Recording and Classification of the Acoustic Environment of Hearing Aid Users

DOI: 10.3766/jaaa.19.4.7

Kirsten Carola Wagener*
Martin Hansen†
Carl Ludvigsen‡

Abstract

This article investigates the different acoustic signals that hearing aid users are exposed to in their everyday environment. Binaural microphone signals from recording positions close to the microphone locations of behind-the-ear hearing aids were recorded by 20 hearing aid users during daily life. The recorded signals were acoustically analyzed with regard to narrow-band short-term level distributions. The subjects also performed subjective assessments of their own recordings in the laboratory using several questions from the Glasgow Hearing Aid Benefit Profile (GHABP) questionnaire. Both the questionnaire and the acoustic analysis data show that the importance, problems, and hearing aid benefit as well as the acoustic characteristics of the individual situations vary a lot across subjects. Therefore, in addition to a nonlinear hearing aid fitting, further signal classification and signal/situation-adaptive features are highly desirable inside modern hearing aids. These should be compatible with the variability of the individual sound environments of hearing-impaired listeners.

Key Words: Acoustic environment, classification, hearing aids, level distribution

Abbreviations: DAT = digital audiotape; FFT = fast Fourier transform; RMS = root mean square; SPL = sound pressure level

Sumario

Este artículo investiga las diferentes señales acústicas a las que están expuestos los usuarios de auxiliares auditivos en sus ambientes cotidianos. Se registraron señales biauriculares de micrófono desde posiciones de registro cercanas a la localización de los micrófonos de auxiliares auditivos retroauriculares, en 20 usuarios de auxiliares auditivos durante su vida diaria. Las señales registradas fueron analizadas acústicamente con relación a las distribuciones de niveles de banda estrecha a corto plazo. Los sujetos también realizaron evaluaciones subjetivas de sus propios registros en el laboratorio usando varias preguntas del cuestionario Perfil de Glasgow...
Everyday speech communication is frequently hampered by background noise. Whereas noise may cause inconvenience for persons with normal hearing, background noise represents a serious obstacle for communication for many hearing-impaired persons even when they are wearing a hearing aid. Background noise may not only mask important components of speech and thereby impede speech comprehension, it may also make communication more troublesome and fatiguing. As it is desired that hearing instruments help in minimizing these problems, more knowledge is needed about the acoustic situations and the environmental background noises to which hearing-impaired listeners are exposed. For example, the degree of masking is fairly predictable and can be calculated if certain characteristics of the noise and speech are known. Important determinants are the level and the spectral distribution of the noise, but other factors such as the steadiness or degree of modulation also play a role. Methods have been developed that permit the prediction of intelligibility of speech by normal-hearing listeners (French and Steinberg, 1947; Kryter, 1962; Houtgast et al, 1980) and by hearing-impaired persons (Fletcher and Galt, 1950; Pavlovic et al, 1986; Magnusson, 1996; American National Standards Institute, 1997). The availability of a precise description of the background noise environments experienced by a hearing-impaired user is a prerequisite for predicting daily communication ability. A complicating factor is the well-known interaction between background noise and speech effort, by which the level and spectral properties of speech are influenced by the type and level of the background noise in which the speech is uttered (Pearsons et al, 1977).

Assessment of speech comprehension in background noise is often included in the clinical routine, but no consensus exists about the type of background noise used to mask speech in clinical tests (Hagerman, 1982; Nilsson et al, 1995; Dreschler et al, 2001; Wagener et al, 1999). It is conspicuous that little correlation seems to exist between the result of such clinical tests and the problems experienced by hearing-impaired persons in their daily life (Gatehouse et al, 2003; Nabelek et al, 2006). Most often, stationary noises with speechlike long-term spectra are used. These noises yield comparable results in different speech tests when the same kinds of speech items are tested (syllables, sentences [Wagener and Brand, 2005]). This is due to the similar long-term spectra of speech and noise when measured in different languages (Byrne et al, 1994). Stationary noises, however, do not represent the daily situations of hearing-impaired listeners. Other masking noises that are more representative, like fluctuating noises or competitive speech or babble, yield significantly different results in speech intelligibility (Bronkhorst, 2000; Wagener and Brand, 2005; Wagener et al, 2006).

A possible cause that contributes to this low correlation could be that the noise used to mask speech in clinical tests might not...
be representative of the noise experienced in everyday communication or considered important by the hearing aid users. In fact, relatively little data about the acoustic environments in which hearing-impaired persons find themselves are available to our knowledge, and assessments by hearing-impaired persons of how various noise types influence their communication are often anecdotal.

This study was designed to address this problem. Thus, the aim of this study has been to collect and analyze samples of typical daily life situations in order to obtain more information about the acoustic situations hearing-impaired listeners are exposed to, including background noises. Although a sizable number of recordings of everyday noise already is available from numerous sources, we were not able to identify any source where all essential information was available and where calibrated recordings could be related to spatial positions where hearing aid microphones typically are located. On account of this we decided to carry out a study where the special situation of a hearing aid user was in focus. The objectives of the study were formulated in the following four research questions:

1. What are typical acoustic situations in the daily environment of hearing aid users?
2. How often are hearing aid users exposed to the signals, and how relevant are the different types of signals for the hearing aid users?
3. How important and helpful do hearing aid users perceive their hearing aids in the different situations?
4. What are the acoustic characteristics of the different signal types?

