Observations on Hearing Aid Users’ Strategies for Controlling the Level of Their Own Voice

DOI: 10.3766/jaaa.20.8.5

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Abstract

Background: Evidence suggests that hearing-aid users have difficulties with own-voice level control, most likely because their auditory feedback is affected by hearing-aid amplification.

Purpose: The purpose of this study was to investigate how changes to auditory feedback affect the voice level of hearing-aid users.

Research Design: A correlational study was set up to investigate the relation between voice level and hearing-aid amplification.

Study Sample: Seven hearing-impaired speakers participated. All were experienced hearing-aid users.

Data Collection and Analysis: The speakers projected their voice to a passive listener across different speaker-listener distances and with different prescriptions of gain in an experimental hearing aid. For each combination of conditions, produced voice level and self-perceived voice level was measured. These data were subjected to an analysis of variance assuming a mixture of random and fixed effects. In addition, all speakers took part in interviews.

Results: Three speakers reacted to the changes in auditory feedback in agreement with previous experiments with normal-hearing speakers: they compensated by changing produced voice level. In contrast, the voice levels in the other four speakers were largely unaffected by the changes to auditory feedback. A secondary observation was that while all speakers increased their voice level with distance, the two subgroups produced different growth rates of vocal level versus distance.

Conclusions: It is hypothesized that the speakers in the former subgroup relied on auditory feedback for solving the experimental task, whereas the latter subgroup had developed an own-voice level-control strategy based on proprioceptory feedback, possibly because they have lost faith in their auditory feedback mechanism, which indeed is changed by both hearing loss and hearing-aid amplification. Comparison to “target” voice levels suggests that proprioceptory feedback is less effective than auditory feedback for achieving adequate level-distance growth rate.

Key Words: Auditory feedback, hearing aids, gain, Lombard reflex, own voice level, proprioception, vocal effort

Abbreviations: 0 dB IG = unity gain, linear setting; AUD = auditory feedback speaker subgroup; CompHiFast = high-gain fast-acting compression prescription; CompLoSlow = low-gain slow-acting compression prescription; Half-gain = half-gain prescription, linear setting; $L_{EQ}$ = equivalent continuous sound pressure level; PRO = proprioceptory feedback speaker subgroup

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Portions of this work were presented orally at the International Hearing Aid Research Conference (IHCON), August 16–20, 2006, Lake Tahoe, CA.
A n important aspect of successful communication is to use the adequate voice level for the occasion (Lane and Tranel, 1971), that is, to master one’s own-voice level control. The most well-known mechanism regarding own-voice level control is the Lombard effect, which refers to the observation that speakers raise their voice level with increasing background noise level, (see Junqua, 1996, for a review). There are, however, several other conditions that impose demands on own-voice level control, for example, overcoming speaker-listener distance. While own-voice level control appears to be trivial for the vast majority of normally hearing people, a substantial subset of hearing-aid users report problems with this. This has recently been shown in a large-scale study that compared a group of hearing-aid users with a normal-hearing control group on many dimensions of own voice (Laugesen et al, 2008a), evaluated by means of the specially developed Own Voice Quality questionnaire (Jensen et al, 2006). Other studies, based on self-report and interviews (Hansen, 1997) and a dedicated own-voice focus group with eight experienced hearing-aid users (Nielsen and Laugesen, 2004), indicate that in broad terms, hearing-aid users tend to speak too softly. The focus-group participants in the study by Nielsen and Laugesen mentioned that this behavior was most pronounced right after being fit with hearing aids or after changing to new hearing aids. Also it was reported that speaking too softly will compromise communication. Eventually, the affected hearing-aid user will realize this and react by making appropriate adjustments to voice level. However, when a hearing-aid user forces herself or himself to speak louder, the self-perceived own-voice sound quality is often degraded (Nielsen and Laugesen, 2004).

