SoundSmoothing:

A New Algorithm to Reduce the Annoyance of Noise

SIEMENS

Abstract

SoundSmoothing™ is a new component of the Siemens "Speech and noise management system." It is the first algorithm to be able to reduce the annoyance of transient noises. The necessity for such a new technique is shown and its technical functionality is explained in detail. SoundSmoothing was evaluated in three independent studies – both in laboratory conditions and in everyday life. The results of these studies clearly prove the benefit of SoundSmoothing for hearing-impaired listeners. SoundSmoothing greatly minimizes the annoyance of transient noises for hearing instrument wearers. Moreover, fitting guidelines for this new technology are given and the use of the options as offered by the fitting software for fine tuning is explained. The new CENTRA products are the first hearing instruments to be equipped with SoundSmoothing.

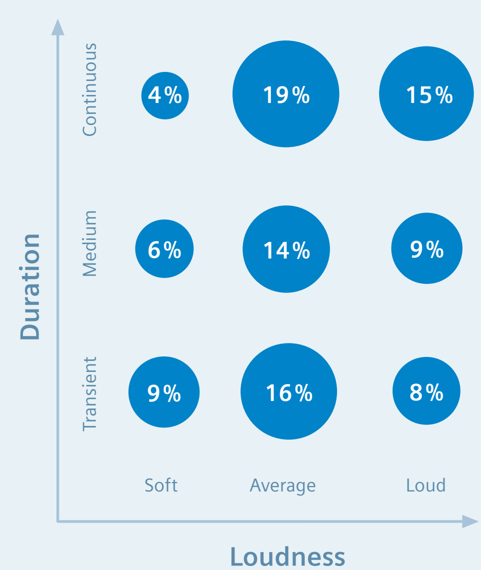
Introduction

Background noise has long been a major issue for hearing instrument wearers. Not only does this noise often reduce speech understanding, but in many cases it creates annoyance, making hearing instrument use an overall unpleasant experience. Research has shown that new wearers of hearing instruments report background noise to become significantly more annoying after being fit with hearing instruments (e.g., Boymans and Dreschler 2000, Surr et al. 2002, Ricketts et al. 2003). In fact, overall, they rate background noise more annoying than the same noise is rated by individuals with normal hearing. This occurs even when the output of the hearing instrument is carefully adjusted to fall below the patient's loudness discomfort level (LDL), suggesting that not uncomfortably loud noise is the problem, but simply noise in general (Palmer et al. 2006). To some extent, this simply is due to the patient's previous reduced loudness perception of these noises. While it is possible that long-term auditory acclimatization may assist the hearing instrument wearer in adapting to these noises (Mueller and Powers 2001), it is also possible that the annoyance may prompt the wearer to stop using the hearing instruments (Kochkin 2005). That is, the annoyance level may prevent them from using the hearing instrument long enough to allow acclimatization to occur. In general, therefore, one goal of the hearing instrument fitting is to minimize the annoyance level for background noise.

In determining how best to reduce annoyance from noise, it is first important to consider the range of noises which the hearing instrument wearers experience in their everyday life. For example, how do these noises vary in intensity and in duration? Some hearing instrument wearers report significant annoyance from loud continuous noises such as that of a motorcycle, while others report annoyance from transient duration soft sounds such as computer key strokes.

To determine the extent of annoyance from different types of noises, and to assess the types of noises commonly encountered, Hernandez et al. (2006) recently completed a study of over 30 new hearing instrument wearers. Using a daily diary, the new hearing instrument wearers compiled a list of what noises they experienced during the first week of hearing instrument use, and also rated their annoyance level for these noises. Annoyance was rated on a 0-10 11-point scale (0 = not annoying at all; 10 = very annoying). The task was not to specifically identify annoying noise, but simply to report all different noises experienced, even the ones that were not annoying. As expected, several wearers reported similar noises; however, even after merging the data, over 100 different environmental sounds were identified.

