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Benefits of Auditory Training with an Open-Set Sentences-in-Babble-Noise

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Featured Application: The paper provides evidence of auditory training that improves speech perception in situations that reflect the daily challenge of speech perception in noise for changing talkers.

Abstract: Auditory training (AT) has limited generalization to non-trained stimuli. Therefore, in the current study, we tested the effect of stimuli similar to that used in daily life: sentences in background noise. The sample consisted of 15 Hebrew-speaking adults aged 61–88 years with bilateral hearing impairment who engaged in computerized auditory training at home four times per week over a two-month period. Significant improvements were observed in sentences comprehension (Hebrew AzBio (HeBio) sentences test) with both four-talker-babble-noise (4TBN) and speech-shaped-noise (SSN) and in words comprehension (consonant-vowel-consonant (CVC) words test), following one month of AT. These improvements were sustained for two months after completing the AT. No evidence of spontaneous learning was observed in the month preceding training, nor was there an additional training effect in the additional month. Participants' baseline speech perception abilities predicted their post-training speech perception improvements in the generalization tasks. The findings suggest that top-down generalization occurs from sentences to words and from babble noise to SSN and quiet conditions. Consequently, synthetic training tasks focusing on sentence-level comprehension accompanied by multi-talker babble noise should be prioritized. Moreover, an individualized approach to AT has demonstrated effectiveness and should be considered in both clinical and research settings.

Keywords: auditory training hearing impairment; aging; speech perception; generalization

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1. Introduction

Auditory training (AT) is used to teach people with hearing loss to make the most of their residual hearing for speech recognition and understanding, thus improving their communication, social participation, and quality of life [1]. The AT can be performed using computer-based auditory training (CBAT) programs that involve low costs for therapists and patients [2]. During the AT, participants perform a series of AT exercises, and the benefits are assessed by comparing performance before and after the training protocols. As AT aims to improve daily communication skills, successful AT should prepare the individual for the challenge of daily discourse. This points to the stimuli to be trained and the generalization level from trained to untrained stimuli.

AT can include analytic tasks of phoneme and syllable discrimination or synthetic tasks of words, phrases, sentences, or comprehension of paragraphs and conversation. This synthetic AT trains top-down abilities that highlight the demands required for real-world communication [3,4]. As opposed to analytic training focusing on sub-lexical features of speech, synthetic training focuses on a more complex level of understanding speech.

According to transfer-appropriate processing (TAP) theory [5], learning depends on compatibility between the learned and tested tasks. The stimuli used in synthetic AT resemble daily communication, so the learning benefits should be better than in the analytic [6]. Indeed, synthetic approaches have been found to be more effective than analytical ones [7].

A second issue to consider in AT is its frequency, amount, and duration, which vary considerably between studies. AT duration ranges from less than 10 training sessions [8–10] to more than 40 [11,12] and mostly includes less than 20 training sessions. Duration and frequency range from 15 to 90 min per session, 1–6 days per week, and up to 4–8 weeks [13]. Lastly, testing the effectiveness of AT should consider individual differences. Current AT studies are not sensitive enough to individual characteristics such as age [14,15], the onset of hearing loss [14–16], and duration of experience with hearing aids (HA) [14–16], on top of participants' hearing ability and speech perception. All these factors may affect AT and should be tested when assessing AT benefits. In addition, it has been suggested that the subjective quality of life focused on social interactions will be affected by AT and should be measured by a self-report questionnaire [16]. Previously, it was shown that participants' baseline speech perception was positively related to their improvement in speech perception tasks following AT [17].

The present study aimed to consider these three issues of AT. The first was to keep high compatibility between the learned stimuli (AT) and those stimuli that people encounter daily, as suggested by the TAP theory [5]. This was done using training composed of sentences spoken by different speakers, accompanied by a four-talker babble noise (4TBN). Second, we addressed the question of frequency, amount, and duration by comparing the effectiveness of one month of AT (four times a week, a total of 16 training sessions) with two months of this training frequency (32 training sessions). Lastly, we referred to the issue of individual differences by testing the effect of individuals' baseline abilities on the effectiveness of AT, assessing it using both subjective and objective measures. To ensure that any possible effect obtained during the month of training was not the result of spontaneous learning, the participants were measured in a no-training month before training, serving as a control condition for the training. In addition, to test for a possible training-conservation effect, participants were measured again two months after completing the training.