Own-voice level control is accomplished through three feedback mechanisms, as explained by Lane and Tranel (1971):

- Visual and verbal feedback (external loop; verbal feedback actively provided by other people, or feedback obtained by the speaker by observing the listeners’ facial expressions, etc.),
- Proprioceptory (or kinesthetic) feedback (internal loop; based on the sense of feel, e.g., monitoring the magnitude of vibration in the speaking organs),
- Auditory feedback (internal loop; hearing one’s own voice through air and body conduction).

Assuming that a hearing-aid user is able to hear external verbal feedback on voice level, there is no reason to believe that the first of these three mechanisms is less available to a hearing-aid user than to a normal-hearing person. In fact, results from Laugesen et al, 2008a, show that hearing-aid users actively rely on visual and verbal feedback to a much greater extent than people with normal hearing, for instance, by making a deliberate effort of observing the speaking partner’s facial expression while speaking. Regarding proprioceptory feedback there is—again—no reason to believe that this mechanism is affected by either hearing loss or hearing aids. Indeed, Perkell et al (1997) reviewed evidence for the availability of proprioceptory feedback to people with hearing loss, based on the observation that late-deafened adults are able to maintain a remarkably good speech quality several years after the onset of deafness. Also, Perkell et al explain the importance of proprioceptory feedback for speech learning in normal-hearing as well as hearing-impaired children. Thus, both visual-verbal feedback and proprioceptory feedback appear to be fully available to hearing-aid users, and they are therefore not expected to be the cause of level-control problems. In contrast, it is clear that the auditory feedback mechanism is affected by both hearing loss and hearing aids, and hence altered auditory feedback is most likely responsible for the problems that hearing-aid users have with own-voice level control.

The ways in which alterations to auditory feedback affect the voice level of normal-hearing test subjects have been carefully studied. Lane et al (1961) reviewed several studies, with the main conclusion that speakers alter their voice level by 0.5 dB per 1 dB of change in auditory feedback—across a wide range of positive or negative controlled manipulations to gain in the auditory feedback path. However, such experiments have to the authors’ knowledge not been replicated with hearing-impaired test subjects. Investigating auditory feedback in hearing-impaired people is, in fact, highly relevant because of the aforementioned changes to auditory feedback introduced by hearing loss and hearing aids. The amplification in hearing aids could, in principle, be designed to remedy the changes to auditory feedback introduced by the hearing loss, but in reality the vast majority of research into amplification for hearing-impaired people has been concerned solely with listening (see, e.g., Dillon, 2001). Another complicating factor is the occlusion effect, which means that in many hearing-aid fittings the auditory own-voice feedback is dominated at low frequencies by body-conducted own voice “amplified” by the occlusion effect, whereas the high frequencies are dominated by the amplified air-borne contribution heard through the hearing aid. The combined effect of the two own-voice contributions is also known as “ampclusion” (Painton, 1993).
METHOD

The experiment involved a small group of speakers, each of whom addressed a listener with a predefined question in a succession of trials where the prescription of gain in an experimental hearing aid was changed among four alternatives. In this way, gain prescription ranged from what was obviously too little to what was obviously too much for own voice. The speakers’ task of stating a question to the listener was deliberately chosen in order to emphasize that intelligible communication should be achieved (Lane and Tranel, 1971). In addition to the variation in hearing-aid gain, a variation in target vocal level was introduced by a variation in the speaker-listener distance (Traunmüller and Eriksson, 2000). The variation in target vocal level was thought to be particularly important to include because of the recruitment associated with hearing loss, and because of the nonlinear gain rules used in modern hearing aids (Dillon, 2001).

The study was approved by the local research ethics committee.

Participants

Seven speakers participated in the experiment: four male, three female. These were selected from the research center’s panel of hearing-aid users with ear canals suitable for the hearing-aid receiver units described below, and sensorineural hearing losses with threshold values as close as possible to the upper limit of the fitting range of the experimental hearing aid, in order to create as much difference as possible among the four gain prescriptions (see below). The mean audiogram and standard deviations are shown in Figure 1 together with the fitting range. All hearing losses were symmetrical at all frequencies, with deviations up to 25 dB. The speakers had between 2 and 35 years of experience with hearing aids and were bilaterally fitted with modern digital aids. The speakers’ own hearing aids were provided by the research center and were fitted and regularly maintained by the research center’s staff of audiologists.

