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Pursuing Analytically the Influence of Hearing Aid Use on Auditory Perception in Various Acoustic Situations

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Abstract The paper presents the development of a method for assessing auditory perception and the effectiveness of applying hearing aids for hard-of-hearing people during short-term (up to 7 days) and longer-term (up to 3 months) use. The method consists of a survey based on the APHAB questionnaire. Additional criteria such as the degree of hearing loss, technological level of hearing aids used, as well as the user experience are taken into consideration. A web-based application is developed, allowing answering the survey questions from any computer with Internet access. The results of the benefit obtained from the use of hearing aids in various acoustic environments, taking into account the time of their use, are presented and compared to the earlier outcomes. The research results show that in the first period of use of hearing aids, speech perception improves, especially in noisy environments. The perception of unpleasant sounds also increases, which may lead to deterioration of hearing aid acceptance by their users.

Keywords: hearing aid, APHAB, hearing aid benefit, hearing loss, evaluation of hearing aid use.

1. Introduction

The assessment of sound perception in hearing aids, especially in the context of benefits that a prosthesis can bring, is a complex issue. Modern hearing aids strive to provide the best possible speech understanding but, at the same time, a natural listening experience to ensure comfort in a variety of listening situations. In theory, all of these features should improve hearing quality and satisfaction for the hearing aid user. However, in everyday practice, both the hearing aid user and the hearing care provider have to make some choices and compromises. Taking into account that the type and degree of hearing loss also has a direct impact on the outcome, the final satisfaction and enjoyment of the hearing instruments can be challenging to predict.

In a study by Wu et al. [1], the performance of hearing aids equipped with basic and advanced (premium) directional microphones, as well as basic and advanced noise cancellation algorithms, was compared in a laboratory environment as well as in real-world, everyday use conditions. Hearing instruments with both directional mode and noise suppression turned off were also used for comparison. Speech understanding, listening effort, sound quality, location, and satisfaction were evaluated. The data collected in the laboratory environment confirmed the superiority of the high-tech solutions over the basic ones in terms of improved speech understanding and localization ability. The data also indicate that these solutions can reduce listening effort and improve perceived sound quality compared to hearing instruments without directional microphones and noise cancellation.

Overall, methods of assessing the effectiveness of hearing aid prosthesis can be divided into objective and subjective [2-4]. Verification relies on the objective measurement of acoustic parameters, i.e., gain and maximum output level as a function of frequency, dynamic characteristics of the hearing aid, i.e., the relationship between the signals at the input and output of the hearing aid [2, 4, 5]. Validation, on the other hand, is an assessment of the benefits of using a hearing aid, satisfaction, and handicap reduction by the use of hearing aids [6]. Validation includes asking the patient about sound quality, ear balance, and comfort of the devices. Also, a variety of questionnaire-based procedures, as well as direct perceptual evaluations of sound by the hearing aid user in a free field, may be used for that purpose [6]. However, one of the most common ways to assess subjective benefit and satisfaction of using a hearing aid are questionnaires of various forms, content, and lengths. Special attention is given to listening to and understanding speech in different competing contexts, e.g., environmental sounds to reflect real-life situations. This is checked with and without hearing aids, providing a measure of subjective hearing aid benefit. In assessing hearing quality, ease of listening, naturalness, clarity, and the ability to identify different speakers, music genres, and musical instruments, as well as a variety of everyday sounds, are taken into account.

APHAB (Abbreviated Profile of Hearing Aid Benefit), though historically is not the first questionnaire introduced in hearing aid practice, it proved its sensitivity during the years of clinical use [5, 7, 8]. Since the APHAB is employed by the authors of this paper, it will be discussed in more detail in the next Section.

The goal of this paper is two-fold. The first one concerns collecting data from the hearing aid (HA) users based on APHAB, both short-term (up to 7 days) and longer-term (up to 3 months). Then, these data are to be compared with the previous study results to analyze whether there is consistency of the HA users' responses when dealing with different groups of users. This is because the data collected will form the foundation for future study, which aims to automatically predict the benefit of the HA user employing a rule-based algorithm and historical data derived from short-term use.

