International Journal of Audiology

ISSN: 1499-2027 (Print) 1708-8186 (Online) Journal homepage: http://www.tandfonline.com/loi/iija20

Effects of a transient noise reduction algorithm on speech intelligibility in noise, noise tolerance and perceived annoyance in cochlear implant users

J. Gertjan Dingemanse, Jantien L. Vroegop & André Goedegebure

To cite this article: J. Gertjan Dingemanse, Jantien L. Vroegop & André Goedegebure (2018): Effects of a transient noise reduction algorithm on speech intelligibility in noise, noise tolerance and perceived annoyance in cochlear implant users, International Journal of Audiology, DOI: 10.1080/14992027.2018.1425004

To link to this article: https://doi.org/10.1080/14992027.2018.1425004

Published online: 15 Jan 2018.

Taylor & Francis
Taylor & Francis Group

International Journal of Audiology 2018; Early Online: 1–10

International Journal of Audiology

Check for updates

Original Article

Effects of a transient noise reduction algorithm on speech intelligibility in noise, noise tolerance and perceived annoyance in cochlear implant users

J. Gertjan Dingemanse, Jantien L. Vroegop, and André Goedegebure

Department of ENT, Erasmus Medical Center, Rotterdam, The Netherlands

Abstract

Objective: To evaluate the validity and efficacy of a transient noise reduction algorithm (TNR) in cochlear implant processing and the interaction of TNR with a continuous noise reduction algorithm (CNR). *Design*: We studied the effects of TNR and CNR on the perception of realistic sound samples with transients, using subjective ratings of annoyance, a speech-in-noise test and a noise tolerance test. *Study sample*: Participants were 16 experienced cochlear implant recipients wearing an Advanced Bionics Naida Q70 processor. *Results*: CI users rated sounds with transients as moderately annoying. Annoyance was slightly, but significantly reduced by TNR. Transients caused a large decrease in speech intelligibility in noise and a moderate decrease in noise tolerance, measured on the Acceptable Noise Level test. The TNR had no significant effect on noise tolerance or on speech intelligibility in noise. The combined application of TNR and CNR did not result in interactions. *Conclusions*: The TNR algorithm was effective in reducing annoyance from transient sounds, but was not able to prevent a decreasing effect of transients on speech understanding in noise and noise tolerance. TNR did not reduce the beneficial effect of CNR on speech intelligibility in noise, but no cumulated improvement was found either.

Key Words: Cochlear implant, maximum comfort level, ClearVoice, SoundRelax, transients, transient noise reduction algorithm, acceptable noise level, speech reception threshold, sound annoyance

Introduction

The focus of a Cochlear Implant (CI) fitting is usually on achieving good speech intelligibility. However, it is also important to consider aspects of listening comfort and sound quality, especially in noisy environments (Mertens et al. 2015). In everyday life, people experience a variety of sounds that differ in their spectro-temporal characteristics, duration or loudness and can be perceived as disturbing, especially when listening to speech. Nowadays, directional microphones and single-microphone noise reduction algorithms are applied in CI processors to reduce the effect of background noises. The single-microphone noise reduction is sometimes named as continuous noise reduction (CNR), because it is mainly effective for noises with a continuous temporal behaviour. Transient sounds, however, will not be affected by CNR.

Transient sounds are characterised by a very fast onset to the peak in sound pressure level (within a few milliseconds), a fast decay and a short duration (from tens of milliseconds up to one second). The peak sound pressure level of the transient is well above the average sound pressure level. Korhonen et al. (2013) reported sound pressure levels and rise times for different recorded transients. The levels varied from 67 dB (A, impulse) for a clicking pen up to 102 dB (A, impulse) for stacking two water glasses. Rise times ranged from less than 1 ms up to 4 ms.