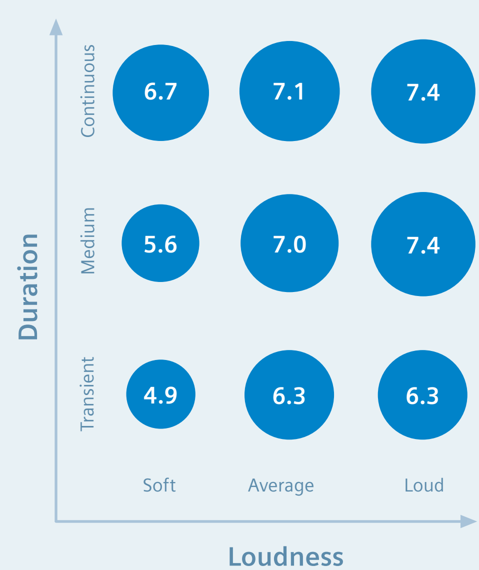
Fig. 1 Occurrence of everyday noise



Distribution of occurrence of everyday noises reported by new hearing instrument wearers categorized according to loudness level and duration.

A panel of five audiology judges, all experienced with real-world noise measurements rated the different noises. Each noise was rated based on what the judges believed would be the most common intensity (soft, average or loud) and the typical duration of the noise (transient, medium or continuous). The distribution of the ratings for the different environmental noises is shown in Figure 1. Observe that the type of noises experienced were distributed relatively equally throughout the different categories, with very similar distribution for the three duration times summed across loudness levels. While it often is long duration (continuous) sounds which are thought of as annoying, note that these findings show that 33% of the environmental sounds reported were of a transient duration – a point we will return to shortly.

Fig. 2 Annoyance of everyday noises



Mean annoyance rating of everyday noises reported by new hearing instrument wearers categorized according to loudness and duration.

Ratings based on 11-point scale:
0 = not annoying at all,
10 = very annoying

The participants in this research rated the annoyance level of the different sounds. This of course is an important distinction, as, if a given environmental sound is not annoying (e.g., birds singing), then this sound is of less concern and it is therefore unlikely, that it would discourage hearing instrument use. As shown in Figure 2, there is not a large difference among the different annoyance ratings given for the environmental sounds. As might be expected, the greatest annoyance was for loud continuous sounds. Observe, however, that even the transient noises were rated as quite bothersome (5.8 averaged across loudness levels), and loud transient sounds were not significantly less annoying than those of medium or long duration.

Solving the Annoyance Problem

A potential solution to the noise annoyance problem is the implementation of digital noise reduction (DNR). DNR was introduced in wearable digital hearing instruments nearly ten years ago. Research has shown that when implemented, digital noise reduction does produce a more pleasant listening experience. That is, when listening to speech in background noise, and DNR "On" is compared directly to DNR "Off," the majority of listeners will prefer DNR "On" (Ricketts and Hornsby 2005). It has been reported that when acceptable noise levels are measured, DNR allows the listener to accept higher levels of background noise (Mueller et al. 2006). Finally, it also has been shown that in real-world everyday listening situations hearing instrument wearers prefer DNR "On" (Powers et al. 2006). For the most part, however, all of this research was related to continuous noises of long duration.

Historically, DNR algorithms have been modulation-based. These systems are most effective in differentiating speech from broadband stationary noise, and when noise is detected as a primary signal, channel specific gain reduction occurs (Mueller and Ricketts, 2005). This method is very successful for reducing the annoyance of any type of continuous noise. For the past several years, Siemens has implemented a second DNR algorithm, which is based on the Wiener Filter – sometimes also referred to as "Spectral Subtraction" (Wiener 1946, Hamacher et al., 2005). This fast-acting noise reduction filter complements the modulation-based algorithm and provides further reduction of stationary broad-band noise. As it is fast-acting, it is effective in reducing unwanted noise during gaps in speech.

If we refer back to Figure 1, observe that 33% of background noise is transient in duration, and that this type of noise is rated nearly as annoying as longer duration signals. What is the best way to address annoyance from these signals? Consider that transient duration signals will not be classified as noise by traditional noise reduction systems. While on the surface, it might appear that fast acting AGCi would be a potential solution, but this approach would also reduce the modulations of speech. Moreover, it is recognized that longer compression time constants are needed to maximize sound quality. What is needed, therefore, is a new type of noise reduction system that is specifically designed to handle annoying transient noise signals.

