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Development of Auditory Analysis Processes in Cochlear Implant Users Through Software Tools

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Abstract

Introduction. Modern technology for auditory prostheses (digital hearing aids, cochlear implantation) creates conditions for auditory rehabilitation of individuals with severe hearing loss and even deafness. In this case, the important task of developing and updating sensory experiences arises, including the formation of the primary auditory–speech analysis processes, the consolidation of new intersensory connections, and the mechanisms of auditory–motor integration, which form the basis for communication and cognitive activity under new interactions with the environment. An effective solution to this psychophysiological problem can be facilitated by using specialized software that provides a targeted training of the perception skills necessary to implement the function of auditory–speech communication in patients with hearing impairments and by objective assessment of the individual progress of their rehabilitation using psychophysical methods. This study aimed to test the effectiveness of using software in sophisticated situations of rehabilitation after cochlear implantation. **Methods.** The specially designed software tools were used to develop the processes of auditory analysis of perception and speech in cochlear implant users of different ages with pre- and post-lingual deafness. The results were assessed according to psychophysical testing based on quantitative indicators of correct recognition and reaction time. Three series of the study were related to the following sophisticated rehabilitation situations: (a) late implantation (n = 32),

(b) auditory analysis of dynamic signals during the perception of prosodic information in speech (n = 36), and (c) in conditions of spatial orientation (n = 25). **Results.** New data and the results of their comparison indicated a significant improvement in the detection and analysis of basic spectral-temporal features of non-speech and speech signals (interruption by a pause, change in a rhythmic pattern of sound stimulation, location and movement of the sound source, phonetic categories and prosodic characteristics of speech), as well as the use of auditory–speech skills by cochlear implant users in everyday situations after training. **Discussion.** In general, experience in the practical use of software tools indicates that it is advantageous to integrate them into methodological tools for cochlear implant centers and auditory training in the education of children with hearing impairments.

Keywords

auditory–speech analysis, cochlear implantation, software tools for auditory training, auditory rehabilitation of deaf people, phonemic awareness, perception of speech prosody, orientation in acoustic environments, auditory–speech function, psychophysical testing

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Introduction

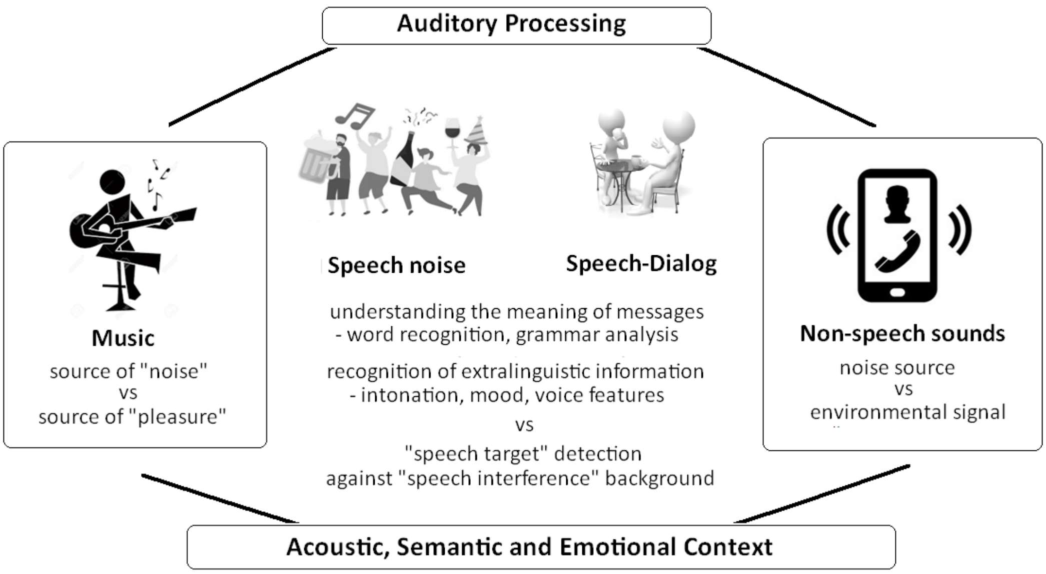
Cochlear implantation is currently the most effective method of restoring auditory perception of deaf people (Wilson & Dorman, 2008; Tavartkiladze, 2013; Rulenkova & Smirnova, 2003; Koroleva, 2016; Korolev & Ogorodnikova 2019). A cochlear implant (CI), surgically inserted into the cochlea of a deaf person, can replace damaged auditory receptors and restore the transmission processes of acoustic information to the central parts of the auditory system through electrical stimulation of auditory nerve fibers (Loizou, 1998; Wilson & Dorman, 2008; Tavartkiladze, 2013; Koroleva, 2016). However, such prosthetics to some extent change the conditions and quality of auditory perception, since the sound signals transmitted by the CI to the central nervous system differ considerably from the signals transmitted by a normally functioning cochlea. After surgical implantation, all patients need auditory–speech rehabilitation aimed at restoration (for post-lingual deafness) and development (for pre-lingual deafness) of the processes of auditory analysis and pronunciation skills in speech (Mironova, Sataeva, & Frolenkova, 2005; Borovleva, 2014; Harris et al., 2016; Koroleva, 2016; Zamiri, Ahmadi, Joulaie & Darouie, 2017; Koroleva, Ogorodnikova, Pak, & Levin, 2017; Koroleva & Ogorodnikova, 2019).

