eta_p^2 = 0.25$; K-SSQ: $F(2, 87) = 6.02, p = 0.004, \eta_p^2 = 0.12$. A post-hoc pairwise comparison using the Bonferroni test showed that the C-AT group had significantly lower ILD ($p = 0.01$), and significantly higher VASI scores ($p < 0.001$) compared to the C-UT group. In addition, no significant differences in spatial acuity ($p > 0.05$) were observed between the C-AT and the A-UT groups. Likewise, the non-parametric Kruskal Wallis test for the ITD revealed a main group effect: $\chi^2(2) = 10.46, p = 0.02$. The Dunn-Bonferroni follow-up test revealed significantly lower ITD thresholds ($p < 0.05$) in the C-AT group when compared to the C-UT and A-UT groups.

The second approach was to study the efficacy of three psychoacoustic tools in group segregation by correlating them with the perceptual K-SSQ rating. The results of the Pearson (ILD and VASI) and Spearman (ITD) tests for each group is shown in **Figure 5**. The scatter plot showed a decrease in ITD and ILD values with a corresponding increase in K-SSQ scores, and, in contrast, an increase in VASI scores paralleled the increase in K-SSQ scores. The correlation coefficient (the text on top of each panel, **Figure 5**) was significant in all groups, which reached moderate to good correlation values in the C-AT and A-UT groups.

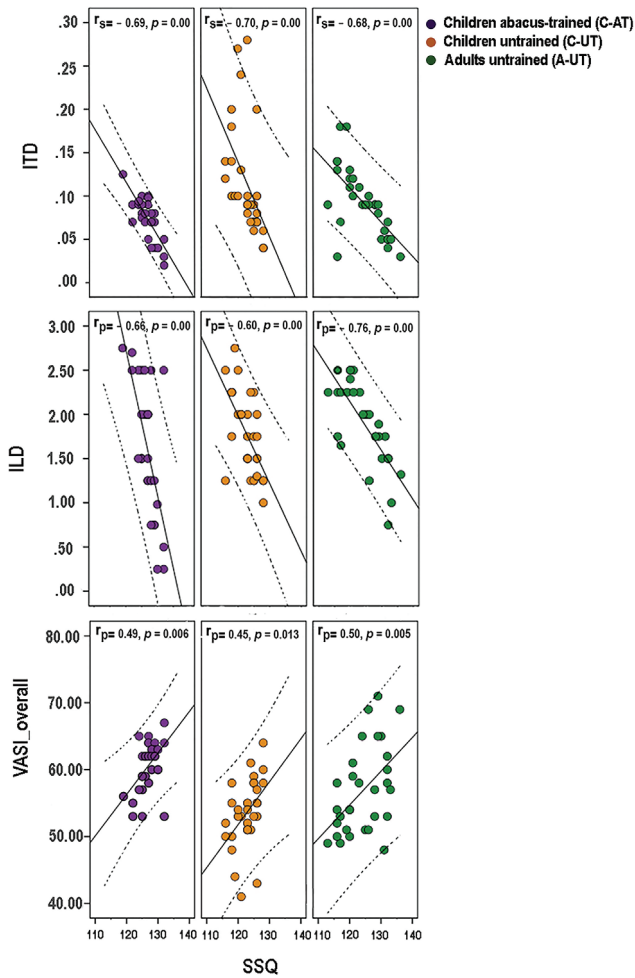


Fig. 5 The degree of correlation between spatial rendering tests (ITD, ILD and VASI) and perceptual measure (spatial portion of the K-SSQ) across groups. The correlation coefficient, tested with Pearson and Spearman models, along with the level of significance, is provided at the top of each panel.

The third set of analyses was to identify the most effective metric for measuring the effects of training, generated using discriminant function analysis (DFA), which, in turn, generated two canonical discriminant functions (DFs), which categorized differences among the groups based on their test scores. Out of the two functions, DF1 was significant (Wilks lambda; $\lambda(4) = 0.67$; $\chi^2 = 34.05$; $p < 0.001$), accounting for 92.3% of the cumulative variance. An examination of the discriminant weights for each test showed the emergence of the VASI as most heavily-weighted metric on DF1 regarding the canonical coefficient, as reflected in **Table 1**.

