Abstract

To address the inability of traditional fitting formulae to accommodate individual preferences in hearing aid settings, learning technology allows users to fine tune their instruments to achieve optimal satisfaction. SoundLearning, the second generation of learning technology from Siemens, allows the user to train not only gain, but also compression characteristics and frequency shape. Like its predecessor DataLearning, SoundLearning functions transparently in the background based on simple adjustments of the volume control made by the users as they go about their daily life. To accomplish this, the spectral content of the input signal and the corresponding volume control setting is continuously sampled and analyzed in order to approximate the user’s preferences for compression and frequency shape. The SoundBalance adjustments on Tek Connect remote control device further contribute to frequency shape learning. Studies have shown that users are able to increase general satisfaction with their hearing aids after training without compromising speech intelligibility. This paper reviews the theoretic and practical advantages of a trainable hearing aid using SoundLearning. The fitting options for SoundLearning are summarized and general fitting guidelines for this new technology are provided.
Introduction

While advanced signal processing technology is essential, in general, benefit from hearing aids is most directly related to the how the instruments are fitted. While hearing aids today have many special features, and more features are added each year, there are still critical aspects of the hearing aid fitting that are the same today as they have been for decades. That is, gain must be appropriate for a variety of input signals, the frequency response must result in the optimal blend of audibility, intelligibility and listening comfort, and loudness perceptions must be appropriate for different listening situations.

To provide a reasonable starting point for the patient, dispensers typically use some form of prescriptive method to assist them in accomplishing the overall fitting goals. This could be a traditional generic prescriptive procedure such as the NAL-NL1 or DSLv5, or a variation of one of these procedures developed by the hearing aid manufacturer for their specific products, such as the Siemens ConnexxFit. Regardless of the fitting method, the goal is to provide initial hearing aid settings of gain, frequency response and compression based on the patient’s hearing loss. These automatic adjustments are then verified through the simulated gain and/or output displayed in the fitting software, or through probe-microphone measurements.

This time-honored method of establishing the fitting parameters is a good “first step”. Unfortunately, there are several limitations. For instance, all settings are geared toward the “average” patient. We know, however, that individuals with the same apparent hearing loss (based on pure-tone thresholds) may have quite different amplification needs and preferences. For example, Keidser and Dillon (2006) show that only 49% of patients have preferred gain that falls within a 6 dB window (+/-3 dB) surrounding the NAL-NL1 prescriptive targets. Even when the proposed NAL-NL2 targets are applied, 40% of patients still have preferred gain that falls outside of the re-adjusted 6 dB window. Moreover, Bentler and Cooley (2001) have shown that loudness discomfort levels have a range of 40-50 dB for individuals with the same hearing loss, which impacts on their overall loudness growth function and dynamic range, increasing further the difficulty of obtaining appropriate loudness perceptions for all input levels using average data.

Other issues also limit the preciseness of the initial fitting. Quite often the adjustments are made in a relatively “sterile” environment (office or clinic), devoid of the typical reverberation and everyday noises of the real world. Even when sound samples are used during the fitting process, patient’s judgments and ratings often are not the same in the clinic, as when they use the hearing aids in their daily activities. We know that different gain is required for different listening situations (Keidser et al., 2005). What appears to be a reasonable remedy to these problems, therefore, is to use a hearing aid which is trainable. That is, the hearing aid “learns” the patient’s preferences while being used in the real world. Dillon et al. (2006) cite several potential advantages of using trainable hearing aids:

- The parameters of the hearing aids can be customized to the user’s preference in their actual listening environment.
- Fewer post-fitting visits for reprogramming would be needed, especially for problem fittings.
- Patients can easily retrain their hearing aids if their listening needs change over time.
- The parameters that can be trained to preferred values exceed what could be accomplished in a clinical visit.
- Because the patients are directly involved in the final fitting, they will have more “ownership” of the hearing aid fitting.