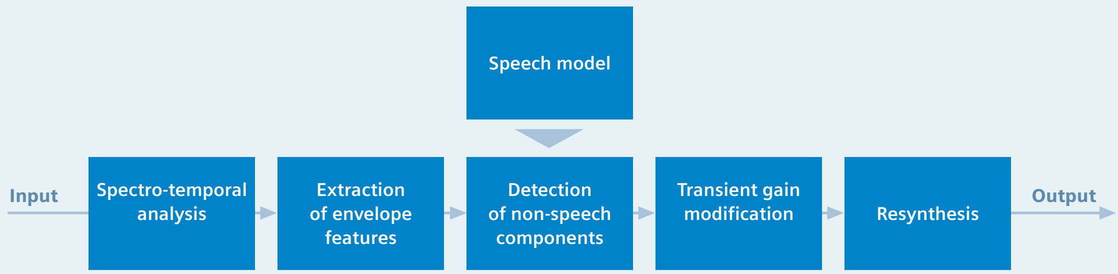
A New Solution: SoundSmoothing

A block diagram of the new SoundSmoothing algorithm is shown in Figure 3. First, spectral and temporal properties of the input signal are determined by a spectro-temporal analysis. The spectral information allows SoundSmoothing to attenuate transient high-frequency or low-frequency sounds without affecting frequency areas not containing transient sounds. The temporal properties are calculated with a very high resolution and an exceptionally low processing delay (< 1ms) in order to shorten SoundSmoothing's reaction time on transient sounds to a minimum.

In the next stage, envelope features are extracted. These then are used to decide whether speech or non-speech sounds are present. For this purpose, the envelope features are analyzed using a speech model. Only for non-speech sounds an attenuation factor is calculated. The amount of transient gain modification is determined by the ratio of peak level to longterm overall RMS level (i.e. the more transient, the more gain reduction).

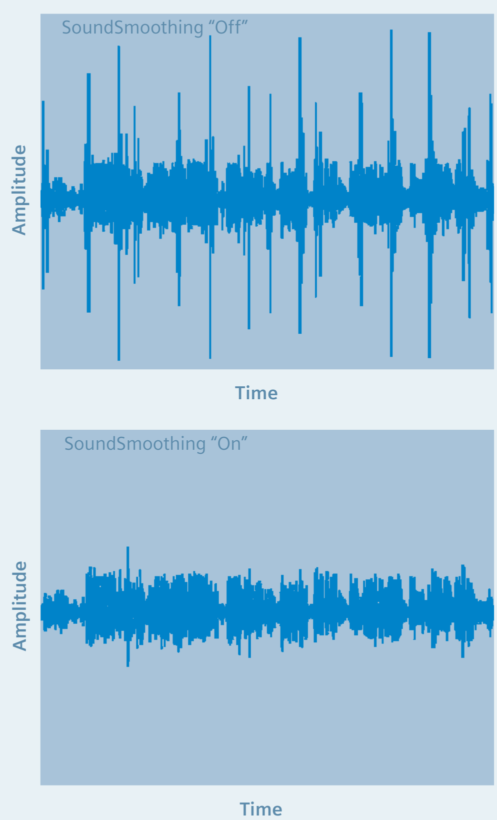
The maximum amount of gain reduction for transients is adjustable as well as the detection threshold. Transient sounds with levels below detection threshold are not attenuated by SoundSmoothing. How these parameters can be set via the fitting software is explained in the section "Software Fitting Options." Finally, the output signal is reconstructed in the "Resynthesis" stage.