2. Materials and Methods

2.1. Participants

The study was conducted following the STROBE guidelines for reporting observational studies. Fifteen HA users (ten women, five men), aged 61–88 years (M = 72.42, SD = 6.21), with post-linguistic hearing loss (hearing loss range 4–50 years, M = 11.73, SD = 12.02), were recruited to the study. Twelve participants were native Hebrew speakers, and three were Hebrew–English bilinguals that used Hebrew as their primary language for over twenty years. They had good cognitive ability with Montreal Cognitive Assessment (Moca) test scores larger than 26 [17] and were able to use a personal computer. Participants were recruited through social media and advertising in audiology clinics from diverse residential areas. One participant (YSH) withdrew from the experiment after two sessions (see demographic data in Table 1).

Table 1. Demographics of the research sample.

ID	Age (Years)	Gender	Duration of Hearing Loss (Years)	Etiology of Hearing Loss	Hearing Loss Level	
					Right	Left
YF	68	F	7	Hole in the eardrum	Mild to moderate	Mild to moderate
HS	66	M	4	Unknown	Mild	Mild to moderate-severe
EM	61	F	8	Chemotherapy	Mild to severe	Moderate-severe
ZK	72	F	4	Unknown	Mild to moderate	Mild to moderate

Table 1. *Cont.*

ID	Age (Years)	Gender	Duration of Hearing Loss (Years)	Etiology of Hearing Loss	Hearing Loss Level	
					Right	Left
ST	75	F	5	Unknown	Moderate	Minimal to mild
HSA	76	F	8	Unknown	Moderate to profound	Moderate to severe
YS	77	M	50	Unknown	Mild to profound	Mild to severe
MS	75	M	10	Unknown	Mild to moderate-severe	Mild to moderate-severe
ND	72	F	10	Unknown	Mild to severe	Mild to severe
EH	70	F	8	Unknown	Mild to profound	Mild to severe
DK	71	F	10	Unknown	Mild to moderate-severe	Mild to moderate
MZ	66	M	14	Unknown	Mild to moderate-severe	Mild to moderate-severe
ZD	75	F	27	Genetic	Moderate-severe to severe	Moderate-severe
NA	74	F	7	Unknown	Mild to moderate-severe	Mild to moderate-severe
YSH	88	M	4	Unknown	Mild to moderate-severe	Mild to moderate-severe

2.2. Training

AT was performed on the participants' personal computers four times a week for eight weeks, for a total of 32 sessions. Each session lasted about 20 min and included one list of 20 sentences presented amidst four-talkers babble noise (4TBN). The participants were asked to write each sentence they heard and to guess when necessary. The sentences were from the HeBio, the Hebrew version [18] of the AzBio sentences test [19]. This test includes 33 lists of 20 sentences, each including 3–12 words (Mean = 7.0, SD = 1.4), spoken by two men and two women (five by each talker). The 4TBN included two males and two females, each saying a different text in Hebrew. The recordings of these four talkers were normalized to have the same root mean square (RMS) amplitudes and were combined into a single recording with a frequency range of 0.5–5 kHz. Before and after the training, the adaptive HeBio [20] was used, with different lists than those used in training, to measure the participants' individual SRTn for sentences in noise. The adaptive HeBio is a 1-up, 1-down adaptive procedure with an initial SNR of +10 dB and an initial step size of 2 dB; when the participants reached an SNR of 0 dB, the step size was reduced to 1 dB until the end of the list. The SRTn threshold was the mean SNR of the last ten sentences in each list. This SRTn was used as the training SNR to ensure participants trained in an SNR level corresponding to 50% accuracy. It was also used to assess the training and was measured before and after the training. The sentences were presented at a comfortable level (minimum 65 dB SPL) with an SNR of −1 to 21 dB, according to the participants' performance.

2.3. Speech Perception (Generalization)

Speech perception before and after training was assessed following a previous protocol [21] in the participant's home and included the adaptive HeBio amidst speech-shaped noise (SSN) [18], Consonant-Vowel-Consonant (CVC) Words in quiet [18], the Digits in Noise (DIN) test [22], and a subjective auditory perception assessment questionnaire [23]. The tests were presented at 65 dB SPL through a loudspeaker positioned at 0 azimuths and a 1 m distance from the participant. The assessment session took 45 min.