As suggested by Figure 1, the fitting range limit was exceeded at 6 and 8 kHz in some cases. This was handled by entering the limit values instead of the real hearing threshold level values into the experimental fitting software. The resulting underamplification with the experimental devices is not expected to cause any problems, since the own-voice signal contains very little energy at these high frequencies (Cornelisse et al, 1991; Elberling and Nielsen, 1993).

Because of the narrow selection criterion on hearing loss indicated in Figure 1, and the demand on ear canal geometry mentioned above, it had to be accepted that the speakers spanned a rather wide range of ages (between 27 and 74, mean 60, and standard deviation 18 years). With regard to the speakers’ voices, it was ensured that the test-subject files contained no remarks about voice pathologies. None of the speakers were professionally trained, while one was an amateur actress.

One listener (the second author) was used throughout the experiment.

Location for Experiment

The experiment was carried out in a quiet corridor that allowed speaker-listener distances up to 22 m. In order to estimate the increase in speaker level required to overcome the level deficit introduced by increasing distance, objective measurements were carried out with a loudspeaker (Tannoy System 1200) at the speaker’s position and a Bruel & Kjaer 4144 microphone. Both were connected to a Bruel & Kjaer PULSE system (a dual-channel frequency analyzer), which delivered a white noise signal to the loudspeaker at a constant level, and measured the sound pressure level at a range of distances. The results are shown in Figure 2 together with a free-field prediction based on the inverse square law. The figure shows that as distance increases, the sound pressure level drops by less in the corridor than in a free field. On the other
hand, the sound pressure spans a much wider range of levels than what was tentatively predicted by traditional room acoustics (Cremer and Müller, 1982). The latter model (result also included in Figure 2) is a combination of the free-field prediction close to the sound source and a diffuse-field prediction for distances beyond the critical distance, which was estimated to be about 1 m in the corridor. The remarkable deviation of the measurements from the room-acoustics model is due to the geometrical shape of the long narrow corridor, which is very far from the more regular "shoebox" shape assumed by traditional room acoustics. A similar observation was made by Wang et al (2005).

**Equipment**

The signal-processing part of the experimental hearing aid was programmed on a general-purpose DSP board (BlueWave Systems) installed in a standard PC, around which the setup was built. The signal-processing structure of the experimental hearing aid allowed both linear and nonlinear amplification to be realized. Sound was picked up by standard hearing-aid microphones (Knowles EK3027CX) installed in otherwise empty behind-the-ear hearing-aid shells, and sound was delivered through standard hearing-aid receivers (Knowles FC6314) driven by laboratory power amplifiers. The receivers were installed in soft silicone inserts that allowed a deep, closed fit in the bony part of the ear canal. In this way, the occlusion effect could be kept to a minimum (Killion et al, 1988), and coupler measurements showed that it was possible to provide gain down to 80 Hz, thus covering the full low-frequency range of speech frequencies. This was important in order to make sure that own-voice level in front of the speaker’s eardrum was determined by the experimental hearing aid and not by the occlusion effect or direct air-borne sound.

The performance of the experimental hearing aid was tested before the actual experiment in terms of coupler measurements and by fitting it to the third author. Real-ear measurements with a probe microphone confirmed that the above specifications could be achieved, while coupler measurements showed that it was possible to deliver distortion-free amplification according to the loudest prescription for all relevant levels of speech, and for hearing losses up to the fitting-range limit indicated in Figure 1. In this way it was ensured that hard clipping from the digital-to-analog converter would not occur during the experiment. The experimental hearing aid contained no further means of output limiting. The most difficult aspect of fitting the experimental device was obtaining a complete seal of the silicone inserts in the ear canal. Moreover, the complete seal was crucial with respect to obtaining the specified low-frequency response and, in turn, keeping direct air-borne sound well below the output from the hearing aid. Therefore, the protocol of the experiment included that before and after each session, the acoustic seal of the silicone inserts was verified by measurements with the Brüel & Kjær PULSE system and probe microphones on both ears of every speaker. The occlusion effect was not measured in each individual. However, great care was exercised to obtain deep fittings of the silicone inserts, and given that the acoustical seal was routinely verified, the occlusion effect would have been very noticeable by the speaker if the silicone inserts had not been sealing in the bony part of the ear canal. The possibility of occlusion-related problems with the experimental hearing aids, for instance, in terms of own-voice sound quality, was discussed with all the speakers in the closing interviews, and this did not lead to any concerns about audible occlusion effect.

