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Cerebral dominance in spatial hearing and working memory abilities in adults with normal hearing sensitivity

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Abstract

Background Cerebral dominance refers to the biological description of the brain, where one cerebral hemisphere is dominant over the other in certain cerebral functions. There is scanty literature on cerebral dominance and its impact on auditory spatial processing and working memory, which is explored in the study.

Methods A total of 45 participants with normal hearing were divided into three groups of 15 participants. The groups were categorized based on scores obtained on the alert scale of the cognitive style checklist as the bilateral dominant, left dominant, and the right dominant group. The spatial hearing was assessed using interaural time difference (ITD), the interaural level difference (ILD), and virtual acoustic space identification (VASI) tests, whereas the auditory working memory abilities were tested using forward span, backward span, ascending digit span, descending digit span, and 2n back tests.

Results MONOVA results indicated that there is no significant main effect of cerebral dominance on all auditory working memory tests. In spatial hearing, although ILD and ILD thresholds were not influenced by cerebral dominance, the main effect of cerebral dominance was seen on VASI accuracy scores. Post-hoc analyses of VASI scores showed that the bilateral dominant group demonstrated significantly better spatial perception scores compared to the left and right dominant groups, with latter groups showing similar performance.

Conclusions While ITD and ILD tests fall short of revealing cerebral asymmetry, VASI's power in capturing cerebral dominance effects makes it a valuable tool in spatial processing assessment. The study's findings highlight the need for assessing cerebral dominance, before administering spatial hearing tests.

Keywords Cerebral dominance, Working memory, Spatial hearing, Virtual auditory space identification test, Dominant-brain

Background

Cerebral dominance refers to the biological description of the brain, where one cerebral hemisphere is dominant over the other in certain cerebral functions [1]. The brain is divided into two halves, left and right, and individuals can be either right-brained or left-brained, or bilaterally dominant. Left-brained individuals excel in skills such as sequencing, mathematics, facts, logic, language/speech, and linear reasoning, while right-brained individuals exhibit superior abilities in imagination, rhythm, arts, music, intuition, and holistic thinking [2]. This labor division in preferential functions of the brain (leftward speech and rightward music) is explained by the acoustic hypothesis, whose doctrine supports processing right hemisphere dominance in processing slow changes in

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spectral properties for tone-like stimuli and left hemisphere dominance for rapid changes in temporal properties for speech-like stimuli [3, 4].

Literature also shows strong evidence of the differential influence of cerebral asymmetry on auditory processing abilities [5–7]. Right ear advantage (REA) in a dichotic listening test with a verbal stimulus indicates that the left hemisphere is dominant for speech processing [8]. According to Kimura [9], the left hemisphere's dominance in speech is represented in superior recognition of verbal stimulus arriving at the right ear. In contrast, the right hemisphere's dominance in melodic-pattern perception manifests as its superior identification of tunes presented to the contralateral ear. In addition, Wang et al. [10] showed that early auditory processing of lexical tones reflects hemispheric lateralization, with marked right and left hemisphere dominance on pitch level and counter processing. Studies on dichotic listening highlight the significance of the right hemisphere in auditory processing in noisy environments [11, 12], leading to discussions about its capabilities in processing auditory noise. Shtyrov et al. [13] suggest a reduced left hemispheric role in speech discrimination tasks, while the role of the right hemisphere increases when listening to speech in noise.

Although literature documents the influence of hemispheric dominance on a few of the auditory processing abilities, its influence on auditory spatial processing and auditory working memory has not been researched. The ability of the listener to tune in with the direction of the sound source is referred to as spatial perception [14]. Human spatial hearing relies on monaural and binaural spatial processing cues. Binaural discrepancies in time (interaural time difference - ITD) and level (interaural level difference - (ILD) aid in locating sound sources in the horizontal plane. Spectral cues generated by the external ear canal and pinna are used to identify sound sources in the front-back and vertical planes [14, 15]. In contrast to spatial hearing which is relies on acoustic cue processing, working memory reflects to the ability of brain to temporarily store and manipulate auditory information. It is the ability of an individual to encode, retain and retrieve auditory stimuli [16]. The present study aimed to explore and document the influence of cerebral dominance on working memory and spatial acuity using a battery of process-specific psychoacoustical tests.

Methods

Participants and study design

The study employed a cohort research design, involving standard group comparison [17]. The participants were chosen using convenient sampling. Forty-five volunteers (males = 18, females = 27) aged 20 to 30 years (M_{age} = 21.37 years ± 1.91 SD) participated in the study. Participants were divided into three groups of 15 participants each: bilateral dominant (BD) (M_{age} 22.26 ± 1.83 years; males = 7, females = 8), left dominant (LD) (mean age: 20.93 ± 1.83 years; 6 males, 9 females), and right dominant (RD) (mean age 21.56 ± 1.53 years; 4 males and 11 females). The sample size required for each group in the investigation was statistically determined using G*Power version 3.1.9.4 [18]. For an effect value of 0.5, the sample size computed using G*power analysis was found to be 12 for each group. Thus, the sample size (n = 15 for each group) considered for the study is tested to be adequate for determining the effects of cerebral dominance on working memory and spatial hearing.

The Alert scale of cognitive style [19] was used to categorize the pattern of cerebral dominance in groups. This scale is a self-administered questionnaire that identifies brain dominance based on an individual's way of thinking [19]. The scale consists of 21 questions, and respondents must choose one appropriate answer (either 'A' or 'B'). Respondents who answer "A" for "1, 2, 3, 7, 8, 9, 13, 14, 15, 19, 20, 21" and "B" for "4, 5, 6, 10, 11, 12, 16, 17, 18" is scored one point. A composite score of (A + B) is computed to classify brain hemisphere dominance using the following classification: strong right hemisphere orientation (21–17), moderate right hemisphere orientation (16–14), bilateral hemisphere balance (13–9), moderate left hemisphere orientation (8–5), strong left hemisphere orientation (4–0). The questionnaire is attached as Additional file 1.