**EXPERIMENTAL SETUP**

**Subjects**

Twenty hearing aid users of different ages and social backgrounds were selected with the aim to represent a multitude of aspects of the total population using hearing aids. All subjects were required to be experienced hearing aid users who were satisfied with their current hearing aid fitting. The subjects were aged between 18 and 81, with an average of 51.4 years and a standard deviation of 18.9. The mean age of the subjects is substantially lower than the average population who use hearing instruments. This low mean age was unintentional. However, the wide range of ages used in this experiment was intentional. The social backgrounds included working people, pupils, students, housewives, and pensioners. Since pensioners, due to their age, constitute the largest group of hearing aid users, six pensioners were selected for this project. All subjects had previously been supplied with hearing aids on both ears, independently from this project. Table 1 shows personal data of the participants as well as information on their hearing aid fitting. The hearing losses of the subjects are given in Figure 1. From this figure containing the left and right audiograms of all 20 subjects, it can be seen that a wide variety of audiometric patterns was included. Most subjects used their two hearing aids frequently (see Table 1). Subject hc52 used hearing aids infrequently, and subject kg54 used hearing aids only on duty.

**Recording Devices**

The subjects were equipped with a portable digital audiotape (DAT) recorder and a microphone headset. They were instructed to use the recording equipment in order to record everyday situations, for instance, at home or at work. Two instances of the microphone headset and two DAT recorders were used during this study. Each particular headset was always used in combination with the same recorder.

![Figure 1. Pure-tone audiometric thresholds of all subjects, specified in dB HL. The thresholds are displayed for all 20 subjects and for the right and left side in the same graph.](image-url)
with the same DAT recorder in order to avoid any changes in the experimental setup (Apparatuses 1 and 2).

Two Sennheiser KE 4-211-2 omnidirectional pressure microphone capsules mounted on a headset were used for the recordings in order to record the acoustic signals from a location close to the microphone positions of behind-the-ear hearing aids. The headset with the microphones was always placed at the same position relative to the ears of all subjects (see Figure 2). The right microphone was marked by a red label, and the left microphone, by a blue label. The microphone signals were preamplified by a custom-built amplifier as recommended in the data sheet of the microphone manufacturer, with the exception of an additional 47

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Sex</th>
<th>Profession</th>
<th>Situation at Home</th>
<th>Style of Hearing Aid</th>
<th>Fitting</th>
<th>Start of Hearing Aid Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>aa26</td>
<td>75</td>
<td>M</td>
<td>Pensioner</td>
<td>2 adults</td>
<td>BTE</td>
<td>nl</td>
<td>01/00</td>
</tr>
<tr>
<td>aa83</td>
<td>18</td>
<td>F</td>
<td>Pupil</td>
<td>3 adults</td>
<td>BTE</td>
<td>nl/d</td>
<td>10/01</td>
</tr>
<tr>
<td>bk57</td>
<td>44</td>
<td>F</td>
<td>Nurse</td>
<td>2 adults, 1 teen</td>
<td>ITE</td>
<td>nl/d</td>
<td>01/95</td>
</tr>
<tr>
<td>di28</td>
<td>73</td>
<td>F</td>
<td>Housewife</td>
<td>2 adults</td>
<td>BTE</td>
<td>nl/d</td>
<td>10/95</td>
</tr>
<tr>
<td>gm60</td>
<td>41</td>
<td>F</td>
<td>Family manager</td>
<td>2 adults, 3 children</td>
<td>BTE</td>
<td>nl/d</td>
<td>05/98</td>
</tr>
<tr>
<td>hc52</td>
<td>49</td>
<td>F</td>
<td>Housewife</td>
<td>3 adults</td>
<td>BTE</td>
<td>a</td>
<td>91</td>
</tr>
<tr>
<td>hm74</td>
<td>27</td>
<td>F</td>
<td>Employee at the doctor</td>
<td>1 adult</td>
<td>BTE</td>
<td>nl/d</td>
<td>na</td>
</tr>
<tr>
<td>jw51</td>
<td>50</td>
<td>M</td>
<td>Technical assistant</td>
<td>3 adults</td>
<td>BTE</td>
<td>nl/d</td>
<td>05/98</td>
</tr>
<tr>
<td>kg54</td>
<td>47</td>
<td>F</td>
<td>Nurse</td>
<td>2 adults, 2 children</td>
<td>ITE</td>
<td>nl/a</td>
<td>01/97</td>
</tr>
<tr>
<td>km54</td>
<td>47</td>
<td>F</td>
<td>Housewife</td>
<td>3 adults, 2 children (16, 20)</td>
<td>CIC</td>
<td>nl/a</td>
<td>na</td>
</tr>
<tr>
<td>lh35</td>
<td>66</td>
<td>F</td>
<td>Pensioner (child protection legislation)</td>
<td>2 adults</td>
<td>ITE</td>
<td>a</td>
<td>08/98</td>
</tr>
<tr>
<td>mg39</td>
<td>62</td>
<td>M</td>
<td>Pensioner</td>
<td>2 adults</td>
<td>BTE</td>
<td>nl/d</td>
<td>na</td>
</tr>
<tr>
<td>oe36</td>
<td>65</td>
<td>F</td>
<td>Housewife</td>
<td>2 adults</td>
<td>BTE</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>rs69</td>
<td>31</td>
<td>F</td>
<td>Employee at job center</td>
<td>2 adults</td>
<td>ITI</td>
<td>nl/a</td>
<td>na</td>
</tr>
<tr>
<td>sj69</td>
<td>31</td>
<td>F</td>
<td>Student</td>
<td>2 adults</td>
<td>BTE</td>
<td>a</td>
<td>na</td>
</tr>
<tr>
<td>th22</td>
<td>79</td>
<td>M</td>
<td>Pensioner</td>
<td>2 adults</td>
<td>BTE</td>
<td>nl/a</td>
<td>06/96</td>
</tr>
<tr>
<td>wh20</td>
<td>81</td>
<td>M</td>
<td>Pensioner</td>
<td>2 adults</td>
<td>BTE</td>
<td>a</td>
<td>96</td>
</tr>
<tr>
<td>wi76</td>
<td>25</td>
<td>F</td>
<td>Student</td>
<td>2 adults</td>
<td>BTE</td>
<td>nl/a</td>
<td>96</td>
</tr>
<tr>
<td>wm49</td>
<td>52</td>
<td>F</td>
<td>Shop assistant</td>
<td>1 adult; often visited by 2 children (23, 29), 1 grandchild</td>
<td>ITE</td>
<td>nl/a</td>
<td>96</td>
</tr>
<tr>
<td>ww36</td>
<td>65</td>
<td>M</td>
<td>Pensioner</td>
<td>2 adults</td>
<td>BTE</td>
<td>nl/a</td>
<td>06/96</td>
</tr>
</tbody>
</table>

