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Evaluation of auditory reality and hearing aids using an ecological momentary assessment (EMA) approach

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ABSTRACT

Knowledge about the acoustic environments experienced by an individual and how the listening experience is affected by hearing loss and hearing aids is important when developing solutions for people with hearing loss. Acquiring this type of knowledge calls for an assessment method that can be applied in real time while a listener experiences a specific listening situation in real life. This ability is a characteristic of the ecological momentary assessment (EMA) methodology. In this article, we report on a study in which 16 participants with hearing loss used a newly developed EMA smartphone app to answer questions about their current listening situation and to compare two different hearing-aid programs in that situation. The participants answered the questions when prompted by the app (according to a predetermined time schedule) or when initiating the app themselves. The participants also evaluated the usability of the app. Besides responses from the participants, the app also collected data from the hearing aids during the assessments. The main results from the study are presented, and potential benefits and challenges of using the EMA approach in hearing research are discussed.

Keywords: Ecological Momentary Assessment, Auditory Reality, Hearing Aids

1. INTRODUCTION

In recent years, hearing aids and other hearing-related assistive devices have become increasingly personalized. These devices are built on audiological signal processing features which adjust based on properties of the current acoustical environment and/or the user's interaction with the device. Therefore, knowledge about the real-life listening situations and environments in which hearing devices are used are of significant relevance to research and development of new hearing solutions. Smeds and Wolters (1) adapted the term "Auditory Reality" from Noble (2) to describe the interdependence of acoustical environments and how they are experienced by an individual.

Different auditory realities imply different unique listening demands with a variety of individual listening intentions and tasks. Wolters et al. (3) conducted a literature study, categorizing listening situations from 10 audiological studies to build a framework of common sound scenarios (CoSS) consisting of three intention categories and seven sub-categories based on listening tasks. The framework provides the opportunity to map out a person's auditory reality in a structured manner and thus allows for structured comparisons of auditory reality between groups and individuals.

A common approach to assessing real-life hearing-aid performance is self-report questionnaires. These questionnaires often assess aspects of hearing and/or hearing-aid use in pre-defined listening situations or entirely without situational context. The retrospective nature of this procedure could introduce a recall bias in terms of a focus on more recently experienced or particularly memorable situations and thus lower the data's ecological validity. As an alternative to retrospective self-reports, the auditory reality can be assessed momentarily, i.e. at the particular time a listening situation is experienced by an individual. This method is often referred to as ecological momentary assessment (EMA) (4). The concept includes repeated subjective assessments in everyday life. Galvez et al. (5) showed the feasibility of using EMA to obtain real-time responses from hearing-aid users during their

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everyday listening experiences. Moreover, construct validity (i.e. the degree to which a measurement reflects what it claims to be measuring) of EMA has been confirmed (6, 7). In practical applications of the EMA method in audiological, auditory and acoustic research, the subjective assessments made by a participant may be combined with simultaneous collection of objective data, e.g. audio recordings (8, 9) or sampling of hearing-aid parameter settings (10).

The majority of previous audiological EMA studies share the aim to gain knowledge about the auditory realities and lifestyles of hearing-aid users and people with impaired hearing in general. The outcomes of these studies can to some extent be related to hearing-aid performance or benefit, but do not explicitly measure these constructs. Some studies have utilized EMA to investigate individual preferences between two different hearing-aid signal processing schemes in the participants' everyday lives using paper and pencil forms (11, 12). This procedure facilitates the alignment of hearing-aid program preference data with auditory reality data. However, it lacks connection to the hearing aids and therefore also information regarding hearing-aid settings and recorded acoustical properties at the time of the assessments.