The organization of the paper is as follows. Section 2 presents the study methodology, including a description of the APHAB questionnaire, its advantages and limitations, as well as data collection. In Section 3, the results obtained are analyzed to assess the short-term (up to 7 days) benefits obtained from hearing aid use, confront current results with the results obtained from the previous study [9], and evaluate the longer-term (up to 3 months) perspective on benefit obtained from hearing aid use. Then, statistical tests are performed to check whether differences between studied HA group users are statistically significant. A discussion on the results is also included. Section 4 concludes the paper by providing overall outcomes as well as outlining how the dataset gathered will be employed in the future study on an automatic assessment of HA benefits based on short- and longer-term predictions.

2. Methods

This Section presents first the APHAB questionnaire form that was employed in the study. The advantages and limitations of this method are briefly discussed. Then, a description of data collection from HA users is described, giving some basic information on the tested group of the HA users.

2.1. APHAB questionnaire form

APHAB is a closed-ended questionnaire that is self-completed by the hearing aid user. It was developed in the mid-1990s as a more "friendly" tool than the previously utilized PHAB (Profile of Hearing Aid Benefit) [10-13]. It contains 24 items (statements) in four subcategories (6 statements per category):

- EC (Ease of Communication) - ability to communicate in silence, effort to communicate under relatively easy listening conditions;
- RV (Reverberation) - ability to communicate in the presence of echoes, explores understanding speech in moderately reverberant conditions;
- BN (Background Noise) - The ability to communicate in the presence of background noise, explores speech understanding in the presence of multiple speakers or other competing listening conditions (environmental noise);
- AV (Aversiveness of Sounds) - degree of acceptance of unpleasant sounds, explores adverse reactions to environmental sounds [10, 13].

Each item is rated on a 7-point scale, i.e., from A to G. The benefit of a hearing aid can be assessed by analyzing the average percentages for each category (EC, RV, BN, AV – called APHABEC, APHABRV, APHABBN, APHABAV in this paper, respectively) [13], as well as by calculating the average value for three (EC, RV, BN – called APHAB3 in this paper) [14, 15] or four categories (EC, RV, BN, AV, the so-called Global Score – called APHAB4 in this paper). APHAB is employed in hearing aid assessment in many countries and languages. So, this is why it is convenient to use.

Although APHAB is one of the most common questionnaires, it also has limitations. Among these limitations are the number of categories of acoustic situations or the variety of acoustic conditions to be assessed. Hence, many attempts were made throughout the decades to develop new forms or tools for evaluating fitting protocols for which APHAB provided a starting point [16-19]. One of the disadvantages may be self-completion of such a survey by a HA user, especially when considering the HA wearer age and overall health condition. Moreover, it is a known fact that HA user is more critical of the benefits HA provides than their family members. Another question arises concerning whether a survey should be open, closed, or mixed.

It should be noted that recently a new approach to the evaluation of auditory reality and hearing aids using an ecological momentary assessment (EMA) appeared [20-22]. It relies on repeated subjective assessments in everyday life. EMA studies involve computer- or smartphone-assisted methodologies for collecting data in natural environments on an individual, momentary, repeated, and often multimodal basis. Researchers using EMA may collect objective and self-report data. Ecological momentary assessment opens up new insight into natural environments and behavior, the impact of hearing impairment, and the improvement of hearing-related abilities with hearing devices [23]. However, there is no definitive answer to which of these approaches is the most advantageous as there are various surveys that still appear in clinical practice. Nevertheless, since APHAB constitutes - to some extent - a standard among HA providers, so that is why it was chosen to be employed in our study. But the more strong argument behind its use is that it was employed in our previous study so that we can compare the consistency of the outcomes. Also, both datasets collected will form the basis for the machine learning approach.