**Note:** Situation at home includes the test subject; a = analog, BTE = behind the ear, CIC = completely in the canal, d = digital, ITE = in the ear, na = no available data, nl = nonlinear.
kΩ resistor that was mounted in parallel to the output in order to avoid clicks when connecting the amplifier to the recorder.

The output of the preamplifier was fed into the “line-in” input of the DAT recorder (Sony TCD-D100). The switches on the DAT recorder affecting the recording of the input signal were set to the line-in input source, a “manual” recording level selector, a sampling frequency of 44.1 kHz, and the maximum record level setting of 10. Care was taken that all of these switches affecting the recording of the input signal were fixed, either by using glue or by deactivating them internally. This was done in order to avoid any unintentional change of the calibration by the user.

**Frequency Response and Absolute Level Calibration**

The frequency responses of the recording devices were measured in the anechoic chamber of the University of Oldenburg. Calibration signals from a CD were played back through a loudspeaker (JBL EON Power 10). The frequency response of the playback system was measured using a B&K 4133 freefield microphone, B&K 2669 preamplifier, and B&K 2610 measuring amplifier connected to a Sony PCM-R500 DAT recorder. This equipment was always used in this study to determine freefield sound pressure levels. The microphone headset was mounted to a B&K dummy head (HATS 4128 D), and the calibration signals were recorded using the portable recording devices. The transfer functions of the microphones of the two recording devices were measured using a wideband noise-input signal presented from the front of the dummy head (azimuth angle 0 degrees). The ordinate of Figure 3 shows the frequency response of the microphones of the recording devices relative to the response of the B&K freefield reference microphone.

The absolute level calibration was obtained by a 1 kHz narrowband noise signal played back via the JBL EON Power 10 loudspeaker at a freefield level of 80 dB SPL. Each apparatus was calibrated at 1 kHz by registering the root mean square (RMS) level of the digitally recorded signal. At all other frequencies, the calibration was performed by including the microphone transfer function information (see Figure 3).

**Linearity of Recording Level and Dynamic Range of Recording Devices**

A pink noise and a white noise were played back at a range of different sound pressure levels in order to test the linearity of the recording devices at all level ranges of interest. The linearity was within ±1 dB over a 60 dB level range for both recording devices. The level of the noise floor representing the lower limit of the dynamic range of the recording devices was determined by means of recording silence in the anechoic chamber. The mean broadband level of the noise floor amounted to –79.0 dB FS (dB re. digital full scale), with a standard deviation of 1.5 dB across the recording channels. This noise level corresponded to a broadband sound pressure level of 40 dB SPL. The upper limit of the dynamic range was determined at different frequencies. The upper limit of the dynamic range was higher than 110 dB SPL for both recording devices at all tested frequencies.

**Long-Term Stability of Sensitivity and Frequency Response**

At the beginning of the study, the recording devices were calibrated in the anechoic room each time before they were given to a subject. The experience during the course of the study showed that the sensitivity and the frequency response were time invariant. Therefore, the control of the calibration was later on performed only once every second week. For this purpose the 1 kHz narrowband noise at a freefield level of 80 dB SPL was used as the calibration signal. It was recorded with the microphone headset mounted to the dummy head using
the portable recording devices. During the study, the sensitivity of the recording devices (that is, freefield sound pressure level in dB SPL minus DAT digital RMS level relative to full scale) was stable within 1 dB from the reference mean value per channel. The mean sensitivity values for each recording channel in combination with the four individual relative frequency responses in Figure 3 were used to convert the digital RMS values of the recordings to sound pressure levels in dB SPL (see the acoustic analysis results section below).

**EXPERIMENTAL DESIGN**

**Recording Phase**

All subjects were asked to record typical situations of their daily life. The translation of the written instruction is as follows:

Dear subject,

In this study we would like to investigate situations of your daily life with respect to their acoustic characteristics. Please record different situations from your daily life for 5–10 minutes each. These could be soft situations,

![Figure 3](image_url)

**Figure 3.** Sensitivity function of the portable recording devices (headset microphones on a person’s head + digital audiotape recorder), defined as output of the recording microphones relative to the output of the freefield reference microphone. The upper and lower panels show recordings with Apparatuses 1 and 2, respectively. Black line: left channel; gray line: right channel.
for example, reading a newspaper, or recordings in loud environments, for example, during a party. All situations are of equal importance for us.

The instruction was kept very short on purpose, with the aim not to induce the subjects to assume that only special situations would be of interest. Rather, we expected that it should be most natural for the subjects to record sound samples that actually did occur in their life, thereby being typical (for them) as well as relevant.

In order to acquaint the subjects with the equipment, they were precisely instructed verbally and in writing how to perform recordings with the portable DAT recorder prior to the start of the recording phase. The recording duration per situation was requested to be about five minutes. Each subject received one digital audiotape with a capacity of two hours. The subjects were given the experimental recording setup for the duration of three or four days (Monday to Thursday or Thursday to Monday). In case of any problems with the task or the recording devices, a telephone hotline was available for them.