To restore the auditory-speech function of deaf patients with CI, an 'auditory' method has been developed. It highlights the systematic development of auditory analysis processes with CI in patients as a priority area of postoperative rehabilitation (Koroleva, 2014). The basis of the 'auditory' method is the idea that surrounding sounds and speech are acoustic signals with common physical and perceptual characteristics, and their processing processes are based on common basic operations of auditory analysis in the higher parts of the auditory system and the brain as a whole. At the same time, the concept of the method allows the identification of different target information in the same acoustic signal. For example, speech in a dialogue situation is primarily the semantics of a statement and extralinguistic information about the state of the interlocutor. In a 'party' situation, the speech of its participants becomes a competing signal that masks the speech message of a target speaker. Thus, the same sound can be a 'useful' signal that the brain seeks to isolate from the environment, or a 'noise' that it must ignore in order to solve the complex perceptual task of isolating an acoustic 'target' (Fig. 1). In this regard, an important point is the absence of pronounced central auditory processing disorders in CI users (Moore, 2012; Musiek & Chermak, 2014; Boboshko, Garbaruk, Zhilinskaya, & Salakhbekov, 2014; Koroleva, 2016; Gvozdeva, Sitdikov, & Andreeva, 2020), as well as organizing adequate auditory training and creating conditions for the development of auditory-speech skills with CIs in everyday communication situations. The use of training and development of hearing skills with CIs under natural conditions provides the possibility of consistent updating and formation of central mechanisms for detecting, distinguishing and recognizing non-speech and speech signals of varying degrees of complexity, auditory-speech memory, auditory selective attention and expanding the base of new auditory images of speech and non-speech signals from their intersensory (primarily audiovisual) connections.

Based on the 'auditory' method and fundamental knowledge about the physiological mechanisms of human speech and spatial hearing, specialists from Saint-Petersburg Research Institute of Ear, Throat, Nose and Speech, Ministry of Health, together with Pavlov Institute of Physiology, Russian Academy of Sciences, have created a set of software tools that provide conditions for teaching and training the auditory-speech function of CI users (Ogorodnikova, Koroleva, Lyublinskaya, & Pak, 2008; Koroleva et al., 2013). The use of this complex makes it possible to implement sophisticated techniques aimed at developing the constant perception of speech signals under conditions of speaker variability (various voice characteristics) and background interference; stimulation with complicated sound sequences with dynamic changes in parameters (interruption with a pause, comparison of rhythmic and melodic patterns, detection of movement of a sound or speech source). Software tools also make it possible to save digital protocols of individual classes and the entire rehabilitation course to assess its effectiveness and the degree of formation of the auditory analysis operation based on the parameters obtained – the number of repeated listenings, the number of correct recognitions, and reaction time (Ogorodnikova et al., 2008; Koroleva et al., 2013; Koroleva et al., 2021). It is also important that the training procedures use visual reinforcement of acoustic stimulation (images/text on the monitor screen) and feedback for the patient. This provides the opportunity to work not only in the classroom mode under the supervision of a speech therapist, but also at home with assessment of results based on express assessment of task completion or intermediate self-testing. We should note that recording current progress and difficulties has an impact on the psychological state of patients and their motivation to continue the course of rehabilitation (Moore, 2012; Koroleva et al., 2021). Recording achievements and difficulties is also considered as an important element in working with patients at risk of refusing to use CIs, including late-implanted deaf adolescents who have a psychological basis for manifestations of communicative and social deprivation (Ermakov, Gorelov, 2022).

