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# Combining MUSHRA Test and Fuzzy Logic in the Evaluation of Benefits of Using Hearing Prostheses

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**Abstract:** Assessing the effectiveness of hearing aid fittings based on the benefits they provide is crucial but intricate. While objective metrics of hearing aids like gain, frequency response, and distortion are measurable, they do not directly indicate user benefits. Hearing aid performance assessment encompasses various aspects, such as compensating for hearing loss and user satisfaction. The authors suggest enhancing the widely used APHAB (Abbreviated Profile of Hearing Aid Benefit) questionnaire by integrating it with the MUSHRA test. APHAB, a self-completed questionnaire for users, evaluates specific sound scenarios on a seven-point scale, with each point described by a letter, percentage, and description. Given the complexities, especially for older users, we propose converting the seven-point APHAB scale to a clearer 100-point MUSHRA scale using fuzzy logic rules. The paper starts with presenting the goals of the study, focused on the assessment of the benefits of hearing aid use, especially in the case of the elderly population. The introductory part includes an overview of methods for evaluating the effectiveness of hearing aid use. Then, the methodology for the data collection is presented. This is followed by a method modification that combines the MUSHRA (MUltiple Stimuli with Hidden Reference and Anchor) test and fuzzy logic processing and the commonly used hearing aid benefit assessment questionnaire, APHAB (Abbreviated Profile of Hearing Aid Benefit). The results of such a process are examined. A summary of the findings is given in the form of fuzzy logic-based rules, followed by a short discussion. Finally, the overall conclusion and possible future directions for the method development are presented.

**Keywords:** hearing aids; hearing loss; APHAB; MUSHRA; hearing aid benefit; fuzzy logic

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## 1. Introduction

Although the term computational audiology already exists [1,2], it concerns only certain areas, such as remote hearing assessment [3], web-based tools for remote hearing testing [3], or automatic audiogram estimation [4]. There is also Alan the Virtual Audiologist, an AI (Artificial Intelligence) chatbot [5,6], which is supposed to answer questions related to audiology. Still, it belongs to limited examples of AI applications in this domain.

Advancements in hearing aid (HA) technology largely focus on improving the signal-to-noise ratio (SNR). Techniques from deep learning-based speech enhancement, like noise reduction, speech enhancement, and directional microphones tailored to the ear's characteristics, have been adopted for hearing aids [7]. Modern devices aim at achieving optimal speech recognition and natural sound quality across diverse listening environments. Technologies include the automatic recognition of current acoustic conditions and adaptive system selection with setting adjustments. While these advancements should enhance hearing quality and user satisfaction, real-world implementation often requires choices and compromises by both users and professionals.

Despite machine learning's growth in various health sectors, its influence in audiology remains limited [8]. This is evident in challenges like hearing aid fittings within healthcare.

Evaluating the benefits of a hearing aid fitting is complex. Objective metrics like gain and frequency response exist, but they do not always correlate with a user's subjective experience. Contemporary hearing aids offer numerous features for improved speech understanding in challenging scenarios, but comparing or measuring these features to determine their daily utility remains elusive.

A wide choice of technologies offered in available hearing aids may make them difficult to compare and evaluate objectively. It results from the fact that the quality and efficiency of the solutions provided in hearing aids, despite them being similar, depending on, among other things, individual configurations and algorithms that manage them. Hearing care professionals usually do not have complete insight and access to these mechanisms. They should rely, in their daily practice, on a manufacturer's indications, their own experience, and feedback from the HA user. On the other hand, the person who has decided to acquire a hearing aid would like a solution that provides a sufficient recovery of hearing and speech recognition in all listening environments.

It should be noted that hearing is the sense through which sounds are perceived; through hearing, people engage with their surroundings, communicate, express thoughts, and receive education. In 2021, the WHO (World Health Organization) published a report entitled: "WORLD REPORT ON HEARING" [9]. According to a WHO report, untreated hearing loss is the third leading cause of years of life with disability worldwide. It affects people of all ages and is a micro and macro problem in the context of the national/global economy. If hearing loss goes untreated, it can negatively affect many aspects of life: communication, language and speech development in children, cognitive function, education, employment, mental health, and interpersonal relationships. Given its high prevalence in the population, Age-Related Hearing Loss (ARHL)—also known as presbycusis—represents a remarkable social and economic burden of hearing loss over a lifetime and is expected to increase with current demographic changes. Recent estimates indicate that more than 42% of people with any degree of hearing loss are over the age of 60. Worldwide, the prevalence of hearing loss (moderate or higher) increases exponentially with age, rising from 15.4% among those aged 60 to 58.2% among those over 90. WHO reports a regional prevalence of 10.9–17.6% among those aged 60–69, increasing to 41.9–51.2% among those aged 80–89 and reaching 52.9–64.9% among those over 90. That is why most of this study's goals are directed toward elderly hard-of-hearing persons.

Measurements of hearing aid effectiveness can address many aspects, including hearing loss compensation, acceptance, gain, or satisfaction with the prosthesis. Due to the specific scope of knowledge, currently, available tools for measuring the effectiveness of fittings are available only to professionals. The development of an easy-to-use and intuitive web application would make it available to both hearing care professionals and HA users. In this way, an objectivized assessment of the effectiveness of prosthetics would be helpful in selecting the most optimal hearing improvement solution and fine-tuning and adjusting it. In turn, at a later stage, it could be used to monitor progress in hearing rehabilitation. Evaluation of given measures might serve in predicting the long-term effects of HA fitting after a short trial period of hearing prosthesis use.

Therefore, the developed method of evaluating the benefits of using hearing prostheses should consider the following:

- Evaluate the most common listening situations encountered by the elderly hearing-impaired person;
- Evaluate the benefits of the hearing instruments by taking into account the degree of hearing loss, the experience of the user, and the type of hearing devices used;
- Evaluate non-acoustic indicators and aspects of hearing device use;
- Be easy to implement in a large number of hearing care settings and take advantage of existing staff resources and typical audiological equipment;
- Allow for a quick assessment of benefits, i.e., the procedure should not be time consuming and tiring;
- Be implemented as an easy-to-use software application.

The basis for the web application was developed by the authors and the method proposed is the APHAB (Abbreviated Profile of Hearing Aid Benefit) questionnaire, which is very commonly used for the self-assessment of HA [10–12]. This application was implemented in a large number of hearing care centers and made available, in a suitably prepared form, to hearing aid users. This investigation was performed as a part of the doctoral dissertation, the so-called implementation doctorate of the first author. The evaluation results serve as a tool for a more objective evaluation of hearing aids and facilitate the person's choice between the various solutions available after just a short period of use (testing).

Although APHAB is one of the most widely used 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, there have been many attempts over the decades to develop new forms or tools for evaluating fitting protocols, for which APHAB was the starting point [13,14]. Another drawback of the method may be the hearing aid user's self-completion of such a questionnaire, especially considering the user's age and general health. In addition, the hearing aid user is known to be more critical of the hearing aid's benefits than family members. Also, the question remains valid whether the survey should be open, closed, or mixed. These issues are shortly explained in Section 1.1.

In general, such a subjective evaluation process is quite cumbersome for hearing aid wearers. Therefore, it was decided to redesign the APHAB survey, noting the need to reduce the time it takes to complete the survey while maintaining its reliability.