Sentence comprehension was conducted using the Adaptive HeBio test. This is an adaptive version of the HeBio, presented amidst SSN. The SSN had frequency ranges and long-term-average-speech-spectra similar to the sentences and were normalized to have RMS amplitudes similar to those of the sentences [18]. The HeBio speech reception threshold in noise (SRTn), with SSN, the signal-to-noise ratio (SNR) for 50% identification, was measured as described for the adaptive HeBio in 4TBN described in the training section. Each testing session included one list, different from those used in the training.

Word comprehension was conducted using CVC words in a quiet test. This test consists of 20 lists of 10 meaningful, one-syllable consonant-vowel-consonant phonetically balanced Hebrew words constructed according to the Arthur Boothroyd words test [24]. Each list contains all the Hebrew consonants (each appears once) and vowels (each appears twice). The lists are also balanced for word frequency in Hebrew. For each participant, 2 lists of 10 words were presented. Participants were instructed to repeat each word they heard and guess if they were unsure. Results were manually recorded by the experimenter (first author) and expressed as the percentage of correct words.

Digits identification using the Digit in Noise (DIN) test. This speech-in-noise test uses digit triplets in steady-state speech noise [25]. In the current study, we used the Hebrew version of the test [22]. The test measures the SRTn in long-term average speech-spectrum noise via a 1-up, 1-down adaptive procedure with a measurement error of 0.7 dB [22]. The noise display level was set at 65 dB SPL. It was first delivered in two practice trials with fixed SNR of +10, then two additional practice trials with steps of 4 dB. In the test, the initial SNR was 0 dB, with steps of 2 dB. Speech in noise threshold (SNR) was defined as the level difference (in dB) between speech and noise display levels, where 50% of the answers were correct. Lower SNR indicates better performance.

A subjective auditory perception assessment questionnaire was conducted. A Hebrew translation of the Qualitative Outcomes Assessment for Customized Learning: Exercises for Aural Rehabilitation (clEAR [QOAC]) [23] was used. The QOAC is a satisfaction questionnaire in English used to assess users of the clEAR subjectively, a listening training software. The questionnaire is divided into 11 questions concerning a conversation with a frequent communication partner and 3 questions concerning a conversation with strangers. In both parts, there is a reference to a conversation with background noise or quiet. The Hebrew version was obtained following a procedure of translation and back-translation.

2.4. Overall Design

To participate in the study, the participants signed an informed consent form, answered a personal details questionnaire, and presented a hearing audiogram to verify their hearing threshold and suitability for the study. Participants then performed the AT four times a week for eight weeks. Speech perception (Generalization) was assessed five times (Figure 1): twice before participants began the training program, one month apart (T1 and T2); following one and two months of AT sessions (T3 and T4); and at follow-up, two months after the end of the training (T5). Participants received the equivalent of USD 85 as compensation for their participation time in the study.