Fig. 3 SoundSmoothing: How it works



Algorithmic implementation of SoundSmoothing

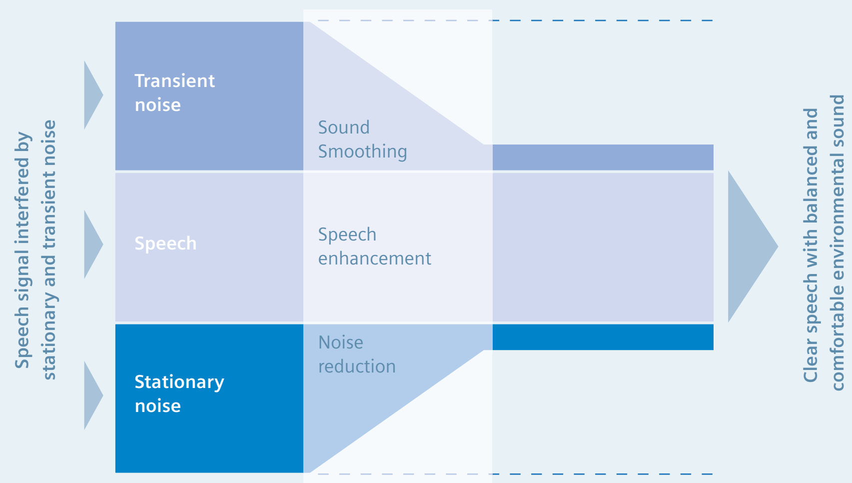
Fig. 4 Effect of SoundSmoothing



Effect of SoundSmoothing on transient peaks of rattling dishes. Top: SoundSmoothing "Off." Bottom: SoundSmoothing "On."

Figure 4 shows the effect of SoundSmoothing on the rattling of dishes. This sound contains many transients and was rated as being one of the most annoying sounds in the earlier mentioned study about annoyance of real world noises. If SoundSmoothing is activated, these peaks are attenuated by up to 40 dB and the resulting sound (Figure 4 bottom) is much less annoying (see also section "Behavioral Studies Using the New Algorithm"). Both conventional noise reduction systems (modulation based DNR as well as Wiener filters) and slow-acting AGC do not have any impact on this type of signal!

Fig. 5 Speech and noise management

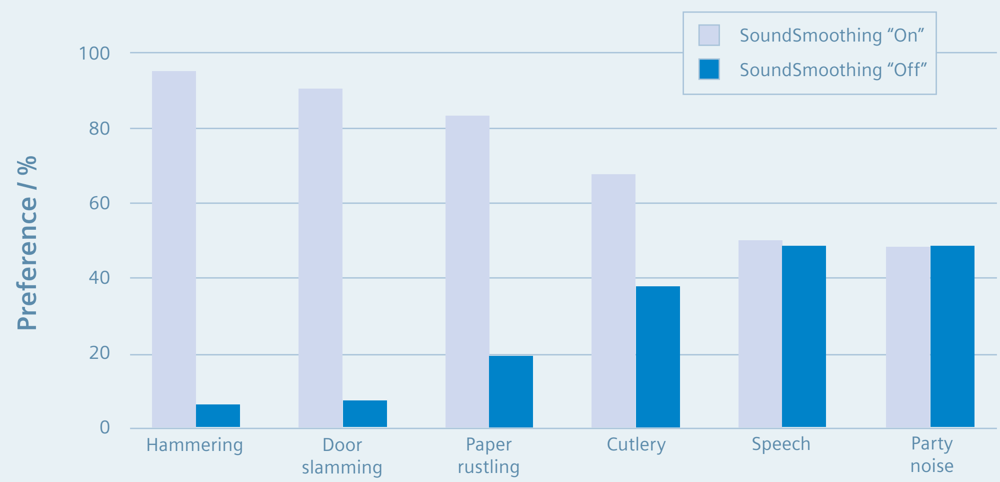


Ideal noise management system combining various types of noise reduction techniques

Combining Different Noise Reduction Techniques

Of course, continuous sounds also can be annoying or may cause increased listening effort when simultaneously present with speech. Therefore, an ideal noise management system combines various DNR algorithms: modulation based noise reduction, Wiener filter and SoundSmoothing. This is illustrated in Figure 5. Whereas modulation based DNR (CENTRA: "Noise reduction") is very efficient when only stationary noise is present, the Wiener Filter (CENTRA: "Speech enhancement") takes over as soon as speech and noise are simultaneously present. Finally, SoundSmoothing reduces non-stationary, transient noises, whether or not speech is present. Note: All these noise reduction techniques efficiently reduce the amount of noise, but do not degrade the sound quality of speech.

Fig. 6 Preference for SoundSmoothing



Percent of participants preferring SoundSmoothing "On" versus SoundSmoothing "Off" for different sound samples using a paired-comparison procedure. Research conducted at the National Acoustic Laboratories, Australia.

