Research Article

Development of a Training Software to Improve Speech-in-Noise Perception in the Elderly with Noise-Induced Hearing Loss

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Highlights

- TFS sensitivity is associated with speech perception in background noises
- TFS damage is related to loss of speech perception in NIHL and presbycusis
- The training based on rehabilitation of TFS can improve SIN perception in the elderly

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ABSTRACT

Background and Aim: The incidence of noise-induced hearing loss (NIHL) is increasing rapidly worldwide. It has been shown that the long-term exposure to noise leads to permanent hearing loss. There is currently no treatment for NIHL and it is mainly managed by preventive measures. This study aimed to develop a training software to improve speech-in-noise (SIN) perception in the elderly suffering from mild-to-moderate NIHL due to temporal fine structure (TFS) damage.

Methods: This is a non-randomized clinical trial conducted on 8 older men aged 60-75 years (Mean age = 68 ± 4.5 years) with mild-to-moderate NIHL at high frequencies (43.75±6.0 dBHL) with at least for five years of work in noisy environment. They received rehabilitation using a researcher-developed training software targeted TFS for five weeks. To assess the efficiency of the training software, the signal-to-noise ratio for 50% correct scores (SNR-50%) was calculated using the word-in-noise test before and after the trial.

Results: The SNR-50% improved significantly in all participants from 13±2.63 dB to 6.10±2.85 dB ($p<0.001$). In the multiple linear regression model, the rehabilitation by the training software predicted 68% of improvement in SNR-50% (coefficient of determination=0.676).

Conclusion: Rehabilitation by the training software developed based on TFS can improve SIN perception in the elderly with NIHL.

Keywords: Noise-induced hearing loss; rehabilitation training; temporal fine structure

Introduction

The most prevalent causes of sensorineural hearing loss (SNHL) worldwide are age-related hearing loss (presbycusis) and noise-induced hearing loss (NIHL) as an occupational disease. It is estimated that 12% of world's population are affected by NIHL [1]. NIHL is quoted to be on average no greater than 75 dB in the high frequencies and no greater than 40 dB in the lower frequencies [2]. High-intensity noise exposure for a very short time causes acute damage to hair cells in cochlea, debilitating their ability to preserve synapses function [3]. Known as acute acoustic trauma, it mainly generates noise intensity of >140 dB HL. Acute acoustic trauma is mostly associated with perforation of tympanic membrane and ear bleeding following noise damage [4]. High-intensity noise exposure for a long period can lead to the death of hair cells and permanent hearing loss [2]. In addition to loud noise, other risk factors such as genetics, male gender, race, old age, smoking, lack of exercise and diabetes increase the risk of NIHL [5].

The signals were transformed into envelope (ENV) and temporal fine structure (TFS) with rapid oscillations. The ENV is an important sound recognition in a quiet environment, and TFS sensitivity is associated with speech perception in the presence of background noises [6, 7]. Previous studies have shown that the TFS damage is related to loss of speech perception in a noisy environment in individuals with both NIHL and presbycusis [6, 7].

