ISSN: 2083-389X
eISSN: 2084-3127
J Hear Sci, 2023; 13(4): 38–45
DOI: 10.17430/jhs/174089


# ASYMMETRIES IN COGNITION AND MEASURES OF INTELLIGENCE IN CHILDREN WITH HEARING LOSSES IN RIGHT OR LEFT EARS

Contributions:
A Study design/planning
B Data collection/entry
C Data analysis/statistics
D Data interpretation
E Preparation of manuscript
F Literature analysis/search
G Funds collection

**Grażyna Gwizda[1AB], Aleksandra Marciniak[2B], Grzegorz Bakalczuk[3E], Grażyna Mielnik-Niedzielska[2F]**

[1] Independent General Psychology Unit, Medical University of Lublin, Poland
[2] Chair and Department of Paediatric Otolaryngology, Phoniatrics and Audiology, Medical University of Lublin, Poland
[3] Department of Obstetrics and Gynaecology, Medical University of Lublin, Poland

**Corresponding author:** Grzegorz Bakalczuk, Department of Obstetrics and Gynaecology, Medical University of Lublin, Staszica 4-6, 20-081 Lublin, Poland; email: grzegorz.bakalczuk@resetnet.pl

**Abstract**

**Introduction:** Hemispheric asymmetry of the central nervous system affects various features of the brain involved in cognitive ability. Functional asymmetry, such as different hearing ability in the left or right ear, will also affect cognitive processes.

**Material and methods:** The aim of this study was to assess how intelligence measures and cognitive abilities in children and adolescents might have been affected by hearing deficits in the left or right ear. The study involved 208 children, 126 who were in an experimental group and 82 in a control group. In the experimental group, there were 26 children who were diagnosed with right-sided hearing loss, 34 with left-sided hearing loss, and 66 with bilateral hearing loss; all children in this group had used hearing devices since diagnosis. We assessed hearing unilaterally and bilaterally and looked for asymmetries in terms of intelligence measures and visual and spatial functioning.

**Results:** Children with bilateral hearing impairment had lower intelligence compared to those without impairment. Children with unilateral hearing impairment had similar intelligence level compared to well hearing children. Children with left-sided hearing impairment had higher intelligence compared to those with right-sided hearing impairment and lower nonverbal intelligence compared to well-hearing children. Children with right-sided hearing impairment had lower verbal intelligence.

**Conclusions:** Hearing impairment has an impact on various measures of intelligence, as well as on the organisation and performance of cognitive processes.

**Key words:** functional brain asymmetry • auditory system • cognitive capacity • child intelligence

---

## ASYMETRIE W POZNANIU I POMIARACH INTELIGENCJI U DZIECI Z UBYTKIEM SŁUCHU W PRAWYM LUB LEWYM UCHU

**Streszczenie**

**Wprowadzenie:** Asymetria półkul mózgowych ośrodkowego układu nerwowego to termin określający zróżnicowane specjalności półkul mózgowych w zakresie poszczególnych zdolności poznawczych. Funkcjonalna asymetria dotyczy nie tylko procesów poznawczych, lecz także zdolności słyszenia.

**Materiał i metody:** Celem tego badania była ocena funkcjonalnej asymetrii mózgu w testach inteligencji i procesów poznawczych u dzieci i młodzieży z niedosłuchem. Do badania przyjęto 208 dzieci. Grupa eksperymentalna liczyła 126 dzieci. Grupę kontrolną stanowiło 82 prawidłowo słyszących dzieci. Oceniliśmy asymetrię poziomu inteligencji, funkcji wzrokowo-przestrzennych oraz funkcji mowy w jednostronnym i obustronnym uszkodzeniu słuchu.

**Wyniki:** Dzieci z obustronnym uszkodzeniem słuchu charakteryzowały się niższym poziomem inteligencji w porównaniu z dobrze słyszącymi dziećmi. Dzieci z jednostronnym uszkodzeniem słuchu miały podobny poziom inteligencji jak dzieci dobrze słyszące. Dzieci z niedosłuchem lewostronnym charakteryzowały się wyższym poziomem inteligencji w porównaniu z dziećmi z niedosłuchem prawostronnym oraz niższym poziomem inteligencji niewerbalnej w porównaniu z dziećmi dobrze słyszącymi. Dzieci z prawostronnym uszkodzeniem słuchu miały niższy poziom inteligencji werbalnej.

**Wnioski:** Ubytek słuchu ma wpływ na poziom inteligencji, organizację i strukturę procesów poznawczych.

**Słowa kluczowe:** asymetria funkcjonalna mózgu • układ słuchowy • zdolności poznawcze • inteligencja dziecka

## Introduction

Hearing loss is becoming a disease of civilisation. Worldwide, more than a billion people struggle with hearing loss. The consequences of hearing loss depend on the age at which the hearing loss occurred, the degree of loss, and its side.