As discussed in the preceeding section, the new SoundSmoothing algorithm introduced by Siemens in CENTRA has the potential to reduce the impact of transient environmental signals, and thereby provides a more pleasant listening experience. It was important, therefore, to conduct behavioral research with SoundSmoothing to determine, if the proven laboratory advantages also were considered a significant improvement by actual hearing instrument wearers.

SoundSmoothing for Different Environmental Sounds

A research project with the new SoundSmoothing algorithm related to annoyance from noise was conducted at the National Acoustic Laboratories in Australia. In this research, a group of 21 hearing-impaired individuals participated in a paired-comparison task, listening to six different noise or speech signals. The participants listened to the given experimental signal processed with SoundSmoothing "On" versus SoundSmoothing "Off." It was a forced-choice paradigm; therefore, the listener had to select one of the two settings as "the winner." The percentage of subjects preferring one condition more often than the other for the six different signals is shown in Figure 6.

In viewing Figure 6, it may be first relevant to focus on the findings for the "party noise" and speech signals. For these two inputs, the participants favored the two different settings equally, probably because they did not hear any difference, but yet were forced to choose one or the other. This was the expected finding, as these are not signals targeted nor affected by the SoundSmoothing algorithm (i.e. they are not transient noises).
In fact, indirectly, this is a positive finding regarding SoundSmoothing, as it confirms that there are no artifacts or interferences that would reduce speech quality.

The most dramatic finding of this research is the strong preference for SoundSmoothing for transient signals. For all noises with a relatively short duration, SoundSmoothing "On" was preferred by the majority of listeners, in most cases by a very large margin.

No Adverse Effects of SoundSmoothing

As has been shown, initial research with SoundSmoothing is very positive. Whenever new signal processing is introduced, however, it is critical to question, if there are any possible negative effects for the wearer when the processing is implemented. With the SoundSmoothing algorithm, it was necessary to confirm laboratory data with regards to two important listening conditions: SoundSmoothing does not affect speech understanding and auditory localization.

To examine the effects of SoundSmoothing on speech understanding, research at the National Acoustic Laboratories conducted aided speech intelligibility testing using the BKB sentences in background noise (paper rustling and cutlery). Testing was conducted for SoundSmoothing "On" versus SoundSmoothing "Off." The results showed no significant effect of SoundSmoothing ($p = 0.85$). That is, as expected, there was no negative effect for speech understanding when the SoundSmoothing algorithm was used.

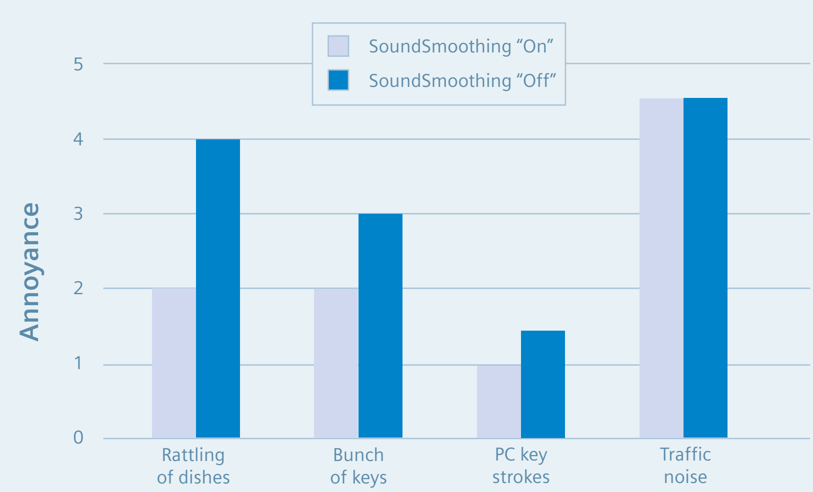
Auditory localization testing also was conducted at the National Acoustic Laboratories. Since SoundSmoothing reduces the slope of the acoustic envelope (to effectively reduce annoyance of transient noise) this research was conducted to investigate whether this signal alteration distorted the spatial location of the signal for the hearing instrument wearer. Localization performance was assessed with SoundSmoothing "On" versus SoundSmoothing "Off" using hammering as stimulus. The localization RMS errors revealed that as a group, there was no significant difference in localization ability as a function of the algorithm turned "On" or "Off" ($p > 0.33$).