Progressive hearing loss is the main symptom of NIHL, but the patients may develop symptoms such as tinnitus, headache, dizziness, insomnia, hypertension, and cardiovascular diseases [8]. Many patients without noticeable hearing loss have difficulty in speech-in-noise (SIN) perception called "hidden hearing loss" [9]. This is related to temporal information damage in cochlea [10]. The most obvious manifestation of auditory processing disorder in the elderly and in people who were exposed to noise is speech impairment in a noisy environment. This phenomenon is the most common complaint of older people and those exposed to noise. Three main factors alone or together can be the reasons for this problem [11]. These factors include peripheral hearing impairment, central hearing impairment, and cognitive impairment. Regarding the first factor, it can be explained that, with aging, hearing sensitivity gradually and progressively decreases (known as presbycusis) and often occurs in both ears. This reduction in sensitivity starts at high frequencies and extends to low frequencies; although it does not interfere with speech comprehension in the early stages, it affects hearing perception with the increase of age. The central auditory system has multiple nuclei that transmit information from the cochlea and nerve to other parts of the auditory system through neural pathways. Regarding the second factor, it can be explained that, with aging, central changes occur in the auditory system in addition to peripheral changes [11]. These changes include a significant reduction in the number and size of nerve cells in the nuclei and auditory cortex, which can occur independently of hearing loss or reduced peripheral nerve input. These changes can lead to impairment in inhibition and perceptual processing such as intensity and frequency differentiation or processing of temporal information [11]. Regarding the third factor, it can be explained that, the ability to perceive SIN is the result of interaction between sensory and cognitive factors. Cognitive functions such as attention, memory, comprehension, decision making, and executive function decrease with aging. Attention and memory affect speech perception in the elderly [11-13]. The SIN perception difficulty can lead to the impairment of linguistic skills and exert an adverse effect on the quality of life.

Pure-tone audiometry is the main hearing test to identify the degree and type of NIHL. In this test, damage is measured by temporary threshold shifts (TTSs). A TTS often returns to normal after several hours [14]. It has been shown that continual TTS cause a permanent threshold shift (PTS) in the outer hair cells of the cochlea [15-18]. A key test for the evaluation of SIN perception is the word-in-noise (WIN) test. This test is used to express signal-to-noise (SNR) ratio for 50% correct score (SNR-50%) [19]. Defined as the ratio of signal power to noise power, SNR is expressed in decibels [17]. SIN testing is commonly used in audiology clinics [20]. There are some pharmacological treatments for NIHL like steroids and antioxidants that can reduce oxidative stress which have not been released yet. Therefore, the development of pharmacological interventions to reduce or prevent NIHL is crucial [18]. Some individuals with NIHL may eventually become candidates for cochlear implantation, but results are highly controversial [21]. Evidence suggests that cochlea damage with NIHL is permanent and cannot be restored. The first human attempts to stimulate the auditory system date back centuries, but systematic auditory training programs began to be used by Itard's efforts in the 18th century. With the development of neuroscientific studies, the phenomenon of sensory deprivation was introduced. The possibility of affecting the central auditory nervous system by auditory training is justified based on auditory neuroplasticity [22].

In this novel study, we aimed to design a training software to improve SIN perception in the elderly with permanent mild-to-moderate NIHL. Our hypothesis is that TFS-based training via learning-related plasticity can improve the SIN perception in the elderly with NIHL.

Methods

Study design and participants

This is a non-randomized clinical trial. It was conducted on 8 older men aged 60–75 years with mild-to-moderate NIHL at high frequencies referred to the audiology clinic at Iran University of Medical Sciences. They had at least five years of work in a noisy place and at least eight hours of work per day. The study process was first explained to them and a written informed consent was obtained from them. They were assured of the confidentiality of their information and were free to leave the study at any time. The inclusion criteria for them were: A mild to moderate high frequency hearing loss at high frequency, age 60–75 years, and having at least five years of professional work in noisy environments. The hearing thresholds of patients were examined in the Audiology Clinic of School of Rehabilitation Sciences at Iran University of Medical Sciences. Mild to moderate hearing loss was defined as the inability to hear tones at <25 dBHL at a frequency of 2000 Hz and at a level between 25–70 dB HL at a frequency of 2000–8000 Hz. High frequency average means the average of 2000, 4000 and 8000 Hz frequencies. The level of hearing loss was examined by pure-tone audiometry. The speech perception difficulty was evaluated by asking subjects whether they had difficulty in SIN perception. A 4-item researcher-made questionnaire was used for this purpose. They had to answer Yes to at least three of four questions to be included in the study. Exclusion criteria were: Unwillingness to participate in the study, abnormal middle ear or conductive hearing loss, head trauma, use of psychiatric or nervous system drugs, central nervous system diseases, a history of seizure attack or epilepsy, and obvious cognitive problems according to the Mini-Mental State Examination results.