The human brain consists of two functionally diverse hemispheres, left and right. Each hemisphere is highly specialised to different functions. Hemispheric asymmetry of the central nervous system refers to diverse specialities of the brain hemispheres in terms of cognitive ability. Dynamic development studies of brain asymmetry have shown that multiple psychological functions are localised to each of the hemispheres. To control basic cognitive processes, each hemisphere operates separately. Functional specialization of the hemispheres is particularly evident for language and spatial vision. Lateralisation is defined as side dominance, which applies not just to body organs but also to cognitive functions [1].

Numerous clinical studies have revealed that the left hemisphere is dominant for verbal functions, statements, judgements, logic, and analysis, while the right hemisphere is dominant for visual perception and spatial imagination, nonverbal functions, visual and spatial perception, and emotions [2–7].

Speech perception is usually localised to the left hemisphere, while speech production is confined mostly to the right. Functional asymmetry applies not only to cognitive processes, but also to hearing ability. Dichotic listening is an experimental procedure used to study hearing lateralisation. Kimura showed that the right ear is dominant in speech perception [8–17] while the left ear is dominant for music and environmental sounds, emotional sounds, and speech tone [13,18–22]. Hearing asymmetry is a result of brain hemisphere lateralisation. Right ear dominance in perceiving speech stimuli is related to the structure of the whole hearing system and its attention processes [10,23]. Neuroimaging studies have confirmed that right ear is anatomically dominant [13,24,25]. Assessment of cortical auditory evoked potentials suggest that the right ear is dominant for receiving and processing verbal stimuli [12]. Right-sided hearing impairment tends to cause problems in language comprehension, communication, and sequential event arrangement, giving rise to dyslectic difficulties [26,27]. Left-sided hearing impairment tends to cause emotional problems and disturbance of music perception and rhythm [27,28]. Studies have revealed a right ear (projecting to left hemisphere) preference for processing verbal stimuli, while the left ear favours nonverbal stimuli. The left ear is dominant in music perception (melodies, harmonies), environmental sounds (dogs barking, birds singing), and emotional content (laughter, crying).

The aim of this study was to assess functional asymmetry in intelligence tests and cognition in children and adolescents with hearing losses in right or left ears. We assessed how the side and level of hearing disability affected cognitive processes and various measures of intelligence in a study group and compared them with a control group. We conclude that hearing impairment affects cognitive ability and this can produce lower outcomes on cognitive tests.

## Material and methods

The work here was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. Informed consent was obtained for experimentation with human subjects, and the work received Bioethics Committee approval (resolution number KE-0254/223/2013). The research did not receive any grant from funding agencies in the public, commercial, or not-for-profit sectors.

Raw data were gathered at the Department of Paediatric Otolaryngology, Phoniatrics and Audiology, Medical University of Lublin, Poland. Derived data supporting the findings of this study are available from the corresponding author on request. The study was conducted at the department during a diagnostic stay and hearing screening of children, but during the study they were all attending public schools.

There were 208 children and adolescents accepted into the study. The experimental group consisted of 126 children aged from 8 to 16 years old (average 13.4 years) suffering from sensorineural hearing insufficiency. They comprised 54 girls (average 12.9 years) and 72 boys (average 13.5 years); 26 children were diagnosed with right-sided hearing loss, 34 with left-sided hearing loss, and 66 with bilateral hearing loss. Among the children with bilateral deafness, hearing loss (30 to 70 dB) was diagnosed during the first 3 years of life; all had used hearing devices since diagnosis. Among the children with unilateral hearing impairment, hearing loss was less than 80 dB (severe deafness).

Bilateral hearing loss was diagnosed at screening. The children had used hearing devices from the age of 1 year old. All were under the care of a speech therapist and psychologist. In the group of subjects with unilateral sensorineural hearing loss, the diagnosis of hearing loss was made in the first years of life, although it was difficult to clearly determine how long the hearing loss had existed. The hearing loss ranged from 80 to 120 dB. In 29 subjects it was a consequence of mumps, in 5 children it was a result of prematurity, in 7 it was congenital, in 2 subjects it occurred after mechanical trauma, in 12 after an infection, and in 5 the etiology could not be determined. At the time of the study, they were all students at mass schools.

The development of the subjects was normal, and speech development was within the limits of age norms.