The hearing-aid microphones were also used for recording the speakers’ voices. Recordings were made with the ProTools™ system running on another PC. A simple block diagram of the setup is shown in Figure 3 (except for the PULSE system mentioned above).

**Hearing-Aid Gain Prescriptions**

As already mentioned, the speakers were receiving amplification through experimental bilateral hearing aids according to four different prescriptions:

![Figure 2. Sound pressure levels measured at various distances from a loudspeaker at the speaker's position, shown together with tentative predictions based on a free-field assumption and traditional room acoustics, as indicated.](image)
• Unity gain, linear setting (0 dB IG)
• Low-gain slow-acting compression prescription (CompLoSlow)
• High-gain fast-acting compression prescription (CompHiFast)
• Half-gain prescription, linear setting (Half-gain)

Out of these, the first (0 dB IG) clearly provides too little gain—in consideration of the hearing losses shown in Figure 1 above—while the last (Half-gain, without a volume control) clearly provides too much gain for a relatively loud signal such as own voice (Cornelisse et al, 1991; Elberling and Nielsen, 1993). The two compression prescriptions were realized with two independent channels divided at 1500 Hz. In both prescriptions the compression kneepoints were 50 dB SPL in both channels. The CompHiFast setting was chosen to mimic a standard fast compression prescription with emphasis on good speech intelligibility (Schum, 1997). Time constants were 10 msec attack and 80 msec release in the low-frequency channel and 5 msec attack and 160 msec release in the high-frequency channel. In order to mimic a prescription with emphasis on listening comfort, the CompLoSlow setting was obtained from CompHiFast by a reduction of gain and an increase of compression time constants. Compression attack times were increased by a factor of two, and compression release times were increased by a factor of 20. The gain reduction was determined for each individual ear as follows.

• Insertion gain as a function of frequency was determined for the CompHiFast prescription corresponding to a steady-state signal with the same long-term spectrum as own voice (Elberling and Nielsen, 1993).
• Below 1500 Hz, the gain reduction for CompLoSlow was the frequency-specific insertion-gain values from above divided by two.
• Above 1500 Hz, gain was reduced uniformly by the average value of the below-1500 Hz gain reductions.

An example of the insertion gain targets of the four prescriptions for a steady-state signal with the same long-term spectrum as own voice is shown in Figure 4. Coupler measurements, as those described above, were used to confirm that the intended difference among the four prescriptions was indeed achieved.

Individual verification of insertion gain targets was not performed. This was left out in order to keep testing time within reasonable limits, and because the most important aspect was the differences among the four prescriptions rather than exactly meeting target gain values.

The four prescriptions were chosen in an aim for clinical relevance, which resulted in a mixture of linear and nonlinear prescriptions. In hindsight, this may have introduced an unnecessary confounding factor, compared to using, for example, four linear prescriptions. However, the difference between linear and nonlinear amplification, as well as the difference in time constants between the two nonlinear prescriptions, did not appear to impact the results.

### Speech Material

In all experimental trials, the speakers stated (the Danish equivalent of) the question “Can you recall when we last had a hard winter?” This question was chosen in consideration of realism (it should be a meaningful question to state under the given circumstances), length (it should be possible to utter the question in a shouting voice without pauses), distinctness (it should not give rise to multiple interpretations...
in terms of pronunciation and stress), and phonetic richness.