The study begins by outlining various methods that constitute the background for the HA use effectiveness assessment. The aspect of objective and subjective evaluation, resulting in verification and validation, is also included. Furthermore, the types of surveys are shortly characterized. Moreover, the literature sources that motivated us to modify the evaluation scale and supported the idea of applying fuzzy logic to the process of obtaining the result are brought in. The subsequent section delves into the data collection approach, followed by a proposed method modification that merges the MUSHRA (MUltiple Stimuli with Hidden Reference and Anchor) test with fuzzy logic processing, tailored to the commonly used APHAB (Abbreviated Profile of Hearing Aid Benefit) questionnaire for hearing aid benefit assessment. The outcomes of this integration are then explored and discussed, with findings summarized as fuzzy logic-based rules. The paper concludes with a summary of the paper content and potential future improvement of this method.

### *1.1. Background of the Study—Evaluating the Effectiveness of Hearing Aid Use*

Methods for assessing the effectiveness of hearing aid use can be divided into objective and subjective categories [15–17]. Objective evaluation is most often associated with the concept of verification, while subjective evaluation is associated with the concept of validation [18].

Verification is the objective measurement of acoustic parameters: amplification and maximum output level as a function of frequency, as well as the dynamic characteristics of the hearing aid, that is, the relationship between the signals at the input and output of the hearing aid [12,15,16]. Measurements are carried out using hearing aid analyzers, a 2 $cm^3$ coupler and/or on the patient's ear using microphone probes (a technique known as in situ, REM—Real Ear Measurement)) [15,17]. Thus, verification of the acoustic parameters of a hearing aid makes it possible to check whether the acoustic signal that reaches the eardrum of the hearing aid user has characteristics that comply with the requirements of a specific, selected fitting method. Validation, on the other hand, refers to the evaluation of the benefits that the use of a hearing aid brings. Such a formal division between validation and verification was also discussed by Mendel, Cox, and Humes [15–17].

Measurements of hearing aid effectiveness, either subjective or objective, can address many aspects, including hearing loss compensation, acceptance, gain, or satisfaction with the prosthesis. Over the past three decades, a variety of questionnaires have been developed to address these aspects, starting with the most frequently used questionnaire, i.e., APHAB [12]. This method was used in our study, so that it will be presented later on.

Another currently used questionnaire is Satisfaction with Amplification in Daily Life (SADL). It is a closed-ended questionnaire that is self-completed by the patient. It was developed in 1999 and designed to measure satisfaction with hearing aids. It contains 15 items rated on a seven-point scale. The score is calculated for each subcategory separately as well as for all of them together (the average of all evaluated 15 elements—Global Score) [19,20]. Hearing Handicap Inventory for Adults (HHIA) and Hearing Handicap Inventory for the Elderly (HHIE) are closed-ended questionnaires completed by the patient. HHIA, developed in 1991, is a revised and updated version of HHIE (developed in 1986). It was designed to assess both hearing impairment/disadvantage and benefit, measuring the change in perceived impairment after wearing hearing aids. Both HHIE and HHIA contain 25 questions in two subcategories (emotional and social consequences and situational effects). They aim to measure the perceived effect of hearing loss. In both the HHIE and HHIA, there are three possible answers to the questions (yes, sometimes, no) [19,20].

Another questionnaire is the International Outcome Inventory for Hearing Aids (IOI-HA). It is a closed-ended questionnaire that is self-completed by the patient. It consists of seven questions rated on a five-point scale (1—lowest/worst rating, 5—highest/best rating). The purpose of the IOI-HA is to assess the benefits, satisfaction, and changes in the quality of life associated with the use of hearing aids. The IOI-HA was designed not as a stand-alone questionnaire but as an add-on, supplementing other self-assessment tools such as APHAB [19,21].

An example of a closed-ended questionnaire is the Speech, Spatial, and Qualities of Hearing Scale (SSQ). It was developed in 2004 to determine the extent of hearing impairment in several areas. Special attention is given to listening and understanding speech in various competing contexts as well as spatial hearing components such as directionality, distance, and movement of the sound source. The SSQ questionnaire contains 49 descriptions of situations and questions relating to them. An abbreviated version of the questionnaire has been developed to facilitate clinical and rehabilitation applications, containing 12 situation descriptions and related questions, rated from 0 ("Not at all") to 10 ("Perfect"). The score can be obtained on four scales, i.e., speech scale (situations 1–4), spatial scale (situations 6–8), hearing quality scale (situations 9–12), and the total average score for all 12 situations. It is described by the acronym SSQ12, as opposed to the full version described by SSQ49 [20,22].

Another questionnaire is the Glasgow Hearing Aid Benefit Profile (GHABP). This questionnaire can be called a mixed questionnaire, combining closed and open forms. It is filled out independently by the patient. It was developed in 1999 as a tool to evaluate the effectiveness of hearing aids and the effectiveness of aural rehabilitation. It contains four defined situations and four situations selected and described by the patient. Each situation is assessed in six areas. Individual items are rated on a seven-point scale [12].

In contrast, COSI (Client-Oriented Scale of Improvement) is an open-ended questionnaire self-completed by the patient. It was developed in 1997 at the National Acoustic Laboratories (NAL) in Melbourne, Australia. It is an open-ended scale in which the patient indicates up to five acoustic situations in which they expect hearing to improve. The hearing aid assessment proceeds in two stages. In the first stage, the hard-of-hearing person declares/identifies the acoustic situations (acoustic environments) that they consider most important. In the second stage, after fitting the hearing aid, the hard-of-hearing person determines the degree of change in hearing in the acoustic situations selected at stage one. At the same time, for the same identified acoustic conditions, patients evaluate their ability to hear/understand in these situations [19].

Other less commonly used questionnaires are the following:

- Hearing Aid Performance Inventory (HAPI—1984) [19,20];
- Hearing Performance Inventory (HPI—1979) and Hearing Performance Inventory-Revised (HPI-R—1983) [19,20];
- Hearing Aid Users Questionnaire (HAUQ—1999 [19];
- Hearing Aid Needs Assessment (HANA—1999) [19];

- Communication Profile for the Hearing Impaired (CPHI—1991) [19];
- Hearing Aid Interview (HAI-2004) [20];
- World Health Organization Disability Assessment Schedule (WHO-DAS II)/WHODAS 2.0—1990 [19,23,24].

The above questionnaires are a starting point for developing new tools for evaluating the effectiveness of hearing aid prosthetics [15] or may be part of a broader testing procedure [21]. An example of a new approach to assessing the auditory experience and hearing aids that have recently emerged using the recording of everyday behavior and situations is EMA (ecological momentary assessment). EMA, widely used in psychological research [25], is a self-report assessment method that can minimize recall error compared to retrospective recall methods. Specifically, EMA typically involves self-reporting the environment and behavior multiple times throughout the day and over multiple days, either at the appropriate time or after engaging in the target behavior.

EMA is distinguished from other self-report assessment methods by four features: (1) the assessments focus on the current state or activity of the participants, i.e., retrospective memory and biased reports are greatly reduced in EMA, even compared to end-of-day diaries, because participants are asked what they were doing, feeling or thinking at that moment or during the past hour; (2) assessments are conducted under specific conditions; (3) assessments involve repeated measurements, to study intrapersonal effects (e.g., how sleep variability affects mood), as well as intrapersonal dynamics over a significant period more extended than typical experiments (e.g., how feelings and behavior change from 1 h, day, or week to another; (4) assessments are conducted in a person's natural environment.

Although EMA was initially developed using paper-and-pencil methods, researchers implementing EMA are increasingly adopting available technologies, such as smartphones and personal digital assistants (PDAs). These mobile EMA (mEMA) methods increase the convenience of reporting, given the availability of smartphones.