The control group consisted of 82 children aged from 8 to 16 years old (mean 13.4). All were patients hospitalised in the Department of Paediatric Otolaryngology, Phoniatrics and Audiology, Medical University of Lublin, Poland. Each patient had normal hearing, which was confirmed by audiometric assessment. The experimental and control groups were matched for age and gender (**Table 1** and **Table 2**). The groups were found to be homogeneous in terms of age (no significant differences between groups; $p = 0.622$). Similarly, the groups were found to be

**Table 1.** Ages of the subjects

| Groups | *N* | Mean | *SD* |
|---|---|---|---|
| Study group | 126 | 13.20 | 3.01 |
| Control group | 82 | 13.40 | 2.61 |

Note: Test statistic $t = 0.494$; DF = 206; $p = 0.622$

**Table 2.** Gender of the subjects

| | Study group | | Control group | |
|---|---|---|---|---|
| | *N* | % | *N* | % |
| Girls | 54 | 42.86 | 42 | 51.22 |
| Boys | 72 | 57.14 | 40 | 42.78 |

Note: Chi-squared = 1.391; DF = 1; $p = 0.238$

**Table 3.** Comparison of the level of general intelligence (full scale), verbal intelligence, and nonverbal intelligence (executive intelligence) in the control group and in the group with bilateral hearing loss

| Scale | Control group | | | Bilateral hearing loss group | | | |
|---|---|---|---|---|---|---|---|
| | *N* | Mean | *SD* | *N* | Mean | *SD* | *t* |
| Full scale | 82 | 106.7 | 11.7 | 66 | 98.9 | 10.6 | 3.490 ($p < 0.001$) |
| Verbal scale | 82 | 106.9 | 12.6 | 66 | 96.9 | 11.9 | 3.493 ($p < 0.001$) |
| Nonverbal scale | 82 | 105.2 | 11.8 | 66 | 100.8 | 9.4 | 1.741 (n.s.) |

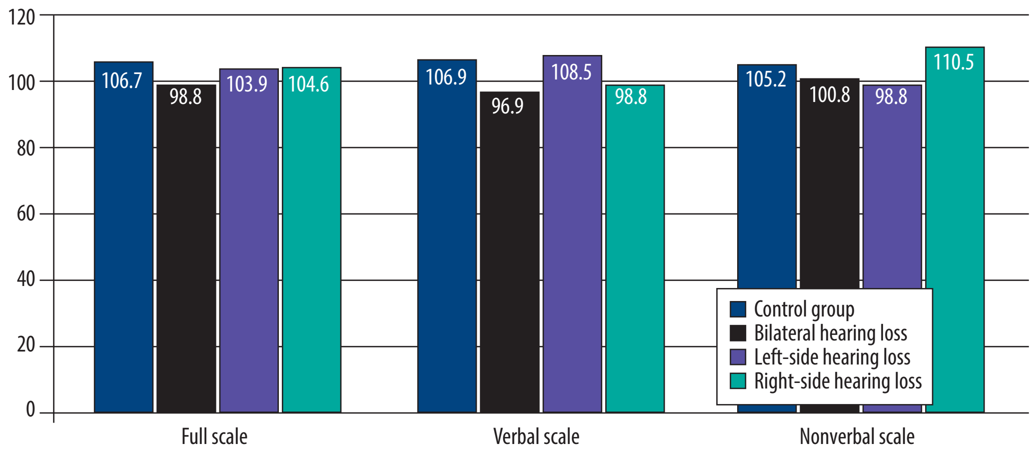


**Figure 1.** Levels of intelligence on the full scale, and on the verbal and nonverbal subscales, in the control group (blue) and in children with bilateral (black), left-sided (violet), and right-sided (green) hearing impairment

homogeneous in terms of gender (no significant differences between groups; $p = 0.238$).

To establish the levels of cognitive abilities and intelligence in patients enrolled for the study, a Polish adaptation of the *Wechsler Intelligence Scale for Children* (WISC-R) was administered [29]. This scale is designed for children aged 6 to 16 years old and consists of two parts – verbal and nonverbal. Each part consisted of five separate tests. We assessed unilateral and bilateral hearing impairments and looked for corresponding asymmetries in levels of intelligence, visual and spatial functions, and speech functions. The children's intellectual development was within age norms (**Table 3**).

Statistical analysis was based on Student's *t*-tests for two independent samples. Verification of results involved calculating the values of Student's *t*-test and comparing them with the values of these functions postulated by the null hypothesis. Normality of distributions was checked using a Shapiro–Wilk test.

## Results

**Figure 1** shows levels of intelligence on the full scale, and on verbal and nonverbal subscales, in the control group and in children with bilateral, left-sided, and right-sided hearing impairment.

Statistical comparison of results in the control group and the bilateral hearing impairment group showed statistically significant differences for all verbal scale subtests. The greatest differences were observed in subtests of vocabulary and understanding ($p < 0.001$), and less for notices ($p < 0.01$), arithmetic ($p < 0.02$), and similarity ($p < 0.05$). Children with bilateral hearing impairment had lower scores on all verbal scales compared to well-hearing children (**Figure 2**). Statistically significant differences were

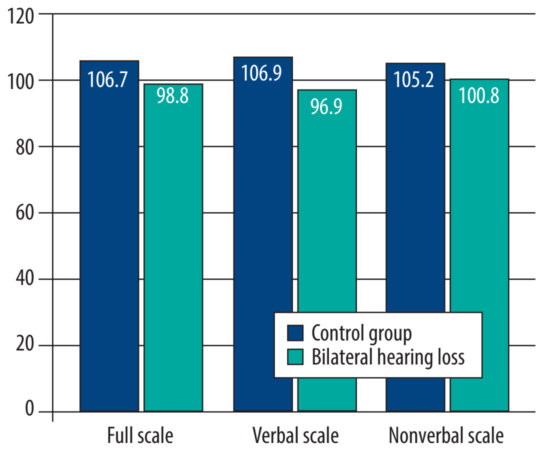


**Figure 2.** Levels of intelligence on the full, verbal, and nonverbal scales in the control group (blue) and in children with bilateral hearing impairment (green)