Measures

To assess the efficiency of training, SIN score was calculated before and after the trial for all participants. We used WIN test developed by Wilson et al. [23] to measure SNR-50%. The WIN test is a clinically viable method using monosyllabic words to quantify SNR loss [23]. In this test, the listeners need to understand monosyllabic words in the presence of background noise using multi-talker babble. The SNR-50% was obtained from the Spearman-Kärber equation [24]. The WIN test was first designed as a 70-word tool that presented ten distinct words at each seven SNRs ranging from 24 to 0 dB in 4 dB decrements. Then, the 70-word list was parsed into two 35-word lists that had equivalent recognition performances. There is also a third list (WIN List 3), which was developed as a practice list to familiarize the participants with the perception of words in the presence of background noise [25]. We used the Persian version of WIN test developed by Mahdavi et al. named as "PARWIN" test, where SNR levels of +4, +8, +12, +16, +20 and +24 dB HL were determined [26].

Binaural sensitivity to TFS cues was measured by the TFS-LF (low-frequency) test developed by Hopkins and Moore [27]. This test is based on the interaural phase difference (IPD) discrimination in bursts of pure tone stimuli, presented to the both ears simultaneously. It is known as a reliable test for evaluating binaural TFS sensitivity at low frequencies. The TFS-LF test is an adaptive test with two alternative forced-choice tasks, including two stimuli intervals. Each interval includes four tones at fixed frequency (250 Hz), presented randomly in either AAAA (with similar phases in two ears) or ABAB sequences (with a phase difference between the second and fourth tones). In order to detect the ABAB sequence that is normally heard as a shift in the position of tone inside the head, the listener should be sensitive to TFS [28, 29].

Training software

The training software was developed with the help of a medical engineering team. It was created in MATLAB software using C programming language [30]. In this software, participants are asked to identify vowel consonant-vowel (VCV) words. It includes a combination of vowels with 16 various consonants (Ata, Aka, Ana, Ala, Ama, Ara, Asa, Asha, Aja, Aba, Apa, Aga, Ada, Ava, Ara, Afa) pronounced by a native speaker. Using a converted analog, the signals are digitized at a sampling rate of 44.1 kHz with 16 bits per sample. With a zero-phase filter, the VCV signal is filtered three times into 16 complementary frequency bands on a log frequency scale ranged from 80 to 8020 Hz. Later, the signal is divided to ENV and TFS by implementing Hilbert transform and only TFS is then preserved. One of 16 stimuli is read to the person while there is a display in front of him/her that contains 16 boxes of VCVs and s/he should click one of the boxes with the mouse. A visual feedback is given to the person in case of correct or wrong click. That is, if s/he clicks the box correctly, the box turns into green color; otherwise, it turns into red and the person receives visual feedback that s/he selected the correct VCV. The rehabilitation training was conducted for five weeks, three times per week, each for 30 min. The WIN test was conducted again one month after training.

Statistical analysis

Data were expressed by using mean, standard deviation (SD), median, interquartile ranges, frequency, and percentage. The paired t-test was used to evaluate the differences between the pre- and post-test phases. The simple linear regression analysis was run to assess the impact of training software on speech perception. In the multiple linear regression model, the dependent variable was adjusted for independent variables of age, years of noise exposure, and degree of hearing loss (dB). Statistical analyses were conducted in SPSS v.24 software. A $p<0.05$ was considered as the significance level.