In addition to the laboratory findings at NAL, subjects from another study conducted at Giessen (see next section) rated localization of signals in everyday life the same for SoundSmoothing "On" versus "Off," indicating that SoundSmoothing has no adverse effect on localization.

Real-World Benefit of SoundSmoothing

A second study recently conducted with CENTRA hearing instruments examined, if the patient benefit of SoundSmoothing measured in controlled experiments also would be observed during real world use. In this study, conducted at the University Hospital of Giessen, Germany, eleven subjects used the hearing instruments in their daily life. Through the use of a daily diary, they were asked to record their annoyance level for several

Fig. 7 Real world annoyance for SoundSmoothing "On " vs. "Off"



Real-world annoyance ratings for SoundSmoothing "On" versus SoundSmoothing "Off." Research conducted at the University Hospital of Giessen, Germany.

typical noises. The degree of annoyance was rated on a 0-10 11-point scale (10 = Very annoying, 0 = Not annoying at all). The hearing instruments were programmed with SoundSmoothing "On" in one program, and SoundSmoothing "Off" in a second program. All other hearing instrument settings were identical for the two programs. The participants were not informed about the difference between programs and were asked to switch between programs whenever they heard any of the selected environmental sounds, and to then record an annoyance rating for each program.

Shown in Figure 7 are the average annoyance ratings for four of the sounds identified in the study. Overall, these subjects had annoyance ratings somewhat lower than observed in other studies. Nevertheless, the same preference pattern was observed. That is, when transient sounds were present, the SoundSmoothing algorithm reduced the annoyance level. Observe that for "traffic noise" no preference was present, an expected finding, as this is not transient noise. These findings are in close agreement with the results reported earlier from the National Acoustic Laboratories, and add further real-world support to the efficacy of the SoundSmoothing algorithm.

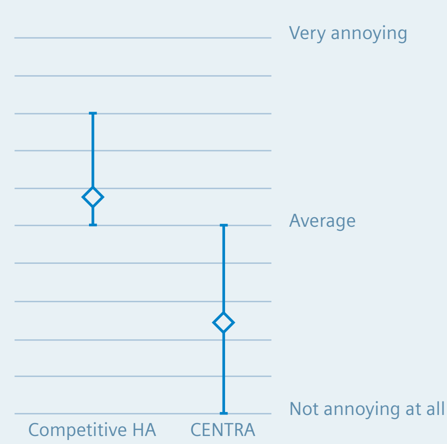
Comparison to Competitive Product

In this final research project, conducted at the Hörzentrum Oldenburg, Germany, Siemens CENTRA hearing instruments equipped with the SoundSmoothing algorithm were compared to another major manufacturer's high-end product. Both products were fitted according to the respective manufacturer's first-fit protocol. This resulted in the activation of noise reduction for both products. The competitive products used the traditional modulation-based noise reduction. The Siemens CENTRA also had modulation-based noise reduction, but in addition had the fast-acting DNR filter ("Speech enhancement") and the new SoundSmoothing algorithm.

Twenty subjects with hearing impairment were fitted with the two different model hearing instruments. They listened to different environmental sounds, and made judgments of annoyance level on a 0-10 11-point scale (0 = not annoying at all; 10 = very annoying). For continuous signals, there was little difference between the two hearing instruments. However, because of the SoundSmoothing feature, there was a significant reduction in annoyance using the Siemens instrument when transient noises were introduced. For example, Figure 8 shows the ratings for the participants for listening to "rustling paper," a background noise that historically has been reported as "annoying" for nearly all hearing instrument wearers. Note the much lower annoyance rating for CENTRA when compared to the competitive instrument. In fact, as shown in Figure 8, there is little overlap between the two instruments, as the 25th percentile of CENTRA is equal to the 75th percentile of the competitive product, and most significantly, the 75th percentile of CENTRA includes the optimum "10" rating of "not annoying at all."

These findings from the Hörzentrum Oldenburg certainly suggest that the SoundSmoothing algorithm provides the desired wearer benefit.