The canonical DFs obtained in the study based on the weights (**Table 1**) are summarized below:

$$DF1 = (0.65 \times ILD) - (0.33 \times ITD) + (0.88 \times VASI) + (0.34 \times K-SSQ) \quad (1)$$

$$DF2 = (1.05 \times ILD) - (0.30 \times ITD) + (0.02 \times VASI) - (0.06 \times K-SSQ) \quad (2)$$

Each participant's score on each of the two DFs was calculated by multiplying each standardized canonical DF coefficient by the test score of each individual on the four associated measures and summing these products. Thus, the

Table 1 Contribution (weights) of spatial acuity tests for the groups in the study (indicated by standardized canonical discriminant function coefficients)

Discriminating variables/tests	Function 1	Function 2
ITD	-0.33*	-0.30
ILD	0.65	1.05
VASI	0.88*	0.02
K-SSQ	0.34	-0.06

Abbreviations: ILD, interaural level difference; ITD, interaural time difference; K-SSQ, Kannada speech, spatial, and quality questionnaire; VASI, virtual auditory space identification.

Note: *The most significant metric in canonical discriminant function.

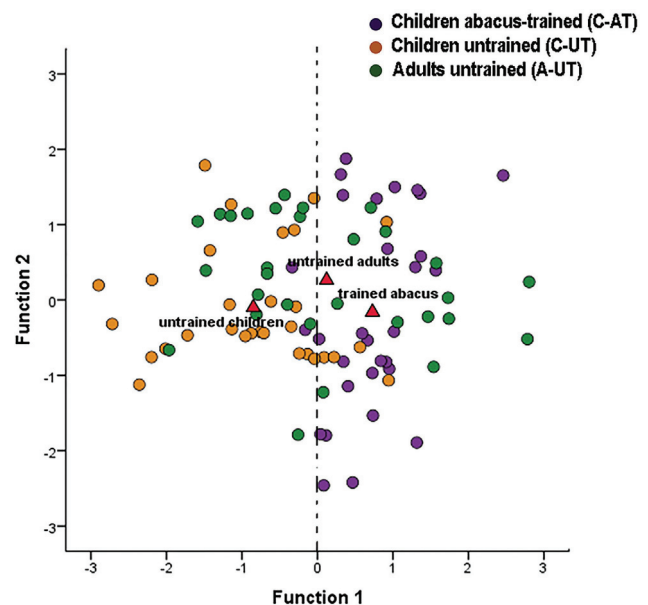


Fig. 6 Grouping participants based on canonical discriminant scores derived from tests of spatial resolution. The reference line (midline) indicates the cut-off scores on Function 1 for group segregation. The circles shaded purple, yellow, and green represent individual participant scores, for each group (see legend), the triangles (red) represent the group median scores.

calculated individual and mean scores for each group (group centroids) on the two discriminant functions are shown in **Figure 6**. It is clear from the figure that the DF1 separates the C-UT group from the C-AT and A-UT groups, which emerged as two distinct clusters that are concentrated on either side of the reference line (**Figure 6**, mid-line).

The error rate in the DF analysis (indicating the accuracy of classification) is shown in **Table 2**. An overall correct classification rate of 57.8% was observed. Errors in classification involved predicting group allocation for 33.33% (10/30 ears) of the A-UT group participants, who were instead classified as C-AT, while 33.33% (10/30 ears) of the C-AT group were misclassified as A-UT, which is indicative of the overlapping performance of these two groups on spatial measures. None of the children in the C-AT group were

Table 2 Accuracy of discriminant function analyses comparing predicted and original group allocations

Original group	Predicted Group Allocation			Total ears
	C-AT	C-UT	A-UT	
C-AT	20 (66.7%)	0.00 (0.00)	10 (33.3%)	30 (100%)
C-UT	2 (16.7%)	20 (66.7%)	5 (16.7%)	30 (100%)
A-UT	10 (33.3%)	8 (26.6%)	12 (40.00%)	30 (100%)

Abbreviations: C-AT, children with abacus training; C-UT, children with no training; A-UT, adults with no training.

misclassified as C-UT, which shows a clear demarcation in spatial acuity performance between these two groups.