Figure 1

A simplified illustration of the complexity of auditory analysis processes under ambiguous conditions of the acoustic signals surrounding an individual



The modular structure of the software package and the range of specified parameters, which allow taking into account the auditory–speech level of auditory and speech perception skills of training participants and the degree of their adaptation to CI, can increase the efficiency of solving the assigned correction tasks (Solodukhin et al., 2020).

The article analyzes the experience and main results of practical using the software package in sophisticated situations, the development of recognition of environmental sounds and categorical discrimination of sound units of speech in a conditional risk group (CI refusal), the analysis of dynamic changes in speech (prosody) and in spatial perception (movement of a sound source) in CI users of different ages and levels of auditory-speech perception skills.

Methods

Methodological conditions and study participants

Series 1

In this part of the work, we assessed the effectiveness of using an updated set of software tools for the development of basic skills in auditory perception of non-speech sounds with various spectral-temporal characteristics and the processes of phonemic analysis of speech signals in prelingually deafened adolescents implanted at an older age (conditionally, a risk group for CI refusal). The training course (6 months) was completed by 32 adolescents aged 9 to 17 years with pre-lingual deafness and experience in using CIs (TEMPO+, OPUS-2; MED-EL) from 6 months to 7 years. Because of the high cost of the CI, all adolescents from this part of the work, as well as participants in other series of similar training (Koroleva et al., 2017), underwent only unilateral prosthetics.

A total of 27 adolescents from the group attended a school for children with hearing impairments, 5 attended a comprehensive school. All teenagers studied with a speech therapist using traditional oral method. Their inclusion in the training course at Saint-Petersburg Research Institute of Ear, Throat, Nose and Speech was determined by dissatisfaction with the results of implantation and/or manifestations of refusal to use CIs.

The prepared course of lessons included exercises on the perception of sound signals of different durations, rhythmic organization, timbres, voice fundamental frequency, and phonemic categories. Auditory analysis skills were developed in parallel with the correction of the pronunciation aspect of speech based on new possibilities of auditory control based on CI. Parents of the learners also carried out independent work with their children on tasks from the set of manuals entitled I Learn to Listen and Speak (Koroleva, 2014).

The results were assessed according to a number of tests: discrimination of environmental sounds (11 everyday sounds with different spectral-temporal characteristics, including the sound of water, the sound of broken glass, the sound of a hammer, the sound of human steps, etc.); perception of the rhythmic pattern of sound sequences (5 patterns of 3 elements of different durations – long/short; for 3 different musical timbres and 3 pitch options); determination of the gender of the voices of speakers (4 speakers, male/female voice); recognition of speech signals of the target speaker under conditions of voice competition (12 words, 2 speakers – a man and a woman). We compared data from testing protocols before and after completing the training course, as well as scores on the Meaningful Auditory Integration Scale (MAIS) and the Use of Oral Speech Scale (MUSS) to assess the processes of spontaneous speech development (Ogorodnikova et al., 2008; Koroleva et al., 2013; Koroleva, 2016; Koroleva et al., 2017).

Series 2

This series was related to the study of the characteristics of CI users' perception of the dynamic characteristics of acoustic signals in speech and music. It is known that CI perception has limitations in distinguishing the pitch of sound signals and changes in voice fundamental frequency (F0), which are important for analyzing the melodic structure of musical works, prosodic information in speech, as well as distinguishing linguistic units in a number of tone languages (Li, Tang, Lu, Wu & Chang, 2021). This position has stimulated a number of studies on the perception of speech intonation by CI users in different language systems (Wang et al., 2012; Chen et al., 2013; Chen, Wong, Chen & Xi, 2014; Marx et al., 2015; Koroleva et al., 2016).

In Russian colloquial speech, the main prosodic categories are interrogative (ascending F0 contour) and affirmative (descending F0 contour) types of intonation structures (Bryzgunova, 1977; Svetozarova, 1982). Their reliable discrimination improves the quality of perception of speech information in communicative situations, and also contributes to improving the quality of perception of music with CIs (Drennan & Rubinstein, 2008; Bradley, 2016; Lehmann & Paquette, 2015).