In recent years, the availability of powerful and flexible smartphone and Bluetooth solutions has enabled the development of custom EMA systems which are easy to set up, convenient to use and highly adaptable to specific research needs. Kowalk et al. (13) developed an open-source system which allowed for EMAs in conjunction with wirelessly transmitted acoustical data from external microphones via custom-built hardware. Kunz et al. (10) used an EMA app that both administered an EMA questionnaire to be answered by a hearing-aid user and allowed simultaneous retrieval of data from the user's hearing aids. Smeds et al. (14) used an approach where a group of hearing-aid users were prompted every 1.5 hours to answer a number of questions relating to the current situation and were asked to make a paired comparison of two programs in their hearing aids. The entire procedure was controlled by a smartphone app, but the approach did not allow direct communication between app and hearing aids.

Based on the approach by Smeds et al. (14), we developed a mobile EMA application for the iOS platform. Like the Smeds et al. approach, the app provides the possibility to collect questionnaire data on the participant's auditory reality, but as an addition, it also allows simultaneous retrieval of data from a pair of connected hearing aids. Furthermore, the app facilitates real-life paired comparisons of hearing-aid programs. The aim of the current study was to evaluate the applicability of this EMA app and to provide insights into the auditory reality of a group of hearing-aid users.

2. METHODS

2.1 Participants

Sixteen experienced hearing-aid users (5 females) with an average age of 66.9 years (SD: 8.3 years) were recruited for the study. They had a mild-moderate sensorineural hearing loss that allowed an open fitting of the test hearing aids. Eight participants were recruited from the pool of test participants at Widex HQ in Lynge, Denmark, while the remaining eight participants were recruited from the pool of test participants at ORCA Europe in Stockholm, Sweden. All written material was accordingly prepared in both Danish and Swedish.

2.2 Experimental procedure

Each participant completed the trial over a period of one week, between two visits to the lab. At the first visit, the participants received information about the study and signed a consent form. This was followed by measuring an audiogram, fitting of test hearing aids, and instructions in performing the task and operating the equipment. At the second visit, the participant handed in the equipment, and an exit interview was conducted.

2.3 Test hearing aids

The test hearing aids used during the trial were Widex UNIQUE 440 FS receiver-in-canal (RIC), fitted binaurally using open ear tips. The hearing aids were fitted individually to each participant according to the Widex fitting recommendations. The hearing aids were fitted with two programs available to the participants. The parameter setting of both programs were based on the prescription made by the proprietary Widex fitting rationale. The only difference was that Program 1 provided approximately 5 dB more static gain than Program 2 in the frequency range from 1 to 2 kHz. During normal use of the hearing aids, the participants could switch freely between the two programs using a remote control or a button on the hearing aid. They were encouraged to do so, but they were not informed about the nature of the difference. During the paired comparisons done as part of the EMA procedure, the participants compared the two programs which were randomly assigned to two buttons on the app user interface, labelled A and B.

2.4 EMA procedure

A proprietary smartphone app was developed to administer the EMA procedure. It was developed to run on an iPhone 7 smartphone, and the participants received such a smartphone, with the app installed, to be used during the trial. Selected screen shots of the app user interface are shown in Figure 1 to demonstrate the look of the app and some of its possibilities. In order for the app to control and receive data from the test hearing aids, a wireless connection was established using a Widex Pro Link device that the participants wore around the neck during the assessments. The Pro Link allowed communication with the smartphone via Bluetooth, while the communication with the hearing aids used a proprietary digital radio-frequency transmission technology (WidexLink).