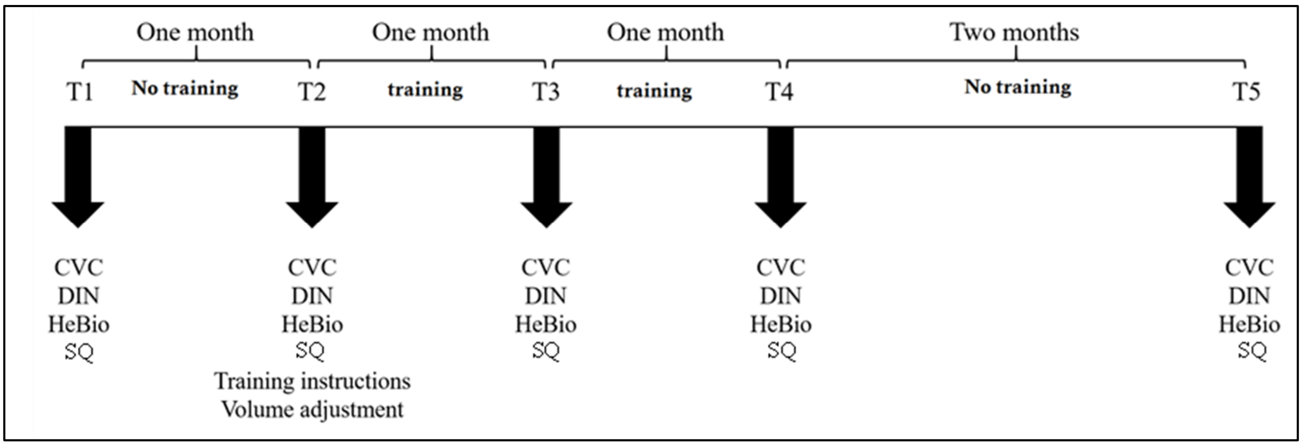

Figure 1. Illustration of the study procedure. T = Test session; CVC = Consonant-vowel-consonant words; DIN = Digit-in-noise test; HeBio sentences test; SQ = Subjective questionnaire.

3. Results

3.1. Spontaneous Learning

Spontaneous learning in the four measures used in the study was tested using a two-way MANOVA with four speech perception tests (HeBio sentences with 4TBN, HeBio sentences with SSN, CVC word in quiet, and DIN) as dependent variables, and the two pre-training sessions (T1 and T2) as a within-subjects variable. No main effect was found ($F(4,11) = 0.332$, $p = 0.851$, $\eta^2 p = 0.108$), suggesting no spontaneous learning in any of the study measures.

3.2. Training Duration

To test whether an additional month of training improved performance, a two-way MANOVA was carried out, with four speech perception tests (HeBio sentences with 4TBN, HeBio sentences with SSN, CVC word in quiet, and DIN) as dependent variables, and the two post-training sessions (T3 and T4) as a within-subjects variable. No main effect was found ($F(4,10) = 2.892$, $p = 0.079$, $\eta^2 p = 0.536$), suggesting an additional training month was ineffective.

3.3. Training and Conservation Effects: Objective Tools

Following the null results of spontaneous learning and two months of training, the scores of each test in T1 and T2 were averaged into a single pre-training score, and the scores of each test in T3 and T4 were averaged into a single post-training score. These scores were compared to those obtained in the conservation session (T5). A two-way repeated measures MANOVA was carried out on speech perception measured by the four speech perception tests, with test session (pre-training, post-training, conservation) as a within-subjects variable (Figure 2). A main effect for Session was observed ($F(8,6) = 5.091$, $p = 0.031$, $\eta^2 p = 0.872$)). A two-way repeated-measures univariate ANOVA for each task showed a main effect for the test session in sentences comprehension (HeBio) with 4TBN ($F(2,26) = 11.59$, $p < 0.001$, $\eta^2 p = 0.47$)), and with SSN ($F(2,26) = 16.37$, $p < 0.001$, $\eta^2 p = 0.56$)), and words comprehension (CVC) in quiet ($F(2,26) = 3.8$, $p = 0.036$, $\eta^2 p = 0.23$)), but not in digits identification (DIN test) ($F(2,26) = 1.59$, $p > 0.05$, $\eta^2 p = 0.11$)). Post hoc Least Significant Difference (LSD) tests showed differences between pre-training and post-training for sentences comprehension (HeBio) with 4TBN (LSD = 2.539, SE = 0.635, $p = 0.002$) and SSN (LSD = 5.557, SD = 1.333, $p = 0.001$), and words comprehension (CVC) in quiet (LSD = 5.893, SE = 1.901, $p = 0.008$), but no differences between post-training and conservation (HeBio sentences with 4TBN: LSD = 0.800, SE = 0.620, $p = 0.219$; HeBio sentences with SSN: LSD = 0.750, SE = 0.422, $p = 0.099$; CVC words in quiet: LSD = 0.536, SE = 2.636, $p = 0.842$).