The study involved 36 patients after unilateral implantation with at least 3 months of experience in the use of CIs (TEMPO+, OPUS-2; MED-EL). In the majority of patients (79 %), surgery was performed on the right ear. Among them, 21 were adult post-lingual patients aged 19–60 years and 15 represented a group of children and adolescents (aged 8–16 years) with pre-lingual deafness. All training participants were presented with a set of speech stimuli consisting of 20 short sentences with affirmative or questioning intonation, spoken by 4 speakers (2 men and 2 women with a F0 range from 90 to 240 Hz). The results were analyzed by comparing the test parameters before and after training.

Series 3

In this part of the study, the potential of spatial perception training in patients with one-side CI was assessed based on additional analysis of the data obtained (Ogorodnikova, Koroleva, Pak, 2020). 25 patients aged 9-39 years with different speech level (10 post-lingual and 15 pre-lingual) were the participants. All participants had more than a month of experience in using CI. In 5 patients, implantation was left-sided (left ear with CI), while in others ones – right-sided (right ear with CI).

Monaural prosthetics provides a high level of development and restoration of human speech communication, but limits the quality of spatial perception (Blauert, 1979; Altman, 2011; Akeroyd, 2014; Kumpik & King, 2019). At the same time, the perceptual basis for its development is preserved and is based on the sensory experience of comparing the spectral and amplitude characteristics of sound stimulation of both ears (Viskov, 1975; Blauert, 1979; Strelnikov, Rosito & Barone, 2011; Akeroyd, 2014; Ahveninen, Kopčo, Jääskeläinen, 2014; Risoud et al., 2018; Kumpik & King, 2019; Ludwig et al., 2021; Dillon et al., 2022). To test the effectiveness of spatial perception training in monaural CI users, a simple methodology scheme was used to organize stimuli using developed software. The stimuli corresponded to sound sequences of 5 clicks, simulating a change in the lateral position of a stationary sound source or its movement based on consistent sound intensity characteristics for 2 real speakers (Ogorodnikova, Koroleva, & Pak, 2005). The patients' tasks included determining the location of the sound source (left or right speaker); virtual motion detection (source standing or moving); distinguishing the direction of virtual movement (moving the source from right to left or left to right).

General research conditions

The groups of patients in different series did not overlap. Testing and training were carried out in a special quiet room without acoustic interference, at a comfortable level of stimulus intensity (65–70 dB SPL). The Logitech S100 speakers located frontally (70 cm from the listener) were used for stimulation. When training spatial perception, the speakers were spaced 1 m apart, at an angle of 45º to the right and left of the central position (in front of a patient's face).

All participants voluntarily underwent training and testing as part of rehabilitation activities. The experimental protocol was in accordance with the guidelines of the Declaration of Helsinki. Each participant gave informed consent to the training and psychophysical testing. For the children participating in the study, informed consent was obtained from their parents. All personal information about participants was deidentified before results were analyzed.