Benefit assessment is also based on free-field measurements:

- Free-field tonal audiogram—an audiometric test is performed twice for a given patient, at a minimum of two-week intervals. The test is performed without a hearing aid and then with a hearing aid in place. The fitting gain is calculated by comparing the hearing threshold waveform curves in the presence of a hearing aid and without a hearing aid for three frequency components: 500, 1000, and 2000 Hz [26].
- Acceptable Noise Level (ANL) test—is a method of determining how much noise a patient can tolerate while listening to the target signal/speaker. The test is conducted by first setting the patient's speech to the most comfortable level (MCL). Then noise, such as speech babble, is added, and the patient is asked to adjust it to the highest level they can accept or "tolerate" while following the story told in the original speech signal. The level selected is called the Background Noise Level (BNL). ANL is defined as MCL minus BNL. This is the lowest SNR that is acceptable to the patient. People with a low ANL (<7 dB) may become regular users of hearing aids because they are willing to put up with amplified noise levels close to the signal of interest. Conversely, people with high ANL (>13 dB) are likely to use hearing aids less often or not at all because they find amplified noise undesirable in too many situations. Of course, there is a large gray area in the middle (ANL values between 7 and 13 dB) for which the acceptance of hearing aids is uncertain [27].
- Speech intelligibility test in silence—the most commonly used verbal material is lists of single-syllable words. The patient's task is to repeat the words given by a speaker 1 m away from the listener. The sound level of the administered test is 65 dB. The percentage of correctly repeated words is tested first when the patient does not have a hearing aid, and then the procedure is repeated with a hearing aid in place. The free-field test is repeated after a minimum of two weeks. The speech intelligibility benefit is expressed as the difference in the percentage of correctly repeated words in the presence of a hearing aid and without a hearing aid [28].

- Hearing in Noise Test (HINT) is a test of hearing in noise that measures sentence recognition against background noise. The verbal material consists of 250 sentences, which are divided into 25 lists. This test can be conducted in silence. In this case, a threshold for sentence recognition is obtained. If the test is conducted in noise, it allows estimating the SNR threshold for speech recognition in noise. By employing this test, it is possible to show the advantage of binaural directional hearing and, thus, binaural prosthetics [29,30].
- Quick speech-in-noise test (QuickSIN) allows for a short (test duration is about 1 min) estimation of the SNR level at which the patient will achieve 50% correct responses. The verbal material contains sentences that consist of five keywords each, presented against a background of noise (four-talker babble noise). The SNR level can be adjusted. Possible settings are 25, 20, 15, 10, 5, and 0 dB [30].

Free-field measurements, along with questionnaires, are often part of elaborate and complex testing procedures for evaluating the HA effectiveness [31]. Also, it should be noted that all the methods recalled are time consuming. To make choosing the HA benefit evaluation method even more difficult, one should also investigate the psychometric scale type on which the HA users rate their answers. They differ widely between methods; however, the reasoning behind them is to rate an item or specify the level of agreement or disagreement for a series of statements. Moreover, the same method may employ a mixture of scales, which is even more complicated for the HA user. It is interesting to see that in some works, for example, fuzzy logic was used to improve the widely used Likert scale, which considers to what extent one agrees or disagrees with the evaluated item [32–34]. One of the aims of these studies was to permit a partial agreement degree instead of a fixed one to reduce the loss and information distortion in the data collection process. The authors also noted that the results obtained in the Likert scale improved by fuzzy logic were more convenient to be analyzed with mean, median, and standard deviation and provided a lower standard error.

Another work of interest is of Völker et al. [35], which proposes to use the MUlti stimulus test with Hidden Reference and Anchor (MUSHRA) in audiology. They modified the original standardized test and argued that MUSHRA modifications make this method accessible for elderly and non-experienced listeners [35]. The idea introduced by Völker et al. [35] inspired us to use the MUSHRA test in our work. We also decided to modify the APHAB results by employing fuzzy logic-based processing. The motivation behind this was that fuzzy logic deals with continuous scale and returned results as rules, easily interpreted by an audiologist or hearing practitioner.

Since APHAB is used in our study [10–12], it will be discussed in more detail.

APHAB is a closed-ended questionnaire that is self-completed by the HA user. It consists of 24 items (statements) in four subcategories (six statements per category):

- EC (Ease of Communication)—the ability to communicate in silence, the effort to communicate under relatively easy listening conditions;
- RV (Reverberation)—the ability to communicate in the presence of echoes, describes understanding speech in moderately reverberant conditions;
- BN (Background Noise)—the ability to communicate in the presence of background noise describes 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, describes adverse reactions to environmental sounds [19,36,37].

Each item is rated on a seven-point scale, i.e., from A to G. Each scale step, from A to G, includes a description and an associated percentage value (see Table 1).

The purpose of using the APHAB questionnaire is the following:

- To predict the likely success of the use of hearing aids [36] or alternative hearing devices [38];

- To compare the functioning of a given person with a hearing aid(s) with the results of a reference group using hearing aids successfully [36];
- To document the benefits of using hearing aids in different environments to improve (eliminate) ineffective fittings as well as to compare the gain using various hearing aids or different hearing aid programs [36];
- To confirm the effectiveness of new selection and tuning procedures for hearing aids or other assistive listening devices [31].

The benefit of a hearing aid can be assessed by analyzing the average percentages for each category (EC, RV, BN, AV) [39], as well as by calculating the average value for three (EC, RV, BN) [11,12] or four categories (the so-called Global Score). This questionnaire is employed in hearing aid assessment in many countries and languages. However, as already mentioned, this is one of the methods that has drawbacks as it is time consuming. Moreover, some questions are not valid for many HA potential users. The APHAB questionnaire was, however, employed in the study to have material for comparing the results when introducing a modified method.

**Table 1.** APHAB questionnaire scale.

| | | |
|---|---|---|
| A | Always | 99% |
| B | Almost always | 87% |
| C | Generally | 75% |
| D | Half-the-time | 50% |
| E | Occasionally | 25% |
| F | Seldom | 12% |
| G | Never | 1% |

## 2. Materials and Methods

To collect data for evaluating the benefits of hearing aids (HAs), a web-based application was developed and implemented. It systematizes and organizes the collection of the obtained results. This application was prepared using the LMS (Learning Management System) Moodle platform [40]. The platform was based on the PHP scripting language, which, among others, influences its high flexibility and full configurability. This e-learning platform was also chosen due to its availability at prosthetic centers, familiarity with its use by potential users, and the possibility of using the database module implemented in the platform. The designed database user interface has a form whose structure can be easily modified thanks to a closed set of fields and labels. The database module of the Moodle platform also allows the configuration of exported data, i.e., as any defined set or as a whole dataset. The application includes 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 Figure 1, a flow chart of the data collection process is shown.

Figure 1 shows the data collection scheme. During the HA potential user's first visit—all standard hearing aid fitting activities are carried out. These include medical history, otoscopy, audiometric examination, and hearing aid fitting. In connection with the benefit assessment, an extended interview is performed, supplemented with questions from the APHAB questionnaire (Questionnaire 1). The part of the questionnaire that relates to the patient's hearing in various situations without hearing aids is completed. After fitting the hearing aids, verbal audiometry is performed without and with hearing aids. Finally, the test subjects are instructed on the operation, use, and care of hearing aids. They are advised to use hearing aids for seven consecutive days, at least 4 h a day. The upper limit of use is not specified and depends only on the subject.