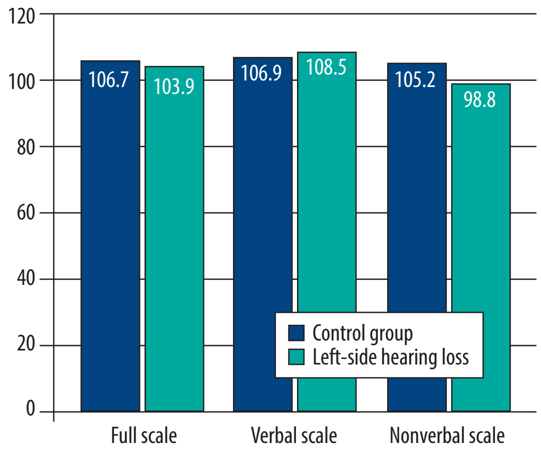


**Figure 4.** Levels of intelligence on the full, verbal, and nonverbal scales in the control group (blue) and in children with left-sided hearing impairment (green)

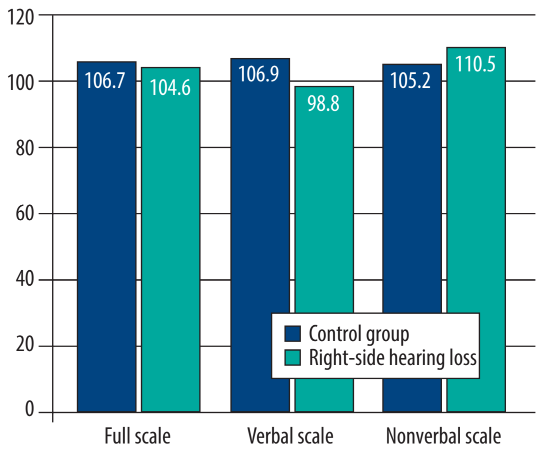


**Figure 3.** Levels of intelligence on the full, verbal, and nonverbal scales in the control group (blue) and in children with right-sided hearing impairment (green)

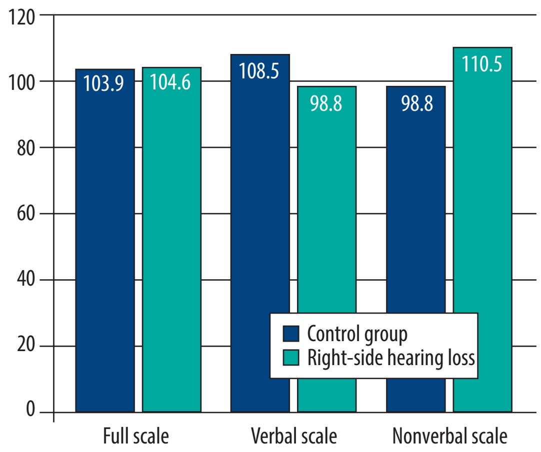


**Figure 5.** Levels of intelligence on the full, verbal, and nonverbal scales in children with left-sided hearing impairment (blue) and in children with right-sided hearing impairment (green)

observed for two subtests of the nonverbal scale – picture ordering ($p = 0.02$) and jigsaw ($p = 0.05$); other subtest outcomes were similar.

The general level of intelligence in the control group and in children with right-sided hearing impairment was similar (**Figure 3**). A statistically significant difference between the groups was observed for verbal intelligence ($p < 0.05$), and verbal intelligence was higher in the control group compared to children with right-sided hearing impairment. On the nonverbal scale, children in the control group achieved lower scores than children with right-sided hearing impairment, but the difference was not statistically significant. Children in the control group achieved statistically higher scores for similarities and dictionary subtests compared to children with right-sided hearing impairment ($p < 0.05$). In other subtests, results achieved by the control group were higher than in children with right-sided hearing impairment, but the differences were not statistically significant. In the subtest involving patterns from blocks, children with right-sided hearing impairment gained statistically higher scores compared to the control group ($p < 0.05$); other subtest outcomes were similar.

Statistical analysis of results in full and verbal scales did not show any significant differences between the control group and children with left-sided hearing impairment (**Figure 4**). Children in the control group achieved statistically significant better results on the nonverbal scale compared to children with left-sided hearing impairment ($p < 0.05$). Children in the control group had higher scores in the picture ordering and jigsaw subtests compared to children with left-sided hearing impairment ($p < 0.05$); other subtests outcomes were similar.