Fig. 8 Annoyance of rustling paper



Annoyance ratings for the Siemens CENTRA compared to a competitive instrument. Results displayed show median ratings, as well as the 25th and 75th quartiles. Research conducted at the Hörzentrum Oldenburg, Germany.

Fitting Guidelines

As has been discussed, SoundSmoothing is an efficient new DNR algorithm that addresses an important concern of the hearing instrument wearer. Some general guidelines regarding the fitting of this algorithm, and patient counseling related to its processing are as follows:

1. SoundSmoothing can be used in conjunction with other DNR processing, or it can be used independently. It is an enhancement, not a replacement for the more traditional DNR techniques that also have proven patient beneficial.
2. There is no specific audiometric profile for the SoundSmoothing algorithm. If transient environmental noise is audible, as it is for nearly all hearing instrument wearers, then it would be expected that SoundSmoothing would reduce the annoyance of these signals.
3. Research has shown that in general both new hearing instrument wearers and experienced wearers will obtain listening benefit from the SoundSmoothing processing. More specifically, results from clinical studies suggest that first time wearers may benefit even more than experienced wearers.
4. There is no negative impact of the SoundSmoothing algorithm, hence, it should be considered routinely for all hearing instrument wearers.
5. Because SoundSmoothing is designed to be sensitive to abrupt signals, the hearing instrument wearer will only notice the benefit of SoundSmoothing when such signals are present. To demonstrate the advantages of SoundSmoothing, therefore, it is recommended that the dispenser presents annoying abrupt sound samples (e.g. hand clapping) to the prospective hearing instrument wearer. Paired comparisons using SoundSmoothing "On" versus SoundSmoothing "Off" in two programs as were used in the research findings previously described may be one such technique for demonstration.

Software Fitting Options

With CENTRA, there are three different SoundSmoothing settings available in each listening program. Essentially, they differ in respect to the maximum gain reduction and detection threshold.

The maximum gain reduction indicates how much attenuation is possible in best case, while the actual gain reduction depends on the slope and the peak level of the transient signal.

Sounds below the detection threshold are not affected by SoundSmoothing. This is employed to ensure that very soft transient signals – which typically are not very annoying and often carry important information – are audible (e.g. the ticking of the clock will not activate SoundSmoothing).

Tab. 1

	Min	Med	Max
Maximal gain reduction [dB]	20	30	40
Detection threshold [dB]	60	50	40

Fitting options of SoundSmoothing

Table 1 shows that maximum gain reduction and attenuation of first wavefront increase from min to max, whereas threshold slightly decreases in general.

When the "Min" setting is selected, SoundSmoothing is optimized for audibility of soft transient sounds. The "Max" setting optimally reduces the annoyance of transient noises. "Med" is the default setting and has been shown in listening tests to be the optimum setting for most typical listening environments.

Fine Tuning

For patients who desire less reduction / more audibility of very soft transient sounds (i.e. clock ticking), reduce the setting. For patients who are highly bothered by transient sounds (e.g. door slamming, cutlery) increase the setting (e.g. max).

Summary

- Background noise in general is especially annoying to hearing instrument wearers and is a leading reason why people do not use their hearing instruments.
- Patient surveys show that annoying environmental noise can be soft or loud, and can have a duration that is short, medium or continuous. Importantly, one third of environmental noises experienced by hearing instrument wearers have a transient duration and these sounds are rated essentially as annoying as noises of a medium or continuous duration.
- Traditional noise reduction algorithms cannot provide the patient relief from transient duration noise, as these sounds are not recognized as noise by the digital classification system.
- A new DNR algorithm introduced in Siemens CENTRA, SoundSmoothing, uses envelope slope adjustment to specifically address the problem of abrupt annoying environmental noises.
- Independent behavioral research has shown that this algorithm is effective in reducing the annoyance of noise. Participants in these studies favored SoundSmoothing for a variety of noise signals and listening tasks both in laboratory and real-world conditions. Moreover, research to date also indicates that SoundSmoothing has no negative effects on speech understanding or localization.
- Since research indicates that SoundSmoothing provides definite patient benefit in real world conditions for noises that are typically encountered by all hearing instrument wearers, it should be routinely considered for all patient fittings.

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The required features should therefore be specified in each individual case at the time of conclusion of the respective contract.