Research with trainable hearing aids

The principle of trainable hearing aids has now been studied for several years, and research reports on this technology are available. For example, Zakis et al. (2007) using a prototype hearing aid, reported that the majority of hearing aids users preferred the trained hearing aid settings to the untrained parameters that were prescribed and adjusted in the clinic. In a related laboratory study, Dreschler et al. (2008) found that patient-based adjustments of hearing aid gain are a reliable method of fine-tuning hearing aid performance.

The first learning hearing instrument, Centra, was introduced by Siemens in 2006. Centra employs DataLearning, a feature which automatically optimizes gain based on volume control changes made by the user over time. The function, benefit and reliability of this new feature were described by Chalupper and Powers (2007) and Powers et al. (2007). Powers et al. report excellent test-retest results for experienced hearing aid users. They state that although there was a large intrasubject range of learning for both test trials (-6 dB to +8 dB), the test-retest agreement was remarkably strong, with a correlation coefficient of 0.87. For nearly all subjects, the magnitude of learning between trials differed by 3 dB or less. The Centra product was also used in a real-world study of preferred gain by Mueller et al. (2008). In this study, it was again shown that preferred gain can vary significantly from the prescribed NAL-NL1 targets, and that the starting point of the training can influence the final preferred gain setting after training. The authors reported, however, that many participants were able, over time, to make gain adjustments that improved their perception of and satisfaction with aided loudness.
While these early studies using trainable hearing instruments have been encouraging, the training involved only overall gain. Although it is possible to conduct independent training in different programs, which then could be used for different listening situations, the goal of a trainable hearing aid is to achieve optimal settings within a single program. A potential limitation of training only overall gain is that a person may train the hearing aid for more gain when soft sounds are present, which in turn would result in more gain for average-level input signal, although the perceived loudness for average-level sounds may have been “just right.” The logical progression in trainable hearing aids, therefore, is to apply “wide dynamic range compression learning,” in which gain is trained as a function of the level of the input signal.

Wide dynamic range compression training

It would seem that the success obtained with the first generation of trainable products would be enhanced if gain were trained independently as a function of the input signal, which functionally is training the compression parameters. The feasibility and benefit of this type of training recently was studied at the Australian National Acoustic Laboratories by Convery et al (2008). The study included 28 participants with sensorineural hearing loss, who were fit bilaterally to the NAL-NL1, with a -3 dB correction for overall gain. The participants were given a small sound recorder and a diary, and were instructed to record sounds in their daily listening environment. At the same time, they rated the loudness of these different sounds on a five category scale (“much louder than preferred”, “louder than preferred”, “just right”, “softer than preferred,” and “much softer than preferred”). The number of different loudness categories per listening situation is shown in Figure 1. The vertical bars represent the percent of participants who rated a given environmental sound the same. Note that for some listening situations, like listening to TV and radio, the loudness ratings were spread across five different categories among listeners. The authors report that for speech in quiet and quiet situations, the majority rated loudness as “just right.” For other situations, however, the majority preferred something other than the prescribed gain. For example, in noise, 55% rated loudness as “louder than preferred” and only 30% had a rating of “just right.” In general, the results showed that about 70% of the ratings were outside a single category of loudness perception.

As discussed, because more than one loudness perception category is used by most patients, just optimizing overall gain specifically for each listening situation does not completely solve the problem. Further analysis of levels within situations revealed that often less gain for loud inputs and more gain for soft input situations was required. This finding suggests that compression-based learning would be more effective than situation-based learning.
In the second part of their study, using the same participants, Convery et al. (2008) tested the effectiveness of simulations of one conventional and two situation-specific learning algorithms. The two situation specific algorithms included compression learning and classifier-controlled learning. The difference between these two algorithms is with compression learning, preferred gain for different levels is learned; whereas with situation-classifier controlled learning, preferred gain for situations as detected by the hearing aid’s classifier is learned, independent of level. Their initial finding was that the prescriptive fitting (modified NAL-NL1) achieved comfortable loudness for about 50% of the listening situations (see Figure 2). As shown in Figure 2, all training algorithms tested have the potential to improve loudness ratings, however, the most successful was the compression learning. When this algorithm was used, comfortable loudness ratings can be achieved for 82% of the listening conditions. The support for compression learning is even more pronounced when individual data are examined. When compression learning is compared to classifier-controlled learning, there is improved loudness perception for 76% of all subjects, compared to only 12% for classifier learning. The remaining 12% noted no difference between algorithms.