Children with unilateral hearing impairment achieved similar results in the general intelligence scale (**Figure 5**), but statistically significant differences were observed in verbal and nonverbal scales. Children with right-sided hearing impairment achieved better results in the nonverbal scale compared to children with left-sided hearing impairment ($p > 0.01$). Children with left-sided hearing impairment gained higher scores on the verbal scale compared to children with right-sided hearing impairment ($p < 0.02$). Children with left-sided hearing impairment scored higher results in all subtests of the verbal scale; only in the notices subtest were the results between the groups not statistically significant. Children with right-sided hearing impairment achieved better scores in picture ordering ($p < 0.05$) and patterns from blocks ($p < 0.01$); other subtest outcomes were similar.

## Discussion

Studies on the cognitive capacities and intelligence of people with hearing impairment are controversial and inexact. The literature shows that intellectual development achieved by patients with hearing impairment are higher on nonverbal scales compared to patients with properly functioning hearing systems. Lower scores can be explained by the neurological basis of hearing impairment [30]. Central nervous system deficiency may result in lower intelligence level. However, if nervous system damage does not occur in patients with hearing impairment, the results of intelligence tests are similar to normal hearing individuals. Studies on the cognitive abilities of children suffering from uni- and bilateral hearing impairment have shown that these children achieve lower scores in reading, vocabulary, word analysis, and orthography subtests, as well as science subjects, compared to healthy peers [31]. Sisco and Anderson studied children with hearing loss using the WISC-R nonverbal scale and compared the results with scores gained by well-hearing children [32]. The average intelligence of the deaf children was lower (98.8), while in the control group it was 100. This difference can be explained by a deficit in speech development, which causes slowing down of the development of numerous psychological skills. Myklebust found that children with hearing impairment have similar levels of nonverbal intelligence compared to normal hearing children, although the verbal score appears to be below average [33]. Similar outcomes were obtained in our study. Children with bilateral hearing impairment achieved lower scores in full and verbal scales compared to the control group (children with hearing impairment gained 98.8 on the general scale, while well-hearing children scored 106.7. These results can be explained by the higher linguistic abilities of healthy children compared to children with hearing deficits. On the verbal scale, children in the control group achieved a better mean outcome (106.9) compared to children with hearing impairment (96.9). There was no significant difference between the groups for the nonverbal scale. All results of tests on the verbal scale, which assess cognitive abilities, showed significantly lower values in children with hearing impairment compared to the control group; nonetheless, in our study the outcomes of children with unilateral hearing impairment did not vary significantly from those achieved by well-hearing individuals.

Unilateral hearing impairment leads to partial deficits in sound receiving capabilities. Children with left-sided hearing impairment had similar levels of verbal intelligence compared to the control group. Left-sided hearing impairment had lesser impact on cognitive development compared to right-sided hearing impairment. Patients with right-sided hearing impairment had lower verbal intelligence, which is similar to the nonverbal intelligence in the control group.

Our study revealed interesting differences regarding results in right- and left-sided hearing impairment groups.

Children with right-sided hearing impairment achieved higher scores on the nonverbal intelligence scale and lower scores on the verbal scale compared to children with left-sided hearing impairment. Jensen et al. and Niedzielski et al. reached similar conclusions – children with right-sided hearing impairment have lower scores on verbal scales [34–38]. Bess and Tharpe showed that children with unilateral hearing impairment have lower scores in auditory, linguistic, and behavioral tests compared to well-hearing peers [31]. According to Bluestone and Klein, unilateral hearing impairment affects linguistic ability by interfering with speech reception in the first months of life, which is a critical period of verbal communication development [35]. Klee and Davis-Dansky showed that children with unilateral hearing impairment have similar linguistic skills compared to well-hearing children [39]. Meanwhile, Culbertson and Gilbert measured linguistic abilities with the *Hiskey–Nebraska Test of Learning Aptitude* and found that children with hearing impairment had lower word recognition scores, and poorer scores on spelling and linguistic tests [40]. Studies on children with profound unilateral deafness have confirmed such children have difficulties with learning. Niedzielska et al. assessed the impact of unilateral hearing impairment on speech and voice quality and showed that children suffering from hearing impairment may experience disturbances to voice and speech [41]; children with hearing impairment that had been present for at least 4 years were diagnosed with omnifarious dyslalia. Jensen et al. suggested that children with right-sided hearing impairment achieved lower results in verbal tests, while children with left-sided hearing impairment had comparable results compared to well-hearing peers [34]. Similar outcomes were obtained in our study.