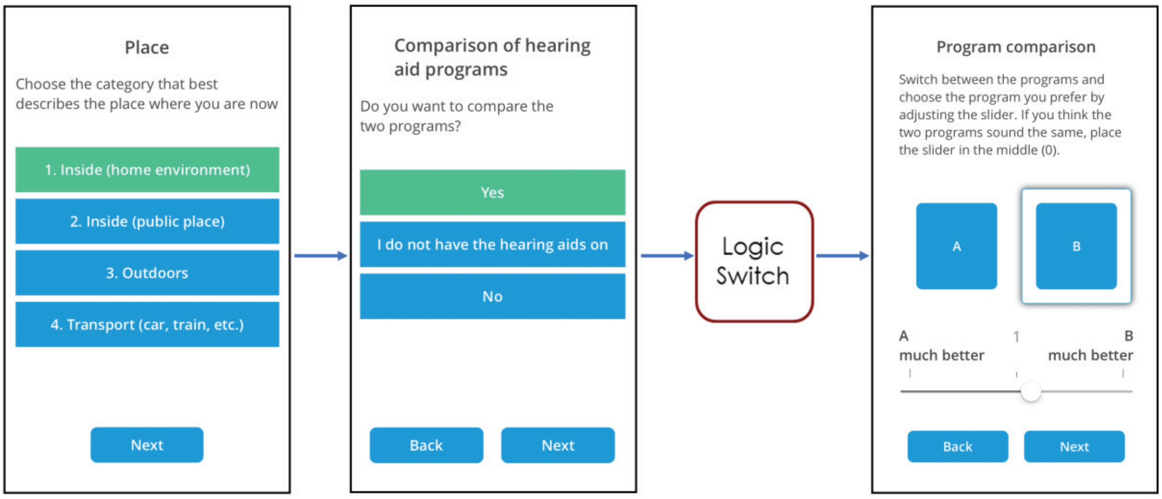

Figure 1 – Selected app screen dumps. From the left: 1) Location (single choice) – green color indicates choice; 2) Decision on program comparison, followed by a logic switch; if "yes" (as indicated by the green color), the program comparison is made, otherwise it is skipped; 3) Program comparison where the participant listens to the two programs "A" and "B" and rates the preference by placing a slider on the scale between -5 and 5, with the selected value (1 in this example) being shown on the screen.

Each assessment was triggered either by an alarm prompt generated by the smartphone approximately every two hours (between 8:30 and 20:30, i.e. seven times a day) or manually by the participant. When the alarm sounded, the participant had the option to either start the assessment or to delay or reject it. The participants had the option to turn off the alarm, e.g. when being in situations where interruptions were intolerable.

When the procedure was initiated, the participant was asked to answer a number of questions in a conditional branching questionnaire that tapped into the current listening situation (auditory reality) and then perform a paired comparison of the two programs available in the test hearing aid. In parallel with each subjective assessment, a number of objective data were retrieved from the hearing aids. All data were stored in the smartphone and sent to a cloud storage (MS Azure).

2.5 EMA questionnaire

The EMA questionnaire used in the study included sixteen questions covering the auditory reality and hearing-aid program preference. Additionally, hearing-aid data such as sound pressure level (registered by the hearing-aid microphones) and sound class (as detected by the hearing aid's sound-classification system) were collected. In this article, we will focus on the following questions and hearing-aid data, with indication of the response/output options:

- **Location (subjective):** 1: Indoor (home environment); 2: Indoor (public place); 3: Outdoors; 4: Transportation (car, train, etc.)
- **Listening task (subjective):** 1: Speech communication, two people; 2: Speech communication, more than two people; 3: Speech communication device; 4: Focused listening (live); 5: Focused listening (media); 6: Monitoring surroundings; 7: Passive listening
- **Sound class (objective):** 1: Quiet; 2: Quiet-s; 3: Urban; 4: Urban-s; 5: Transportation; 6: Transportation-s; 7: Music; 8: Party; 9: Party-s. Here, "-s" indicates that speech was detected.
- **Hearing-aid program preference (subjective, *optional*):** Comparison of two programs, A and B (randomly assigned to Program 1 and 2 in each assessment), on a scale between -5 and 5 where negative and positive numbers indicate the magnitude of preference for program A and B, respectively, and 0 indicates no preference.

These location and listening task categories were adapted from the EMA approach used by Smeds et al. (14), where the listening tasks directly reflect the Common Sound Scenarios (CoSS) framework (3). The sound classes correspond to those available in the test hearing aid (15). As indicated, the preference rating was optional, meaning that the participant was given the option to skip this question in the EMA procedure, e.g. in a situation where it was inconvenient to perform the comparison or where the participant was not wearing hearing aids.