Individuals with bilateral cerebral dominance were taken into the BD group, while those with strong left hemisphere orientation and moderate left hemisphere orientation were taken into the LD group. Similarly, individuals with moderate right hemisphere orientation and strong right hemisphere orientation were categorized in the RD group.

Inclusion criteria

The participants included in the study met these inclusion requirements: (1) participants must be aged between 20 and 30 years, (2) normal hearing sensitivity in both ears (threshold ≤ 15 dB HL at each octave from 0.25 to 8 kHz for air conduction and ≤ 15 dB HL at each octave from 250 to 4 kHz for bone conduction), (3) no reported history of attention or cognitive or neurological problems, (4) individuals with no knowledge of formal musical training, and (5) participants without musical aptitude as revealed by a score of < 18 in the Mini-PROMS [20].

Informed consent and ethical guidelines

All participants involved in the study provided written informed consent. The researchers followed the institutional board's bio-behavioral research ethics guidelines.

Procedure

The inclusion criteria were met by all 45 individuals in the study. All the participants were subjected to a battery of auditory spatial and working memory tests. The spatial hearing was evaluated using ILD, ITD, and the virtual acoustic space identification (VASI) tests, while working memory was assessed using the forward span, back span, ascending span, descending span, and 2n back span tests. The test battery is depicted in detail in Fig. 1. The total time of testing for each participant was approximately 60 min, with a counterbalanced order of testing across the study participants. Rest periods were offered during testing to avoid fatigue.

Tests of binaural resolution-interaural level difference (ILD) and interaural time difference (ITD)

The two tests for binaural resolution, i.e., interaural time (ITD) and interaural time (ILD) differences were carried out by presenting a stimulus to both ears. For each of the two tests, the stimuli were routed by Sennheiser HD 200 headphones (Wedenmark, Germany) connected to a laptop (8 GB RAM, Windows 11, Intel Core i4 processor). A three-interval forced choice method was run using a psychoacoustic toolbox [21] in MATLAB version R2014a loaded on a Dell laptop (8 GB RAM, Windows 11, Intel Core i4 processor). A three-down one-up procedure was used. The converged value of the reversals estimated ITD and ILD thresholds corresponding to 79.44% psychometric function.

The test run was initiated after successful familiarization trials, which were composed of ten runs. During each run, three consecutive 250 ms noise bursts were given sequentially, each with a 10 ms cosine ramp (44,100 sampling frequency, 16-bit, stereo) at 60 dB SPL presentation level. Two of the three stimuli are standard, whereas the third was a variable stimulus. The participants were verbally instructed to locate the variable stimuli in each run and press the number corresponding to the order where the variable stimulus appeared using the keyboard. Inherent interaural differences in time and level in variable stimuli in ITD and ILD tasks were perceivable as differences in lateralization. For example, delay in time for the right ear (ITD) and higher amplitude to the right ear (ILD) results in stimuli being lateralized to the right ear in the variable stimuli, while the same in the standard stimuli (without binaural time or intensity changes) were centralized. The variable stimuli were adaptively manipulated with delays of 20 ms (initial level) to 0 ms for the ITD task, while for the ILD task, the level changed from 20 to 0 dB. The change in the time or level depended on the participant's response. The delay was halved in ITD tasks after two successive correct detections, while in

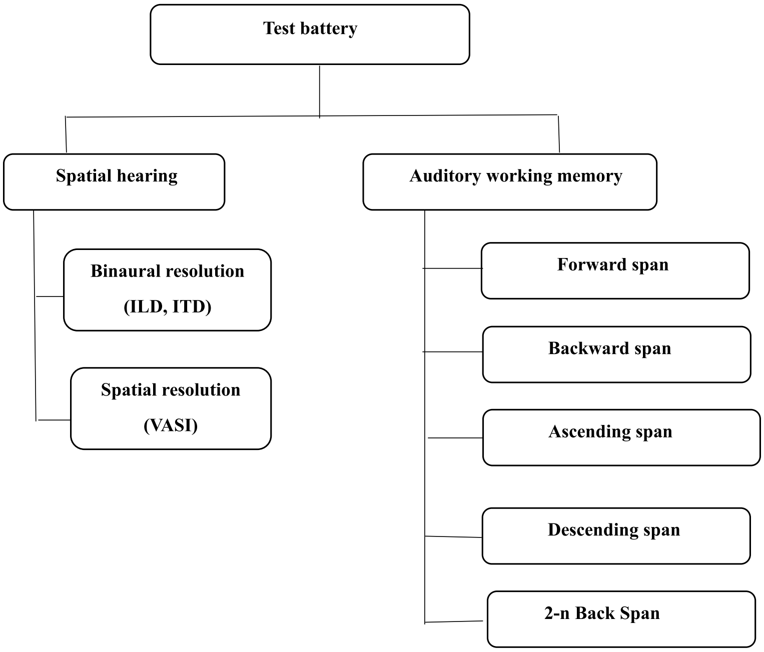

Fig. 1 Schematic representation of different tests assessing spatial hearing and auditory memory

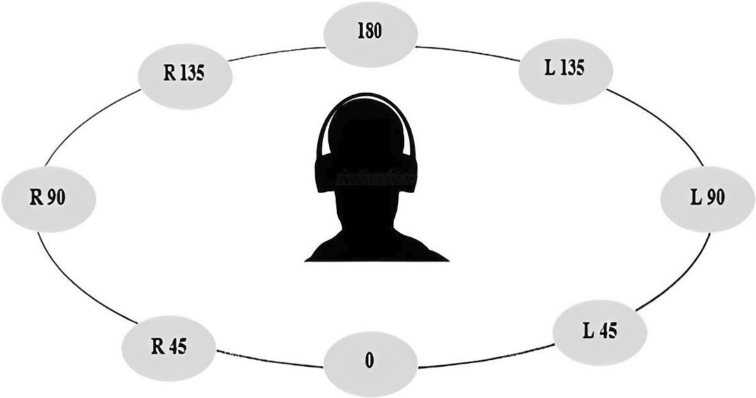

Fig. 2 A schematic representation of a head interface used in VASI for stimulus presentation and response acquisition

the ILD tasks, the step size was 2 dB. Testing was continued till ten reversals, and the last four reversals were averaged. The converged value of the reversals resulted in ITD and ILD thresholds that corresponded to 79.44% psychometric function.