Laboratory Evaluation

After the subject returned from his or her recording phase, the recordings were digitally transferred to a computer, using a Sony PCM-R500 DAT recorder and an RME Digi-Pad 96/8 digital sound card interface. The duration of the recorded material varied between 46 and 121 minutes among the subjects, with an average of 84 minutes. Every sample recording exceeded three minutes; most recordings lasted about five minutes. All recordings were long enough to allow cutting out a one-minute segment that represented the recorded situation appropriately. From each recording, a representative, continuous section of one-minute duration was selected by the experimenter. This selection was made at our informed discretion. These representative one-minute sequences were used in further evaluation.

Depending on the amount of recorded material, a number of 8–25 (mean = 17) sequences were selected per subject and stored on a CD. Subsequently, their own recordings were presented to the subjects in the laboratory via headphones in a sound-insulated booth. During the laboratory session, each subject was asked to describe and assess his or her recorded situations by means of a questionnaire. The English translation of the questions and response alternatives on this questionnaire are given in the appendix. The questionnaire included several questions from the Glasgow Hearing Aid Benefit Profile questionnaire (questions 3–8 in the appendix [Gatehouse, 1999]). In addition to these questions, subjects were asked whether they recognized the situation. They were asked to give a description of the situation, to specify the frequency of occurrence of the situation, and to assess the importance of the situation. The subjects filled in the questionnaire for each of their one-minute sequences. The time period between the recording phase and the laboratory session varied from three weeks to four months. The different durations did not seem to have any implication for the resulting questionnaire analysis (see the questionnaire evaluation section below).

RESULTS

There was no correlation between the duration of having the recording setup at home and the duration of recorded situations. All subjects recorded several situations, some with and some without speech, except for subject lh35, who recorded only one situation with a short conversation and the remaining situations without conversation. Many subjects were curious to be informed about the aim of this project. One can speculate that some subjects recorded situations that they believed would be important for this study but which did not occur very often in their daily schedule.

Grouping of Acoustic Situations

A total number of 349 individual situations were recorded and assessed by the different subjects. All of these situations were classified into larger groups and subgroups. This grouping is presented in Figure 4, showing the three main groups: “conversation with background noise” (subdivided into “2 people” and “more than 2 people”), “conversation without background noise,” and “situations without conversation.” Sometimes a sample could not be identified by only one single situation. Therefore, it was possible to attribute multiple situations to a given sample (for instance, reading/office work
and telephone/TV/radio or traffic/car/bike and going for a walk/gardening). The sum of the percentages of occurrences therefore exceeded 100 percent.

Further on, additional information was always registered independently for each signal, for example, presence of own voice, wind noise, or noise from mechanical contact with the microphone. A proportion of 50.7 percent of the situations involved signals with speech (conversation with and without noise, telephone/TV/radio [speech], lecture/church/cinema/theater). However, 11.2 percent of the recordings contained only a little speech, and the own voice was recorded in 47.6 percent of the situations. In addition, 16.6 percent of the situations contained wind sounds; 12.3 percent contained the sound of microphone contact; 6.3 percent contained audible reverberation; and 18.1 percent of the situations were recorded outdoors, which could be attributed to the fact that the recordings took place during the summer season.

In order to condense the questionnaire and acoustic data (see the sections on questionnaire evaluation and acoustic analysis) for this article, the classification groups were summarized into larger groups, given in Table 2. Note that the 11 groups listed there do not have a one-to-one correspondence to the situations displayed in Figure 4. The groups listed in Table 2 were combined due to their thematic content without regard to any level or questionnaire result. In addition, the results of the broadband sound level analysis are presented in the same table.

**Questionnaire Evaluation**

The answer to the first question of the questionnaire: “Do you recognize this situation?” was no in 19 cases out of 349. If the subjects did not recognize the situation, they were told about the experimenter’s opinion about the situation. In 13 cases, the subjects were able to recognize the situation after that description. The remaining six unrecognized situations were classified using the experimenter’s opinion about the situation. Therefore they were included in the acoustic

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Classification groups with subdivisions and their particular relative frequencies of occurrence. The main groups had the following percentages of occurrence: “conversation without background noise,” 11.5 percent; “conversation with background noise, 2 persons,” 17.8 percent; and “conversation with background noise, more than 2 persons,” 10.3 percent. Note that the sum of occurrences of the last group, “situations without conversation,” was not equal to the remainder up to 100 percent, as the situations could sometimes be classified into more than one subdivision.
Table 2. Group-Pooled Short-Term (τ =125 msec) Broadband Sound Pressure Levels by Percentile

<table>
<thead>
<tr>
<th>Signal Group</th>
<th>Occurrence (%)</th>
<th>Sound Pressure Level (dB SPL) by Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5th</td>
</tr>
<tr>
<td>Café/restaurant/crowd of people/shopping</td>
<td>5.2</td>
<td>55.7</td>
</tr>
<tr>
<td>Conversation with background noise, 2 people: “Conv2Noise”</td>
<td>17.8</td>
<td>49.8</td>
</tr>
<tr>
<td>Conversation with background noise, more than 2 people: “Conv2MoreNoise”</td>
<td>10.3</td>
<td>51.7</td>
</tr>
<tr>
<td>Conversation without background noise: “ConvQuiet”</td>
<td>11.5</td>
<td>47.3</td>
</tr>
<tr>
<td>Work with machines/housework</td>
<td>24.4</td>
<td>48.1</td>
</tr>
<tr>
<td>Music/concert/lecture/church/cinema/theater</td>
<td>8.9</td>
<td>49.6</td>
</tr>
<tr>
<td>Others</td>
<td>10.9</td>
<td>44.1</td>
</tr>
<tr>
<td>Reading/office work</td>
<td>8.3</td>
<td>41.0</td>
</tr>
<tr>
<td>Telephone/TV/radio (speech): “TelTVRadio”</td>
<td>9.7</td>
<td>46.6</td>
</tr>
<tr>
<td>Outdoor: traffic/car/bus/train/bike</td>
<td>10.0</td>
<td>56.0</td>
</tr>
<tr>
<td>Outdoor: going for a walk/gardening</td>
<td>3.4</td>
<td>51.0</td>
</tr>
</tbody>
</table>
Figure 5. Box plots of the answers to the six questions of the questionnaire for different situation groups (compare Table 2). The median is given by the asterisks; the box gives the 25th and 75th percentiles. The minimum and maximum scores are given by the error bars. The number of judgments is given above the particular error bars.
Figure 5 Cont.
Figure 5 Cont.
machines/housework,” “reading/office work,” and “going for a walk/gardening” were, on average, rated as “less important.” Hearing in all other situations was rated “important” on average. The importance ratings also vary a lot across subjects.