As the VASI test was the most significant metric (►Table 1) for segregating the group differences, elaborate analyses of the effect of training on spatial acuity of the three groups were performed using the VASI confusion matrix. The stimulus-response grid was analyzed in detail to understand location-wise spatial acuity, within and across-hemifield spatial errors. The location-wise spatial acuity scores of the VASI test with the mean and one standard deviation are shown in ►Figure 7.

The mean VASI scores were higher in the C-AT and A-UT groups, while the C-UT group scored lower VASI scores. These group differences in the VASI test were statistically verified using one-way repeated measures ANOVA (8 locations × 3 groups), which showed a significant main effect of groups [$F(2,87) = 29.79, p = 0.00, \eta p^2 = 0.41$ [and locations] $F(7,609) = 67.69, p = 0.00, \eta p^2 = 0.44$] and interaction between groups and locations [$F(14,609) = 6.025, p = 0.00, \eta p^2 = 0.12$]. The follow-up one-way ANOVA for group effect was measured at each VAS location separately, and the corresponding Bonferroni pairwise comparisons are shown in ►Table 3.

Apart from the overall accuracy for VASI scores, the spatial judgment errors at the right and left directional planes analyzed using within-hemifield errors, across hemifield errors (symmetrical), and across hemifield errors (asymmetrical) are shown in ►Table 4. The mean of the errors observed in the within-group confusions were higher than that of the other errors (across symmetrical and asymmetrical).

A detailed analysis of the errors within groups was performed for each of the locations using one-way repeated measures ANOVA (8 locations × 3 groups), which revealed the main group effect for each position: R45: $F(2,87) = 6.73,$