It is well known that hearing-aids users frequently perceive transient sounds as disturbing. Hernandez, Chalupper, and Powers (2006) reported that about one-third of the annoying background noises commonly encountered by new hearing instrument wearers were of a transient type. In that study transients were defined as noises with a duration of <1 s. A fast onset was not required. The perceived annoyance of these transient noises was slightly lower than the annoyance of continuous noises, but still substantial (6.3 on a 0–10 annoyance rating scale). The automatic gain controls (AGC) of hearing aids usually use a fast-acting system to cope with transient sounds, but for transients with a very fast onset the AGC is often too slow. Hence transient noise reduction (TNR) systems have

Correspondence: J. Gertjan Dingemanse, Department of ENT, Erasmus Medical Center, room D126, PObox 2040, Rotterdam, 3000 CA, The Netherlands. E-mail: g.dingemanse@erasmusmc.nl

(Received 13 July 2017; revised 22 December 2017; accepted 2 January 2018)
ISSN 1499-2027 print/ISSN 1708-8186 online
DOI: 10.1080/14992027.2018.1425004

Abbreviations

ANL	acceptable noise level
ANOVA	analysis of variance
BNL	background noise level
CI	Cochlear implant
MCL	most comfortable level
M-level	maximum comfort level or upper stimulation level linked to MCL
CNR	continuous noise reduction
RMS	root mean square
SNR	signal-to-noise ratio or speech-to-noise ratio
SRTn	speech reception threshold in noise at 50% intelligibility
T-level	stimulation level at hearing threshold
TNR	transient noise reduction.

been developed to reduce the disturbing effects of transient sounds in hearing aids. Several studies have evaluated the efficacy of a TNR in hearing aid users with various transient noises and outcome measures, such as subjective ratings or paired comparisons for speech clarity, annoyance, comfort, loudness and speech perception tests (DiGiovanni, Davlin, and Nagaraj 2011; Keidser et al. 2007; Korhonen et al. 2013; Liu et al. 2012). The results of these studies suggest that TNRs are most effective for loud transients and are not detrimental for speech perception.

Compared to hearing aids users, the perceived disturbing effects of transient sounds are not necessarily the same for CI users, due to the different way of sound processing and the use of electric stimulation. However, data on sound annoyance in CI users are scarce and we were only aware of a study of Mauger, Arora, and Dawson (2012). They described noise annoyance ratings of CI recipients for steady-state noise, 4-talker and 20-talker noise presented together with speech at 65 dB(SPL). The steady-state noise condition was rated as highly annoying (75/100 on a numberless scale), but annoyance was substantially reduced by their noise reduction algorithm (19/100). The babble noise conditions were rated as moderately annoying (54/100 for 4-talker noise and 61/100 for 20-talker noise) and the ratings were less influenced by noise reduction (41/100 for 4-talker noise and 30/100 for 20-talker noise).

Similar to hearing aids, cochlear implant processors use an AGC to keep the signal within the electrical dynamic range of the patient and to prevent discomfort due to sudden loud sounds (Vaerenberg et al. 2014). In most CI processors, the AGC is a dual time constant AGC, with both a fast detector and a slow detector (Boyle et al. 2009; Khing, Swanson, and Ambikairajah 2013; Stone et al. 1999; Moore, Glasberg, and Stone 1991). Stobich, Zierhofer, and Hochmair (1999) investigated the effect of an intense transient (a ‘‘chink’’ with peak sound pressure level of 100 dB) in CI users that used a CI processor with a dual time constant AGC. The transient was spliced onto the beginning of a sentence presented at 85 dB SPL. They found that the dual time constant compression system handled the transient within the speech effectively, making the transients less detrimental for speech perception. However, there is room for improvement, as the attack time of most fast-acting AGCs is 3–5 ms. This is still too slow to catch the onset of many transients and the amount of reduction is unlikely to be sufficient to prevent discomfort. Therefore a TNR have recently been introduced in cochlear implant systems that is capable to reduce transients with onset-to-peak levels within 1 ms. Dyballa et al. (2015) investigated the effect of a TNR in CI users on speech intelligibility in quiet and in two types of transient noise: repetitive hammer blows and dishes (clinking cups and spoons). The noises had a peak level of 90 dB (SPL) and a RMS level of approximately 70 dB (SPL). Speech perception in quiet was not affected by the algorithm. The speech reception threshold in noise was significantly improved by 0.4 dB for the dishes noise and 1.7 dB for the hammering noise.

In everyday situations, transients may be mixed with continuous background noises, for example in a kitchen where transients from clinking bowls or plates are concurrent with continuous noise from an exhaust hood. In such situations, TNR and CNR may be activated simultaneously in a CI processor or hearing aid. It is unknown if a combination of TNR and CNR has additional positive or negative effects on sound perception. Transients may cause less functioning of a CNR. If a transient sound occurs, the instantaneous SNR estimate of a CNR algorithm becomes positive (the signal level is above the estimated noise level that is based on a longer time window) and less attenuation is applied by the algorithm. If there are many transients the estimated noise level may become inaccurate. A TNR may reduce the high peak levels and prevent from less functioning of the CNR, resulting in a positive interaction between CNR and TNR in conditions where transients and continuous noises are mixed. Next, a combination of TNR and CNR may reduce the sound annoyance and increase the noise tolerance more than each algorithm alone.