Test of spatial resolution-virtual auditory space identification test (VASI)

Virtual acoustic space identification (VASI) [22] test employs virtual acoustic techniques to simulate direction by combining noise bursts with non-individualized head related transfer functions (HRTFs). VASI test has been empirically used in the assessment of spatial acuity within normal-hearing adults [23], and musicians [24] and has promising applications in the clinical population [25].

VASI testing was administered using a paradigm player [26] and the stimulus was given through Sennheiser HD 200 headphones (Wedenmark, Germany) at 60 dB SPL. VASI consists of eight virtual precepts, which are represented in Fig. 2. At eight different virtual locations, the stimulus was presented five times randomly, so there was a total of 40 presentations. For recording the response, the participants were instructed to click the mouse on the location shown on the graphical user interface, as represented in Fig. 2.

Each accurate identification VAS location received a score of one. Local specific and overall accuracy and reaction time scores were computed. The test results were instantly saved to an Excel file and tabulated for statistical analysis.

Tests for working memory

A series of working memory tests (Fig. 1) were conducted using the auditory module Smrithi Shravan software [27]. Working memory was assessed by presenting a string of stimuli to the participant at 60 dB SPL through Sennheiser HD 200 headphones (Wedenmark, Germany). Figure 3 gives the representation of the battery of auditory memory tests used in the study. The stimuli were series of digits (0 to 9, except 7) presented binaurally in Indian English spoken by a female speaker. The participants were instructed to listen carefully to the stimuli and perform a working memory retrieval associated with the task.

Forward span test and backward span

In this case, digit sequences were provided auditorily, and subjects were directed to enter the keys on the keyboard in the same (forward span) or reverse order (backward span) as presented. The interstimulus interval was one second. The above-mentioned spans were tracked using the adaptive staircase technique. If the response is correct, the difficulty level is increased by one level; if the response is incorrect, the difficulty level is reduced. This up-down was performed on six runs, and the average of the past four runs was used to estimate the mid-point of forward/backward span. The maximum score in both of these tests was also computed as the highest number of digits that were recalled by the participant.

Ascending span test and descending span test

Sequences of numerals were provided in auditory mode, as digits 0–9 were displayed on the screen. The individuals were directed to arrange the digits presented in ascending or descending order and type the keys on the computer. The above-mentioned spans were tracked using the adaptive staircase technique. If the response is correct, the difficulty level is increased by one level; if the response is incorrect, the difficulty level is reduced. This up-down was performed on six runs, with the average of the last four runs used to estimate the baseline and the mid-point of ascending/descending span. The maximum score in both of these tests was also computed as