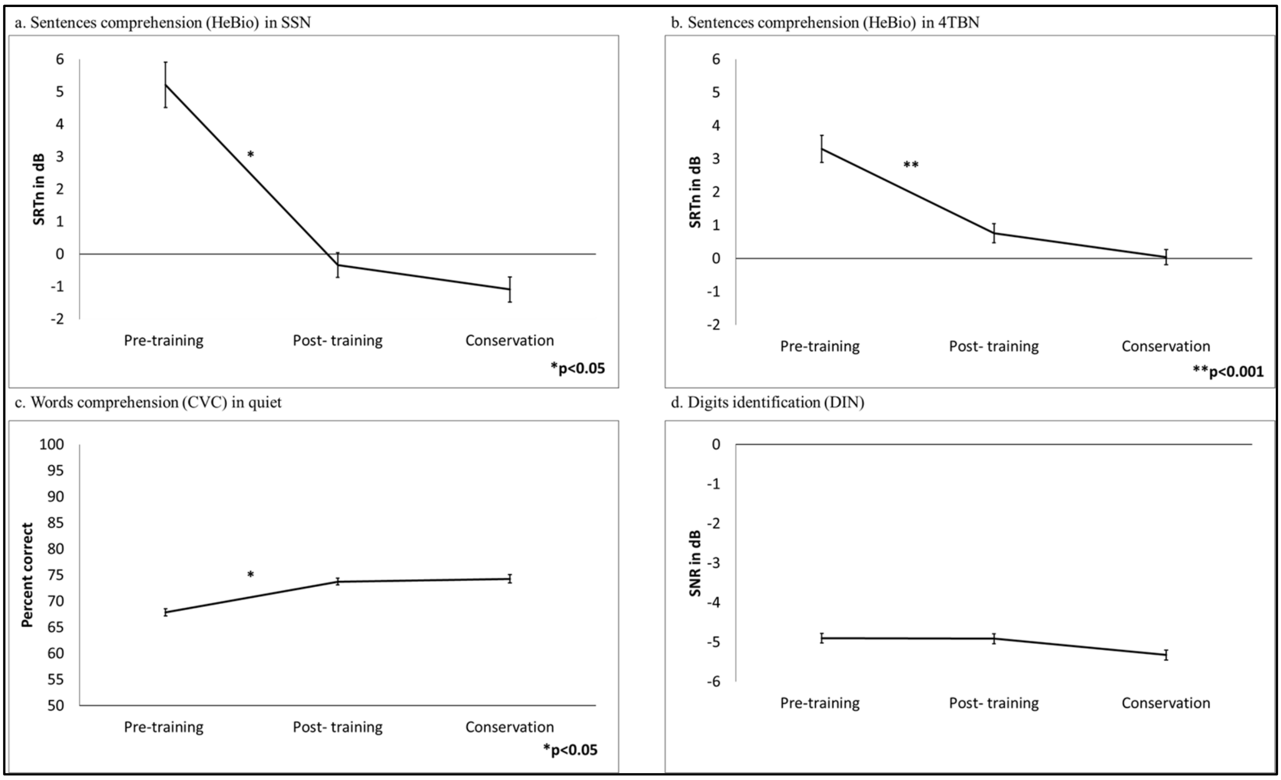

Figure 2. SRTn thresholds (SNR for 50% identification rate) for HeBio and DIN and accuracy scores (percent correct) for CVC words of the averaged pre- and post-training scores and conservation score for the speech perception measures: (**a**) sentences comprehension (HeBio) with SSN; (**b**) sentences comprehension (HeBio) with 4TBN; (**c**) words comprehension (CVC) in quiet; and (**d**) digits identification (DIN).

3.4. Training and Conservation Effects: Subjective Tools

A three-way repeated-measures ANOVA was carried out with scores on the subjective speech perception questionnaire as a dependent variable and test sessions (T1 to T5), background conditions (quiet and noise), and the conversation partner (partner and stranger) as between-subjects variables (Figure 3). The main effects for subjective speech perception were observed for background conditions (F(1,13) = 109.04, $p < 0.001$, $\eta^2 p = 0.89$)) and conversation partner (F(1,13) = 15.67, $p = 0.002$, $\eta^2 p = 0.55$)). As expected, a conversation in noisy conditions was rated worse than a conversation in quiet, and a conversation with a stranger was rated worse than a conversation with a familiar partner. No main effect was observed for the test session (F(4,10) = 1.73, $p = 0.220$, $\eta^2 p = 0.41$)), and no interactions for background conditions X conversation partner (F(1,13) = 2.34, $p = 0.150$, $\eta^2 p = 0.15$)), background conditions X session (F(4,10) = 0.39, $p = 0.812$, $\eta^2 p = 0.13$)), conversation partner X session (F(4,10) = 0.39, $p = 0.809$, $\eta^2 p = 0.14$)), or background conditions X conversation partner X session (F(4,10) = 0.58, $p = 0.683$, $\eta^2 p = 0.19$).