**Procedure**

For the part of the experiment considered in this paper, each speaker participated in a practice round (using own hearing aids) and one session that consisted of 20 trials, each of which considered a specific combination of the five speaker-listener distances and four gain prescriptions. The task of the speakers was to ask the above question to the listener according to the instructions:

Your task is

- to speak with the level you would normally use for a situation like this,
- to repeat the question until you think the level of your voice is adequate.

Having done that, the speakers were asked to rate the self-perceived level of their own voice on the scale shown in Figure 5, considering only the last (i.e., satisfactory) version of the question. It was verbally explained to the speakers that the listener would remain passive in this session, and all speakers immediately accepted the fact that no feedback on voice level was provided.

In the experiment, distance was varied in five steps (1.5, 3, 7, 15, and 20 m), and in this way the adequate voice level for the occasion varied from a normal relaxed speaking voice up to a highly raised voice (and even shouting for some speakers). In order to blind the speakers to the metric distance, the distance was signaled to the listener through a letter code, and the listener would place himself along the corridor accordingly. Distances as well as gain prescriptions were selected randomly by the control software, and the selection of gain prescription was blinded to speaker, listener, and experimenter (the first author, who operated the control software and instructed the speakers). The speakers’ voices were recorded (by the third author) separately for each trial (recall the experimental setup in Figure 3).

In addition, the complete experiment comprised another two sessions, in which the listener supervised the speakers into using the voice level that was found adequate by the listener. Those results are reported elsewhere (Laugesen et al, 2008b), while the average supervised speech levels for each distance will be used below as an estimate of “target” voice level.

After the final session, all speakers were interviewed (by the first and second authors) about the experiment and about daily-life own-voice issues with hearing aids in general. All interviews were recorded on minidisk.

**Data Extraction**

There are three sets of data available from the experiment: the ratings of self-perceived voice level, the recordings of the speaker’s voice, and the interviews. The rating data were simply read off the response sheets and entered into a spreadsheet. The voice recordings were edited to contain only the last valid utterance, each of which was subsequently synthesized into a single broadband long-term average sound pressure level ($L_{eq}$), by the use of the appropriate calibration spectrum. Finally, the relevant parts of the interviews were transcribed and analyzed. Because observations from the interviews are used only sparingly, and in consideration of the length and the focus of this paper, the interview data are not separately presented in the section below.

**RESULTS**

Already during data collection it became clear to the experimenter and the listener (the first and second author) that the speakers used one of two radically different strategies when solving the experimental task. Thus, the observation was made that three out of the seven speakers used a voice level that allowed them to rate their self-perceived voice level at 0 (labeled ADEQUATE) at each distance and for each gain setting. As a consequence, these three speakers varied their produced vocal level dramatically as gain was changed. For example, at the shortest speaker-listener distance of 1.5 m they would use voice levels that ranged from a very soft voice to a substantially raised voice—where the latter voice level obviously was inadequate. Apparently, these speakers relied entirely on their auditory feedback mechanism when solving the experimental task, and thus essentially behaved in the same way as the normal-hearing speakers that participated in previous experiments reviewed by Lane and Tranel (1971). In contrast, the other four speakers largely ignored the modifications to auditory feedback introduced by the variations in gain prescription and were in this way on average closer to producing voice levels that were adequate for
the listener. Since the listener was providing neither verbal nor visual feedback (this was confirmed in the follow-up interviews with the speakers), a process of elimination suggests that these four speakers mainly relied on their proprioceptory feedback mechanisms in solving the experimental task. From now on, the two subgroups will be referred to as the AUD (auditory feedback) and PRO (proprioceptory feedback) subgroups, respectively.

As a supplement to the above observation of two distinct subgroups of speakers, the outcome data were subjected to cluster analysis (tree-clustering, single linkage, Euclidean distances)—despite that a cluster analysis performed with such a small number of observations is questionable. In any case, separate analyses of both outcome variables (LEVEL rating and own-voice L\text{EQ}) suggest that the speakers are clustered in two subgroups. The composition of the clusters is the same for the two analyses and furthermore in agreement with the observation-based grouping from above.