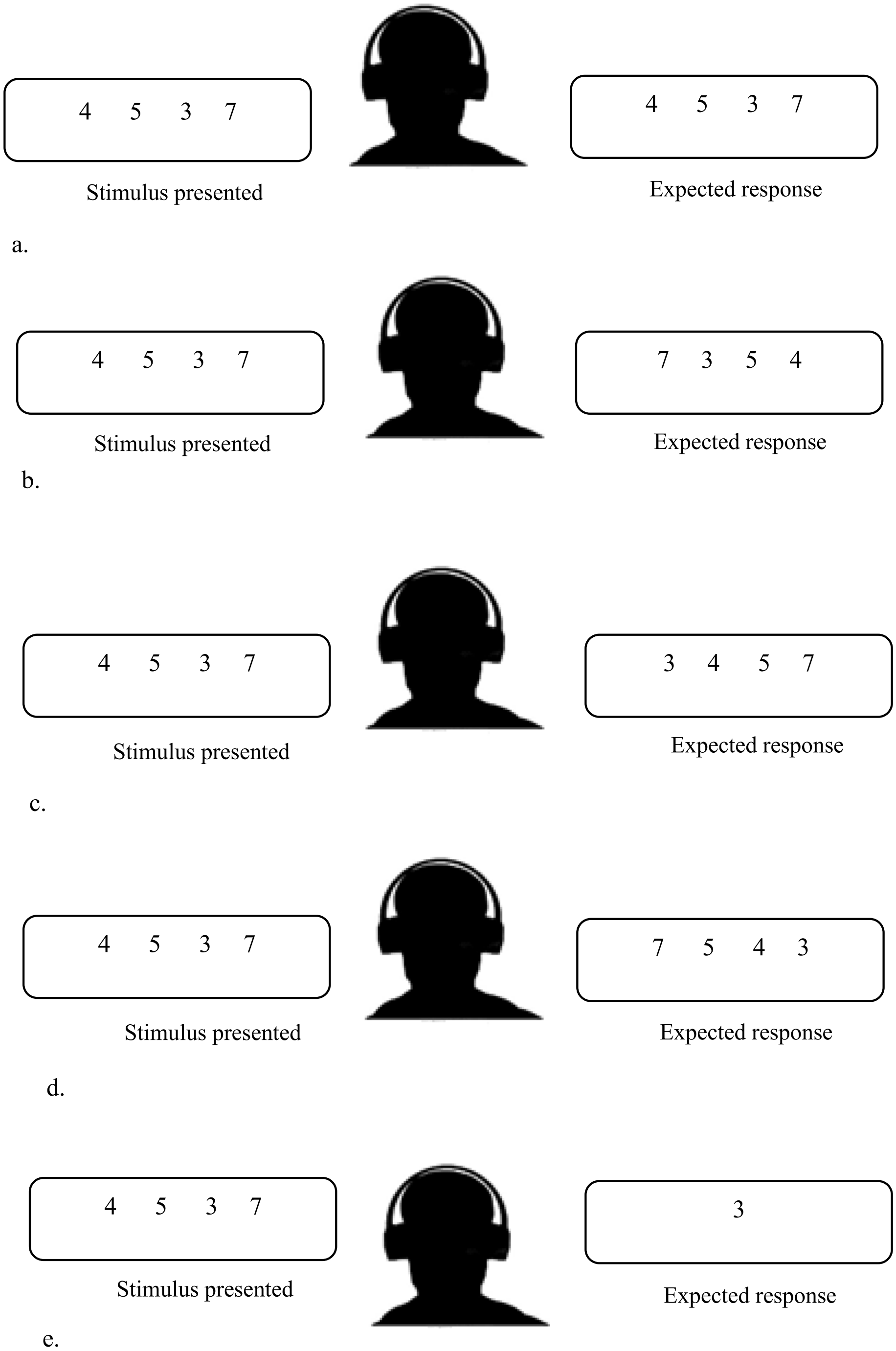

Fig. 3 Schematic representation of auditory memory tests conducted in the study. **a** forward span test, **b** backward span test, **c** ascending span test, **d** descending span test, and **e** 2n back test

the highest number of digits that were recalled by the participant.

2-n back span

In the 2n-back task, the current stimulus is judged whether it is matched with one that previously presented 'n' places in a sequence. In the 2-n backtest, the participant is instructed to select the last but two stimuli in each stimulus run. The software calculated the scores and response times for each test once it was completed. The scores were expressed as the number of correctly judged 2n-back.

The maximum point, midpoint, and average reaction time was recorded for the forward span test, backward span, ascending span test, and descending span test from the participants of the study. For the 2-n backtest, only the maximum score and reaction time were recorded.

Statistical analysis

Statistical Package for Social Sciences version 25 (IBM Corp., Armonk, NY, USA) was used for descriptive and inferential statistics. In descriptive analysis, mean and standard deviation was computed for all the test results. Shapiro–Wilk test of normality was administered to determine the normality of the collected data. Multivariate analysis of variance (MANOVA) was administered for determining the main effect of groups (if any). Further, for post hoc analysis Bonferroni test was administered.

Results

Effect of cerebral dominance on spatial hearing

Shapiro Wilk's findings indicated that the data were normally distributed ($p > 0.05$), thus parametric tests were used for analysis. The mean and standard deviation of all spatial hearing tests (ITD, ILD, and VASI-reaction time, accuracy score) is given in Table 1. ITD, ILD thresholds and VASI reaction time was comparable across the three groups while VASI accuracy scores were observed to be better in the bilateral hemisphere group than in the right and left dominant groups.

Inferential statistics using MANOVA test indicated that there is no main effect of cerebral dominance for ITD [$F(2, 42) = 0.46$, $p = 0.95$, $\eta_p^2 = 0.02$], ILD [$F(2, 42) = 0.85$, $p = 0.43$, $\eta_p^2 = 0.03$] and VASI reaction response [$F(2, 42) = 0.49$, $p = 0.61$, $\eta_p^2 = 0.02$]. However the significant main effect of cerebral dominance was found for VASI accuracy scores [F (2, 42) = 8.66, $p = 0.001$, $\eta_p^2 = 0.43$]. Further, the Bonferroni test results showed that participants who demonstrated bilateral hemispheric competence had significantly higher overall VASI accuracy scores than the right ($p = 0.01$) and the left ($p = 0.001$) hemisphere dominant groups. No statistical difference in overall VASI accuracy scores was observed between the latter two groups ($p > 0.05$).

Effect of hemisphere dominance on location-wise VASI accuracy scores

The effect of hemispheric dominance on VASI scores at each location is shown in Fig. 4. From visual inspection of Fig. 4, it can be indicated that the right dominant group had a better score in the left spatial location and the left dominant group a better score in the right spatial location.

Results of MANOVA indicated that cerebral dominance had a main effect on locations away from midline in the horizontal axis [R 45-F (2, 42) = 8.01, $p = 0.001$, $\eta_p^2 = 0.27$; R 135-F (2, 42) = 9.23, $p = 0.001$, $\eta_p^2 = 0.31$; L135-F (2, 42) = 4.10, $p = 0.02$, $\eta_p^2 = 0.16$; and L45-F(2, 42) = 4.75, $p = 0.01$, $\eta_p^2 = 0.19$]. Post-hoc Bonferroni test showed that individuals with bilateral dominance showed significantly higher VASI scores than left and right dominant groups. While the scores of left and right hemisphere dominant groups were similar across all the virtual locations ($p > 0.05$), the advantage of bilateral dominance was dependent on the location of the target stimuli, as shown in Table 2. The bilateral dominant group demonstrated significantly higher VASI scores compared to the right dominant at R 45 and R 135 locations. The former group also significantly outperformed left dominant group when the virtual source was away from the midline in the on left plane (L 45 and L 135).

Effect of cerebral dominance on working memory

Descriptive statistics of working memory tests including mean and standard deviation for maximum, mid accuracy scores and reaction time for all three groups is shown in Figs. 5 and 6, indicative of similarity in performance across the groups ($p > 0.05$).

There was no statistical main effect of cerebral dominance on working memory in terms of the maximum score, mid score, and reaction time in the 2n back, forward span, backward span, ascending digit span, and descending span tests according to the MANOVA analyses, as reported in Table 3.