Our results of unilateral hearing impairment allow us to state that long-term deprivation of auditory stimuli may lead to a deficit in cognitive development. Lack of arousal coming from auditory organ towards certain regions of the cortex could result in functional reorganisation of the brain [42,43]. Both hemispheres function differently and independently control basic cognitive functions. Functional differentiation of hemispheres is noticeable mostly in regard to linguistic and visual and spatial functions. Studies have shown that the left hemisphere is more engaged in control of verbal functions, while the right hemisphere manages visual and spatial functions. Similar asymmetries are expected to apply to the auditory sense. Sounds received by the left ear are conducted towards the right hemisphere and conversely for the right ear. Cognitive difficulties depend on the side of hearing impairment and involve functions that are localised on the opposite side. Our study showed that children with right-sided hearing impairment had more developed non-verbal skills and less developed verbal skills. Linguistic functions are localised to the left hemisphere and nonverbal functions are localised to the right hemisphere, so, compared to well-hearing children, children with right-sided hearing impairment have lower verbal scale scores, but higher scores in visual and spatial analysis and synthesis. Children with right-sided hearing impairment have higher scores on nonverbal scales and lower scores on verbal scales compared to children with left-sided hearing impairment. Children with left-sided hearing impairment have similar scores on verbal scales compared to well-hearing children. Studies have shown specific development of cognitive functions in children and adolescents with hearing impairment. Stachyra derived similar outcomes [44]; he suggested that different development of cognitive capabilities of children with hearing impairment could be a result of diverse sensory preferences used in cognition and various impacts of speech on mental skills. Sound deprivation affects cognition in a characteristic way for deaf people, which depends on the side of hearing impairment.

Recent studies on hearing dysfunction have focused on assessing the cortex and its organisation. The brain recognises sounds and reacts appropriately [45]. Our study has confirmed that hearing impairment does affect cognitive development and brain organisation. The cognitive profiles of children with hearing dysfunction reflect neuropsychological outcomes of functional reorganisation of the brain and alterations in cognitive development, suggesting that there are specific profiles of how cognitive functions develop in children with hearing impairment depending on the kind (bilateral/unilateral) and side of dysfunction.

Studies using functional magnetic resonance imaging suggest that hearing impairment leads to functional reorganisation of the cortex [42,43]. In cases of congenital deafness, an inactive auditory cortex begins to process visual stimuli instead. In such cases, hearing aids are not as beneficial as when deafness is acquired at later ages. When the auditory cortex is deprived of auditory stimuli, it is recruited for processing and decoding of information provided to the brain by the eye and sent through visual pathway neurons [46].

Our study revealed that children with hearing impairment had better visual and spatial skills. This observation might be explained by sensory compensation, which means that mechanisms are initiated which aim to compensate for disabilities [47]. The literature suggests that the visual perception of patients with hearing dysfunction is more developed, and some studies have measured the specific visual capabilities of these patients. Lewis et al. showed that patients with hearing impairment can reproduce visual forms better than well-hearing people [44]. However, Prillwitz showed that patients with hearing impairment had poorer performance in comprehending relations between invisible elements [44]. Despite minor differences, most studies have confirmed a specific profile of visual and spatial ability in patients with hearing loss. Our study has revealed that children with bilateral hearing impairment had higher scores in comprehending visual material, as well as in visual and spatial analysis and synthesis, compared to well-hearing peers. Auditory plasticity is an interesting phenomenon when describing the cognitive abilities of patients with hearing impairment. Rapidly developing neuroimaging techniques of the central nervous system make it possible to measure processes and mechanisms over time in different regions. Recent studies indicate that the brain has the ability to reorganise and compensate for a deprived auditory input, which slowly begins to alter [42,43]. Patients with hearing impairment undergo functional reorganisation, so that auditory stimuli are processed by regions normally responsible for visual analysis [42]. Auditory deprivation leads to alterations in the hearing system. Studies using functional magnetic resonance have revealed that, during unilateral stimulation, there is symmetrical activation of both hemispheres in patients with unilateral hearing impairment, whereas in normal people cortical responses to unilateral sound stimuli are observed only collaterally [48]. Plastic alterations which take place in the cortex of patients with hearing impairment may result in diverse developmental profile of cognitive capabilities. Similar outcomes were obtained in our study.

## Conclusions

Recent studies have helped us to better understand the way the nervous system of people with hearing impairment reorganises. Longitudinal studies factoring in the length of hearing impairment, the age of hearing aid application, and the time the auditory path has received stimulation can be useful in devising the best therapeutic procedures. Recognition of how the cortex reorganises and achieves a specific cognitive profile in people with hearing impairment is valuable in supporting optimal training and rehabilitation methods.

Our study did not take into account many factors important in the development of communication in a child with hearing loss. Consequently, future studies need to take into account variables such as gender, lateralisation, duration of hearing aid use, and the effect of family environment and rehabilitation on the development of communication skills.

## Statements and declarations

The authors declare there are no conflicts of interest. Data and materials are available on request.

## References

1. Mroziak J. [Functional equivalence and asymmetry of the brain hemispheres]. Warszawa: Polska Akademia Nauk; 1992 [in Polish].
2. Milner B. Psychological defects produced by temporal lobe excision. Res Publ Assoc Res Nerv Ment Dis, 1958; 36: 244–57.
3. Zangwill O. Asymmetry of cerebral hemisphere function. In: Garland H, editor. Scientific Aspects of Neurology. London: Livingstone; 1961.