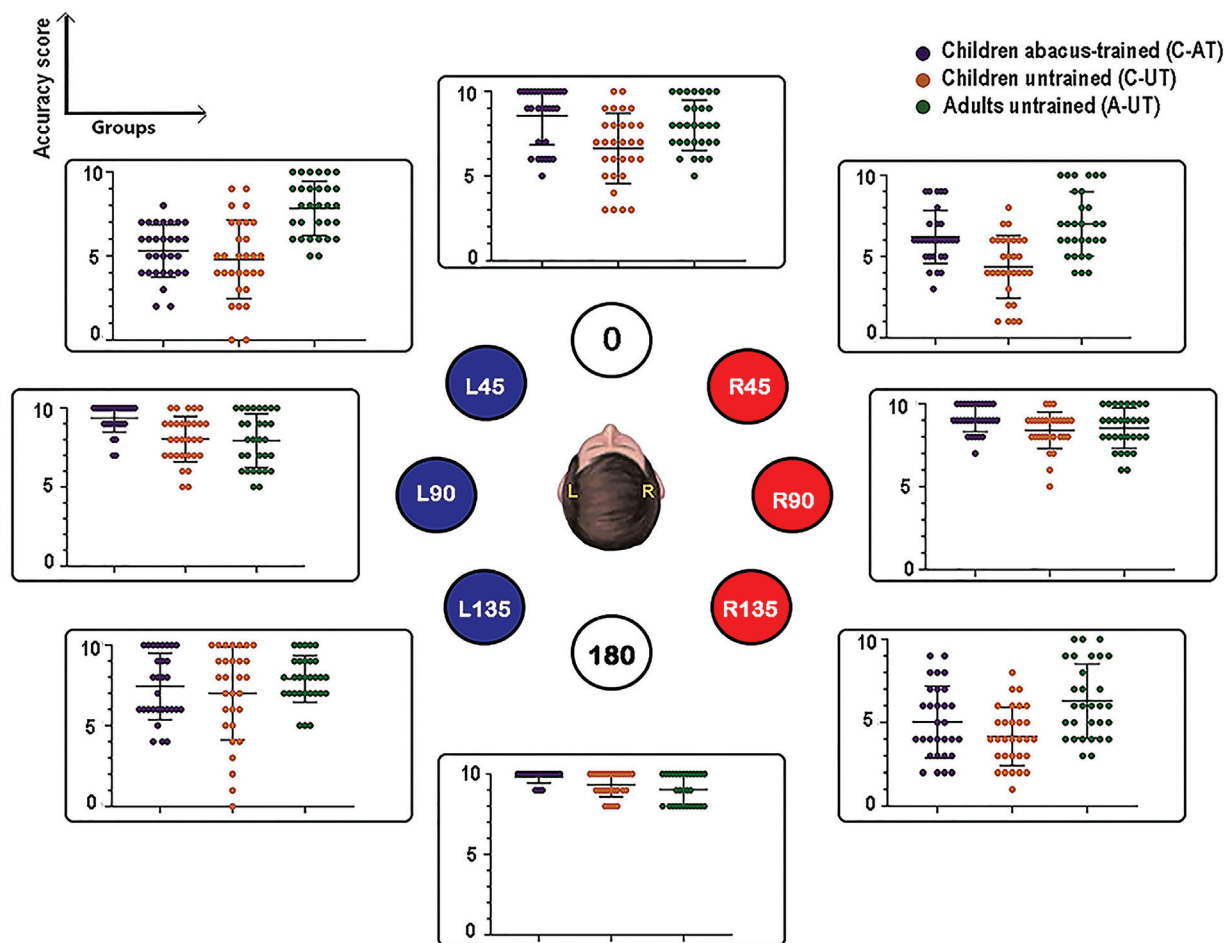


Fig. 7 Comparison of the spatial acuity (VASI) scores across the eight virtual locations among the three groups. The inner dummy head panel represents the eight VAS locations used in the study while the outer panels denote the scatter plot VASI scores of each participant (scatter dots) for the C-AT (purple dots), C-UT (yellow dots), and A-UT (green dots) groups.

Table 3 Results of one-way ANOVA for the effect of group on VASI score (along with effect size, η_p^2) across the eight virtual locations

Virtual location	F value (2, 87)	Bonferroni pair-wise comparisons	
		C-AT	C-UT
R45	15.98, $p = 0.00$, $\eta_p^2 = 0.27$	$p = 0.001^{***}$	$p = 0.001^{***}$
R90	4.06, $p = 0.08$, $\eta_p^2 = 0.08$	$p < 0.001^{***}$	$p > 0.05$
R135	5.36, $p = 0.06$, $\eta_p^2 = 0.11$	$p > 0.05$	$p = 0.006^{**}$
180	6.99, $p = 0.02$, $\eta_p^2 = 0.14$	$p = 0.039^*$	$p = 0.001^{***}$
L135	1.24, $p = 0.29$, $\eta_p^2 = 0.03$	$p > 0.05$	$p > 0.05$
L90	9.96, $p = 0.00$, $\eta_p^2 = 0.19$	$p = 0.001^{***}$	$p < 0.001^{***}$
L45	22.62, $p = 0.00$, $\eta_p^2 = 0.34$	$p < 0.001^{***}$	$p < 0.001^{***}$
0	7.62, $p = 0.001$, $\eta_p^2 = 0.15$	$p = 0.001^{***}$	$p = 0.017^*$

Abbreviations: A-UT, adults with no training; ANOVA, analysis of variance; C-AT, children with abacus training; C-UT, children with no training; VASI, virtual auditory space identification.
 Note: The results of the Bonferroni test for the pairwise comparisons of the groups across each location are also shown in the table.

$p = 0.002$, $\eta_p^2 = 0.13$; R90: $F(2,87) = 5.37$, $p = 0.006$, $\eta_p^2 = 0.11$; L90: $F(2,87) = 14.02$, $p < 0.001$, $\eta_p^2 = 0.24$; L45: $F(2,87) = 17.19$, $p < 0.001$, $\eta_p^2 = 0.28$. However, the main group effect was absent for the back locations in both hemifields: R135: $F(2,87) = 2.34$, $p = 0.10$; L135: $F(2,87) = 0.25$, $p = 0.78$. The Bonferroni pairwise comparison showed that the spatial errors observed in the C-AT and A-UT groups were similar ($p > 0.05$), and were significantly lower ($p < 0.05$), than the C-UT group, as shown in ►Figure 8.