Discussion

The present study is a preliminary attempt aimed to study the influence of cerebral dominance on spatial hearing and working memory. The spatial hearing was assessed

Table 1 Mean and standard deviation of ITD, ILD, and VASI in the bilateral, right, and left dominant group

Spatial hearing test	Bilateral dominant		Right dominant		Left dominant	
	Mean	SD	Mean	SD	Mean	SD
ITD (ms)	0.26	0.22	0.27	0.21	0.267	0.138
ILD (dB)	3.9	1.15	3.7	1.041	4.216	1.164
Overall VASI–reaction time (ms)	2378.89	659.67	2594.25	638.89	2549.72	596.90
Overall VASI–accuracy score	23.73	2.12	18.26	5.039	19.66	3.10

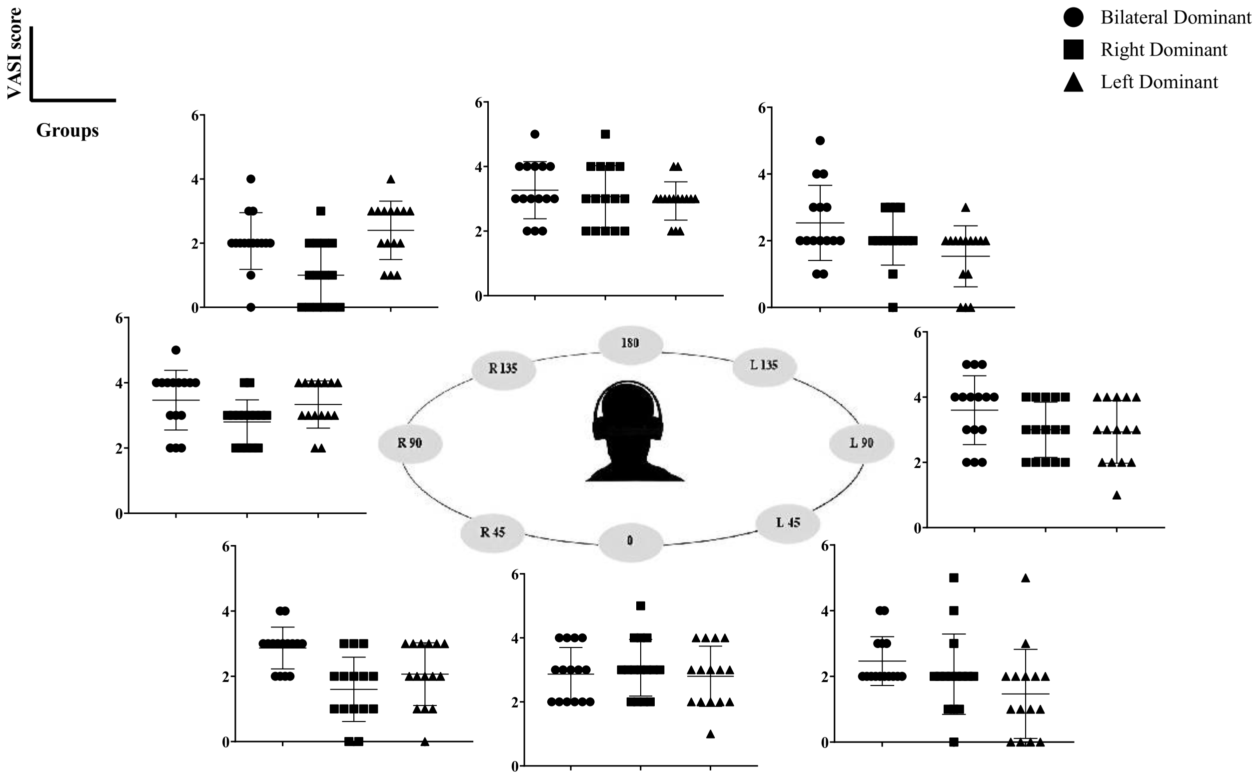

Fig. 4 Representation of scores across different spatial location for bilateral dominant (BD), right dominant (RD) and left dominant (LD)

Table 2 VASI score comparison at different spatial location for different groups using Bonferroni analysis

Spatial location	Group 1	Group 2	Mean difference	Standard error	*p* value
R 45	Bilateral dominant	Right dominant	1.26	0.32	0.001***
	Bilateral dominant	Left dominant	0.80	0.32	0.49
R 135	Bilateral dominant	Right dominant	1.06	0.34	0.01**
	Bilateral dominant	Left dominant	-3.33	0.34	1.000
L 135	Bilateral dominant	Right dominant	0.46	0.34	0.57
	Bilateral dominant	Left dominant	1.00	0.34	0.02*
L 45	Bilateral dominant	Right dominant	0.73	0.433	0.29
	Bilateral dominant	Left dominant	1.33	0.433	0.01**

Note: * - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$

through ITD, ILD, and VASI, whereas memory abilities were assessed on a comprehensive test battery which included forward span, backward span, ascending digit span, descending digit span, and 2n back tests.

The findings of the study indicated that cerebral dominance has no impact on ITD and ILD thresholds. However, cerebral dominance is observed to have a significant impact on overall VASI accuracy response. Compared to left and right dominant groups, individuals exhibiting bilateral dominance scored higher on virtual source identification, while there was no statistically significant difference in overall VASI scores in the former groups. The stronger capturing power of VASI in detecting cerebral asymmetry changes can be attributed to the advantages derived from its stimulus construction. The virtual stimuli for the VASI test were created using Slab 3D [28] HRTFs. The anatomical markers of the manikin (pinna shape, the head, and torso effects), in conjunction with sound waves coming from particular directions, produce direction-specific HRTFs. The physical interactions of the sound with the manikin generates all relevant acoustic cues (ILDs, ITDs, and spectral cues) for spatial