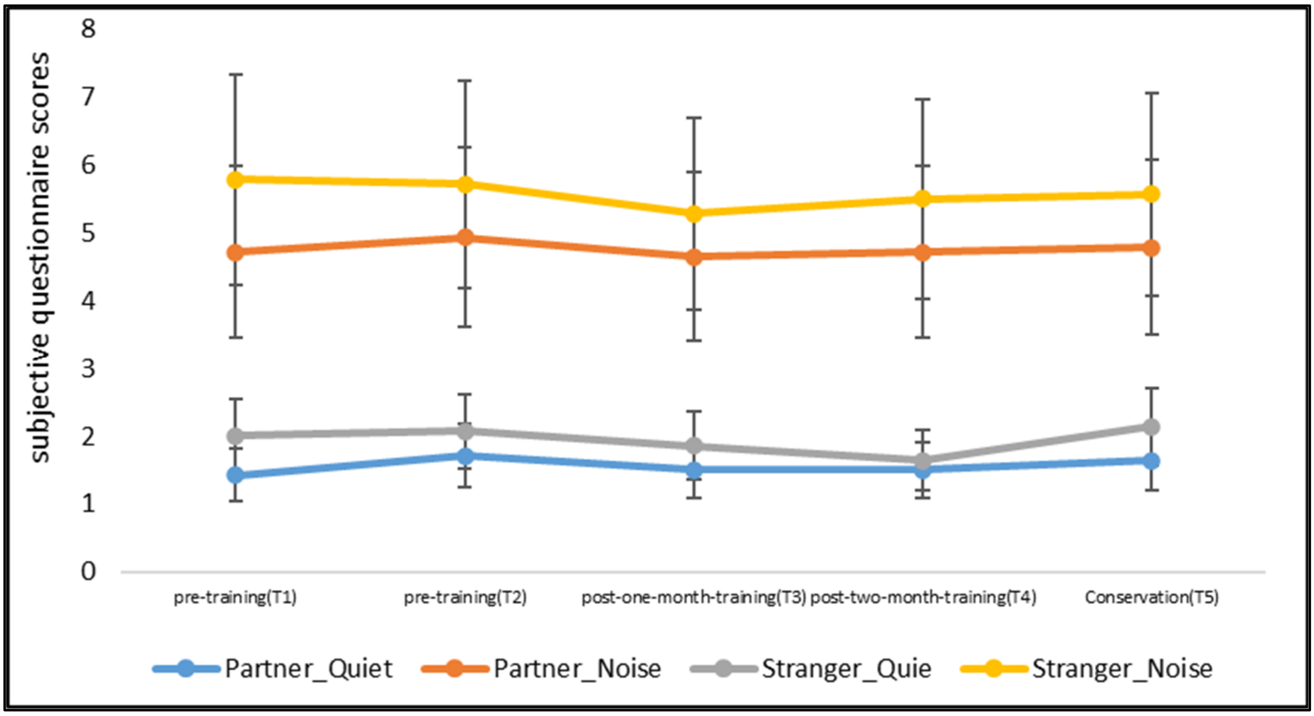

Figure 3. Scores for the subjective assessment of speech perception.

3.5. Individualized Analysis

The average score of the two pre-training sessions is the baseline speech perception score: T1 and T2. The degree of change in the speech perception tasks due to AT was calculated as the difference between the post- and pre-training scores. This score was correlated with the pre-training score in order to test whether the participants' pre-training baseline speech perception ability could predict the degree of change in speech perception due to AT (Figure 4). Pre-training SRTn of sentence comprehension (HeBio) with 4TBN and SSN predicted the degree of change due to AT in both conditions, showing a larger improvement when baseline SRTn was higher (worse). However, they did not predict the degree of change in the word-level tests, namely, the accuracy of the word comprehension test (CVC) and SRTn of digit identification (DIN). Pre-training word comprehension (CVC) accuracy in quiet did not predict the degree of change in any of the tests. However, pre-training SRTn of digits identification (DIN) predicted the degree of change of the sentence comprehension (HeBio) test with both 4TBN and SSN.