Discussion

The main purpose of the present study is to determine the advantages of abacus training on spatial processing in schoolchildren. Additionally, the maturity effects were compared to those of adults using spatial acuity tests. Descriptive statistics showed observable differences in the mean performance of the C-AT group from the C-UT group on all spatial acuity tests. The results of the MANOVA and equivalent non-parametric tests revealed group differences. The post-hoc tests showed similarity in spatial performance among the C-AT and A-UT, with both groups exhibiting better spatial acuity compared to C-UT. The superiority of the C-AT over the C-UT reflects the transferability of the effects of abacus training—which uses predominantly visual domain—on the auditory spatial domain. The similarity between the C-AT and A-UT indicates an expedition of the auditory spatial maturity process, secondary to abacus training in children. Considering the highly-plastic young auditory system in childhood, the transfer of positive effects of abacus training to the spatial domain denotes its promising implications in the pediatric population with spatial deficits.

The spatial betterment in the C-AT group, whose scores become comparable to those of the A-UT group, can be attributed to two reasons. Firstly, abacus training accelerates spatial maturation processes, overriding the deficits of both the peripheral and central structures in the immature auditory systems of the younger participants of the C-AT group. The anatomical structures (peripheral and central) are not fully developed at birth. The pinna achieves its adult size by 9 years of age,⁴⁰ a maturation which plays a vital role in spatial perception. As the child grows, the pinna matures, and the location abilities refine and vary over time, with the spatial acuity varying from 45° at 2 months of age to over 30° by 6 to 7 months.⁴¹ This capacity is further refined in school-age gradually from 19°,⁴² reaching an ability to discriminate sound sources varying in 1° or 2° in the frontal

Table 4 The mean error in azimuth and variability (standard deviation in parenthesis) within and across symmetrical and asymmetrical VASI errors

Virtual locations	Within errors			Across hemifield errors					
	C-AT	C-UT	A-UT	Symmetrical			Asymmetrical		
				C-AT	C-UT	A-UT	C-AT	C-UT	A-UT
R45	1.73 (0.73)	2.63 (1.12)	1.73 (1.35)	0.00 (0.00)	0.00 (0.00)	0.33 (0.18)	0.00 (0.00)	0.67 (0.25)	0.67 (0.25)
R90	0.40 (0.40)	0.78 (0.55)	0.90 (0.82)	0.00 (0.00)	0.00 (0.00)	0.06 (0.25)	0.00 (0.00)	0.03 (0.18)	0.00 (0.00)
R135	1.97 (1.07)	2.33 (1.20)	1.71 (1.04)	0.15 (0.46)	0.16 (0.36)	0.06 (0.26)	0.00 (0.00)	0.33 (0.18)	0.16 (0.37)
180				0.07 (0.27)	0.53 (1.00)	1.20 (1.77)			
L135	1.10 (0.83)	1.28 (1.33)	1.27 (1.09)	0.03 (0.18)	0.03 (0.18)	0.03 (0.18)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
L90	0.25 (0.31)	1.00 (0.78)	1.01 (0.73)	0.07 (0.39)	0.00 (0.00)	0.03 (0.18)	0.00 (0.00)	0.03 (0.18)	0.20 (0.55)
L45	2.20 (0.88)	2.38 (1.14)	0.96 (1.01)	0.00 (0.00)	0.03 (0.18)	0.03 (0.18)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
0				0.19 (0.49)	1.16 (1.62)	3.13 (3.05)			

Abbreviations: A-UT, adults with no training; C-AT, children with abacus training; C-UT, children with no training; VASI, virtual auditory space identification.
 Note: Blank space indicates no relevant comparisons.