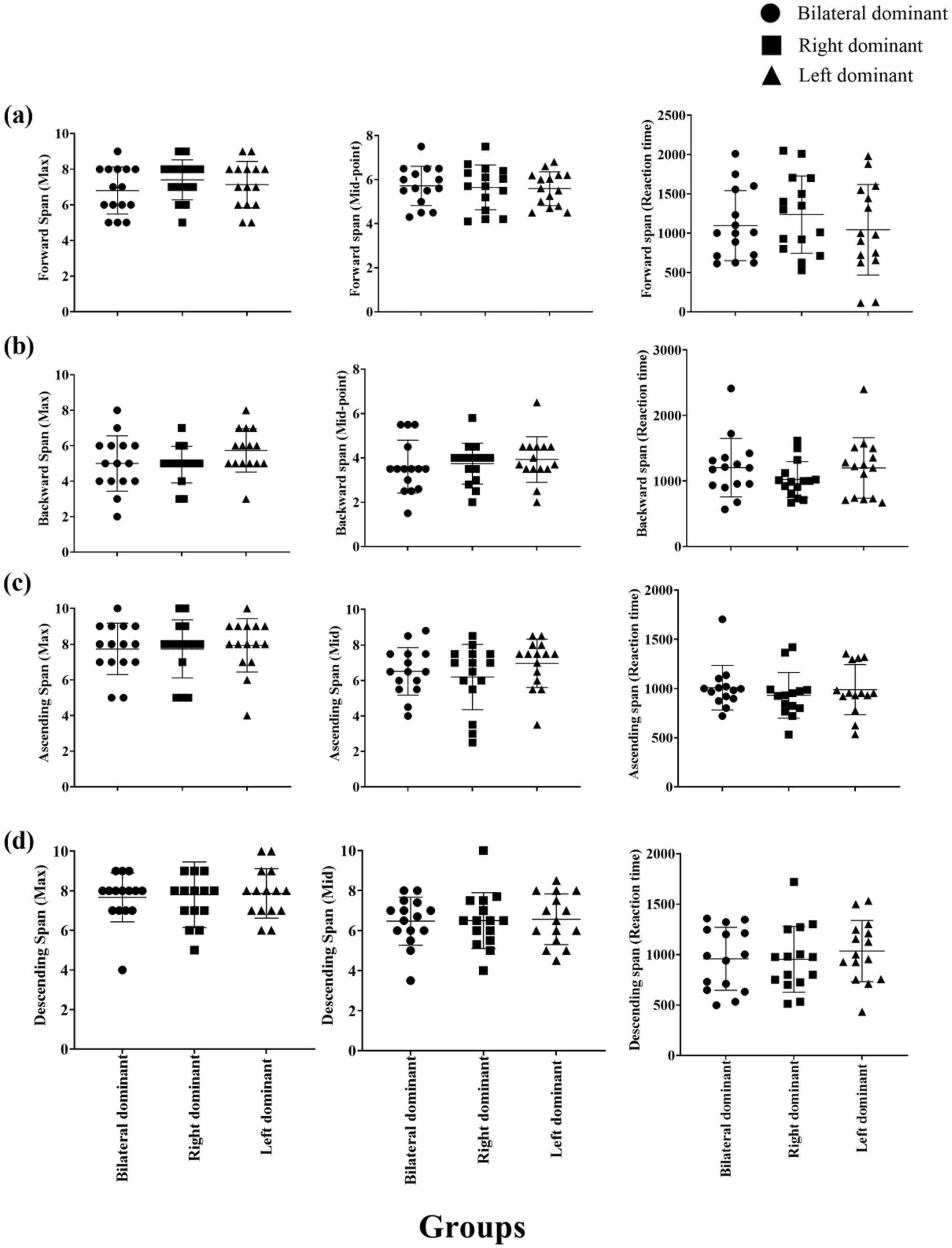

Fig. 5 Scatter plot representing maximum score (right panels), mid score (centre panels) and reaction time (left panels) of **a** forward span, **b** backward span, **c** ascending, and **d** descending span test

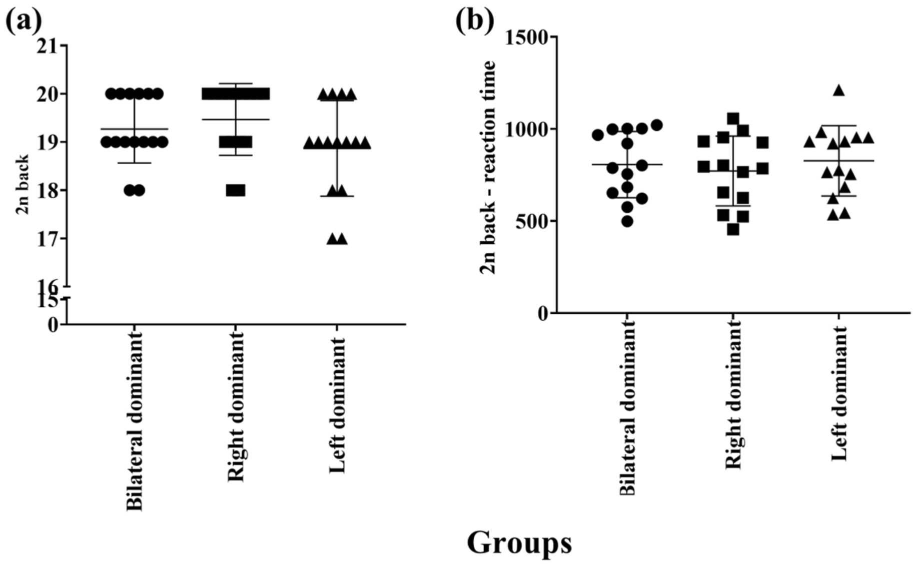

Fig. 6 Scatter plot representing **a** maximum score and **b** reaction time of 2n back test

Table 3 Results of MONOVA analysing the main effect of cerebral dominance across different scores in working memory tests

Test		*F(2,42)* =	*p*
Forward span	Maximum score	0.86	0.42
	Mid score	0.74	0.92
	Reaction time	0.07	0.93
Backward span	Maximum score	1.77	0.18
	Mid score	0.34	0.70
	Reaction time	0.24	0.78
Ascending digit span	Maximum score	0.08	0.91
	Mid score	0.94	0.39
	Reaction time	0.11	0.88
Descending span	Maximum score	0.08	0.92
	Mid score	0.21	0.97
	Reaction time	0.43	0.65
2n back	Maximum score	1.26	0.29
	Reaction time	0.12	0.88

perception. The use of standardized HRTFs in the VASI test would have facilitated the integration of the available binaural (ITD and ILD) and spectral cues considered integral for the construction of virtual auditory stimuli [29]. The presence of all the essential cues for spatial hearing in VASI enriched its value in the assessment of cerebral dominance when contrasted with using ITD or ILD tests where only one dimension of spatial hearing is accounted for (ITD measures temporal changes in spatial processing; ILD measures intensity changes in spatial processing).