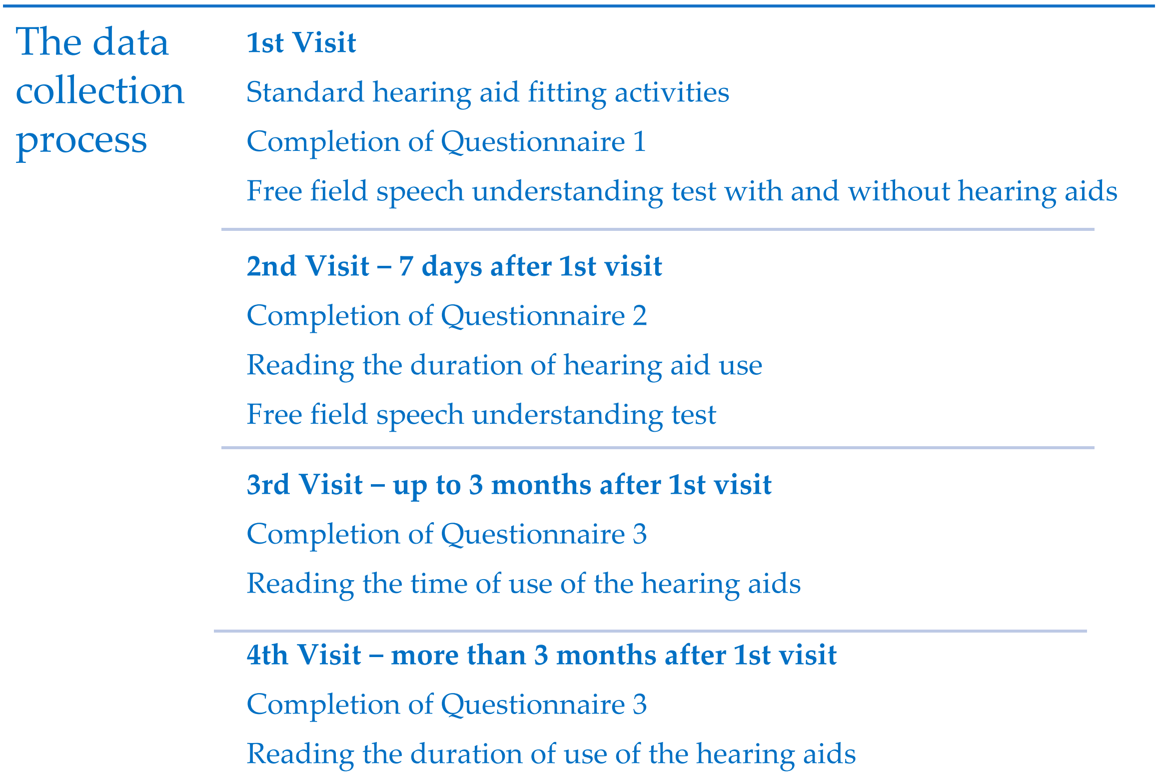



**Figure 1.** Flow chart of the data collection process.

A second visit is made as standard after seven days of the HA use. The purpose of this visit is to determine the short-term benefits of using the prescribed device. For this purpose, an interview is conducted with the patient using Questionnaire No. 2. One of the most important elements of this visit is reading the data from the hearing aids and recording it in the hearing aid software. Based on this, Questionnaire No. 2 is supplemented with the actual time of use of the hearing aids, which can be determined on an hourly basis. This is an important parameter that is then considered when evaluating the benefits of hearing aids. This is because it turns out that there is a discrepancy between the patient's declared use of the hearing aids and the actual state. This makes it possible to evaluate the patient's subjective benefits in relation to the objective parameter, which is precisely the duration of use of the hearing aids. The next step is to retest the comprehension of monosyllabic words in the free field and to fill out the second part of the APHAB form. This time, the questions are about hearing in different situations with hearing aids. The differences in the answers given at the first (Questionnaire 1) and second visit (Questionnaire 2) represent an assessment of hearing improvement in the situations mentioned.

Overall, the form includes questions that relate the HA user to the immediate environment and primarily check their reactions to the change in the patient's perceptual abilities. Finally, a question relates to the patient's plans for future hearing aid use and, thus, for lasting improvements in hearing and speech understanding abilities. The purpose of this question is to see how much the short-term benefits of using hearing aids might influence the decision to purchase them. The questionnaires also provide space for additional patient comments and suggestions.

The third visit takes place before the end of the 3rd month of braces use. During this visit, the goal is to interview the patient using Questionnaire 3 to assess the benefits of using hearing aids. It includes a reading of the hearing aids, a determination of the actual use time, and the APHAB form. The last visit takes place after three months of hearing aid use. During this visit, the goal is to interview the patient using Questionnaire 3 to assess the benefits of using hearing aids. It includes a reading of the hearing aids, a determination of the actual use time, and the APHAB form.

The authors designed and developed a method for evaluating the benefits of using hearing aids based on the APHAB questionnaire supplemented by the free-field speech comprehension score (with and without hearing aids), the model and acoustic parameters of the hearing aids used (the way the sound is delivered to the eardrum, the diameter of the tube, the diameter of the vent), the user's general opinion on the comfort and convenience of their use, and the duration of use of the hearing aid(s). It was tested on two groups of subjects (more than 500 in total). The effect was checked in the short (7 days) and long-term (up to 3 months) use of hearing aids. The results were published in two earlier articles [41,42]. To test the relationship between the degree of hearing loss and the gain from hearing aid use as determined by the APHAB questionnaire, statistical analysis was performed employing multivariate analysis of variance (MANOVA).

In assessing the short-term benefit, all the multivariate tests conducted (i.e., Wilks' lambda, Hotelling–Lawley's trace, Pillai's trace, and Roy's largest root) yielded statistically significant results at the $p \leq 0.0089$ level for the first group and at the $p \leq 0.0075$ level. Therefore, it was possible to conduct a one-way analysis of variance (ANOVA) for each category and, in addition, post-hoc tests, i.e., Tukey's reasonable significant difference tests, which made it possible to distinguish hearing losses in a given environment whose pairs of means are significantly different.

Based on the analyses, it can be concluded that in the short term for the BN category (i.e., the ability to communicate in the presence of ambient noise) and the average for the three categories (EC, RV, BN—global index for conversational situations), statistically significant differences were obtained for hearing losses of moderate degree relative to the other degrees of hearing loss, indicating that it is possible for this group of hearing losses to assess the achieved effect after short-term use.

Overall, comparing the results obtained for the two groups of subjects [41,42] it was found that members of one of the groups scored better overall. This may be due to the hearing assessment scale used in the APHAB form. The combination of letters, percentages, and descriptive scales may present difficulties in interpretation for the subjects, the vast majority of whom are elderly.

*Method Modification*

Based on the above observations, the concept of modifying the questionnaire was developed, i.e., transforming the APHAB scale into a scale compatible with the MUSHRA (MUltiple Stimuli with Hidden Reference and Anchor) test as suggested by Völker et al. [35] while using fuzzy logic in the data processing. The MUSHRA test is used in evaluating the sound quality of hearing aids, both by people with hearing loss and normal hearing [40,43,44]. Fuzzy logic, on the other hand, finds application even in hearing aid adjustment procedures using volume scaling [45]. Moreover, the modified questionnaire includes, with each sound situation listed, two additional questions: "Does the situation described above occur?" and "If the above situation occurs, is it important/relevant?" The collected responses from respondents are intended to help eliminate situations that do not occur or occur infrequently, which will translate into a possibly shorter questionnaire.

A block diagram showing the classical APHAB method along MUSHRA-fuzzy logic-based processing is contained in Figure 2.

MUSHRA and fuzzy logic-based methodology—a brief description of the test procedure and algorithm for estimating the gain using the instruments is shown in Figure 3.

The HA user's task is to rate hearing (sound quality) without and with hearing aids on a 100-point scale, according to the mapping shown in Figure 4, for a sample situation of the BN category: "When I am in a crowded grocery store, talking with the cashier, I can follow the conversation." Moreover, because of the decision to redesign the questionnaire, it was decided to leave all the questions from the APHAB survey, and the possibility of listening to an audio example illustrating the sound situation being evaluated was added. For assessing hearing quality, the MUSHRA test seems a natural choice, especially since it is used to evaluate the sound quality of hearing aids, both by people with hearing loss and people with normal hearing.