2.2. Collecting user data

The aim of the current study is to evaluate the most common listening situations faced by an elderly hard-of-hearing person and the benefits of hearing aids. This is carried out as a comparison to the earlier assessment [9]. That is why it was decided to use the APHAB questionnaire in the method described. This choice was also dictated by the fact that a broad set of listening situations is available on the form. Besides, because the form is of a closed-form type, various comparisons can be made. For example, it is possible to compare the effectiveness of two different hearing device types or settings for the same user. In the case of a large number of subjects, it is possible to determine an overall trend for one particular kind of hearing aid or for an entire family of hearing devices.

To collect data for evaluating the benefits of hearing aids (HA), a web-based application was developed and implemented in 200 hearing aid dispenser sites [9]. It systematizes and organizes the collection of the obtained results. The application was prepared using the LMS (Learning Management System) Moodle platform [24]. Data can be exported as any defined subset or as a whole dataset. Export can be done in two formats: plain-text CSV or open document format ODS.

The application includes three types of surveys that are closely related to the HA user's subsequent visits. They indicate actions to be performed at successive stages of the user's service; therefore, they should be completed in the proper order. In addition to the APHAB questionnaire, Survey 1 includes questions about one's experience with hearing aids, space for entering the average hearing loss, free field test results, and additional comments. Survey 2 includes additional questions and the APHAB questionnaire, mainly to gather information about the HA user's overall opinion on comfort and convenience, space for entering the parameters of the hearing devices used, free field test results, and additional comments. Questionnaire 3 is a shortened version of Questionnaire 2 and consists of the APHAB questionnaire, additional questions about the comfort of the hearing aids, and space for free-form input and other comments.

Figure 1 shows the flow chart of the data collection procedure of the current study. Unlike previous studies, the third stage of data collection has been added.

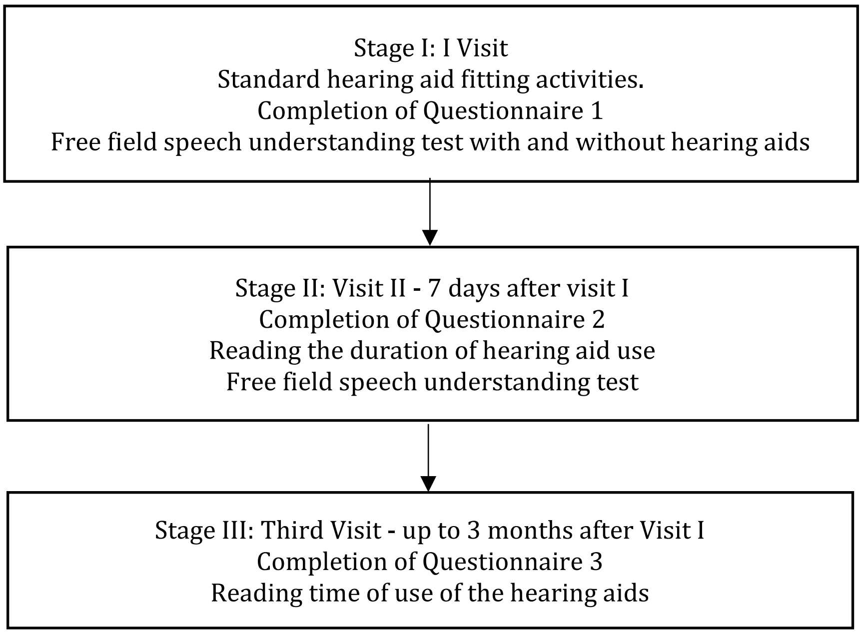

Figure 1. The flowchart of the data collection.

Participation in the study was voluntary; test participants gave their written consent to collect these data. Overall, the number of users was 408. However, there were many drop-outs because of the long and tiring procedure, as well as commuting problems. Finally, a total of 287 subjects, including 190 men (average age 69.0, standard deviation 12.2) and 97 women (average age 69.1, standard deviation 11.1) with different levels of hearing loss (i.e., monaural, binaural, symmetrical, and unsymmetrical) and using different hearing aids participated in the study.