4. Bogen JE, Gazzaniga MS. Cerebral commissurotomy in man. J Neurosurg, 1965; 23: 394–9. https://doi.org/10.3171/jns.1965.23.4.0394
5. Levi-Agresti J, Sperry R. Differential perceptual capacities in major and minor hemispheres. Proc Natl Acad Sci, 1968; 61(3): 1151.
6. Bogen JE. The other side of the brain. I. Dysgraphia and dyscopia following cerebral commissurotomy. Bull Los Angeles Neurol Soc, 1969; 34(2): 73–105.
7. Bogen JE. The other side of the brain. II. An appositional mind. Bull Los Angeles Neurol Soc, 1969; 34(3): 135–62.
8. Kimura D. Physiological Psychology. Reading: Addison-Wesley; 1963.
9. Kimura D. Left-right differences in the perception of melodies. Q J Exp Psychol, 1964; 16: 355–8. https://doi.org/10.1080/17470216408416391
10. Kimura D. Functional asymmetry of the brain in dichotic listening. Cortex, 1967; 3: 163–78. https://doi.org/10.1016/s0010-9452(67)80010-8
11. Milner B. Hemispheric specialization scope and limits. In: Schmitt FO, Worden F, editors. The Neurosciences: Third study. Cambridge: MIT Press; 1974.
12. Sobótka S, Pizło Z, Budohoska W. Hemispheric differences in evoked potentials to pictures of faces in the left and right visual fields. Electroencephalogr Clin Neurophysiol, 1984; 59: 441–53. https://doi.org/10.1016/0168-5597(84)90003-0
13. Hugdahl K, Brønnick K, Kyllingsbæk S, Law I, Gade A, Paulson OB. Brain activation during dichotic presentations of consonant–vowel and musical instrument stimuli: a $^{15}$O-PET study. Neuropsychologia, 1999; 37: 431–40. https://doi.org/10.1016/S0028-3932(98)00101-8
14. Corballis PM, Funnell MG, Gazzaniga MS. Hemispheric asymmetries for simple visual judgments in the split brain. Neuropsychologia, 2002; 40: 401–10. https://doi.org/10.1016/S0028-3932(01)00100-2
15. Bamiou DE, Sisodiya S, Musiek FE, Luxon LM. The role of the interhemispheric pathway in hearing. Brain Res Rev, 2007; 56: 170–82. https://doi.org/10.1016/j.brainresrev.2007.07.003
16. Brancucci A, Della Penna S, Babiloni C, Vecchio F, Capotosto P, Rossi D, et al. Neuromagnetic functional coupling during dichotic listening of speech sounds. Hum Brain Mapp, 2008; 29(3): 253–64. https://doi.org/10.1002/hbm.20385
17. Kochanek K, Dajos-Krawczyńska K, Piłka A, Biegun K, Skarżyński H. [Evaluation of the reproducibility of the results of the dichotic digit test (DDT) in school-aged children]. Otorynolaryngologia, 2015; 14(2): 79–88 [in Polish].
18. Price CJ. The anatomy of language: contributions from functional neuroimaging. J Anat, 2000; 197(3): 335–59. https://doi.org/10.1046/j.1469-7580.2000.19730335.x
19. Belin P, Zatorre RJ, Lafallie P, Ahad P, Pike B. Voice-selective areas in human auditory cortex. Nature, 2000; 403: 309–12. https://doi.org/10.1038/35002078
20. Borod JC. The Neuropsychology of Emotion. Oxford: University Press; 2000.
21. Zatorre RJ, Chen JL, Penhune VB. When the brain plays music: auditory–motor interactions in music perception and production. Nat Rev Neurosci, 2007; 8: 547–58. https://doi.org/10.1038/nrn2152
22. Zatorre RJ, Halpern AR, Bouffard M. Mental reversal of imagined melodies: a role for the posterior parietal cortex. J Cogn Neurosci, 2010; 22: 775–89. https://doi.org/10.1162/jocn.2009.21239
23. Kinsbourne M. The cerebral basis of lateral asymmetries in attention. Acta Psychol, 1970; 33: 193–201. https://doi.org/10.1016/0001-6918(70)90132-0
24. Zatorre RJ. Discrimination and recognition of tonal melodies after unilateral cerebral excisions. Neuropsychologia, 1985; 23: 31–41. https://doi.org/10.1016/0028-3932(85)90041-7
25. Belin P, Zilbovicius M, Crozier S, Thivard L, Fontaine A, Masure MC, et al. Lateralization of speech and auditory temporal processing. J Cogn Neurosci, 1998; 10(4): 536–40. https://doi.org/10.1162/089892998562834
26. Lieu JEC, Tye-Murray N, Karzon RK, Piccirillo JF. Unilateral hearing loss is associated with worse speech-language scores in children. Pediatrics, 2010; 125(6), 1348–55. https://doi.org/10.1542/peds.2009-2448
27. Kurkowski Z. [Auditory lateralization and language communication disorders]. Audiofonologia, 2002; 21: 179–86 [in Polish].
28. Kurkowski Z. [Unilateral deafness – single-ear hearing]. Audiofonologia, 2000; 17: 143–51 [in Polish].
29. Matczak A, Piotrowska A, Ciarkowska W, Wechsler D. [D. Intelligence Scale. Wechsler Intelligence Scale for Children – modified version (WISC-R)]. Warszawa: Pracownia Testów Psychologicznych Polskiego Towarzystwa Psychologicznego; 1991 [in Polish].
30. Vernon M. Fifty years of research on the intelligence of deaf and hard-of-hearing children: a review of literature and discussion of implications. J Deaf Stud Deaf Educ, 2005; 10: 225–31. https://doi.org/10.1093/deafed/eni024
31. Bess FH, Dodd-Murphy J, Parker RA. Children with minimal sensorineural hearing loss: prevalence, educational performance, and functional status. Ear Hear, 1998; 19: 339–54. https://doi.org/10.1097/00003446-199810000-00001
32. Sisco FH, Anderson RJ. Current findings regarding the performance of deaf children on the WISC-R. Am Ann Deaf, 1978; 123(2): 115–21.
33. Myklebust H. The Psychology of Deafness. 2nd ed. New York: Grune & Stratton; 1964.
34. Jensen JH, Johansen PA, Børre S. Unilateral sensorineural hearing loss in children and auditory performance with respect to right/left ear differences. Br J Audiol, 1989; 23: 207–13. https://doi.org/10.3109/03005368909076501
35. Niedzielski A. [Cognitive processes in people with impaired hearing in the light of selected research methods]. Lublin: Uniwersytet Medyczny w Lublinie; 2011 [in Polish].
36. Niedzielski A, Humeniuk E, Błaziak P, Gwizda G. Intellectual efficiency of children with unilateral hearing loss. Int J Pediatr Otorhinolaryngol, 2006; 70(9): 1529–32. https://doi.org/10.1016/j.ijporl.2006.02.011
37. Niedzielski A, Humeniuk E, Blaziak P, Czochra T. Sensorineural hearing loss and intellectual development in children. Annales Universitatis Mariae Curie-Sklodowska, Sect D, 2006; 40(16): 139–43.
38. Niedzielski A, Mielnik-Niedzielska G, Blaziak P. [Influence of profound unilateral hearing loss on developement of intellectual ablities in children]. Pol J Environ Stud, 2006; 15(6B): 603–5 [in Polish].
39. Klee TM, Davis-Dansky E. A comparison of unilaterally hearing-impaired children and normal-hearing children on a battery of standardized language tests. Ear Hear, 1986; 7: 27–37. https://doi.org/10.1097/00003446-198602000-00006
40. Culbertson JL, Gilbert LE. Children with unilateral sensorineural hearing loss: cognitive, academic, and social development. Ear Hear, 1986; 7: 38–42. https://doi.org/10.1097/00003446-198602000-00007