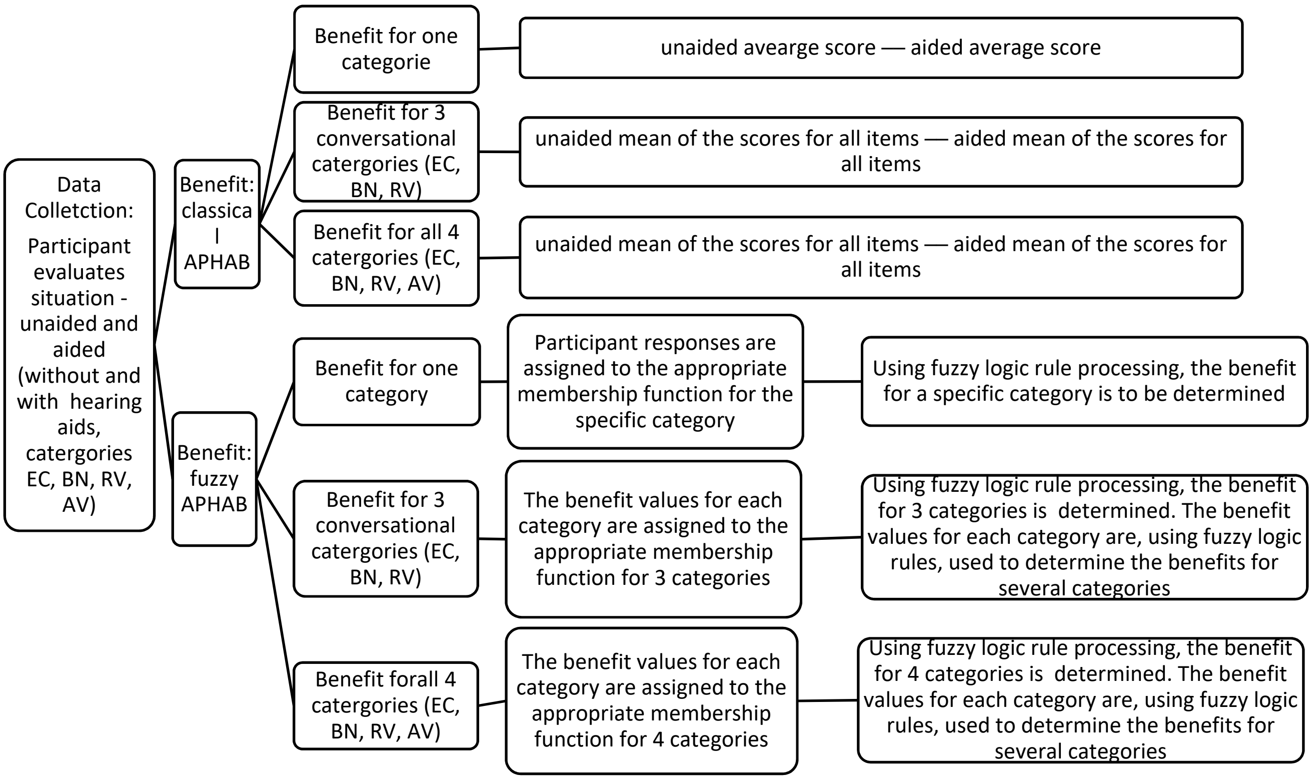



**Figure 2.** Block diagram of the HA benefit evaluation using the classical APHAB method and MUSHRA-fuzzy logic-based approach.

MUSHRA and Fuzzy Logic

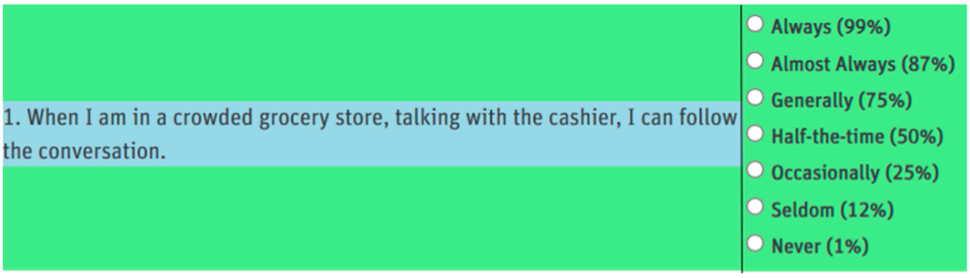
1. The person tested selects from 24 sound situations the ones they encounter or the ones that are most meaningful to them (following the "classical" approach to the APHAB questionnaire, the test person should evaluate each situation. When the subject has difficulty answering because they have not experienced a particular situation, in that case, a HA user should be helped to find a similar one)

2. The person tested assesses hearing in these situations without hearing aids; according to the MUSHRA scale from 0 to 100, the lower the number on the scale, the less often the situation is true.

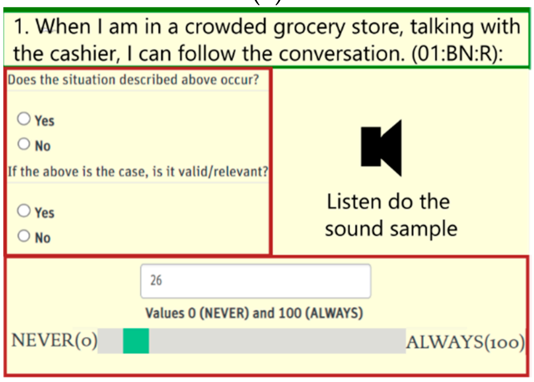
3. The person tested evaluates hearing in these situations with hearing aids after seven days, six weeks, and three months of hearing aids use.

4. Based on the assessments, the hearing aid gain is determined for each situation category (EC, BN, RV, AV) and the joint gain for three (EC, BN, RV) or four categories.

**Figure 3.** Description of the test procedure and algorithm for estimating apparatus benefit in the modified method.




(**a**)




(**b**)

**Figure 4.** Mapping the APHAB scale (**a**) to the MUSHRA scale (**b**).

The HA user's responses are then assigned to the appropriate membership function for the specific category. In Figure 5, one can see an example of a membership function for the EC category. The membership functions are the same for all four categories (EC, BN, RV, AV).

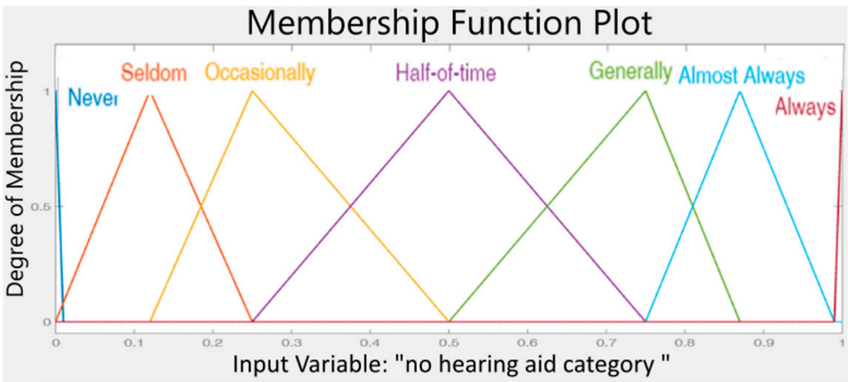



**Figure 5.** Example of membership function for the EC category.

Based on the user's evaluation, using fuzzy logic rule processing, the benefit for a specific category is to be determined. In Figure 6, one can see an example of the benefit scale of the EC category.