Training the frequency response

Another dimension of the hearing aid fitting where learning can be helpful is frequency response shaping. Even when loudness has been learned for different input levels, it is possible that the balance of gain between low and high frequencies will need adjustment. There are several reasons for this.

First, recall that prescriptive methods (e.g., ConnexxFit, NAL-NL1, DSL v5.0) have been developed to, among other things, provide “comfortable” listening and optimize speech intelligibility for a variety of listening situations. This optimization, however, is based on real ear gain and output. When the hearing aids are programmed, average correction factors are used to estimate what 2-cc coupler gain will deliver the desired real-ear results. We know, however, that there is considerable individual variability in these correction factors. Even if coupler values are known to match the desired target gain (e.g., measured by the dispenser), it is difficult to predict real-ear gain from coupler gain on an individual basis due to the variability in the components of the CORFIL: real-ear unaided gain (REUG) (Valente et al., 1991), real-ear coupler difference (RECD) (Saunders & Morgan, 2003) and microphone location effects (MLE) (Fikret-Pasa & Revit, 1992). In a related study, Aazh and Moore (2007) report that when hearing aids were programmed to meet NAL-NL1 target, when real ear insertion gain (REIG) was conducted, 64% of cases failed to fall within +/-10 dB of the target at one or more of the following frequencies: 0.25, 0.5, 0.75, 1, 1.5, 2, and 4 kHz. If probe-microphone measures were routinely conducted at the time of the fitting, this factor would not be an issue because the hearing aids easily could be adjusted to meet the desired real-ear values. Several surveys have shown, however, that no real ear verification is conducted for the majority of people.
fitted with hearing aids (Mueller, 2005). A learning of frequency response therefore, would allow the patient to correct some of these dispenser fitting errors.

A second advantage of a learning frequency response is that even when prescriptive targets are met, they may not be appropriate for a given individual. The shape of the prescriptive frequency response is based on average data. A hearing aid user may have different frequency resolution than average, or a different loudness growth function than predicted for a specific frequency region. Also, cochlear dead regions may be a factor. It is frequently true that while the audiogram might indicate the need for a substantial amount of gain in the higher frequencies, if cochlear dead regions are present, this increased audibility might not equate to increased intelligibility. In some cases, amplification in cochlear dead regions actually reduces intelligibility. A trainable frequency response allows the user to modify gain in these high frequency regions so that intelligibility is optimized.

A final advantage relates to the fact that many individuals prefer a different frequency response for different listening situations. That is, the response preferred for listening in quiet in low reverberation might be quite different than the response preferred for listening in noise in a reverberant setting. In a recent study, Keidser et al. (2005) used an adaptive procedure to have their subjects select their preferred frequency response slope for twenty different listening conditions. They report that the preferred response slope mostly depended on the difference in signal-to-noise ratio (SNR) between frequency bands. Subjects preferred less gain in frequency bands where noise was more intrusive; and they preferred less gain to optimize listening comfort rather than for speech understanding. They further reported that the preferred response slope also depended on the slope of the audiogram. Assuming that multiple memory hearing aids are used, and that different memories are used for different listening conditions, a trainable frequency response can optimize frequency-specific gain for each of these situations.

In order to enable patients to teach preferred frequency response, a respective control must be available. Whereas volume controls have been used by hearing instrument wearers for decades, there has been no research with treble controls so far. Thus, Latzel & Stephan investigated the patient benefit of learning gain and learning frequency response (2008). Their study shows that by using a treble control, patients were able to increase their general satisfaction with their hearing aids and reduce listening effort (Figure 3).