To ensure proper comparability with the previous study outcomes [9], only the results of test participants with binaural symmetric hearing loss of the same degree were further considered as other cases were under-represented in the data obtained. A total of 110 cases were further analyzed and compared with the results of the previous study [9]. There were 71 men (average age 70.2, standard deviation 12.3) and 39 women (average age equals 72.1, the standard deviation is 9.1).

As in the previous study [9], an additional selection criterion was applied, i.e., the use of hearing aids of one manufacturer belonging to the same family but with two technological levels (A and B; B had a higher technological level than A).

3. Data analysis

As already said, the goals of the current study were as follows:

- Assessing the short-term (up to 7 days) benefits obtained from hearing aid use;
- Comparing current results with the results obtained from the previous study [9];
- Assessing the longer-term (up to 3 months) perspective on benefit obtained from hearing aid use.

The following criteria for the classification of results were adopted: a benefit of ≤ 0% means deterioration of hearing, i.e., ineffective hearing aid use. A benefit of <10% is considered to be small, though positive. The next two ranges were adopted according to Cox [25], who proposed the level of 10% in the case of APHAB3 and APHAB4 indicators and 22% for individual factors such as APHABEC, APHABRV, APHABBN, APHABAV.

3.1. Analyses and discussion

Benefits obtained during the short-term use of hearing aids with different technology levels were already presented in our earlier paper [9]. Table 1 presents the structures of hearing losses from previous and current studies. The number of participants differs between that study and the current one. Moreover, there were changes in the number of mild and moderate hearing losses between the studies). Our previous study [9] showed that 109 test participants' results were evaluated and analyzed. At the same time, it should be emphasized that the current results were obtained on a new, independent group of 110 participants. For this reason, the structure of the participants with regard to hearing loss has changed. From the current group of subjects, as many as 24 participants stayed in the 3rd month (long-term) study phase.

Table 1. The structure of hearing losses of the participants.

		Participants from the previous study. Short-term use (7 days) [9]	Participants of the current study. Short-term use (7 days)	Participants of the current study – up to 3 months
WHO grade of hearing impairment [26]	MILD	28	17	1
	MODERATE	73	84	20
	SEVERE	8	9	3
	Total	109	110	24

The analyses started with the context of APHAB3 and APHAB4 (HA refers to hearing aid). APHAB4 was used because it takes into account unpleasant sounds. Moreover, the previous study showed that benefits are reduced when accepting unpleasant sounds (APHAB4) is considered in the assessment. Fig. 2 presents current results for the short-term use, and Fig. 3 illustrates results for the longer-term use of hearing aids.

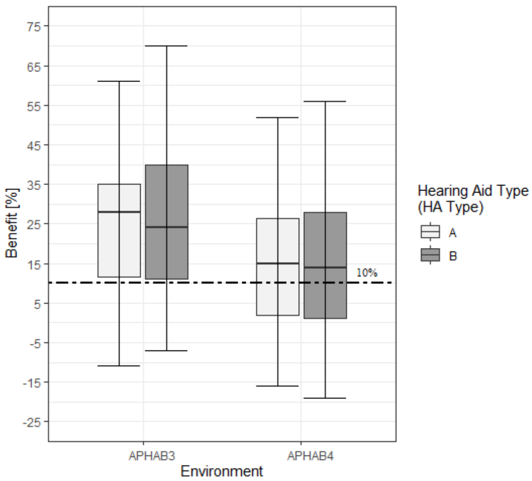

Figure 2. Benefit of the short-term (7 days) use of two types of hearing aids for 110 users determined by indicators APHAB3 and ABHAB4.

To observe to what extent the technology level of HA affects the benefit achieved for up to the 3rd month of use. Overall, the users of type B hearing aids get better results than type A hearing aids, both for APHAB3 and APHAB4. To check whether these results differ significantly, a statistical analysis was performed. The assumption of the normality of variables was checked using the Shapiro-Wilk test. These variables had a normal distribution; therefore, the ANOVA test was used to check the statistical significance of differences between both types of hearings separately for indicators APHAB3 and APHAB4, however, not showing a statistically significant result.