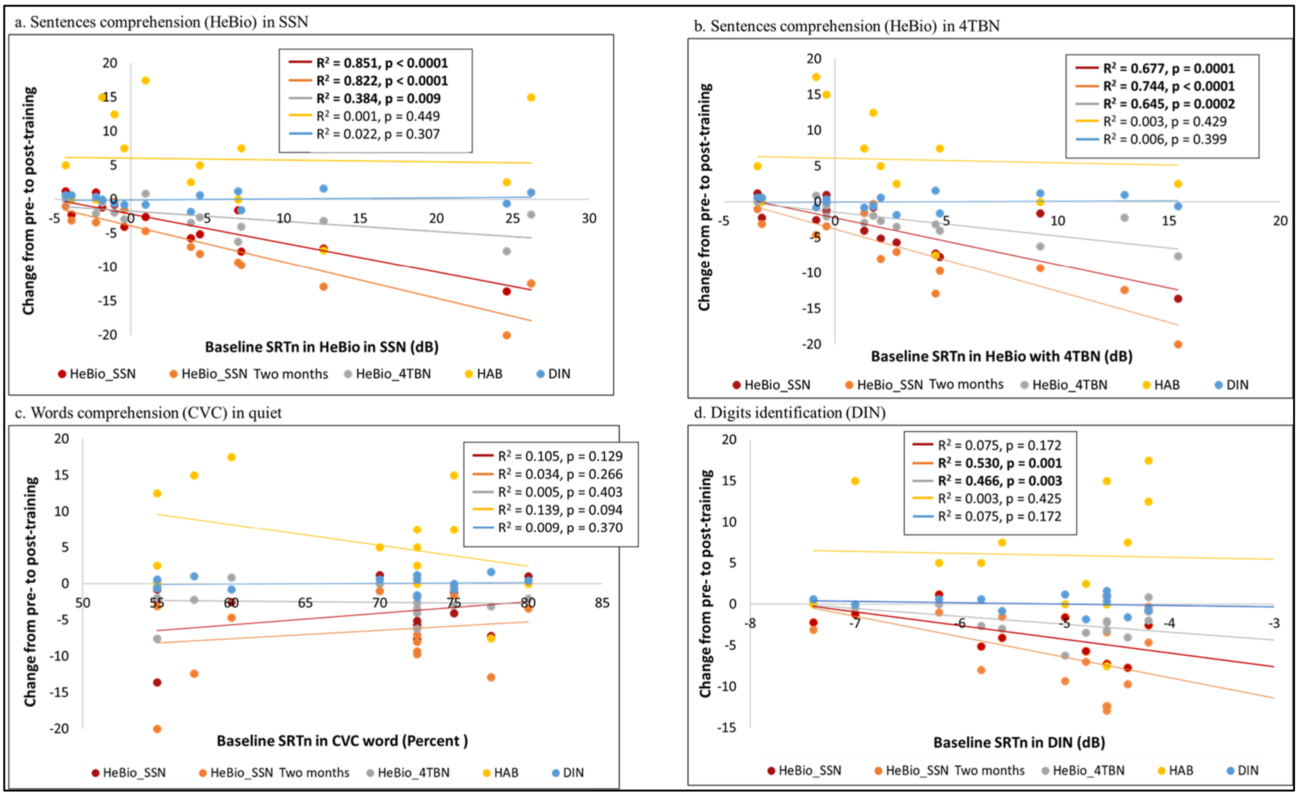

Figure 4. Prediction of the degree of change in speech perception tasks according to participants' pre-training score in (**a**) sentences comprehension (HeBio) with SSN; (**b**) sentences comprehension (HeBio) with 4TBN; (**c**) words comprehension (CVC) in quiet; and (**d**) digits identification (DIN). Regression analysis results in bold indicate a significant relationship.

4. Discussion

The present study aimed to test the effect of AT that simulates the challenge of daily communication: sentences spoken by different talkers amidst multi-talker background noise. The effect of this AT was tested for improving the objective and subjective speech perception of HA adult users. This was carried out by testing the generalization of the AT to different background noise (SSN) and lower-level speech perception (words). In addition, spontaneous learning and conservation of AT were tested, as well as the effect of AT duration (one versus two months). Importantly, the relationship between the individuals' pre-training speech perception and the benefit of the AT was measured.