Results

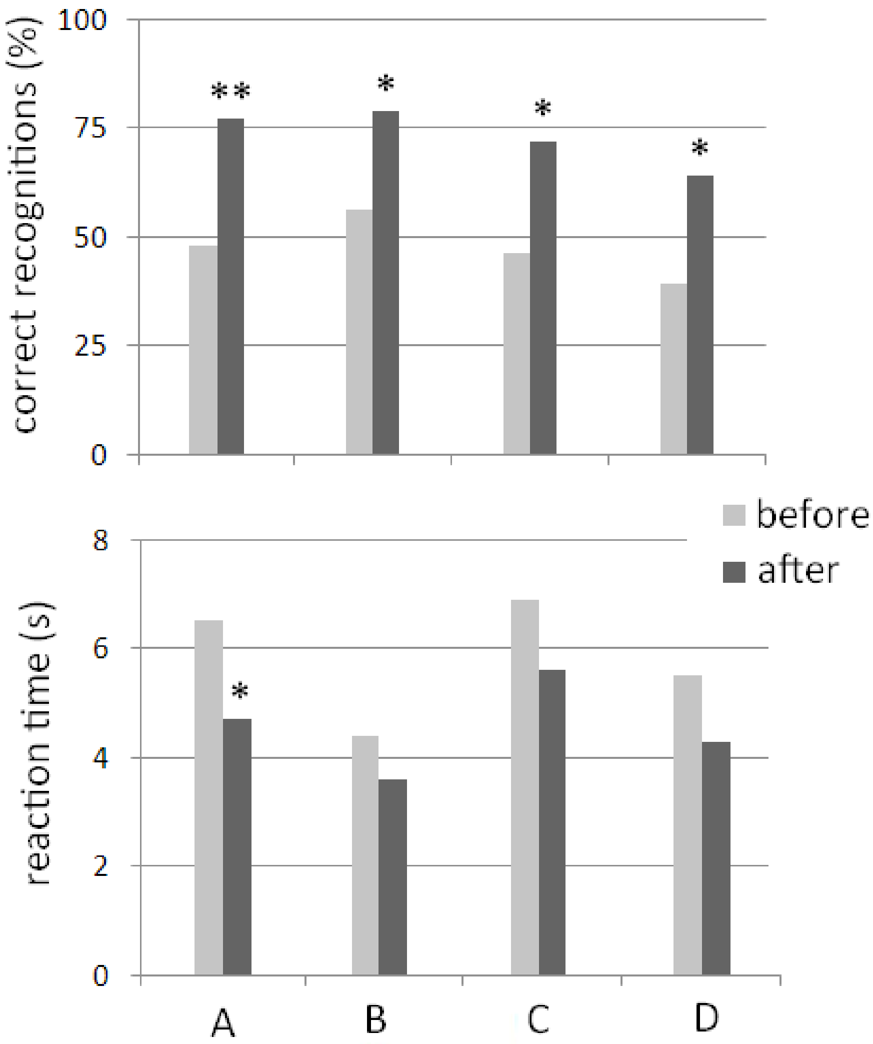
Series 1

The results of testing before the training course showed that the majority of adolescents at risk of CI refusal had not sufficiently developed the basic operations of auditory analysis, especially when the conditions of perception become more complicated – recognition in a situation of voice competition (simultaneous pronunciation of different words by male and female speakers).

After a course of classes using well-designed software for the development of auditory–speech analysis, a significant improvement in performance in the group was noted, which was observed both in terms of the proportion of correct recognitions (N) and reaction time (T) (Fig. 2). At the same time, individual dispersion in results remained very significant, especially for the reaction time implementation.

Figure 2

Test results before and after the training course in the group at risk of refusing to use CIs

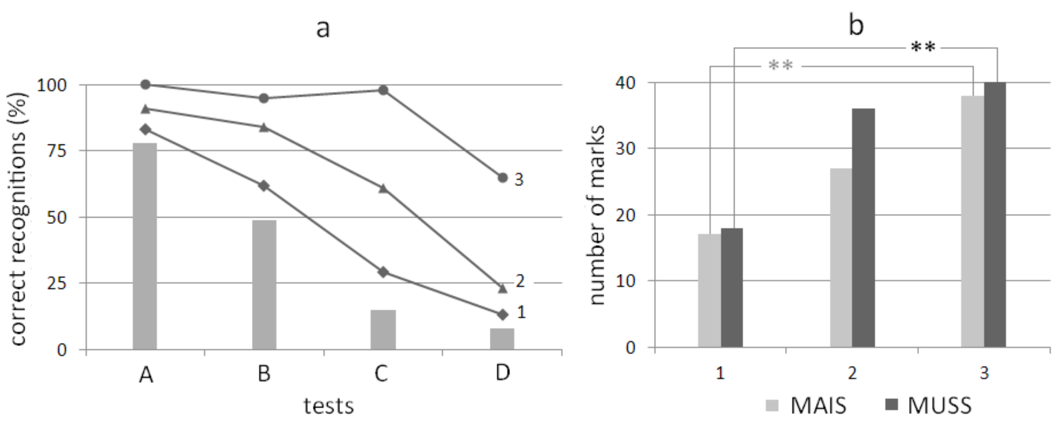


Note. *Comparison of recognition test performance indicators: A – environmental sounds, B – speaker voices (male/female), C – rhythmic pattern of sound sequences; D – speech signals (words) of a target speaker in conditions of voice competition. Vertical: number (%) of correct recognitions (top), reaction (s) time (bottom). Designations *, ** – level of significance of differences according to the Wilcoxon test (p <0.05 and p <0.01, respectively).*

With regard to phonemic categories, positive dynamics of recognition was also observed (Fig. 3a). For most of the adolescents in the group, it was accompanied by an increase in motivation for auditory perception in CIs. The trend towards expanding the use of listening skills and oral speech in everyday situations was also confirmed by the data obtained on the Meaningful Auditory Integration Scale (MAIS) and the Use of Oral Speech Scale (MUSS) (Fig. 3b). There was no significant improvement in the parameters evaluated only in 3 adolescents with cochlear anomalies.