On post-doc Bonferroni tests, the bilateral dominant group was observed to have significant advantages over both the right and left dominant group in the spatial processing of virtual stimuli (Table 1). Bilateral dominance has better VASI response than right or left because of whole brain activity, which enhances the better integration of ITD and ILD as well as spectral cues from both ears. Both hemispheres are necessary for an effective sound localization. Lesion studies often indicate contralateral localization deficits after unilateral lesions [30–33], indicating that one hemisphere is sufficient to precisely localize sounds in the contralateral region. On the other hand, studies on sound localization frequently report more precise location estimations when integrating input from different hemispheres [34–36], showing that combining information from bilateral auditory cortices is ideal. Specifically, some empirical research demonstrates that listener behavior affects spatial tuning in the auditory cortex [37, 38] when participant is actively localising sounds [39, 40]. Both these pieces of evidence may enhance the functional link between the bilateral auditory cortices, which in turn changes the neural representation of sound location in each hemisphere [41]. Thus, during passive listening, there is only a weak interhemispheric connection, and each hemisphere only has a partial picture of the mostly contralateral sound locations. In this instance, unique spatial information is integrated post hoc by combining the brain activity in each hemisphere using a location decoding method, leading to more precise location estimates. This 'bilateral gain' has been demonstrated in population coding studies that measured neural responses during passive listening [36, 42] which is the case in ITD and ILD tasks. As stimulus only lateralized to right side in both ITD and ILD tasks (see methods), the test was less challenging, and only passive attention was employed. But during VASI task, the use of randomly presented virtual stimuli made the task more challenging and sensitive to the effects of cerebral dominance.

In addition, location-specific VASI accuracy score results indicated that the right dominant group had a better score in the left spatial location and left dominant group acheived better score in right spatial location, owing to the fact of contralateral neural connection of nervous system [43–45]. This also corelates with lesion studies indicating contralateral localization deficits after unilateral lesions [30–33]. MANOVA results for location-specific VASI scores showed that VASI accuracy at 0, 180, R 90 and L 90 are not influenced by cerebral dominance. The VASI scores were comparable across groups in these locations. Cerebral dominance influence is observed at R 45, R 135, L 45 and L135 (Table 2). The VASI scores of bilateral dominant group was statistically higher than right dominant at R 45 and R 135 and from left dominant at L 45 and L 135. Bilateral dominance has pronounced effect at spatial locations away from mid-line, indicating better integration of spatial cues in this group.

Additionally, the results showed that cerebral dominance has no influence on working memory (Table 3). In terms of maximum score, mid score, and response time, the performance of the three study groups was comparable in all the working memory tests including the forward span, backward span, ascending digit span, descending digit span, and 2n back test. This suggests that working memory is unaffected by cerebral dominance. The effect of cerebral dominance is not prominent in this study, as we employed simple cognitive tasks, but complex cognition tasks can be affected by hemispheric differences, which can be explored in future.

Conclusions

It can be concluded that there is no influence of cerebral dominance on simple working memory tasks. In spatial hearing, VASI emerged as important test for inclusion in spatial test battery, as it best captures the differences in cerebral dominance. As a potential clinical implication, this study emphasises the significance of identifying brain dominance before administering spatial hearing tests.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43163-023-00461-9.

Additional file 1. Alert scale of cognitive scale.

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Authors' contributions

BN, NT, and BR wrote the article. NKV edited it. BN, NT, and BR performed audiological tests under guidance of NKV. All authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

Clearance was obtained Ethics approval and consent to participate. This study was approved by the ethical committee of Institutional ethical board (REF/AUD9/2022–23) of All India Institute of Speech and Hearing, Mysuru, India. Written informed consent was obtained from the participants.

Consent for publication

The participants gave written informed consent for the publication of the data and materials contained within this study.

Competing interests

The authors declare that they have no competing interests.

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References

1. Bear M, Connors B, Paradiso MA (2020). Neuroscience: exploring the brain, enhanced edition. Jones & Bartlett Learning
2. Sperry RW (1961) Cerebral organization and behavior: the split brain behaves in many respects like two separate brains, providing new research possibilities. Sci 133:1749–1757
3. Zatorre RJ, Belin P, Penhune VB (2002) Structure and function of auditory cortex: music and speech. Trends Cogn Sci 6:37–46
4. Zatorre RJ, Belin P (2001) Spectral and temporal processing in human auditory cortex. Cereb Cortex Oxford University Press 11:946–953
5. Bernhard R, Henning S, Hidehiko O, Ryusuke K, Christo P (2007) Left hemispheric dominance during auditory processing in a noisy environment. BMC Biol 5(1).
6. English L (2016). Right hemisphere involvement in auditory processing: a review. Inq J 8(10):1–10.
7. Obrzut JE, Conrad PF, Boliek CA (1989) Verbal and nonverbal auditory processing among left-and right-handed good readers and reading-disabled children. Neuropsychologia 27:1357–1371
8. Westerhausen R, Hugdahl K (2008) The corpus callosum in dichotic listening studies of hemispheric asymmetry: A review of clinical and experimental evidence. Neurosci Biobehav Rev 32:1044–1054
9. Kimura D (1967) Functional asymmetry of the brain in dichotic listening. Cortex 3:163–178
10. Wang X-D, Wang M, Chen L (2013) Hemispheric lateralization for early auditory processing of lexical tones: Dependence on pitch level and pitch contour. Neuropsychologia 51:2238–2244
11. Sequeira SDS, Specht K, Hämäläinen H, Hugdahl K (2008) The effects of background noise on dichotic listening to consonant–vowel syllables. Brain Lang 107:11–15
12. Specht K, Reul J (2003) Functional segregation of the temporal lobes into highly differentiated subsystems for auditory perception: an auditory rapid event-related fMRI-task. Neuroimage 20:1944–1954