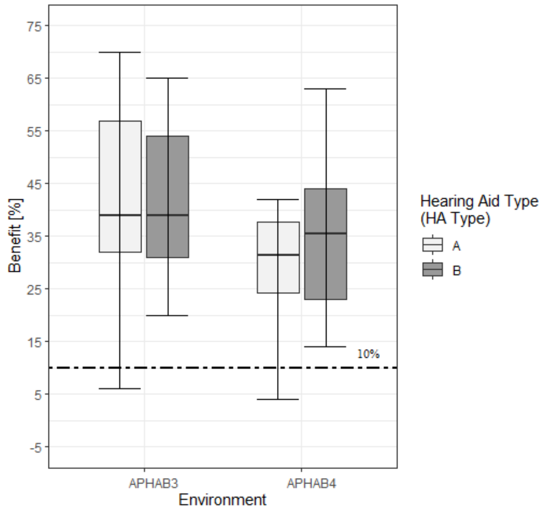

Figure 3. Benefit of the longer-term (up to 3 months) use of two types of hearing aid use for 24 of 110 users determined by APHAB3 and ABHAB4 indicators. Dashed line labeled 10% indicates significant benefit in the case of global indicators [25].

Of course, it is possible to analyze benefits obtained in various listening environments during short- and longer-term use of hearing aids with technology levels of A and B, conditioned by EC, BN, RV, and AV environment. Similar to the previous investigations, a statistical analysis was carried out to check whether the differences visible in the benefits achieved by the users of the A and B ([9], p. 6/724, Tab. 3) type hearing aids are statistically significant. For variables, which have a normal distribution, the ANOVA test was used. For those variables that did not have a normal distribution, the non-parametric Mann-Whitney test was employed for the statistical analysis. The conducted analysis showed, as before, that the differences between the results obtained in the A and B hearing aids are not statistically significant. This is an interesting conclusion as this shows that there are more important factors than technology, only. However, even though the differences obtained with the two types of hearing aids (A and B) are not statistically significant, the benefits of using them differ significantly depending on the acoustic environment of the hearing aid wearer. The best result was obtained in the case of communication in noisy environments (BN), and the worst result concerns the acceptance of unpleasant sounds (AV).

Since the analysis of the results for types A and B hearing aids does not give statistically significant differences, in the further part of the work, the analysis of the results was carried out without taking into account the type of hearing aids. Table 2 presents significant benefits for APHAB (29) individual indicators (EC, RV, BN, AV) according to previous and current results.

Table 2. Benefit for APHAB individual indicators (percent of the participants whose benefit was ≥22% for individual factors EC, RV, BN, AV).

	Short-term use (7 days), previous study [9]	Short-term use (7 days), current results	Up to 3 months of use, current results
ABHAB >22%	109 subjects	110 subjects	24 subjects
EC	64.22%	50.91%	72.00%
BN	77.98%	72.73%	91.67%
RV	42.20%	40.00%	75.00%
AV	8.26%	4.55%	0.00%

It is interesting to observe that the benefit of short-term use of hearing aids for users with varying degrees of hearing loss, determined by using global indicators (DHL – degree of hearing loss), differs between the two studies (see [9, Fig. 4]). The previous analysis concluded that the greatest benefit from short-term use of the devices concerned users with moderate and a mild degree of hearing loss. Contrarily, when applying the same analysis for the new data (see Fig. 4), it occurs that the most considerable benefit from short-term use of the devices concerns users with severe and a moderate degree of hearing loss.

Further analysis leads towards conclusions on the use of HA up to three months, i.e., it can be observed that the greatest benefit from the longer-term use of the devices refers to the users with a moderate degree of hearing loss (see Fig. 5). As in previous analyses, the benefits are reduced when the acceptance of unpleasant sounds (APHAB4) is considered in the overall assessment.