2.6 Exit interview

Structured exit interviews were conducted for all participants at the end of the one-week field trial period to assess the participants' experiences with the EMA app. The participants were asked about the user-friendliness of the app (e.g. ability to read text and operate buttons) and the acceptance of the app and the equipment (e.g. the frequency and sound of alarms and the task of carrying around the equipment). The participants' task was to respond to a number of statements using a five-point Likert scale with the response options strongly disagree, disagree, neutral, agree, and strongly agree.

2.7 Data analysis

Compliance was calculated as the proportion of completed triggered EMA questionnaires relative to the total number of alarms (49 per participant during the one-week trial).

Auditory reality data were descriptively analyzed as proportions of questionnaires that were completed in each category of location, listening task and sound class. For simplicity, some of the sound classes were combined into a single sound class (i.e. Quiet and Quiet-s were combined into Quiet, Urban and Urban-s were combined into Urban, Transportation and Transportation-s were combined into Transportation, and Party and Party-s were combined into Party). Hence, nine sound classes were reduced to five.

Hearing-aid program preference data were descriptively analyzed via boxplots to visually assess whether the preference depended on the location, listening task or sound class. Mixed-effects linear regression was done with hearing-aid program preference as dependent variable and participant ID as a random effect to assess whether there was a significant effect of location, listening task or class on hearing-aid program preference.

Exit interview questionnaire answers were descriptively analyzed as number of participants who answered within the same category for each question.

3. RESULTS AND DISCUSSION

In total, the 16 participants completed 648 EMA reports (assessments). An overview of descriptive statistics is presented in Table 1, including the number of completed (triggered and user-initiated) EMA questionnaires, the number of paired hearing-aid program comparisons, the compliance, and the time used to complete the EMA reports. It can be seen that the average user completed 39 triggered questionnaires (corresponding to 79% of the times an alarm was received) and two self-initiated questionnaires during the one-week trial. Not surprisingly, a large variation was observed across participants in terms of how many EMA reports were completed. The most active participant completed more than twice as many triggered questionnaires as the least active participant, and the number of paired comparisons differed by a factor of almost six. There may be various reasons for these observed differences. One could be that some participants are more willing than others to 'expose themselves' by using the needed equipment and performing the tasks in the company of other people, and another could be that some participants spend more time than others in situations which may be considered less suited for doing the assessments (i.e. work meetings, driving a vehicle, etc.). Furthermore, it could be speculated that the length of the questionnaire made some participants more likely than others to skip a triggered questionnaire. These reasons were all supported by comments made at the exit interview. All in all, the variation in the amount of data generated by each individual participant seems natural and an inherent characteristic of this type of EMA study. A consequence of the individual variation is that the methods used to analyze data from EMA studies need to be able to handle the variation in number of data points per participant.

Table 1 – EMA data overview. Mean, SD, and range across the 16 participants are indicated. Compliance was calculated as percentage of questionnaires that were completed when triggered by the alarm. Total number of alarms was approximately 49. *Range of individual means.

	Mean ± SD	Range
Number of completed triggered questionnaires	39 ± 8	22 – 49
Number of user-initiated questionnaires	2 ± 2	0 – 6
Number of paired comparisons	25 ± 10	8 – 45
Compliance (%)	79 ± 17	33 – 94
Time to complete (minutes)	3.4 ± 3.4	2.0 – 5.1*

On average, it took 3.4 minutes to complete an EMA report, but there was also a large individual variation on this measure, and in some cases, it took much longer to complete the report. It should be noted that eight of the EMA reports took longer than ten minutes to complete and four of these reports took longer than 30 minutes. This is likely because the participants left the app for some time and then came back to the questionnaire at another point, or they did not click on "end" immediately after completing the questionnaire. Such cases obviously challenge the 'momentary' aspect of the EMA procedure, and it can be discussed whether these longer reports should be removed from the analysis.

Figure 2 shows how the assessments were distributed within the self-reported location, self-reported listening task, and the sound class detected by the hearing aids. An overall observation, across the three distributions, is that majority of the assessments were made in quiet home environments while the participants were involved in passive or focused listening. This is not very surprising, given the sample of participants, of which many were retired and expectedly spent considerable time at home.