Analytic Approach

The division of the speakers into the AUD and PRO subgroups described above poses a problem to the statistical analysis of the results. While it would be preferable to consider only the three original experimental variables, SPEAKER, DISTANCE, and PRESCRIPTION, this approach is misleading because the three aforementioned variables are unable to explain the variance that belongs to the grouping of the speakers. The alternative is to introduce an additional moderator variable denoted FB_MODALITY (feedback modality), which can take on the values AUD or PRO explained above. Such a model is suitable for explaining the variance in the outcome variables, but it is, of course, problematic that the grouping variable is derived a posteriori from the data. Nevertheless, the latter approach has been taken in the analysis that follows.

Thus, the results were analyzed by means of a mixed-model ANOVA (analysis of variance), with SPEAKER as a random factor and the rest as fixed factors. Only main effects and second-order interactions are considered, and throughout a 0.01 limit for statistical significance is assumed.

Basic Statistics

The basic tests of significance regarding the two outcome variables are shown in Table 1. The fact that the FB_MODALITY variable appears in several significant interactions is no surprise considering how the variable was constructed. However, the presence of these significant interactions supports the relevance of including the variable, as well as its nature as a moderator variable.

The various significant results are illustrated and discussed below. Note that the results below are determined from statistical models that include only the significant effects from Table 1 and that this slightly changes both the significance levels and the plotted marginal means.

### Self-Perceived Own-Voice Level

The significant main effect of PRESCRIPTION on the LEVEL rating is not illustrated separately, since it is readily discernible from the plot of the significant interaction between PRESCRIPTION and FB_MODALITY, which is shown in Figure 6. As already mentioned, the AUD subgroup basically gave the LEVEL rating 0 (corresponding to “adequate”) to all four prescriptions, whereas the PRO subgroup spans a range of almost four scale units on the LEVEL scale, ranging from -1.6 (to the soft side) with 0 dB IG and gradually up to 2.2 (to the loud side) with the Half-gain prescription.

It should be mentioned that in accordance with the lack of a main effect of DISTANCE on self-perceived voice level, the same picture as in Figure 6 appears if results are plotted separately for each distance (not shown).

### Broadband Level of Vocal Productions

The complement of the results in Figure 6 regards the vocal productions, as characterized by the own-voice L\text{EQ}. The statistical analysis from Table 1 again suggests a significant interaction between PRESCRIPTION and FB_MODALITY, which is illustrated in
Figure 7. As expected, these results show that the speakers in the AUD subgroup changed their produced vocal level dramatically in order to compensate for the variations in auditory feedback and to achieve the ADEQUATE self-perceived LEVEL ratings shown in Figure 6 for all four prescriptions. The PRO subgroup exhibits a similar tendency, but to a much lesser degree, which indicates that the PRO subgroup in fact was only partly able to suppress the variations in auditory feedback brought about by the experiment.

Returning now to the other significant results in Table 1, the main effect of PRESCRIPTION is already clear from Figure 7—voice level goes down as gain goes up. The significant random main effect of SPEAKER suggests that there is a non-negligible variance among the seven speakers in their overall mean levels, that is, the different speakers systematically used different sound pressure levels to make themselves heard across a distance. This observation is further discussed in Laugesen et al (2007) and was also noted previously by Traunmüller and Eriksson (2000) and Brown et al (1996).

The significant main effect of DISTANCE is the obvious one, that voice level goes up as distance increases; this is not illustrated separately but is easily seen from the plot of the significant interaction between DISTANCE and FB_MODALITY in Figure 8. Thus, the two dashed curves in Figure 8 suggest that speakers in both subgroups (AUD and PRO) assess the distance across which they have to speak and adjust the level of their vocal production accordingly. However, the speakers in the AUD subgroup apparently produce a steeper growth in level with distance than those in the PRO subgroup. This observation raises the question about which subgroup’s level-growth rate is more correct. This can be assessed by drawing on the results from the subsequent session of this experiment (Laugesen et al, 2008b). As explained above, in that part of the experiment the listener acted as an interventor who supervised each speaker into speaking at the level that was adequate for the particular distance, from the listener’s point of view. Thus, these supervised levels can be interpreted as a “target,” which the speakers should aim at in the “unsupervised” part of the experiment considered here.