Figure 3: Mean ratings of satisfaction and listening effort in real life when using VC only, or gain combined with treble training. Left: Satisfaction rating from "very dissatisfied" to "very satisfied". Right: Listening effort rating from "no effort at all" to "very often strenuous".
New solution: SoundLearning

As discussed, there are many factors which must be considered when determining the most appropriate gain, output and frequency response for a hearing aid user. The more this process can be individualized, the greater the possibility of a successful result. Improving upon the DataLearning technology, Siemens has introduced a new generation of trainable hearing aids with a feature called SoundLearning. This new learning algorithm is designed to optimize gain, compression and frequency shape to better meet patients’ needs regarding preferred sound loudness and tone.

How SoundLearning works

SoundLearning and DataLearning share some basic principles:

• Learning is accomplished by averaging the user actions of the past week(s). For DataLearning about one week is sufficient for reliable learning. For SoundLearning, however, at least two weeks are necessary for optimal results. The time constant for SoundLearning is doubled, as more data is required to reliably determine preferred gain at different levels.
• For telephone programs, learning is completed already after 4 hours.
• The preferred settings are learned independently in each program.
• Learning occurs continuously in the background and the optimized setting is applied at the next power on.
• The audiologist can compare initial and learned settings, and restore initial settings as necessary.

In addition to learning overall volume like in Data Learning, SoundLearning is able to learn compression as well as frequency-shaping.

Learning compression

In hearing aid fittings, some patients find the gain and compression settings prescribed by a fitting formula appropriate for all input levels. For those patients who need the same amount of gain adjustment made to all input levels, learning overall gain (as in DataLearning) is sufficient. If the required gain adjustment varies with input level (e.g. less gain preferred at high levels, more for soft levels) which is often the case, then compression parameters must be modified.

In SoundLearning, wearers do not have to directly adjust the compression ratio. Instead, they teach the hearing aid their preferred gain at different input levels by simply adjusting the volume control (Figure 4). Based on this adjustment, the hearing aid calculates the best matching gain and compression setting.
Learning frequency shape

SoundLearning optimizes level-dependent gain in four learning bands independently. For 16-channel devices, each learning band comprises four compression channels. Because compression learning occurs independently in multiple bands, it is also able to learn level-specific frequency shapes. There are two ways to teach frequency shape:

(1) direct learning via SoundBalance, and
(2) indirect learning due to situation-dependent spectral intensity distribution.

Wearers can directly “teach” their preferred frequency response using SoundBalance. This is the treble control on the Tek Connect remote control that allows the users to adjust high frequency gain. SoundBalance adjustments are made in addition to VC adjustments so that gain adjustments as sampled by SoundLearning are a summation of VC and SoundBalance input. This way, SoundLearning simultaneously optimizes loudness and frequency shape.

Frequency shape learning may also take place in SoundLearning with a standard VC without SoundBalance. Levels are measured separately in four different frequency bands when volume adjustments are made. Therefore, for all incoming signals, different input levels in different frequency regions can result in different learned preferences for each of the four bands. An example of this is illustrated in Figure 6 with a long-term averaged speech signal. If the volume for loud speech is decreased by the hearing aid wearer, SoundLearning will decrease gain for high levels in Band 1 only, whereas in Band 3 and 4 gain for soft sounds will be reduced. Therefore, frequency shape may change simply with VC adjustments.

Figure 6: The levels of all incoming signals are measured in four independent frequency bands.

Behavior of VC

Unlike DataLearning, which adjusts the power-on position of the VC, SoundLearning adjusts the complete VC range. Therefore, as SoundLearning shifts the VC range by the amount of learned gain, over time, a higher gain and output level is possible. To avoid the increased risk of feedback, the actual maximum gain for the VC is limited by the critical gain margin. If no individually measured critical gain curve is available, average values will be used based on the selected acoustical parameters (vent size, ear hook). In addition, multichannel output compression protects against loudness discomfort.