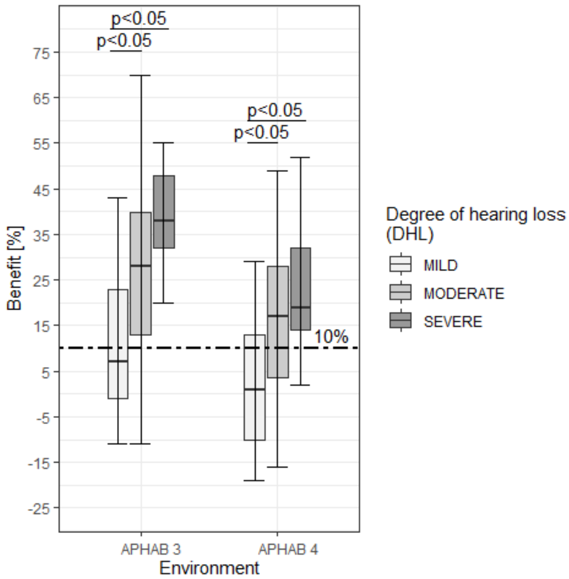

Figure 4. Benefit of short-term (7 days) use for 110 subjects (current results) determined by indicators APHAB3 and ABHAB4 in the context of various degrees of hearing loss. Dashed line labeled 10% indicates significant benefit in the case of global indicators [25].

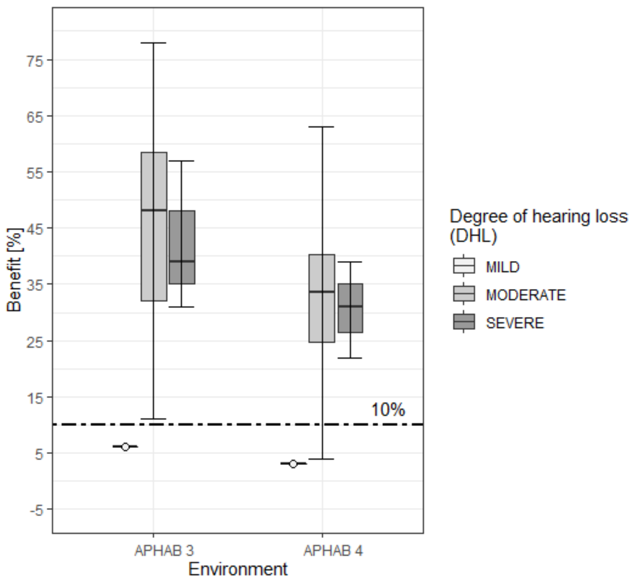

Figure 5. Benefit of longer-term (up to 3 months) use for 24 from 110 subjects determined by indicators APHAB3 and ABHAB4. Dashed line labeled 10% indicates significant benefit in the case of global indicators [25].

Finally, analyzing the results for individual environments, it occurred that in the case of mild hearing loss, HA wearers benefit the most from communication in noisy (BN) situations and in reverberant (RV) (see Fig. 6). The percentage of receiving benefits in reverberation is 25%, and the unpleasant sounds accept only about 7%. In moderate hearing loss, the benefit from hearing aid use is the highest among all other conversational situations (EC, BN, RV). The percentage of users benefiting in individual environments (benefit ≥22%) is approximately 55% for EC, 77% for BN, 40% for RV, and only 5% for AV. For people with severe hearing loss, the results are different. In this case, an efficient benefit is achieved at approx. 89% in

EC and 89% in BN, but – at the same time – it is one of the worst for situations related to accepting unpleasant AV sounds. In other conditions, short-term use of hearing aids does not bring sufficient benefit.

Benefit related to speech communication was assumed as the most essential . So far, for the analyzed group of HA users conducting a conversation, for the APHAB3 indicator, sufficient benefits are gained by 75% of users with the mild and severe degree and over 93% with the moderate degree. It is also not surprising that when the evaluation process considers the acceptance of unpleasant sounds, then all the indicators fall, and the percentage of benefits decreases significantly below 75%. This is because such disturbing loud sounds are again heard, which is typical of sensorineural hearing loss.