To determine the benefit for a single category, fuzzy inference systems with two to twelve inputs and one output were used. The number of rules for these systems is 49 and 294, respectively. They were reviewed by the audiology specialist. An example system with four inputs is shown in Figure 7. An example of a rule list for a system with two inputs is shown in Table 2.

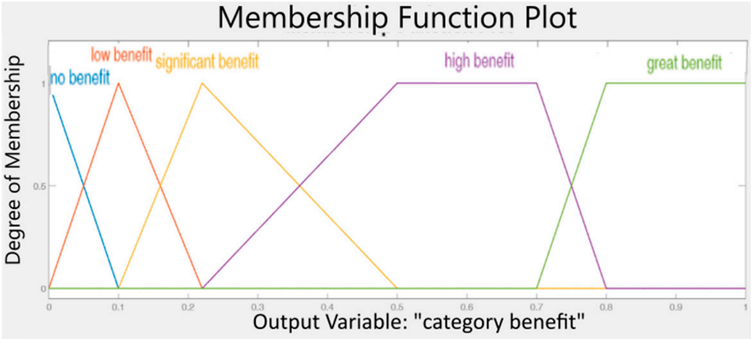



**Figure 6.** Example of EC category benefit scale.

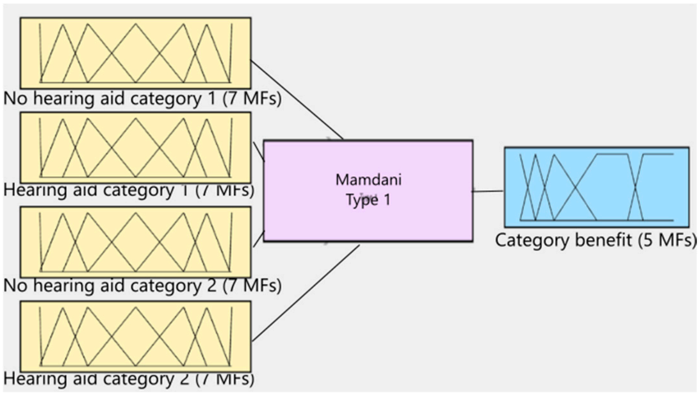



**Figure 7.** Example fuzzy inference system with four inputs and one output for determining benefit in one category.

**Table 2.** Example from a rule list for a system with two inputs.

| | | Evaluation | | | Evaluation | | Rating of Benefit |
|---|---|---|---|---|---|---|---|
| IF | Category without HA | Never | OR | Category with HA | Never | THEN | No benefit |
| IF | Category without HA | Never | OR | Category with HA | Seldom | THEN | Low benefit |
| IF | Category without HA | Never | OR | Category with HA | Occasionally | THEN | Low benefit |
| IF | Category without HA | Never | OR | Category with HA | Half-of-time | THEN | Significant benefit |
| IF | Category without HA | Never | OR | Category with HA | Generally | THEN | High benefit |
| IF | Category without HA | Never | OR | Category with HA | Almost always | THEN | Great benefit |
| IF | Category without HA | Never | OR | Category with HA | Always | THEN | Great benefit |
| IF | Category without HA | Seldom | OR | Category with HA | Never | THEN | No benefit |
| IF | Category without HA | Seldom | OR | Category with HA | Seldom | THEN | No benefit |
| IF | Category without HA | Seldom | OR | Category with HA | Occasionally | THEN | Low benefit |
| IF | Category without HA | Seldom | OR | Category with HA | Half-of-time | THEN | Significant benefit |
| IF | Category without HA | Seldom | OR | Category with HA | Generally | THEN | High benefit |
| IF | Category without HA | Seldom | OR | Category with HA | Almost always | THEN | Great benefit |
| IF | Category without HA | Seldom | OR | Category with HA | Always | THEN | Great benefit |
| IF | Category without HA | Occasionally | OR | Category with HA | Never | THEN | No benefit |

The benefit values for each category thus obtained are, using fuzzy logic rules, to be used to determine the benefit for several categories. In Figure 8, one can see an example of the benefit membership function of the EC, BN, and RV categories.

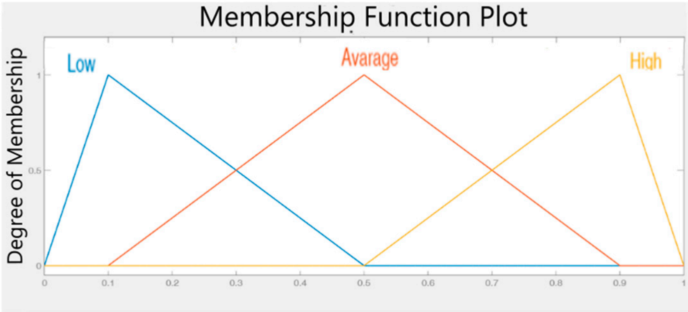



**Figure 8.** Example of the benefit membership function of EC, BN, and RV categories.

The benefit scale for several categories is identical to that for a single category (see Figure 5). To determine the benefit for a single category, fuzzy inference systems with three (EC, BN, RV categories) and four (EC, BN, RV, AV categories) inputs and one output were employed. The number of rules for these systems is 27 and 81, respectively. An audiology specialist reviewed the rules. An example system with three inputs is shown in Figure 9.

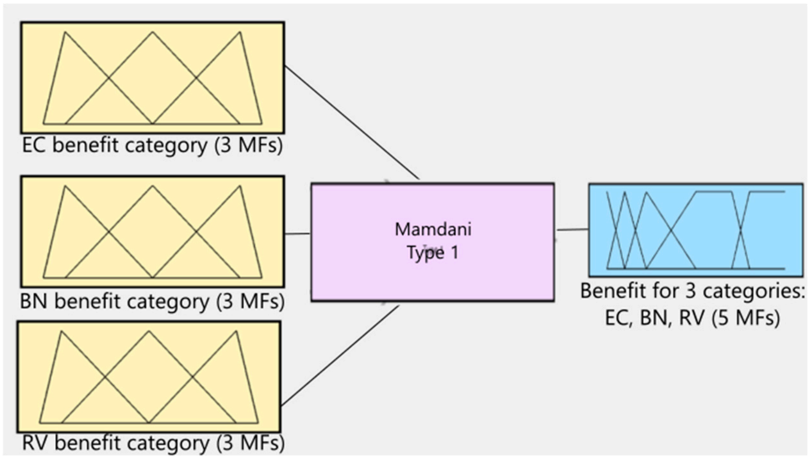



**Figure 9.** Example fuzzy inference system with three inputs and one output for determining benefit in three categories.

## 3. Results

The participants in the study were 16 people, namely 12 men (mean age 69.5; standard deviation 8.7) and four women (mean age 76.5; standard deviation 11.0), with bilateral symmetrical (12 subjects: 9 men and three women) and asymmetrical (4 subjects: three men and one woman) hearing loss of mild (according to the 1991 WHO scale [46]) (8 subjects: seven men and one woman) and moderate (8 subjects: five men and three women) degrees.

Thus, at present, data were acquired from 16 subjects, of which only 8 had a second visit (after seven days). However, they all indicated which of the 24 sound situations occurred in their environment and which did not. Table 3 presents a summary of their responses, and Figure 10 shows an analysis of these data for each subject separately, taking into consideration the number of assessed sound situations.

As seen in Table 3, according to the respondents' assessments, not all situations occur. When a situation does not happen, respondents (according to the instructions for completing the APHAB questionnaire) are encouraged to imagine an acoustically similar situation and rate their hearing in this hypothetical situation. However, this may cause the questionnaire to be filled out "by force," so to speak, which may result in less respondents' involvement in the evaluation process.