Figure 7: Example showing how SoundLearning shifts VC range by the amount of learned gain. The left panel shows VC range in the four learning bands before learning. After learning, as illustrated in the right panel, the complete VC range is shifted by the amount of learned gain.
Evaluation

A study with experienced hearing aid users with mild-to-moderate hearing loss examined the patient benefit from SoundLearning. In Session #1, hearing instruments (Siemens Pure 700) capable of SoundLearning were programmed bilaterally, using probe-microphone verification, with gain and output targets that were on average 3 dB less than the NAL-NL1 prescribed targets (i.e., similar to proposed NAL-NL2). Speech intelligibility testing in quiet (Freiburger Einsilber; presentation levels of 50 dB SPL and 65 dB SPL) also was conducted. SoundLearning and binaural synchronization using e2e wireless were activated, as well as features such as automatic directional technology and digital noise reduction, and subjects were instructed to adjust gain and treble according to their preferences as they go about their daily life.

After one week, in Session #2, the hearing instruments were read out and real ear gain was measured. Speech intelligibility was also assessed for the participants using the learned setting. After an additional week of learning, the same measurements were repeated in Session #3. Thereafter, volume and treble control were deactivated and SoundLearning was switched off. For the final home trial, one memory was programmed with the initial setting and another with the learned setting. Participants were instructed to fill out a questionnaire comparing the two programs and choose their preferred program.

In agreement with previous studies (Chalupper & Krämer 2007), large individual differences were observed in this study. Results showed that averaged across patients, there was no difference between the initial and the learned setting for frequencies below 1000 Hz. For high frequencies, SoundLearning resulted in a reduction of gain for soft input levels (Figure 8). There are small differences between the learned gain after week 1 and week 2, indicating that learning is mostly, but not completely finished after one week.

Despite the reduction in the higher frequencies for soft inputs, learning did not have a significant effect on speech intelligibility for either the 50 dB SPL or 65 dB SPL presentation levels (Figures 9 & 10). There was also no significant group effect for soft speech. While some patients were able to improve speech understanding with SoundLearning, there was one subject (SR) who reduced the high frequency gain of his hearing aids substantially, and as a result, there was a significant 20% reduction in speech understanding. Most subjects, however, were able to teach gain and treble without degrading speech intelligibility.
The results of the questionnaires from the final field study revealed that all subjects except SR preferred the learned setting for both sound quality and overall impression (Figure 11). Subject SR rated sound quality for both settings equally, but strongly preferred the initial setting with regard to overall impression because subjective speech understanding was much better.

The results of this research have three main implications for clinical practice:

- With SoundLearning, the majority of patients are able to optimize the setting of their hearing aids in everyday life without degrading speech intelligibility.
- To ensure that as many patients as possible receive the maximum benefit from learning hearing instruments, audiologists must counsel patients on the consequences of volume and treble changes. Additionally, audiologists should review the learned settings after one to two weeks and if necessary, reset the learned values.
- The use of acoustic information such as input level and spectrum to learn compression ratio and frequency shape can increase patient benefit from their hearing aids in every day life.

**Fitting guidelines**

As has been discussed, SoundLearning is the next generation of learning features in hearing instruments that will help both patients and clinicians in selecting the optimal gain, compression, and frequency response. Some general guidelines regarding the fitting of this algorithm, and patient counseling related to its functionalities are as follows.