Results

The clinical characteristics of participants are presented in Table 1. They had a mean age of 68±4.5 years and high frequency average of 43.75±6.0 dB, indicating that most of them were suffering from moderate hearing loss. Their mean length of noise exposure was 7.6±2.0 years, indicating that most of them had been exposed to noise for a longer period. The mean value of SNR-50% at baseline was 13±2.63 dB (Table 1). After training, the SNR-50% decreased to 6.10±2.85 dB. All participants had a low SNR-50% after training by the TFS-based training software (Figure 1). It could significantly improve SNR-50% (95% CI: 5.30–9.50; $p<0.001$). The

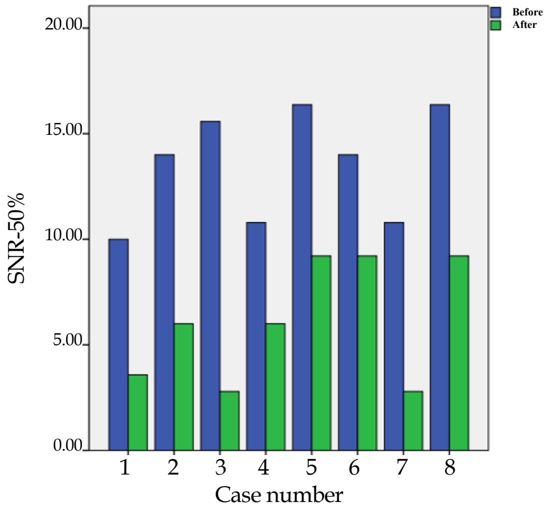

Figure 1. Word in noise scores before and after training. SNR-50%; signal-to-noise ratio for 50%

multiple linear regression model showed that the TFS-based training software was able to predict about 68% of improvement in SNR-50% (R2 = 0.676). Moreover, in the coefficients model, training with the software was linked to lower SNR-50% (β=–7.40; 95% CI: –10.43 to –4.47; $p<0.001$).

Discussion

Hearing loss is one of the top five health problems and the most prevalent occupational health problem worldwide. The World Health Organization conducted a comparative risk assessment to ascertain the contributions of 26 risk factors to the global burden of disease. Five occupational risk factors accounted for an estimated 37%

Table 1. Characteristics of participants

Participants	Age (year)	Length of noise expose (year)	High frequency average (dB HL)
1	63	11	33
2	74	8	46
3	61	5	38
4	69	9	46
5	73	6	50
6	68	7	43
7	66	6	51
8	70	9	43
Mean (SD)	68 (4.53)	7.62 (1.99)	43.75 (5.99)

of back pain, 16% of hearing loss, 13% of chronic obstructive pulmonary disease, 11% of asthma, 9% of lung cancer, 8% of injuries, and 2% of leukemia worldwide [31]. It is estimated that 23% of people between 65–75 years of age suffer from mild to moderate hearing loss (5). Moreover, it has been demonstrated that hearing loss is associated with deteriorated cognition and memory [32]. Aging reduces auditory processing capabilities including both temporal and spectral perception. In the elderly, even with normal peripheral hearing thresholds, the central auditory system may show defects in speech processing and perception in the presence of noise due to poor temporal and spectral processing. This defect in many older adults with peripheral hearing loss may worsen SIN speech perception. Due to the possibility of plasticity at the level of both auditory cortex and auditory brainstem, even in old age, the problems of the elderly related to poor speech perception in the presence of noise can be partially compensated by appropriate short-term rehabilitation.