From Figure 8 it is clearly seen that the unsupervised vocal levels produced by the AUD subgroup follow the supervised target much more closely than those produced by the PRO subgroup, which show a shallower growth function. Thus, even though the AUD subgroup produce a much larger variation in vocal level at a particular distance when the amount of auditory feedback is varied, the AUD subgroup is better than the PRO subgroup at producing the adequate increase in vocal level as distance increases.

Finally, the objective measurements from the corridor in Figure 2 show that if the speakers had compensated perfectly for the level deficit with increasing distance, they would have raised their voice by 14 dB from the 1.5 to the 20 m distance. All three sets of results in Figure 8 show a smaller range of levels, although the target results come close to the 14 dB from Figure 2. Close examination of the results shows that this is mainly because the voice level curves in Figure 8 are shallower toward the shortest distances than what is predicted from Figure 2. This, in turn, occurs because there is a limit to how much a speaker can lower his or her voice without going into a whisper.
which would have been inadequate under the circumstances of the experiment.

DISCUSSION

Number of Participants

It may well be argued that the conclusions from the present study are drawn from a very small population of speakers (N = 7). However, a conservative limit of statistical significance was assumed at the outset (p < 0.01), and as may be seen from Table 1, all effects taken into consideration are within this limit with very broad margin. In addition, the mere fact that the speakers so clearly clustered themselves into the pivotal AUD and PRO subgroups makes the results worthwhile to report.

Own-Voice Level-Control Strategies

In view of the results from the literature that were mentioned in the introduction, it is a surprise that some of the speakers in the present experiment ignored auditory feedback and instead relied on proprioceptory feedback. Thus, in the voice-feedback experiments reviewed by Lane and Tranel (1971), all speakers apparently behaved as if they relied entirely on auditory feedback, and there is no mention of speakers with unexpected strategies. Similar observations can be made regarding the so-called Lombard test (Sullivan, 1963), in which the test subject is presented with loud noise under headphones and the influence on vocal level is measured. This test inherently assumes that the test subjects rely entirely on auditory feedback, and even if Lane and Tranel (1971) refer to observations of deviant behavior in the Lombard test, the broad picture is that the Lombard reflex is “extremely stable and robust” (Pick et al, 1989).

These considerations suggest that relying heavily on proprioceptory feedback for own-voice level control is learned behavior, which occurs in people who for some reason have “lost faith” in their auditory feedback mechanism. For the participants in the present experiment, the most likely reason for this loss of faith is the change to auditory feedback introduced by hearing aids, which in fact can be quite dramatic, particularly if the hearing aid is equipped with a volume control, has several different listening programs, or automatic features that manipulate gain (e.g., dynamic range compression or a noise management algorithm). Such problems were indeed brought up in the interviews. Thus, two people mentioned situations in which the noise management algorithm in their hearing aid decreased the background noise, which had made them speak too softly. Another person had experienced that when the hearing aid was running low on battery, amplification was reduced, which caused this person to speak too loud. It should be noted, though, that not all participants—who were all active, experienced hearing-aid users—had developed a level-control strategy based on proprioception. Explanations for the observed AUD/PRO grouping were sought for in the interviews, in the participants’ hearing-aid fitting histories (linear versus nonlinear amplification, closed versus open fittings), and by looking for systematic differences in the other available predictor variables (gender, age, and hearing threshold levels). However, these efforts did not reveal any striking AUD/PRO group-specific differences. Particularly the lack of awareness about the proprioceptory strategy that was apparent from the interviews suggests that developing an own-voice level-control strategy based on proprioception happens unconsciously. (Regarding the interview data, it should be noted that the AUD/PRO grouping was discovered during the experiment. Hence, the difference in strategy, the interpretation of the speakers’ instructions, and the use of the scale to measure self-perceived voice level [Figure 5] were discussed systematically only with the speakers that came in last, and in any case before the interviewers had had time to reflect on the discovery.)