- While there is no specific audiometric profile for SoundLearning, patients with narrow residual dynamic range may find it especially beneficial.
- Research has shown that in particular, experienced hearing instrument users will benefit from SoundLearning. When used with first time users, counseling on the effects of SoundBalance and the volume control on speech intelligibility is important.
- Since there is no drawback to using SoundLearning, it is recommended to use this feature regularly, especially the first weeks after First Fit.
- For bilateral fittings, coupling of programs and VC should be activated. The recommended starting VC ranges for learning are 16 (+/-8) dB and 24 (+/-12) dB.
- The clinician can set up two identical programs: one with SoundLearning enabled and one without. This way, the patient can always return to the initial setting and decide if the new SoundLearning settings are preferable.
- Even with SoundLearning, accurate audiometric data are required to have a good starting point for the learning period.
- The recommended learning period for achieving reliable results is two weeks.
- Patients who do not want to have hearing instruments with controls or find volume adjustments cumbersome should be encouraged to teach their new hearing instruments with a remote control (such as TEK Connect) for two weeks or more until preferred settings are reached.

![Figure 11: Preference ratings for initial programmed fitting versus the learned setting during the real-world field trial. Results displayed are medians and interquartile ranges.](image)
Software fitting options

SoundLearning, along with DataLearning, can be accessed in Connexx by selecting the “Learning” button. All learning information is displayed so that the clinician can review the learned preferences of the wearer.

The SoundLearning screen displays the following information (Figure 12).

- General: start and read out of the logging period.
- Usage analysis: program usage, analysis of the acoustic environment that the hearing aid was in, number of VC changes.
- Learned preferences: selection of programs for automatic application of SoundLearning, learned settings, option to apply or reset learned settings.

Since SoundLearning makes sense only as long as the hearing instrument’s settings remain constant during the period of logging, a reset of SoundLearning is strongly advised after any change of the hearing instrument’s fitting curves. Similarly, SoundLearning is reset automatically if First Fit is run. In addition, if e2e wireless coupling is activated later in the fitting process, a reset of SoundLearning is necessary. The range within which SoundLearning can change gain below the compression kneepoint is restricted to +/-8 dB to ensure the audibility of soft sounds. Above the compression kneepoint, the combined effects of gain and compression ratio learning can amount to +/-16 dB.

All logged information is stored automatically each time a Connexx session is saved. Learned values can be displayed as gain curves or channel gain. The clinician has the flexibility to enable SoundLearning in one or more programs. The clinician can also decide whether or not the instrument should automatically apply the learned values at each power-on. If not, the clinician has the opportunity to apply or reject the learned values at the next fitting. By selecting the “Reset” button, all learned preferences are discarded and learning begins again from the settings most recently used as a starting setting. By selecting the “Confirm” button, learned preferences can be programmed to the hearing instrument and further learning can continue from these settings (Figure 13).

Figure 12: An example of usage analysis as displayed in the SoundLearning screen in Connexx.
Summary

To compensate for the inadequacies of prescriptive formulas in customizing hearing instrument fittings to individual sound comfort and loudness preferences, learning hearing aids are a means of allowing users to adjust their hearing instruments to the ideal settings. SoundLearning, Siemens’ second generation learning algorithm, allows users to train their hearing aids to achieve not only preferred overall gain, but also gain for different input levels (through compression learning). Additionally, frequency shape, especially for the higher frequencies, can also be trained. The learning occurs completely in the background; and operates simply based on the user’s volume and treble control adjustments. SoundLearning accomplishes these by constantly logging the spectral content of input signals and corresponding VC levels. Based on these data, the hearing aid recalculates gain and compression settings to approximate user preferences in four different frequency regions. The SoundBalance feature on Tek allows users to adjust high-frequency gain in addition to VC changes, allowing users to teach their preferred frequency shape.

Studies have shown that patients are able to efficiently use SoundLearning and train their hearing aids to improve their general satisfaction without sacrificing speech intelligibility. While SoundLearning is suitable for all adult users regardless of hearing aid experience or audiological profile, it is especially beneficial for experienced users who have a limited dynamic range. Reliably learned settings can be obtained after about two weeks of learning. Through Connexx, the clinician has a full range of fitting flexibility with SoundLearning, such as enabling it in one/more programs and applying/discard learned settings.

In conclusion, SoundLearning, the new learning algorithm from Siemens, further increases satisfaction for the hearing aid user and streamlines the fitting process for the clinician.
References