Figure 3

Results of recognition of phonemic categories (a) and assessments on the scales of auditory integration and the use of oral speech (b) in patients at risk



Note. *Designations: a – identification of isolated vowels (A); identification of vowels in syllables (B); consonant identification (C); identification of consonants in syllables (D); columns – initial data (before the training course); curves 1–3 – average scores at the stages of training (1, 3, 6 months of training); b – 1, 2,3 average scores on the Meaningful Auditory Integration Scale (MAIS) and the Use of Oral Speech Scale (MUSS) after 1, 3 and 6 months of training; ** – level of significance of differences (p <0.01, Wilcoxon test).*

Overall, these series confirmed that pre-lingually deafened children implanted during adolescence have significant potential for auditory–speech development with CIs (Koroleva et al., 2017). To activate it, perceptual training is required, which aims to form the basis for auditory analysis of non-speech and speech signals. At the same time, the use of new software increases its effectiveness and promotes the constant use of CIs in children and adolescents with a deficit of sensory experience and insufficient development of the central auditory processing, creating more favorable conditions for the spontaneous development of their listening, speech, and language skills.

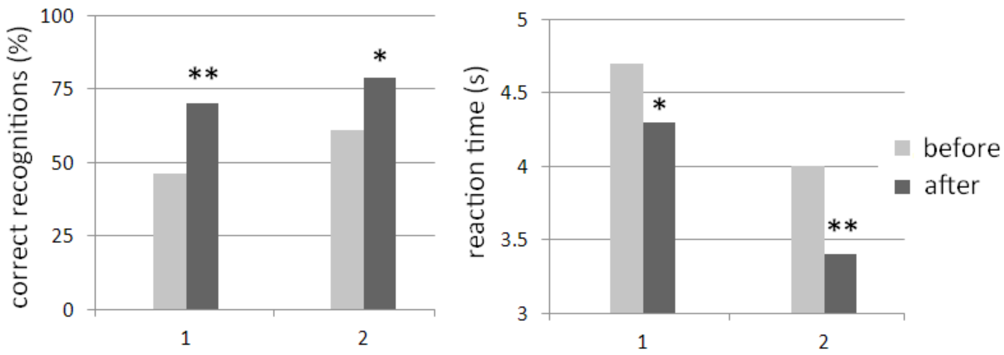
Series 2

It was found that 54% of adult post-lingual CI users were able to adequately identify phrasal intonation in the first course of rehabilitation at the level of 65–70% of correct recognitions. At the same time, a significant proportion of such patients (46%) showed perceptual difficulties and a lower rate of intonation recognition (on average, 61 ± 3.5%). In pre-lingual adolescents with CIs, recognition of intonation in speech before the training was even worse and, on average, did not reach the level of 50%.

Training in perception and discrimination of intonation structures (5 training sessions) resulted in a significant improvement in the situation in all patients (Fig. 4).

Figure 4

Results of intonation perception by adolescents with pre-lingual deafness (1) and adults with post-lingual deafness (2) before and after targeted training using software



Note. *Y-axis: % correct recognitions (left); reaction time (right). Designations: *, ** – level of significance of differences (p <0.05 p <0.01, Wilcoxon test).*

Thus, in post-lingual CI users, the number of correct answers exceeded the level of reliable recognition of 75% and amounted to 79 ± 2.7%, and the reaction time became 600 ms shorter. In the pre-lingual group, recognition improved by 24%, reaching an average level of 70%; reaction time decreased by 400 ms.

It is important that the data obtained indicate that modern CI technologies provide conditions for adequate perception of speech intonation in the Russian language. At the same time, some implanted post-lingual adults who do not have central auditory disorders are capable of spontaneous learning in relation to the identification of acoustic features relevant for recognition of basic intonation structures (changes in the F0 contour) already in the initial period of CI using. Adults who initially demonstrate poor intonation perception scores require targeted training, as do pre-lingual children and adolescents. The data are consistent with the results of modern studies using material from other languages (Karimi-Boroujeni, Dajani & Giguère, 2023).