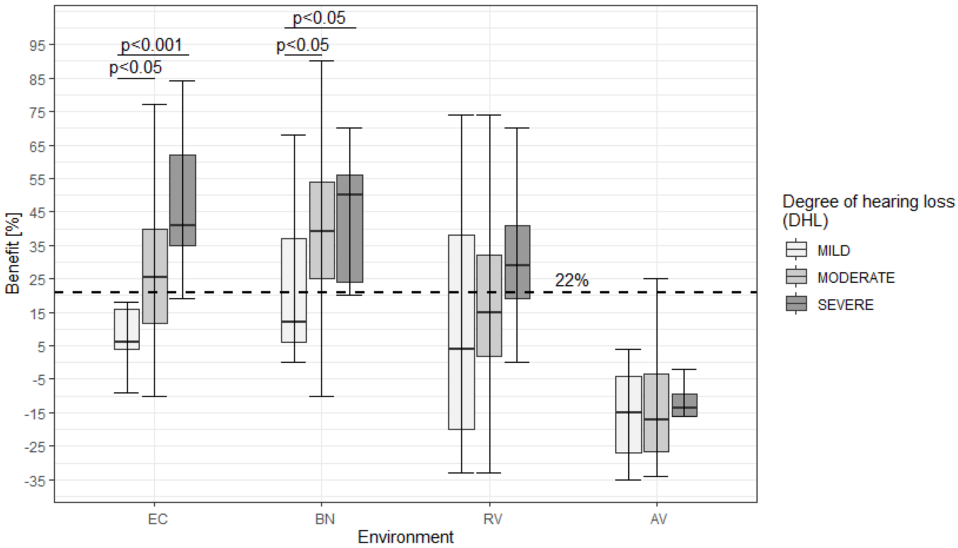

Figure 6. Benefit of short-term (7 days) use for 110 subjects (current results) determined separately for four environments in the context of various degrees of hearing loss. Dashed line labeled 22% indicates significant benefit for individual indicators [25].

Due to only one observation being present for the mild hearing loss, then it will not be considered further After a longer time of hearing aid use (max. three months), it can be noticed that benefit is significantly higher, especially for noisy BN situations. In the moderate hearing loss, the percentage of users benefiting in the individual environment is approximately 76% for EC, 95% for RV, 80% for RV, and 0% for AV. For people with severe hearing loss, the efficient benefit is achieved at approx. 67% in EC, 100% in BN, 67% in RV, but 0% in AV.

For statistical analysis, multivariate analysis of variance (MANOVA) was used for variables EC, BN, RV, AV, APHAB3, and APHAB4 (Fig. 6 and Fig. 7)

For short-term benefit, all the multivariate tests carried out (i.e., Wilks' Lambda, Hotelling-Lawley Trace, Pillai's Trace, and Roy's Largest Root [27]) yielded statistically significant results at $p \leq 0.0075$.

For longer-term benefit, all the multivariate tests carried out (i.e., Wilks' Lambda, Hotelling-Lawley Trace, Pillai's Trace, and Roy's Largest Root) did not provide statistically significant results "$p \geq 0.0691$". That is why it was not possible to conduct a one-way analysis of variance (ANOVA) for individual variables.

For short-term benefit, a one-way analysis of variance (ANOVA) for individual variables was conducted to investigate the difference in each indicator as a function of the degree of hearing loss. EC, BN, APHAB4, and APHAB3 were indicators, i.e., environments for which statistically significant differences between the compared groups were obtained. For these groups, Tukey's test was performed. It allowed in the given environment for distinguishing hearing loss in the given environment, whose pairs of averages differ significantly. It was found that in the case of variable EC, statistically significant differences occurred between moderate-mild (p = 0.0234) and mild-severe (p = 0.0005) hearing loss. In the case of the BN variable, statistically significant differences were found between the mean for moderate-mild hearing loss (p = 0.0093) and mild-severe (p = 0.0403). For the APHAB4 variable, statistically significant differences were found between the mean for moderate-mild hearing loss (p = 0.0175) and mild-severe (p = 0.0105). The APHAB3 variable brought statistically significant differences between the mean for mild-severe (p = 0.0020) hearing loss and moderate-mild (p = 0.0190).