13. Shtyrov Y, Kujala T, Ahveninen J, Tervaniemi M, Alku P, Ilmoniemi RJ et al (1998) Background acoustic noise and the hemispheric lateralization of speech processing in the human brain: magnetic mismatch negativity study. Neurosci Lett 251:141–144
14. Blauert J (1997). Spatial hearing: The psychophysics of human sound localization. MIT press
15. King AJ, Schnupp JW, Doubell TP (2001) The shape of ears to come: dynamic coding of auditory space. Trends Cogn Sci 5:261–270
16. Kaiser J (2015). Dynamics of auditory working memory. Front Psychol. 6:613
17. Schiavetti N, Metz DE (2006). Evaluating research in communicative disorders. Allyn & Bacon
18. Faul F, Erdfelder E, Lang A-G, Buchner A (2007) G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods 39:175–191
19. Crane LD (1989). The Alert scale of cognitive style. West Mich Univ.
20. Law LNC, Zentner M (2012) Assessing musical abilities objectively: construction and validation of the profile of music perception skills. PLoS One. 7(12):e52508
21. Grassi M, Soranzo A (2009) MLP: A MATLAB toolbox for rapid and reliable auditory threshold estimation. Behav Res Methods 41:20–28
22. Nisha KV, Kumar AU (2017) Virtual auditory space training-induced changes of auditory spatial processing in listeners with normal hearing. J Int Adv Otol 13(1) :118–27
23. Nisha KV, Kumar UA (2016) Effect of localization training in horizontal plane on auditory spatial processing skills in listeners with normal hearing. J Indian Speech Lang Hear Assoc. 30:28
24. Nisha KV, Durai R, Konadath S (2022) Musical training and its association with age-related changes in binaural, temporal, and spatial processing. Am J Audiol 31(3):669–683
25. Nisha KV. Effects of training regime on behavioural and electrophysiological correlates of auditory spatial processing in individuals with sensorineural hearing impairment. Doctoral Thesis submitted to the University of Mysore; 2018. Available from: http://192.168.100.26:8080/xmlui/handle/123456789/70
26. Paradigm Stimulus Presentation Software 2007. Available from: http://www.paradigmexperiments.com
27. Kumar UA, Sandeep M (2013) Development and test trail of computer based auditory-cognitive training module for individuals with cochlear hearing loss. Unpubl Dep Proj Mysuru AIISH.
28. Wenzel EM, Miller JD, Abel JS. Sound Lab: a real-time, software-based system for the study of spatial hearing. In: 108th AES Convention. Paris, France: The Audio Engineering Society; 2000. 1–27
29. Li S, Peissig J (2020) Measurement of head-related transfer functions: a review. Appl Sci 10:1–40
30. Clarke S, Bellmann A, Meuli RA, Assal G, Steck AJ (2000) Auditory agnosia and auditory spatial deficits following left hemispheric lesions: evidence for distinct processing pathways. Neuropsychologia 38:797–807
31. Jenkins WM, Merzenich MM (1984) Role of cat primary auditory cortex for sound-localization behavior. J Neurophysiol 52:819–847
32. Malhotra S, Hall AJ, Lomber SG (2004) Cortical control of sound localization in the cat: unilateral cooling deactivation of 19 cerebral areas. J Neurophysiol 92:1625–1643
33. Malhotra S, Stecker GC, Middlebrooks JC, Lomber SG (2008) Sound localization deficits during reversible deactivation of primary auditory cortex and/or the dorsal zone. J Neurophysiol 99:1628–1642
34. McAlpine D, Jiang D, Palmer AR (2001) A neural code for low-frequency sound localization in mammals. Nat Neurosci 4:396–401
35. Ortiz-Rios M, Azevedo FA, Kuśmierek P, Balla DZ, Munk MH, Keliris GA et al (2017) Widespread and opponent fMRI signals represent sound location in macaque auditory cortex. Neuron 93:971–983
36. Stecker GC, Harrington IA, Middlebrooks JC (2005) Location coding by opponent neural populations in the auditory cortex. PLoS Biol. 3:e78
37. Lee C-C, Middlebrooks JC (2011) Auditory cortex spatial sensitivity sharpens during task performance. Nat Neurosci 14:108–114
38. van der Heijden K, Rauschecker JP, Formisano E, Valente G, de Gelder B (2018) Active sound localization sharpens spatial tuning in human primary auditory cortex. J Neurosci 38:8574–8587
39. Atiani S, Elhilali M, David SV, Fritz JB, Shamma SA (2009) Task difficulty and performance induce diverse adaptive patterns in gain and shape of primary auditory cortical receptive fields. Neuron 61:467–480
40. Fritz J, Shamma S, Elhilali M, Klein D (2003) Rapid task-related plasticity of spectrotemporal receptive fields in primary auditory cortex. Nat Neurosci 6:1216–1223
41. van der Heijden K, Rauschecker JP, de Gelder B, Formisano E (2019) Cortical mechanisms of spatial hearing. Nat Rev Neurosci 20:609–623
42. Stecker GC, Middlebrooks JC (2003) Distributed coding of sound locations in the auditory cortex. Biol Cybern 89:341–349
43. Brancucci A, Babiloni C, Babiloni F, Galderisi S, Mucci A, Tecchio F et al (2004) Inhibition of auditory cortical responses to ipsilateral stimuli during dichotic listening: evidence from magnetoencephalography. Eur J Neurosci 19:2329–2336
44. Breebaart J, van de Par S, Kohlrausch A (2001) Binaural processing model based on contralateral inhibition III. Dependence on temporal parameters. J Acoust Soc Am. 110:1105–17
45. Langers DRM, van Dijk P, Backes WH (2005) Lateralization, connectivity and plasticity in the human central auditory system. Neuroimage 28:490–499

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