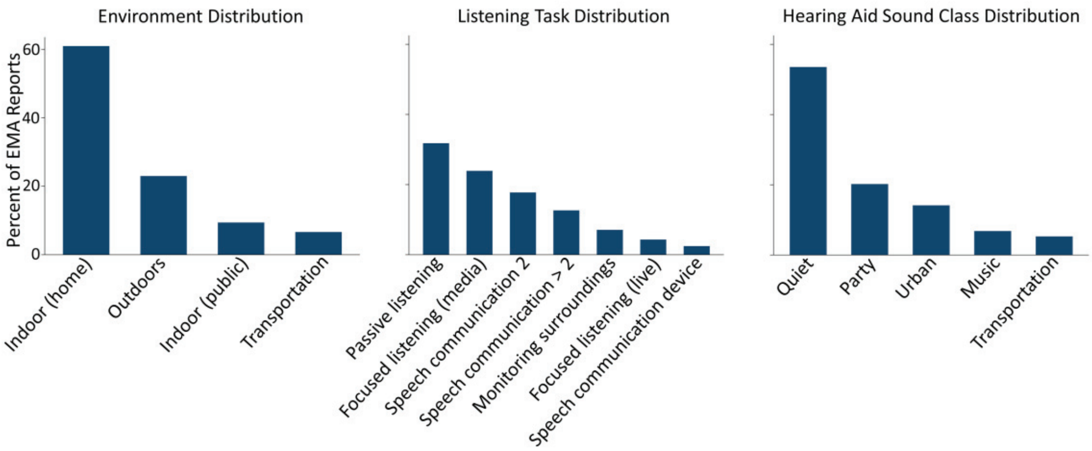

Figure 2 – Auditory reality (on group level). Distribution (in percent) of EMA reports within each category of location (left), listening task (center) and hearing-aid sound class (right). The categories are sorted in descending order according to the number of reports in each category. *N*=648 completed questionnaires.

With an overall compliance of 79%, the distributions shown in Figure 2 are expected to provide a rather accurate indication of the participants' auditory reality (on a group level). The distributions within the location and listening task categories are in good agreement with distributions observed in a previous EMA study reported by Smeds et al. (14) who used a similar EMA approach (but with no ability to retrieve hearing-aid data). It should be acknowledged that some participants likely found it more convenient to perform the EMA task in quiet passive-listening situations at home than in other scenarios, e.g. social settings that involve active communication. Thus, the distributions associated with the situations that participants rejected to assess when they were prompted by the app may have looked different than those shown in Figure 2.

Paired comparisons of the two hearing-aid programs were done in 396 EMA reports. Figure 3 shows box plots of the preference ratings. The overall observation is that the median value is very close to zero, indicating no preference, in most of the locations, listening tasks and sound classes. In a few cases (during transportation and when using a speech communication device), a trend towards a preference for program 2 was observed. However, a large variation in preference ratings is also seen, with individual preferences for both programs observed in all categories. A mixed-effects linear regression model showed no significant effect of the listening environment (β=0.23, 95% CI: -0.01 - 0.47, *P*=0.07), listening task (β=0.01, 95% CI: -0.09 - 0.11, *P*=0.89) or sound class (β = -0.05, 95% CI: -0.27 - 0.16, *P*=0.61) on the subjective preference of the hearing-aid program. The most obvious explanation for the lack of significant effects is that the experimental contrast was quite subtle, and some participants reported that they were not able to hear a difference in many situations. However, the large preferences observed for both programs for individual participants show that the contrast indeed was audible and caused a clear preference for some of the participants.