Thus, the results of this part of the study also confirm a significant increase in correct responses and a decrease in reaction time after targeted training, which indicate the development and consolidation of the central auditory analysis of the dynamic characteristics of speech signals (intonation change in a speaker's tone of voice). Furthermore, CI users, along with an improvement in the perception of speech intonation, noted an increase in the quality of everyday communication and the conditions of general communicative interaction.

Series 3

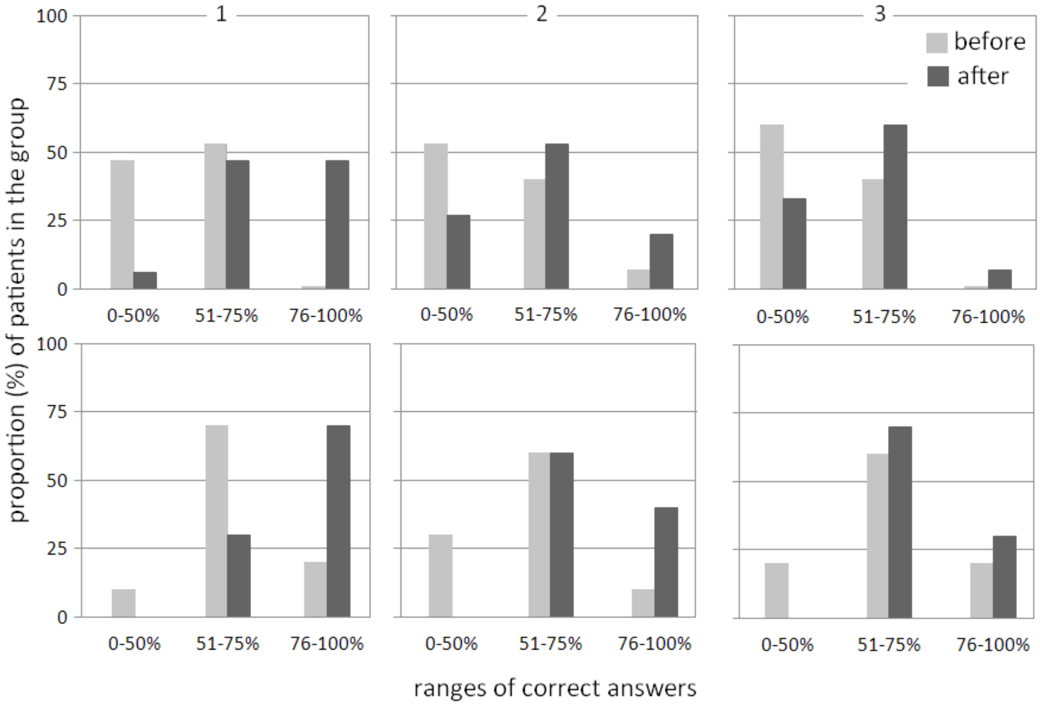
When performing tasks related to spatial orientation for the first time, the vast majority of patients (92 %) required additional explanations and running through the entire set of test stimuli. There were also pronounced differences in the initial ability of auditory spatial perception, especially in the group of pre-lingual CI patients. This was clearly evidenced by the distribution of their results in different series of measurements according to the ranges of the obtained scores, highlighting the proportion (% in the group) of 'unsuccessful' patients (less than 50% of correct recognitions), patients with average scores (from 51 to 70% of correct recognitions) and 'successful' patients – from 71 to 100% recognition (Fig. 5).

Therefore, the auditory assessment of spatial characteristics caused serious difficulties in the majority of patients, especially in the group with pre-lingual deafness and when performing tasks with dynamic changes in stimulation characteristics. These problems indicated the advisability of conducting training in spatial perception and including tasks in it that enable the formation/restoration of skills in auditory analysis and ongoing monitoring of perceptual signs of movement of a sound source during monaural prosthetics.

The positive impact of training was confirmed by an increase in the number of patients demonstrating higher recognition levels (score ranges) for all test tasks. It was most pronounced in pre-lingual patients, in whom at the beginning of measurements the average rate of correct determinations of the lateral position of a stationary sound source fluctuated around the level of random responses (49.4 ± 8.5), and after training it significantly exceeded it (73.5 ± 6.2). When detecting movement and determining its direction, the achieved level of correct recognition was lower and amounted to: 66 and 62 % (pre-lingual patients) and 73 and 71% (post-lingual patients), respectively. In general, the increase in the number of correctly completed test tasks after training was significant ($p < 0.01$ by Wilcoxon test). The change in reaction time does not reach the level of significance, but is also well expressed and, on average for the group of patients, decreases by 860 ms.