**Table 3.** Respondents' answers regarding the presence or absence of sound situations.

| APHAB Item Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Occurs** | 13 | 12 | 8 | 12 | 14 | 9 | 12 | 10 | 14 | 14 | 13 | 13 | 7 | 13 | 8 | 7 | 11 | 8 | 8 | 12 | 5 | 12 | 6 | 9 |
| **Does not occur** | 2 | 3 | 7 | 3 | 1 | 6 | 3 | 5 | 1 | 1 | 2 | 2 | 8 | 2 | 7 | 8 | 4 | 7 | 7 | 3 | 10 | 3 | 9 | 6 |

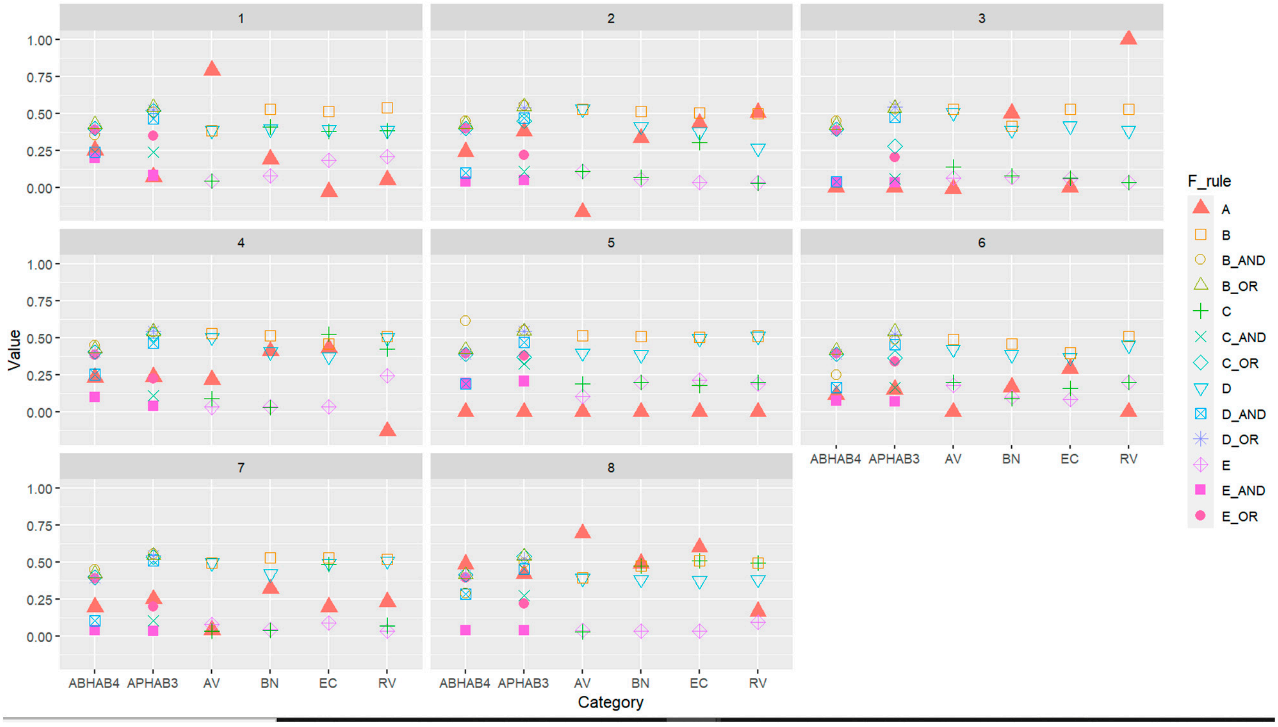



**Figure 10.** The results of the analysis of the benefit using classical APHAB and fuzzy logic rules that was conducted for eight subjects.

According to Figure 3, there are some rules derived from the data obtained in the MUSHRA-fuzzy logic-based analysis:

1. Classically, the gain is calculated as the difference between average ratings without hearing aids and average ratings in hearing aids (denoted as A—in Figure 10).
2. In a modification of the method using fuzzy logic to determine the profit in a given category (EC, BN, RV, AV), the following rule variants were used:
3. **IF** Category without HA Evaluation **OR** Category with HA Evaluation **THEN** Rating of benefit—in this case, the number of inputs of the system will correspond to the number of evaluations made in the category, i.e., from 2 to 12 (denoted as B—in Figure 10).
4. **IF** Category without HA Evaluation **AND** Category with HA Evaluation **THEN** Rating of benefit—in which case the number of system entries will correspond to the number of assessments made in the category, i.e., from 2 to 12 (denoted as C—in Figure 10).
5. **IF** Mean of category without HA Evaluation **OR** Mean of category with HA Evaluation **THEN** Rating of benefit—in this case, the number of inputs of the system will equal 2 (denoted as D—in Figure 10).
6. **IF** Mean of category without HA Evaluation **AND** Mean of category with HA **Evaluation THEN** Rating of benefit—in this case, the number of inputs of the system will equal 2 (denoted as E—in Figure 10).
7. In a modification of the method using fuzzy logic to determine the expected profit for the three categories (EC, BN, RV), the following rule variants were used:

8. **IF** Benefit of EC category Evaluation **OR** Benefit of BN category Evaluation OR Benefit of RV category Evaluation **THEN** Rating of benefit—in this case, the number of inputs of the system corresponds to the number of categories.
9. **IF** Benefit of EC category Evaluation **AND** Benefit of BN category Evaluation AND Benefit of RV category Evaluation **THEN** Rating of benefit—in this case, the number of system inputs corresponds to the number of categories.
10. In a modification of the method using fuzzy logic to determine the expected profit for the four categories (EC, BN, RV, AV), the following rule variants were used:
11. **IF** Benefit of EC category Evaluation **OR** Benefit of BN category Evaluation **OR** Benefit of RV category Evaluation **OR** Benefit of AV category Evaluation **THEN** Rating of benefit—in this case, the number of inputs of the system corresponds to the number of categories.
12. **IF** Benefit of EC category Evaluation **AND** Benefit of BN category Evaluation **AND** Benefit of RV category Evaluation Benefit of RV category Evaluation **AND** Benefit of AV category Evaluation **THEN** Rating of benefit—in which case the number of system inputs corresponds to the number of categories.

The following charts in Figure 10 show the benefit of HA determined according to the above rules for the eight subjects.

The mean benefit values obtained using individual rule sets were compared for eight subjects. The Student's t-test was used for this purpose. Only for two categories, i.e., BN (Figure 11) and RV (Figure 12) and one set of rules, i.e., Set B, were the differences between the profit means statistically significant. For the BN category, the $p$ value obtained was equal to 0.0043, and for the RV category, $p$ = 0.0218. For the remaining categories and sets of rules, either the data distribution was not normal or the differences were not statistically significant.