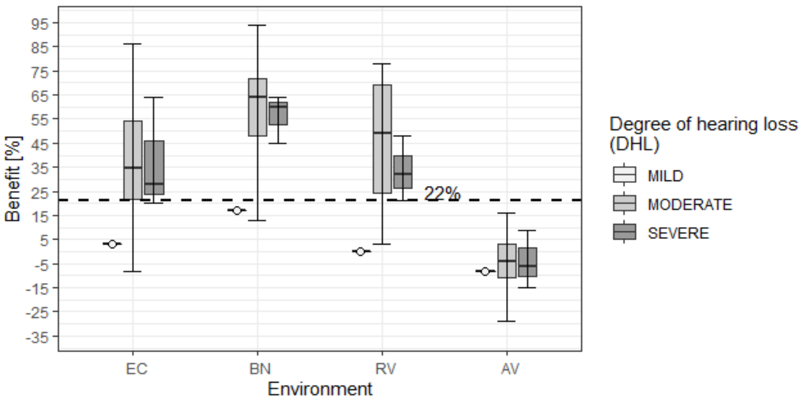

Figure 7. Benefit of the longer-term (up to 3 months) use for 24 of 110 subjects determined separately for four environments in the context of various degrees of hearing loss. Dashed line labeled 22% indicates significant benefit for individual indicators [25].

4. Conclusions

Analyzing the benefit of hearing aid use in each of the environments separately (see Table 2), it was found that in all environments considered, comparing short-term hearing instrument use, participants in the previous study scored better. The greatest difference (compared to the previous study) was seen in assessing the benefits of communicating in quiet environments. This may be due to the proportion (structure) of hearing loss in both groups of subjects (see Tab. 1). There were more subjects with mild hearing loss in the group of 109 users (28) than in the group of 110 subjects (17), while there were fewer subjects with moderate hearing loss (73 in the group of 109 users, 84 in the group of 110 subjects).

At the same time, in both the previous and current studies, the greatest improvement through the use of hearing aids is reported when communicating in noisy environments. This may suggest that modern hearing instruments are quite efficient at selecting and enhancing speech signals against noise. Also, this may shorten the period of adaptation to the hearing aids. It is noteworthy that respondents who used their hearing aids for more extended periods of time (up to 3 months) reported an improvement of over 90%.

The lowest rating of benefits (in both groups) was for the perception of unpleasant sounds. It can be concluded from this that improper fitting of hearing instruments (too much gain or too high maximum power output of hearing aid) in this context may discourage the decision to use them and mask the potential benefits that hearing instrument use may bring in the long term. This shows that when fitting hearing aids at the first visit, special attention should be paid to carefully adjusting the acoustic parameters responsible for the perception of unpleasant sounds. The adaptation of unpleasant sounds will increase over time, after a longer period of hearing instrument use. It is also worth noting that although the effect of hearing instrument technology on the benefit is not statistically significant, B hearing instrument users report higher long-term effects (APHAB3 and APHAB4).

Overall, such an evaluation using a subjective process is quite arduous for the HA wearers. Moreover, the statistical analysis used to data does not appear to be a sufficient tool that can help shorten and redesign the APHAB survey while maintaining its reliability. This is seen on the basis of data analysis when nearly the same number of HA users took part in both studies, the previous and the current ones, mainly differing in mild and moderate hearing loss cases. The authors intend to use other tools for HA use benefit assessment, in particular, rule-based inference.

Additional information

The authors declare no competing financial interests.

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