The upper left and upper right panels of Figure 5 show that the subjects did record situations that either occur often in daily life or are important with regard to hearing in these situations. This shows that the subjects did record relevant everyday situations as they were asked to do in the recording instructions.

Problems in the Situations

The problems in the situations can be addressed by the fourth question of the questionnaire: “To what extent do you have problems in this situation?” The scores ranged from 0 to 4, with a higher score indicating increased problems. The median problem ratings averaged across subjects and the corresponding results of the different situation groups are given in the middle left panel of Figure 5. All median problem ratings were equal to or below 1, indicating only few problems in the situations. The lowest problem ratings (median = 0) were given in the situations “conversation without background noise,” “working with machines/housework,” “others,” and “reading/office work.” In the situations “conversation without background noise” and “reading/office work” a maximum rating of 2 was given. For the situation category “others” a maximum rating of 4 was given, and in all other situations the maximum problem rating was 3.

Worries in the Situations

The worries in the situations can be described via the fifth question of the questionnaire: “To what degree are you worried, annoyed, or irritated in this situation?” The scores ranged from 0 to 4, with a higher score indicating increased worries. The median worries ratings averaged across subjects and the corresponding results of the different situation groups are given in the middle right panel of Figure 5. All median worries ratings were equal to or below 1, indicating only few worries in the situations. The lowest worries ratings (median = 1) were given in the situations “café/shopping,” “conversation with background noise, 2 people,” “telephone/TV/radio,” and “traffic/car/bike.” There is large variability in ratings across subjects, with maximum ratings of 3 and 4 in the different situations.

Hearing Aid Usage and Benefit

In this article, of the remainder of the questionnaire we only consider questions 6 (“How long do you proportionately use your hearing aid in this situation?”) and 7 (“How helpful is your hearing aid in this situation?”). Questions 8 (“To what extent do you have problems with your hearing aid in this situation?”) and 9 (“How content are you with your hearing aid in this situation?”) gave quite similar results as the response to question 7. This was expected, since all three questions deal with the subjective helpfulness of the hearing aid.

The lower left panel of Figure 5 shows box plots (medians, 25th and 75th percentiles, minima, and maxima) of the questionnaire results to question 6 about the duration of hearing aid usage. Except for three situations the hearing aids were on average used frequently (at least three-quarters of the time). The hearing aids were used less in the situation groups “going for a walk/gardening” (median = one-quarter of the time), “conversation with background noise, more than 2 people” (median = between one-quarter and one half of the time), and “reading/office work” (median = between one half and three-quarters of the time). In all situation groups except two (“music/lecture,” “others”), the 25th and 75th percentiles covered the whole range between minimum and maximum. Thus, there were large individual differences in hearing aid usage in all situations.

The lower right panel of Figure 5 shows box plots of the questionnaire results to question 7, about the helpfulness of the hearing aid. All medians showed that the hearing aids received a minimum assessment of helpful in all situation groups. It can be seen that hearing aids were assessed as being most helpful in quiet conversations. The hearing aids were judged to give only a little help for 25 percent of the subjects in the situation groups “café/shopping,” “conversation with background noise,” “telephone/TV/radio,” and “traffic/car/bike.” Except for “conversation without background noise” (largest benefit), the benefit
of the hearing aids varied between “absolutely useless”/“helps a little” and “quite helpful”/“perfect.” This showed that the benefit of the hearing aid was very different across subjects and situations. However, the hearing aids were always useful in situations with conversation.

**Acoustic Analysis**

The traditional acoustic description of a recorded signal is the spectrum of the signal. Typically, a large number of spectra of shorter sections of the signal are averaged to yield the “long-term average spectrum,” which contains less temporal information as it describes the average across successive temporal sections of the signal. Instead, successive short-term spectra could also be combined to form the spectrogram, presenting the distribution of signal energy over frequency and time.

As this investigation focuses especially on the acoustic environment of hearing aid users, and as modern hearing aids make use of nonlinear, level-dependent amplification, an alternative approach was chosen here: The acoustic analysis was performed in terms of a level analysis. The distribution of the short-term levels was calculated for the octave frequency bands with center frequencies from 125 Hz to 8 kHz as well as for broadband (0–22 kHz) for the different signal classification groups. The acoustic analysis is presented by means of different sound pressure level histograms in this section.

**Group-Wise Pooled Level Distributions**

As a first step of the analysis, all recorded signals of one particular classification group were analyzed with regard to their acoustic sound pressure levels (SPLs). The recordings from the two recording devices and from the right and the left channel were transformed into dB SPL by use of the individual transfer functions and absolute level calibrations of the four microphones described in the recording devices section above. After the transformation, the levels were treated together. The short-term level distribution of each signal was calculated by determining the broadband RMS levels of nonoverlapping, rectangularly windowed time frames of 125 msec duration in accordance with Dunn and White (1940). The levels of all signals belonging to the same classification group were pooled, and a level histogram with a resolution of 1 dB was calculated for each group. Note that signals of the same group of situations often exhibit a typical, known shape. For example, speech in quiet normally shows a two-peaked distribution, the peak at the lower levels resembling the speech pauses. However, this shape can get lost by pooling short-term levels of different signal recordings, for example, when speech in quiet is recorded at different overall levels.