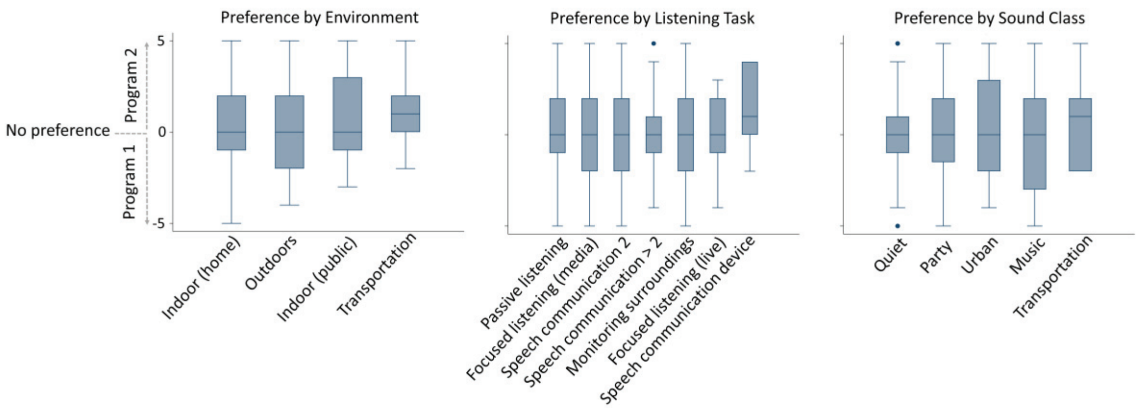

Figure 3 – Hearing-aid program preference in different listening environments (left), listening tasks (center) and sound classes (right). Negative ratings indicate a preference for Program 1, while positive ratings indicate a preference for Program 2. The boundaries of the box represent the 25th and 75th percentile. The line within the box indicates the median. Error bars indicate minimum and maximum values. Filled circles are the outliers. The order of categories reflects the order in Figure 2. *N*=396 paired comparisons.

Although no group effects were observed in this study, the ability to assess an experimental contrast within different auditory-reality categories is one of the major assets of including a paired comparison approach in the EMA procedure. It also allows analyses on an individual level, e.g. to investigate whether participants with different auditory realities have different hearing-aid preferences. From a clinical perspective, this could also make the EMA method a facilitator in a data-driven dialogue between end-user and hearing care professional (the person fitting the hearing aids), giving the latter objective insights in the auditory lifestyle and needs of the end-users.

Besides assessing their auditory reality and making paired comparisons of the two hearing-aid programs, the participants were also asked to evaluate the app and the EMA procedure used in the study. The distribution of the participants' responses to a selected sample of questions asked during the exit interview are presented in Figure 4. A general observation, across questions, is that the participants found the app to be easy to use. Thus, 15 of the 16 participants agreed that, all in all, it was easy to handle the app. The questions with the lowest number of participants agreeing with the statement, and thereby showing the least satisfaction, were the ones relating to the alarm used to prompt the participants. Especially the question on the frequency of the alarm had markedly fewer participants strongly agreeing than the other questions. This indicates that the chosen frequency of alarms (2 hours between alarms) may have been close to or even beyond the limit of what participants are willing to accept. This assumption is supported by statements made during the exit interview by some participants who said that they would prefer more time between alarms. However, the effect of the alarm frequency on annoyance may have been confounded by the effect of the length of the questionnaire, assuming that the time associated with completing a long questionnaire makes a given alarm frequency more annoying. All in all, the choice of alarm frequency and the length of the questionnaire is a delicate balance between not overworking, annoying or demotivating the participants, and at the same time, the wish to make detailed assessments in as many situations as possible.