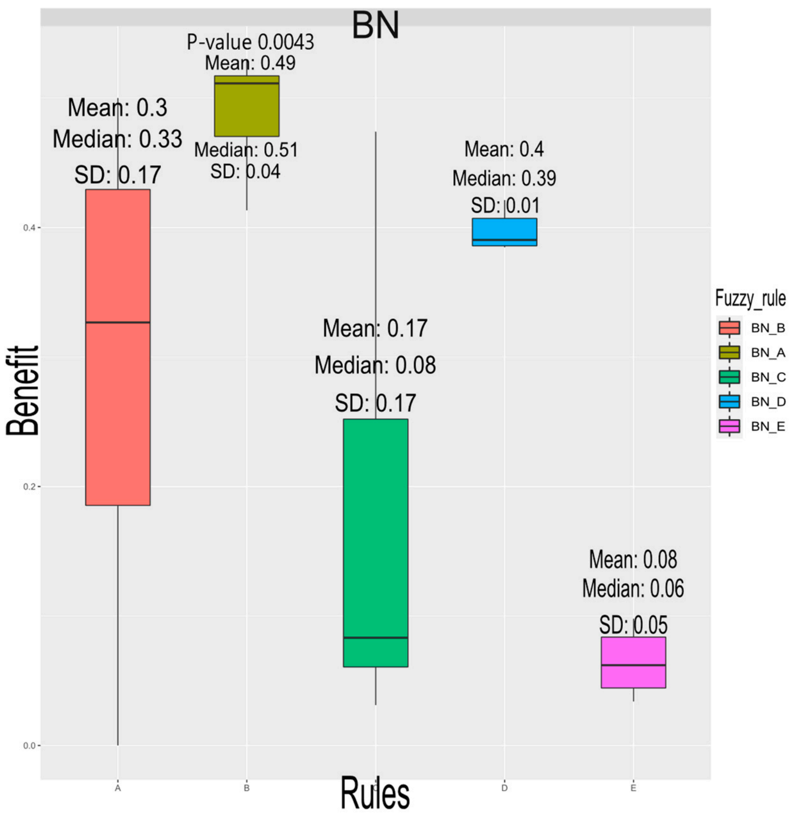



**Figure 11.** Statistical analysis for BN category.

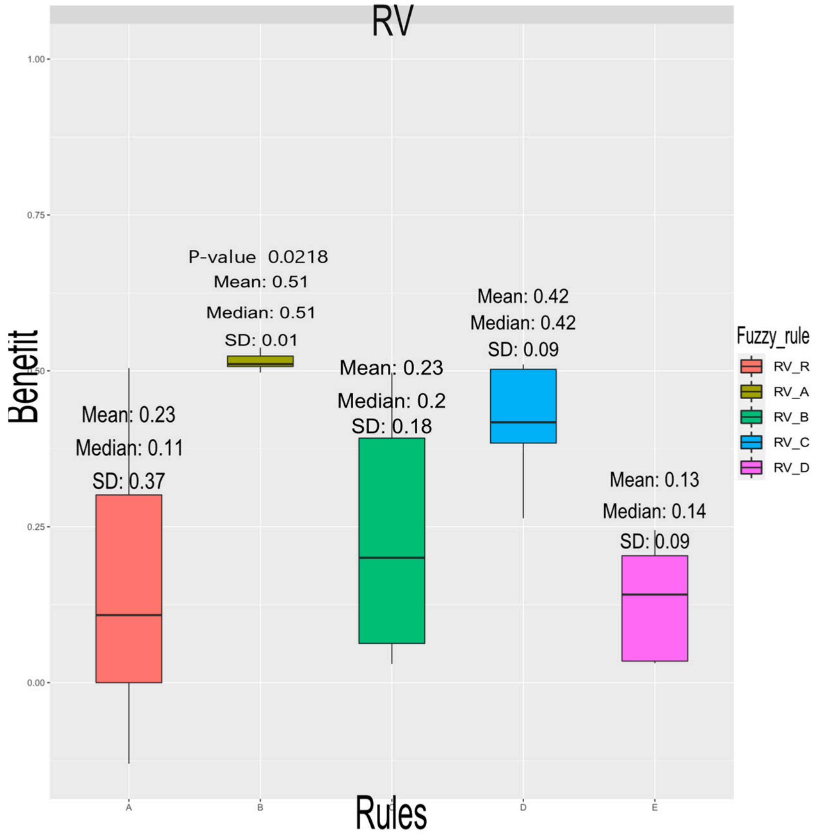



**Figure 12.** Statistical analysis for RV category.

## 4. Discussion

As part of the proposed study, a web-based application was developed and implemented at about 200 hearing aid centers. The main limitation of the method is its duration. It is tiring and does not always adhere to the user's environment. ABHAB's 24 questions are too many and too long for most respondents. That is why the web application was then redesigned and rebuilt to modify the method, which allowed for evaluating and visualizing the HA use benefit in an easier way for potential users. The main point of the modified method was to employ MUSHRA subjective tests for translating the results into APHAB by utilizing fuzzy logic-based processing. Moreover, the modified solution eliminates questions that do not regard the HA user. The method may enable them to evaluate the fitting of hearing aids not only at the hearing aid center but also at home or in other acoustic environments that are particularly important to them. Moreover, it may become a cost-effective solution conforming to the "Integrated people-centered ear and hearing care" (IPC-EHC) H.E.A.R.I.N.G. report recommendations [9].

Direct conversations with patients and audiologists show that the adopted method still has the weaknesses of the original APHAB method. The main limitation is the large number of questions, which is cumbersome for older people. Also, their scope, in the case of some questions, goes beyond situations that an older adult deals with on a daily basis. Other researchers have also come to a similar conclusion [11]. As a result, this can lead to inaccurate answers or even misinterpretation. For this reason, it seems that in the future it would be desirable to develop a somewhat narrower range of questions dedicated to this age group of hearing aid users.

Therefore, work is currently underway to shorten the questionnaire. Undoubtedly, shortening it would be a great improvement. However, there remains the question of the reliability of the shortened questionnaire, which would need to be tested and proven. After collecting more data, one could be tempted to analyze it using rough set-based [47] analysis to identify the questions with the highest and lowest weight. The rough set-based methodology refers to experiments that consist of training and testing models that predict the value of each of the decision classes. Classes are associated with expected changes in APHAB measures, which depend on individual characteristics, HA type, time of use, and APHAB measures measured prior to therapy. Decision-making models shall aim to predict to which quartile range the future EC, BN, RV, AV, APHAB3, APHAB4, absolute changes in these values, and relative changes will reach (measured during the second visit). Various variants of continuous variable discrete methods, reduction determination methods, rule generation methods, and inference voting methods are to be selected.

## 5. Conclusions and Future Research Aspects

In this paper, we present a framework for evaluating the effectiveness of hearing protection with hearing aids that could be tailored to the needs and prevailing conditions in the acoustic environments where older adults most often reside. We reported apparent benefits for a hard-of-hearing person who becomes the HA user for the first time. We also show that it is possible to predict the person's benefit in the future. Furthermore, we propose a rule-based approach to HA fitting that may speed up the process. However, the method should be statistically validated, engaging more HA users to become a reliable working solution.

It is worth noting that a new approach to assessing auditory reality and hearing aids has recently emerged using the method of recording everyday behavior and situations (EMA, ecological momentary assessment), widely used in psychological research [25]. EMA is a self-report assessment method that can minimize recall error compared to retrospective recall methods. EMAs increasingly use publicly available technology, such as smartphones and personal digital assistants (PDAs). These mobile EMA (mEMA) methods add to the convenience of reporting.

In a review article [48] on predicted satisfaction with hearing aids, the authors indicate that speech-in-noise tests may significantly impact HA use satisfaction, suggesting a greater role for assessing speech perception in noise in aural rehabilitation. Thus, the prospective work should supplement the method by testing speech intelligibility in the presence of noise.

Also, future development should be directed toward hearables, i.e., an ecosystem that includes wireless consumer electronic products worn in, on, or around the ear, e.g., headphones coupled to a smartphone. These types of devices are already approved by the FDA (Food and Drug Administration) for HA purposes [49]. Since they include combinations of infotainment, hearing assistance, health monitoring, etc., based primarily on consumer electronics, they might be easily transferred to healthcare sectors [50]. Thus, such a methodology proposed by the authors could be one of the core applications for HA fitting. Moreover, as indicated in some reports, a more extended observation of the HA use benefit should be considered [51]. Undoubtedly, implementing the application in mobile form on a smartphone is also a future development area for the method.

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