To further explore this effect we performed another analysis that quantified the distribution of several “shape” parameters of the individual recordings of the same situation group. This is presented in the section on statistical analysis of classification-group-wise level histograms.

From the level distributions, the 95th, 90th, 50th (the median), 10th, and 5th percentiles were calculated. Inspection of all level data showed that the mean and median of the short-term levels per signal group were always very close to each other. The grand average of the absolute difference between mean level and median level across all center frequencies and all signal groups was as low as 1.7 dB. Therefore only the median levels are further interpreted here. The percentiles of the broadband short-term SPLs of each group are given in Table 2.

The lowest median sound pressure level of 52.3 dB SPL occurred in the situation “reading/office work”; the highest median sound pressure level of 84.8 dB SPL occurred in the situation “traffic/car/bus/train/bike.” The median sound pressure levels of the situations “conversation with background noise” were around 68 dB SPL. All other median sound pressure levels were in the narrow range between 59.5 and 66.1 dB SPL. This narrow range of median levels may seem surprising at first. However, it has to be considered that the data analysis was performed for the pooled set of recordings for one group. For further discussion, see also the statistical analysis of classification-group-wise level histograms subsection.

In the same manner as explained for the broadband level analysis, the short-term level analysis was performed for all octave bands with center frequencies between 125 Hz and 8 kHz for all recorded signals per classification group. The octave bandpass
filtering was performed in the spectral domain by applying a rectangularly shaped spectral window with a bandwidth of one octave to the fast Fourier transform (FFT) spectrum of the signal \( N_{\text{FFT}} = 5500 \approx 124.7 \) msec. The short-term level distribution of each octave band filtered signal was calculated as explained before, that is, the individual sensitivity differences between channels and recordings devices were taken care of and the RMS levels of nonoverlapping, rectangularly windowed time frames of 125 msec were calculated. The levels of all octave band signals belonging to the same classification group were pooled, and a level histogram with a resolution of 1 dB was calculated for each group.

The results of the narrowband analysis are shown in Figures 6 and 7 for the different situation groups. As could be expected, the level, as a trend, generally decreases as the octave center frequency increases. If the situation contains extraneous noise such as traffic or “outdoor” noise, the lowest octave contains the largest intensities of all octave bands. In other cases, where speech is the dominant acoustic source, 250 Hz and 500 Hz tend to be the bands contributing most of the sound intensity. The situation “reading/office work” was observed to be an outlier because it showed an extremely high occurrence of very low levels at the two highest frequencies, 4 kHz and 8 kHz, compared to the levels at high frequencies in other situations (see the bottom right panel of Figure 6).

Regarding the very highest octave band at 8 kHz, the situations “music/lecture,” “others,” and “telephone/TV/radio” also showed an especially high percentage of low SPLs in that octave (see Figures 6 and 7).

### Statistical Analysis of Classification-Group-Wise Level Histograms

The acoustic description of group-wise pooled level distributions gives an overall estimate of the signal levels and their relative occurrence for each of the classification groups. It is important to consider that each of the histograms presented depicts the pooled short-term levels of signals pertaining to one signal group. One interesting feature seen in this analysis is that a large range of levels can occur in most of the classification groups; that is, even in a situation that would usually be considered to have a medium or low level, some very high SPLs can occur. An example of this would be conversation in quiet, reading, or office work. This is due to short events that influenced the short-term levels reported here but did not dramatically influence the long-term level. Coughing, sneezing, and clearing one’s throat by the hearing aid user are examples of short but loud events that occurred in some of the subjects’ recordings during the otherwise quiet situations. Other examples are closing a door or moving a chair across a wooden floor. Conversely, very small short-term levels can occur in situations usually considered as having a high level.

Therefore, in order to further characterize the level distributions of each specific classification group, the following analysis was performed. The classification group \( j \), with \( j \) ranging from 1 to \( M \), the number of different groups, may comprise \( N_j \) different one-minute recordings, \( s^{(j)}(t) \), with \( i = 1 \ldots N_j \) and the \( N_j \) are typically different for different \( j \). For each \( s^{(j)}(t) \), a separate short-term level histogram was calculated, that is, an estimate of the probability distribution \( f^{(j)}(L) \) as a function of the short-term level \( L \). The general shape of each function \( f^{(j)}(L) \) was then characterized by its mean \( \mu^{(j)} \), the median \( M^{(j)} \), the standard deviation \( s^{(j)} \), the infimum (minimal value) \( I^{(j)} \), and the supremum (maximal value) \( S^{(j)} \). For each of these values pertaining to the same group \( j \), a box plot was calculated. It shows the lower quartile, the median, the upper quartile, and the whiskers, which extend to the most extreme values within 1.5 times the interquartile range. Data values outside the whisker are plotted using a separate symbol per each data point. Note that the box plots show a statistical description on a metalevel because the data entering each box plot are themselves statistical descriptors of the underlying histograms \( f^{(j)}(L) \).

Moreover, it is obvious that the pooled level histograms as shown in Figures 6 and 7 will not correctly identify/characterize the different individual situations that were pooled into one classification group. The reason will typically be that the level distributions shown here are based on the pooled signals of each classification group. As an example, consider several different recordings of the identical situation but at different overall sound levels. This could be a presentation of a one-minute section of the same radio news broadcast but at different
Figure 6. Octave band short-term level histograms of the first eight different classification groups. The level resolution was 1 dB.
volume settings of the amplifier. Then each individual short-term level histogram will exhibit the same “shape” of the level distribution, that is, the same higher moments of the distribution, but their means will be shifted to different locations according to the overall level of each situation. This can result in a smearing of the shape of the pooled level histogram of all recordings. The pooled level histogram will of course reflect the overall acoustic level distribution of that type of situation, but it might not be representative of an individual one-minute situation, with regard to its individual average level, median level, quartile levels, and extreme levels.