Figure 5

Distribution of pre-lingual (top) and post-lingual (bottom) patients according to the range of correct recognitions of spatial signals before and after training



Note. *Y-axis – the proportion (%) of patients in the group: 1 – data on location of a stationary sound source (right/left); 2 – data on detecting movement of a sound source (standing/moving); 3 – data for determining the direction of movement of the sound source (left-to-right/right-to-left).*

Comparison of the results obtained in this series supports the possibility of developing spatial hearing and acoustic orientation abilities after unilateral cochlear implantation (Strelnikov et al., 2011; Kumpik & King, 2019; Dillon et al., 2022). At the same time, the effectiveness of training has been confirmed in patients of different ages with different speech status before prosthetics and using a simple stimulation scheme that is available for clinical practice and the organization of classes in audiology centers and in special education for children with hearing impairments. It is also important to note the decisive role of the use and development of software in this area of training, without which it is methodologically difficult to provide adequate conditions for training spatial perception and automation basic acoustic orientation skills.

Discussion

The results of the study show that the restoration process of speech hearing in CI users is influenced by several internal factors, including the period and causes of deafness, the development of the central processes of auditory–speech analysis (sensory experience and speech status before deafness), and motivation to use CIs. Their appropriate assessment plays an important role in the organization of rehabilitation measures. Of great importance is the further development and use of software tools that make it possible to obtain an adequate assessment of the degree of development and automation of perceptual skills in CI users. Moreover, their use in training courses significantly expands the methodological capabilities and range of directions for the development of auditory analysis processes, as well as for the correction of individual rehabilitation programs and the basis for the spontaneous development of auditory–speech function with CIs. Furthermore, the data obtained demonstrate the possibility of achieving such results even in late-implanted adolescents who had problems using CIs (risk group).

The results indicate a significant improvement in the ability to discriminate speech prosody and to localize sound sources in the majority of post- and pre-lingually deafened CI users after targeted education and auditory training. They reveal the potential for the targeted development of basic processes of auditory–speech analysis, responsible for the adequate interpretation of speech and extralinguistic information whilst communication, as well as for the perception of the dynamic characteristics of sound signals during acoustic orientation (Chen et al., 2013; Ahveninen et al., 2014; Koroleva & Ogorodnikova, 2019; Ogorodnikova et al., 2020; Koroleva et al., 2021; Li et al., 2021; Ludwig et al., 2021).

Conclusion

The use of the software package in complicated situations presented in three series of studies contributed to the progress in the restoration and development of auditory–speech function and spatial perception in CI users of different ages and levels of auditory and speech skills. The following conclusions can be drawn from the results of the study:

- Pre-lingually deafened adolescents have the basis for developing auditory–speech perception with cochlear implants (CIs), despite missing a sensitive period for the development of auditory–speech centers in the brain.
- In order to form, develop, and restore the auditory processing in both pre- and post-linguistic CI users, targeted training of the auditory–speech function is required.
- Modern CI models provide a functional basis for the development of perceptual skills associated with the identification and analysis of complex dynamic characteristics of acoustic signals (speech intonation, sound source movement).
- The use of software greatly expands the scope of listening skills training for the rehabilitation of CI patients, enables continuous assessment of their results and

corrections to training, and contributes to the growth of motivation for the use of CI in everyday situations and the spontaneous development of speech.

- Experience in the development and practical application of the software package suggests that it should be included in methodological tools to assess the dynamics and efficacy of the rehabilitation of patients with CI, not only in cochlear implant centers, but also in territorial hearing centers and educational institutions where children with hearing impairments are studied.

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Inna Vasil'evna Koroleva developed the research design, selected and tested patients, analyzed the results, wrote the Introduction and Conclusion sections.

Anna Aleksandrovna Balyakova participated in training for patients (series 1), analyzed primary data and interpreted the results of the series.

El'vira Ivanovna Stolyarova participated in training for patients (series 2), analyzed primary data and interpreted the results of the series.

Sergei Pavlovich Pak developed the methodological framework, participated in training for patients (series 3), analyzed primary data and interpreted the results of the series.

Elena Aleksandrovna Ogorodnikova generalized and analyzed the results, described the methodological framework, prepared illustrative materials and the list of references, prepared and edited the text of the manuscript.

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Conflict of Interest Information

The authors have no conflicts of interest to declare.