Generalization is the biggest challenge of AT, and the scientific literature reflects mixed evidence regarding the ability to successfully generalize AT to untrained speech perception tasks [7,26–31]. Therefore, to maximize the benefit of AT, we chose stimuli that simulate the main challenge in daily communication, which includes speech perception at the sentence level, in an open set, and accompanied by 4TBN. This is considered synthetic training and is suggested by the literature as the most effective AT [7,16,32]. Indeed, the results showed that this AT was generalized to different sentences, to words (CVC words in an open set), and to different noise conditions (quiet and SSN). The AT was not generalized to DIN. This could be because this is a closed-set screening task and may be less sensitive to AT-related changes. The findings suggest that AT affects in a top-down manner, in which training with complex stimuli (sentences, 4TBN) is generalized to simpler stimuli (words, SSN). The previous finding supports this conclusion and shows that AT of sentence level can affect and improve speech perception of both words and sentences, and AT of sentences in chatter noise can affect and improve sentences in SSN noise [7,33,34].

All speech perception tasks tested in the present study did not show a spontaneous learning effect when no training was made available in the first month of testing. This supports previous findings reported by some researchers [21,35] and contradicts others who reported on spontaneous learning in speech perception tasks [16]. Nonetheless, it lays the ground for relating the improvement found in the speech perception tasks to the training rather than to spontaneous learning.

Two additional questions in the study were related to the effect of training duration (one versus two months) and its conservation. One month of AT was enough to improve speech perception both in the trained and the untrained tasks, and an additional month of training did not add to this effect, similar to some studies [31,36]. In addition, the conservation of the training benefits was observed two months after the end of the training in all tasks. Preservation of AT benefits was similarly observed in previous studies [26,36,37]. All these findings suggest that one month of AT with complex stimuli (sentences with 4TBN) is sufficient for improving speech perception, and longer training has minimal or no benefit. Although a second month was not required for better AT, it may be required for conservation. Future studies should explore this question, as no conservation following one month of training was tested in the present study.

Contrary to the objective tools, the subjective assessment did not show any change with training. It showed, as expected, worse scores in noisy conditions than in quiet and with a foreign conversation partner than a familiar one [33,38,39]. Previous studies showed subjective change following AT only for new HA users [40]. Thus, it is possible that for long-term HA users, as tested in the present study, a larger AT effect needs to occur for them to feel and report it subjectively.

The generalization of AT is affected by individual differences among the trained population. The analysis examining individual differences in baseline speech perception showed that lower initial speech perception predicted greater generalization. This can be explained by the wide range of hearing loss, from mild to profound, observed in the present study's participants. The significant improvement in speech perception tasks of sentences with SSN or 4TBN was predicted by lower initial speech perception in the sentence tasks. Speech perception baseline in sentences predicted the improvement in sentence tasks but not in word tasks (CVC words and DIN). Speech perception baseline in the DIN task predicted the improvement in sentence tasks but not in word tasks. The speech perception baseline in the CVC words task did not predict any improvement.

The main limitation of the current study is that the trained stimuli were from the same pool of sentences as the untrained sentences. This may weaken our conclusion of generalization if not for the fact that it was observed for different sentences, different noise conditions, and also for words. The main strength of the current AT is that it uses sentences spoken by different talkers and accompanied by multi-talk babble noise, which makes it very similar to the stimuli participants will encounter in their daily communication. Thus, if generalization is generally weak, as was reported in many studies [7,26–31], it is recommended to use trained stimuli that are very similar to the untrained ones.

In summary, a home-based computerized AT for older HA users using sentence-level auditory training amidst 4TBN resulted in improvement in speech perception of sentences and words amidst wider noise bands (4TBN and SSN). The improvement observed in the current study resulted after one month of training, and the additional training time did not have a considerable effect. Therefore, more extensive training does not appear necessary. The findings suggest that there is a top-down generalization from sentences to words and from babble noise to SSN and quiet. Therefore, synthetic training tasks should be chosen at the sentence level. In addition, an individualized approach to auditory training may be justified based on the ability to predict improvement on generalization tasks (better performance among those with poorer baseline speech perception capacity).

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data from the study can be shared with interested parties by personal communication with the corresponding author.

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