The results of this analysis are shown in Figure 8 for the broadband case. As the individual octave band results showed a generally similar trend, the graphs for these data were omitted, and only the broadband data will be discussed here. To interpret the subfigures in Figure 8, consider the median SPLs of all recorded one-minute signals of the group “music/lecture” as an example. The upper left subfigure reveals that 31 signals belonged to that group. The 31 individual median level values are considered members of another distribution with a median of 65 dB SPL, and lower and upper quartiles of 58 and 86 dB SPL, respectively. A large interquartile range of any of the four statistical descriptors can mean that the recorded signals of the same classification group exhibit diverse sound levels, despite inclusion in the same group. Conversely, a narrow box plot indicates that all group members exhibit a more similarly shaped level distribution per each one-minute signal. This is, for example, the case for the minimal (short-term) levels of all 12 “going for a walk/gardening” recordings and for the median sound levels of all 18 “café/shopping” recordings, except for one outlier.

It is difficult to identify a general pattern or to draw a general conclusion from the data shown in Figure 8, but an overall trend is evident. The SPLs of different representations of typical everyday situations as listed in Figure 4 can vastly differ from each other. The maximal differences of corresponding levels, for instance, the median levels of a one-minute situation within the same situation group, can range from merely 10–15 dB to clearly above 40 dB, depending on the group.

DISCUSSION AND CONCLUSIONS

This study addresses the sound environment of hearing aid users during their daily life when using their hearing aids. On the one hand, this was done with the aim to classify the sound environment in which hearing aid users use their hearing aids into several generic situations or “classes.” At the same time, an analysis of the acoustic sound pressure levels associated with these situations was carried out and focus was put on a precise acoustic calibration of
Figure 8. Statistical metadescription (medians, standard deviations, minima, maxima) of the shapes of individual broadband (10 Hz–22 kHz) short-term level histograms of all one-minute signals belonging to the same classification group.
Figure 8 Cont.
the recording equipment. The results show that it was possible to instruct subjects with a large range of ages to record their daily acoustic surroundings in a self-paced manner. All subjects could perform the recording task, and they chose to record a wide variety of situations, for example, in private and in workplace surroundings, at both soft and loud levels, with steady-state or highly dynamic temporal envelopes.

**Grouping of Acoustic Situations**

The questionnaire analysis revealed that the subjects recorded situations that were important to them or that they were often exposed to. The amount of usage of their hearing aids differed a lot among subjects, although they judged their hearing aids to be very helpful on average.

Different methodologies could have been applied in order to solve the “classification problem,” that is, to find a set of “classes” of situations that would partition all situations into distinct and meaningful subsets. One could imagine a kind of automatic classification that would perform an analysis of all recorded material. For example, modern hearing aids make use of certain classification algorithms in order to properly adjust their gain settings. These algorithms can successfully distinguish speech from noise or nonspeech most of the time. However, correct detection of music already poses a problem for these algorithms, and music could be classified as either speech or noise—or as changing back and forth between these two, depending on the genre of the music. In listening to the total amount of recorded material, the automatic classification approach was deemed completely infeasible. In view of the unpredictable situational content of all recordings, no automatic algorithm exists to our knowledge that could handle an error-free classification into more than two–three classes. Instead, it was decided to select a number of situations of fixed duration from the total recordings of each individual subject. The decisions as to how to select situations that represented all the recordings of one subject were individually made by the same experimenter. Care was taken that the proportions of the selected situations should reasonably represent the overall proportions of situations in the total recordings per each subject. This empirical method was deemed very appropriate because the aim was to investigate what kind and what variety of social situations would be encountered by different hearing aid users, including their distribution of occurrences of situations. After this kind of data selection, the next step of data analysis was to classify the selected situations into subsets, starting at the verbal descriptions of each selected situation. Also here it was decided that a fully automatic data analysis approach, like in vector quantization or cluster analysis methods, was infeasible for this study. Instead, classes were hand sorted into categories with the aim of yielding a certain number of generic categories. This task was not straightforward, and therefore focus was put on an informative character rather than mathematical rigor.

Each recorded selection was classified into one of 11 general classes, for example, “conversation with background noise, 2 people,” but it was possible that the same recording could also exhibit parts where more than two persons would converse. This led to the effect that the occurrence percentages could add up to more than 100 percent.

It was observed that 50.7 percent of the situations were signals with speech. The participant’s own voice was recorded in 47.6 percent of the situations. Further, 27.5 percent of the situations were signals with housework sounds. Keep in mind that these situations could sometimes overlap. One should also remember that the sampling of situations gathered during this project was not guaranteed to exactly represent one person’s overall percentages of occurrence—or that of the average hearing aid user. Still, in view of these percentages, one can conclude that hearing aids need not only amplify (other peoples’) speech. It is important that one’s own speech is also amplified appropriately, and this requires a different gain setting due to the different level and spectral shape of one’s own voice compared to “normal speech.” Moreover, nonspeech sounds play a clearly important role for hearing aid users, as a first-order extrapolation from percentage of occurrence to percentage of time during the day means: a large percentage, approximately 50 percent, of daily time was made up of nonspeech. Therefore, the amplification schemes of modern hearing aids should correspondingly allow for appropriate gain settings. Until today, literature
about optimal hearing aid gain settings for nonspeech or for speech at nonnormal levels (Schmidt, 2006) is very scarce.