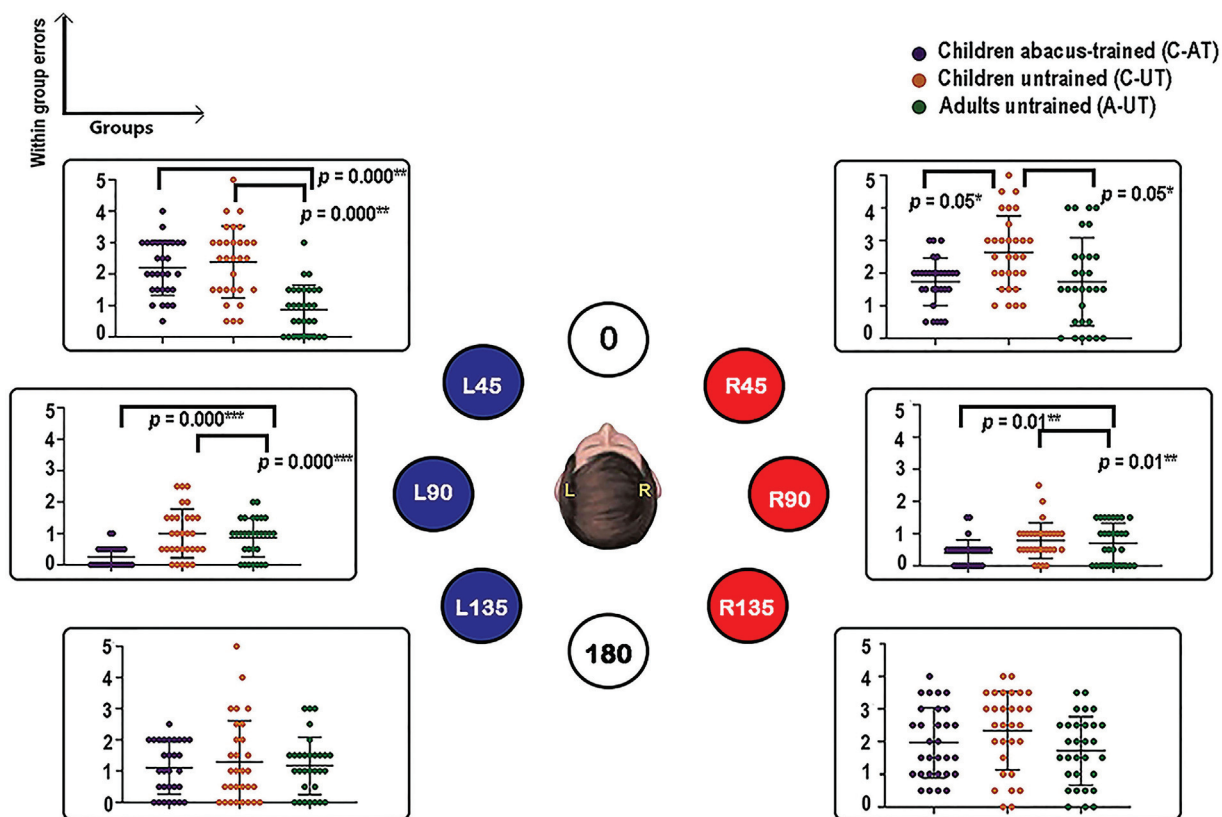


Fig. 8 Comparison of the spatial acuity (VASI) scores for within-hemifield errors across the eight VAS locations between the three groups. The inner dummy head panel represents the eight VAS locations used in the study, while the outer panels denote scatter plot VASI scores of each participant (scatter dots) for the C-AT (purple dots), C-UT (yellow dots), and A-UT (green dots) groups. The vertical error bars for each group denote interquartile deviation, while the central line on the error bars represents the median value of the observations at each VAS position.

plane.⁴³ The central and cortical processes, (superior olivary complex and the occipito-parietal cortex), underlying these maturational changes have also been noted to refine over time.⁴⁴ Kaiser et al.⁴⁵ identified stimulus-specific gamma activity (55–70 Hz) in lateralized to occipito-parietal cortex contralateral to ear of stimulation for spatial stimuli (45° to right and left of mid-sagittal plane). This topography could be considered consistent with the auditory dorsal “where” stream, but it might also indicate an involvement of visual spatial imagery.⁴⁶ Thus the otherwise pronounced improvements observed in the visuospatial processing with abacus training, seem to cross-modally improve auditory spatial perception, due to the underlying commonality in the anatomical structures. Secondly, the heightened spatial acuity abilities in the C-AT group can be attributed to cognitive mediation by abacus training. The stimuli provided by abacus training is known to not only improve mathematical expertise in children, but also bring in plausible cognitive developmental change in multiple abilities such as working memory,^{10–12} storage,¹³ retrieval,^{14,15} fluid intelligence,¹⁶ and inductive reasoning.¹⁷ The role of three cognitive processes in particular: attention, memory, and representation are also indicated to play a major role in auditory spatial processing.⁴⁷