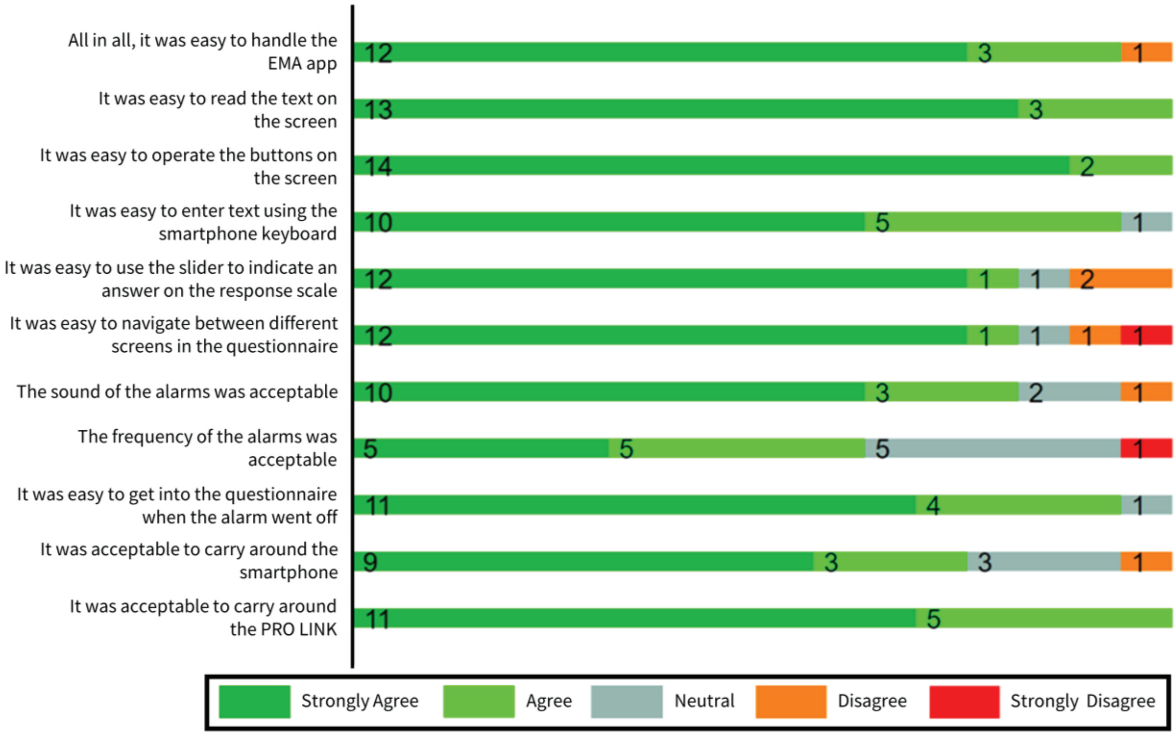

Figure 4 – Usability of the EMA app and procedure. The numbers on the colored bars indicate the number of participants who answered in that category. *N*=16 participants who answered the usability questionnaire at the exit interview.

Comments made by several participants during the interview indicate that the EMA procedure used in the present study could be improved by allowing the app to run on the participant's own smartphone (eliminating the need to carry two smartphones), and to establish a direct wireless connection between smartphone and hearing aids (eliminating the need to carry the Pro Link device). For practical reasons, it was not possible to implement these functionalities in the version of the app used in this study, but based on the comments, it seems likely that such functionalities would be able to further improve both usability ratings and compliance.

4. FINAL REMARKS

The results obtained in this study demonstrate the potential of the EMA approach to gather subjective and objective data on a participant's auditory reality in a variety of different real-life situations. The observed compliance of 79% indicates that the applied EMA procedure was generally accepted by the participants. A similar conclusion may be drawn from the subjective ratings of the usability of the EMA app and the equipment needed to run the EMA procedure. However, there was large individual variation in compliance and usability ratings, indicating that some participants had issues with parts of the EMA procedure, such as the alarm frequency and the number of questions that had to be answered in each EMA report.

While no significant effects were found on a group level in the comparison of two hearing-aid programs, the results showed the potential of the EMA approach to make a direct perceptual comparison of different hearing-aid programs in real-life situations and relate the results to the data on the participants' auditory reality. The large variation in program preference highlights the importance of personalized hearing solutions. End-users are different and whether they prefer one program or the other is likely highly dependent on what listening intention is important to the individual at a particular point of time. The strength of the EMA method is the ability to provide insights into the variation in individual preferences during different everyday listening activities. Hence, the method can contribute to the continuing efforts to improve individualized hearing care.

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