Finally, 18.1 percent of the situations were recorded outdoors. This percentage was likely affected by the recording period occurring in the summer. A lower percentage of recordings made outdoors could be expected during wintertime. It remains unanswered what effect this would have had on the sound level measurement.

Acoustic Analysis

Different methodologies could have been applied for the analysis of the SPL distributions. Given the statistical nature of the recorded material and the unpredictability regarding the recorded situations, it was decided that a traditional, well-understood method would be most appropriate for a sound level analysis. To this end, short-term levels were calculated for nonoverlapping rectangular windows of 125 msec long. Note that this duration should not be mistaken for the 125 msec “fast” setting of a conventional SPL meter due to its effectively exponential temporal window, resulting from a low-pass filtering of its RMS estimator circuit. The difference is small, however, and does not alter the conclusion that can be drawn from the level distributions.

An attempt to differentiate the acoustic analysis for one’s own voice as opposed to external signals showed no clear trend or statistically significant differences. The acoustic analysis was therefore performed for the pooled signals (per situation).

One surprising observation of this study is that the short-term level distributions of the different classification groups exhibited a large range of levels. This can partly be attributed to the fact that natural recordings never consist of a “pure” situation alone but, rather, contain atypically loud or soft parts, as shown in the group-wise pooled level distributions section. Most often, for situations like coughing or sneezing, these will be of shorter duration and of relatively seldom occurrence. Dealing with this kind of signal inside a hearing aid will therefore typically not pose a problem, as many modern hearing aids offer special features for adaptive gain control that go beyond standard amplitude compression.

Another aspect of the level distributions seems to be of larger importance for hearing aids that aim at delivering the optimal amplification for each listening situation. Many fitting rules for prescribing hearing aid gain as a function of signal frequency and level have been based on the assumption of one or more idealized “standard” listening situations, like “normal speech,” “loud speech,” and the like. A target gain will be prescribed for one or more of these acoustic situations, as in DSL[i/o] (Cornelisse et al, 1994), the Cambridge rule (Moore et al, 1999), or NAL-NL1 (Dillon, 1999).

The rationale to prescribe gain for some typical and important listening situations seems highly valid. However, in light of this article, it becomes clear that a category like “normal speech,” although well defined in standards like, for example, the speech intelligibility index (American National Standards Institute, 1997), can mean a large range of different long-term and short-term levels in “normal life.” The hearing aid user might nevertheless expect all different “instances” of such a typical situation to be amplified correctly. The same is true for the other acoustic situations that were observed in the recorded material. Fortunately, this problem can be solved by multichannel compression inside the hearing aid. However, as mentioned earlier in the discussion about grouping of acoustic situations, further research seems necessary to establish more knowledge about optimal gain settings for speech at nonnormal levels and for nonspeech signals.

Alongside amplitude compression, many modern hearing aids try to achieve a signal classification in order to enable or disable further adaptive features of the hearing aid. One such feature is an automatic noise-reduction algorithm that relies on some distinction of the incoming signal into classes like speech/nonspeech or noisy/nonnoisy. Many automatic algorithms are based on an analysis of the modulation spectrum or the short-term level distribution of the signal, the two being mostly equivalent to each other. The acoustic analysis of situations with speech in background noise revealed the large range of short-term levels that can appear at the hearing aid microphones. This demands noise-reduction algorithms.
that can selectively increase or decrease gain, to compensate for the large level ranges for all different kinds of situations with speech in noise.

In light of this study, along with a non-linear hearing aid fitting, further signal classification and signal/situation-adaptive features are highly desirable inside a modern hearing aid. However, when assessing their benefit for the hearing aid user in the clinic, it seems appropriate to use a number of different types of signals and noises.

Acknowledgments. We are grateful to Birger Kollmeier and Thomas Brand for their support and contribution to this work. We would like to thank Sandra Fobel, Birgitta Gabriel, and Melanie Ostendorf for support in the measurements.

REFERENCES


APPENDIX: QUESTIONNAIRE

The following questions and response alternatives were used on the questionnaire in order to characterize the recorded situations. The response alternatives were mapped to ordinal scale values that are also given to the right of each answer.

1. Do you recognize this situation?
   1. No 0
   2. Yes 1

2. How often does this situation occur in your daily life?
   1. Less than once a week 0
   2. Once to three times a week 1
   3. Four to seven times a week 2
   4. Once daily 3
   5. Twice to three times a day 4
   6. Four to five times a day 5
   7. More than five times a day 6

3. How important is it for you to hear well in this situation?
   1. Unimportant 0
   2. Less important 1
   3. Important 2
   4. Very important 3

4. To what extent do you have problems in this situation?
   1. No problems 0
   2. A few problems 1
   3. Moderate problems 2
   4. Great problems 3
   5. Cannot stand the situation 4

5. To what degree are you worried, annoyed, or irritated in this situation?
   1. Not at all 0
   2. Just a little 1
   3. Moderate 2
   4. Quite a bit 3
   5. A lot 4

6. How long do you proportionately use your hearing aid in this situation?
   1. Never 0
   2. About one-quarter of the time 1
   3. About half of the time 2
   4. About three-quarters of the time 3
   5. All the time 4

7. How helpful is your hearing aid in this situation?
   1. Not applicable 0
   2. Hearing aid is absolutely useless 1
   3. Hearing aid helps a little 2
   4. Hearing aid is quite helpful 3
   5. Hearing with the hearing aid is perfect 4

8. To what extent do you have problems with your hearing aid in this situation?
   1. Not applicable 0
   2. No problems 1
   3. Little problems 2
   4. Moderate problems 3
   5. Great problems 4
   6. Cannot stand the situation 5

9. How content are you with your hearing aid in this situation?
   1. Not applicable 0
   2. Not content at all 1
   3. A little content 2
   4. Moderately content 3
   5. Very content 4
   6. Exhilarated about the hearing aid 5