Complimentary to the aforementioned findings, the correlational analyses also revealed a higher relationship of

psychoacoustic tests (ITD, ILD, and VASI) with perceptual ratings (K-SSQ), specifically for the C-AT and A-UT groups. This finding showed that the improved spatial acuity in the C-AT and A-UT groups helped in the better correlational values of psychoacoustic tests with the perceptual K-SSQ measure, which was in contrast to a poor correlation observed in the C-UT group. In addition, the discriminant function analysis (DFA) clearly demarcated the C-AT and A-UT into a separate cluster, which was different from the discriminant score of the C-UT group. The DFA was heavily weighted on the VASI test, which emerged as the most significant metric to segregate the group differences. This finding is suggestive of the greater sensitivity of the VASI test in assessing group differences on auditory spatial processing. The spatial perception task of the VASI, unlike those of the ITD and ILD, involves multiple cues in the stimuli for presentation. These include the integration of all three cues of spatial perception, that is, intensity, frequency, and time. The inclusion of all cues facilitates precise spatial judgments, which in turn were reflected in the establishment of group differences in DFA, making the VASI the most sensitive test of spatial perception.

The detailed analyses of spatial judgment accuracy and errors using location-wise VAS scores showed that C-AT group exhibited fewer spatial errors and higher accuracy of spatial judgments, which was on par with the A-UT group. This finding was complimentary to the descriptive and

inferential statistics, as aforementioned. The reduced spatial errors in each VAS location for C-AT suggests an accelerated auditory spatial judgment accuracy in C-AT participants whose spatial abilities were fine-tuned to the adult level at a much younger age. This finding shows cross-modality transfer of visuospatial learning, such as abacus training, to the auditory spatial domain at a young age, which supersedes the maturational processing operating at this age and aids children in reaching adult-like spatial function. Probing into the links of abacus training in the visual domain to the transfer of its effects to the auditory spatial domain, it is of utmost relevance to understand the physiology of auditory spatial perception. The detection of sound location often involves distinct cognitive processes such as alerting, orienting, and reorienting responses to the sound direction.⁴⁸ Drawing parallels to the spatial processing in the auditory domain, the C-AT also use cognitive processes such as attention span, working memory, and retrieval skills to perform mathematical calculations in the abacus.^{49,50} Anatomically, while the dorsal auditory pathway contributes to the sound location perception, the visual magnocellular and parvocellular pathways aid in visuospatial perception of location. The visuospatial memory and phonological loop, which drive auditory working memory, are closely-related processes of working memory.²¹ Positive effects of abacus training are documented regarding visuospatial perception.^{20,51} Given the overwhelming similarities in the functional mechanisms involved in visual and auditory spatial processing, and the benefits of abacus training in the visual domain, the transferability of effects of the same to auditory spatial domain can be explained. In addition, abacus training can positively influence the central executive control,²¹ which regulates attention, a prerequisite skill for spatial processing in both the auditory and spatial domains.

Conclusions and Implications of the Study

The findings of the present study provide high-level evidence of the transferability effect of abacus training to the auditory spatial domain in schoolchildren. Despite the physiological limits of the immature neural framework, the abacus-trained children had a performance equivalent to that of adults on psychoacoustic tests. This sheds light on the role of abacus training in accelerating auditory spatial maturation. The study findings have rehabilitative implications in the field of Audiology for the potential treatment of process-specific deficits observed in children with central auditory process disorder (CAPD), auditory neuropathy spectrum disorder (ANS), or learning disabilities (LDs), in whom spatial processing is compromised.

Limitations and Future Directions

The present study was performed with variables that were limited to the abacus-trained or untrained groups. Although improvements in the auditory spatial processing and maturation subsequent to abacus training have been confirmed in the children in the study, it remains unclear whether this

beneficial effect is merely a placebo effect due to the lack of a comparable active control group. The short and long term effects of abacus training on spatial acuity were not delineated in the current study. Further research probing into the abacus training benefits and its retention effects using longitudinal designs with an active control groups are needed to validate the study findings.

Research is also warranted to explore the influence of gender differences, the duration, and the level of abacus training on the auditory spatial processing. It would also be interesting to study spatial processing in the abacus-trained geriatric population to understand its impact on the aging auditory system.

Conflict of Interests

The authors have no conflict of interests to declare.

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