This clinical trial was conducted on older men with mild to moderate NIHL. The NIHL is preventable but chronic noise exposure is linked to the cochlear damage and permanent hearing loss [33]. It is not completely curable. Preventive measurements like wearing protective earplugs, monitoring noise levels regularly in workers, and attending hearing education programs are the main therapeutic techniques for NIHL [34]. Exogenous antioxidants, calcium antagonists, and glucocorticoids are potential pharmacological treatments for NIHL. Since the pathogenesis of NIHL is multifactorial, the effectiveness of medical treatment is limited [18]. Due to strict observance of ethical considerations, there is scant research on development of hearing loss after exposure to noise in humans. The bulk of studies have focused on people working in noisy workplaces and the results have been limited to the prevention management [35]. To the best of our knowledge, this is the first study on elderly population exposed to noise for a long period, targeting rehabilitation of their TFS. All subjects had worked for at least five years in a noisy environment. In some of them, the last exposure to noise in workplace dated back to more than 10 years ago. However, they were still suffering from permanent hearing loss. This suggests that hearing loss induced by noise for a long period is probably permanent. This study builds on the fact that failure to apply TFS speech cues can be as a main driver of SIN perception in the elderly [7]. Deteriorated processing of TFS information in cochlea is significantly linked to the loss of SIN perception in noisy environment in both NIHL and presbycusis. It has been shown that noise and aminoglycoside antibiotics (e.g. kanamycin) not only destroy hair cells, but also reduces the sensitivity of cochlea and contribute to its fine-tuning [36]. In the noise-exposed population, fibers with the broadest tuning curves experienced the greatest reductions in phase locking in background noise. Broader tuning allows more background noise into the receptive field of the neuron, thereby decreasing phase locking to the TFS of the relevant signal to a greater degree [36]. Even though the bandwidths of normal-hearing auditory-filter tends to rise with the general sound level, the declining strength of vector with rising noise level in normal-hearing fibers is chiefly associated with lower SNR. Hence, the dependence on the overall level will be lower when SNR is constant. Thus, this debilitated TFS coding in the background noise with cochlear hearing loss seems to be caused by a wider cochlear tuning instead of a greater sound level. It is possible that the participants in our study had both NIHL and presbycusis; however, the rehabilitation in our study can equally improve SIN perception in both NIHL and presbycusis.

In this study, a new training software was developed for the rehabilitation of older adults with NIHL and improve their SIN perception. The software was developed based on the recognition of VCV words. The improved ability to differentiate VCV words (without presenting their envelope and keeping their TFS) is probably explained by the progress of speech perception in noisy environment in individuals with SNHL [37]. The rehabilitation was carried out for five weeks, three times per week but the length of each session varied among participants. The findings of this study showed a significant progress in SIN perception in 8 participants after rehabilitation by the training software. The efficiency of training software was evaluated using the WIN test and SNR-50% measurement [38]. Previous trial studies have depicted that WIN test is a suitable clinical instrument for the assessment of word-recognition in background noise [23-25].

The main strengths of this study were well-designed structure in establishing the efficacy of treatment, ease of follow-up to evaluate the impact of rehabilitation, minimization of confounding factors, and high internal validity. However, this study had some limitations, including small sample size and not assessing older women which undermines its external validity. The length of study to assess the efficiency of rehabilitation was only five weeks. According to Hebb theory (1949), long-term potentiation is responsible for learning and memory. Long-term potentiation is the increase in synaptic transmission power associated with the repeated use of the involved neurons. Auditory training and other behavioral interventions increase synaptic activity and, thus, facilitate behavioral changes. Interestingly, these changes are measurable even months after the cessation of stimuli [22].

In auditory training due to impairment of the central nervous system, it is extremely important to pay attention to plasticity. The plasticity of the brain can be evaluated after four weeks. Further research with a longitudinal design is recommended using the developed training software in elderly population. The different lengths of exposure to noise among subjects can be a bias due to unreported confounding.

Conclusion

The training software developed for the rehabilitation of temporal fine structure can improve speech-in-noise perception difficulties in the elderly with noise-induced hearing loss.

Ethical Considerations

Compliance with ethical guidelines

This is a non-randomized clinical trial (ID: IRCT2019625044006N1) approved by the Ethics Committee of Iran University of Medical Sciences, Tehran, Iran (Code: IR.IUMS.REC.1398.003).

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Authors' contributions

PRF: Conceptualization, study design, acquisition of data, data collection, software design, writing original draft; FJ: Investigation, project administration, supervision, SJS: Investigation, project administration, supervision, writing review and editing; MK: Validation, statistical analysis.

Conflict of interest

The authors declare that they have no conflict of interest.

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