41. Mielnik-Niedzielska G, Wroczek-Glijer E, Kurkowska E, Broda T, Blicharz R, Niedzielski A. [Voice and speech behavior in children with unilateral hearing loss]. Audiofonologia, 2001; 19: 203–7 [in Polish].
42. Cieśla K. [Plasticity of the auditory system: studies using neuroimaging methods]. Now Audiofonol, 2013; 2(3): 16–23 [in Polish].
43. Anderson CA, Lazard D, Hartley DE. Plasticity in bilateral superior temporal cortex: effects of deafness and cochlear implantation on auditory and visual speech processing. Hear Res, 2017; 343: 138–49. https://doi.org/10.1016/j.heares.2016.07.013
44. Stachyra J. [Cognitive abilities and mental capabilities of students with hearing impairment]. Lublin: Wydawnictwo UMCS; 2001 [in Polish].
45. Pluta A, Wolak T, Skarżyński H. [Study of hemispheric dominance for speech function using magnetic resonance imaging technique]. Now Audiofonol, 2014; 3(3): 9–16 [in Polish].
46. Matusiak M, Skarżyński H. [How does a very young brain hear, and what if it can't hear?] Wszechświat: tygodnik popularny poświęcony naukom przyrodniczym, 2019, r. 137, t. 120, z. 1/3 [in Polish].
47. Obrębowski A. [Hearing loss and speech disorders in children]. Otolaryngologia, 2004; 3(2): 51–4 [in Polish].
48. Moore DR, Devlin JT, Raley J, Tunbridge E, Lanary K, Floyer-Lea A, et al. Effects of long term unilateral hearing loss on the lateralization of fMRI measured activation in human auditory cortex. In: Syka J, Merzenich MM, editors. Plasticity and Signal Representation in the Auditory System. New York: Springer; 2005, 335–46. https://doi.org/10.1007/0-387-23181-1_34