A more daily-life example of learning to rely on proprioceptory feedback for voice level control can be (informally) observed with users of portable music

Figure 8. Marginal (least squares) means of the own-voice $L_{EQ}$ for the DISTANCE*FB_MODALITY interaction ($p < 0.00001^*$). "Target" levels are also shown, taken from Laugesen et al, 2008b, in terms of listener-supervised own-voice $L_{EQ}$ values averaged across all speakers and prescriptions.
players with headphones. New users typically speak much too loud for the surroundings if they speak while listening to music; that is, they behave according to the Lombard reflex. With experience, many users of such players learn to suppress the Lombard reflex and become able to produce speech at reasonable levels while listening to music. This necessarily involves ignoring auditory feedback and relying on proprioceptive feedback (as well as the third mechanism: visual and verbal feedback).

**Clinical Relevance**

While the above observations about the AUD and PRO subgroups are both striking and interesting, it should be emphasized that they have been made in an experiment where the gain prescription of the experimental hearing aid was constantly changing among four very different alternatives, and where the speakers were deprived of visual and verbal feedback for solving the level-control task. This is, of course, not representative of daily life. As mentioned in the introduction, hearing-aid users will in general adjust to the auditory feedback provided by their hearing aids and eventually learn to perform own-voice level control reasonably well. This means that the practical consequences of these results mainly concern the period of time after being fitted with new hearing aids (or the first hearing aids). During this period the course of adaptation to the new hearing aids—with respect to own-voice level control—may depend on whether the individual is inclined to rely on auditory or proprioceptive feedback. Formulating specific counseling strategies based on these observations requires further work.

Finally, it is interesting that the problem of own-voice level control in hearing-impaired people (with or without hearing aids) was recognized as early as 1947 when Carhart suggested teaching own-voice level control to hearing-impaired people through "kinesthetic control," which clearly is the same mechanism that is described as proprioceptive feedback in the present study. Thus, already then it was acknowledged that proprioceptive feedback is a usable alternative to auditory feedback when the auditory feedback is affected by hearing loss and eventual hearing-aid treatment. The active use of visual and verbal feedback as a means to perform adequate own-voice level control was also outlined by Carhart (1947).

**CONCLUSION**

This paper has described an experiment in which hearing-impaired users of amplification solved an experimental task of own-voice level control, while they were deprived of the visual-verbal feedback cue for voice level control. At the same time, auditory feedback was changed from trial to trial by a change in hearing-aid amplification. In addition, the demand on vocal level was varied by changing the speaker-listener distance.

The key result of the study is the observation that the effect of variations in amplification—and thereby auditory feedback—manifested itself in two distinctly different ways. One subgroup of speakers offset the changes in amplification by changes in produced vocal level, such that their self-perceived own-voice levels were always rated as "adequate." Apparently, these people relied primarily on their auditory feedback mechanism in solving the experimental task. The remaining speakers largely ignored the variations in amplification and showed only very small variations in vocal level at a given distance. On the other hand, their self-perceived level ratings were greatly influenced by the variations in amplification. Apparently, this subgroup relied primarily on proprioceptive feedback in solving the experimental task. According to the literature, the standard behavior (of normal-hearing test subjects) is to rely on auditory feedback, and hence we surmise that relying on proprioceptive feedback is learned behavior.

Another interesting distinction between the two subgroups regarded the ability to produce an adequate growth rate of vocal level with distance. Thus, by comparing to the voice levels that were found to be adequate by the listener in a supervised condition, it appeared that in the present unsupervised condition the speakers that relied on auditory feedback were better at producing the adequate growth rate of vocal level versus distance, compared to those that relied on proprioceptive feedback who produced a too shallow growth rate. This result indicates that relying on proprioceptive feedback for own-voice level control is an effective way of suppressing changes to auditory feedback (e.g., introduced by hearing aids) but that the proprioceptive feedback mechanism is less reliable than auditory feedback for controlling voice level as a function of speaker-listener distance.

**REFERENCES**


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