As only limited information was available about how transient sounds are perceived by CI-users and about the potential benefit of TNR, we wanted to investigate the efficacy of TNR in CI-users on speech perception, noise tolerance and annoyance. Our tests were performed in a group of experienced CI users, using a subset of realistic sound recordings with transients that were able to activate the TNR algorithm. Furthermore, we investigated the effect of these transients without algorithm to learn more about the need for TNR. We wanted to answer the following research questions:

(1) How annoying and how detrimental for speech intelligibility in noise are transients that are able to activate a TNR algorithm applied in CI users?
(2) Does the application of TNR in CI users increase the speech intelligibility in noise, the noise tolerance and reduce perceived annoyance for transients in speech and noise?
(3) Does the combined application of TNR and CNR in CI users result in a cumulated improvement in speech intelligibility, noise tolerance and perceived annoyance in noisy backgrounds that contain transient sounds?

Materials and methods

Participants

Sixteen CI users were included in the study, as indicated by an a priori power analysis (see Data analysis). The sixteen participants ranged in age from 40 to 81 years (group mean 66 years; SD =12.0). All participants were unilaterally implanted with an Advanced Bionics cochlear implant (HiRes 90K implant). The average duration of implant use was 7.4 (SD 3.7) years with a minimum of one year of use. All participants used at least 14 active electrodes and the HiRes Optima-S sound coding strategy. In the daily used programme, all but two used the CNR algorithm

ClearVoice and all but three did not use the TNR algorithm SoundRelax. The input dynamic range (IDR) setting was between 55 and 63 dB (13 participants had an IDR of 60 dB). Free field thresholds were better than 40 dB HL (average of 500, 1000, 2000 and 4000Hz) for all participants and for nine participants better than 30 dB HL. Four participants wore a hearing aid in the non-implanted ear, but the hearing aid was switched off during the tests. Without hearing aids all participants had severe hearing loss of at least 100 dB HL pure tone average (PTA), except two who had a PTA of 80 and 92 dB HL. All participants were Dutch native speakers. For inclusion in this study, a phoneme score of at least 70% on clinically used Dutch consonant-vowel-consonant word lists (Bosman and Smoorenburg 1995) was required. Participants were required to sign a written informed consent form before participating in the study. The Erasmus Medical Center Ethics Committee approved the study protocol for use with CI recipients.

Cochlear implant algorithms

The study used an Advanced Bionics Naida Q70 sound processor, which contains a TNR algorithm called SoundRelax and a CNR algorithm called ClearVoice. Both are proprietary algorithms of Advanced Bionics (Stäfa, Switzerland). The TNR algorithm detects transients by comparing a fast following envelope and a slow following envelope of the broadband incoming signal. First, the absolute peak level of the noise transient (fast envelope) has to exceed 78 dB SPL. Second, the transient has to rise rapidly above the slow envelope level by at least 20 dB, with a level change of at least 20dB/ms. If these criteria are met, the level of the transient is attenuated. If the transient level is between 20 and 26 dB above the slow envelope level, the attenuation is 14 dB and if the transient level is greater than 26 dB above the slow envelope level, the attenuation is 20 dB. After activation of the TNR algorithm, the amount of level reduction decreases exponentially to zero within 200 ms. The TNR algorithm is designed to have minimal impact on the speech signal, which was confirmed by a study of Dyballa et al. (2015). The TNR acts early in the signal processing path, before the automatic gain control (AGC). The AGC of the sound processor has a dual-time-constant compression: a slow-acting compressor (attack time 240 ms, release time 1500 ms) becomes active when the input level exceeds the compression threshold of 63 dB SPL and the fast-acting compressor (attack time 3 ms, release time 80 ms) becomes active at a threshold of 71 dB SPL, thus avoiding uncomfortable loudness. Both compressors have a compression ratio of 12:1 (Boyle et al. 2009) and act on the broadband signal.

CNR algorithm ClearVoice has the aim to improve overall signal-to-noise ratio (SNR) by suppression of frequency channels lacking useful information for understanding speech. The CNR algorithm is applied behind the AGC and is active in the different frequency channels. Within each channel, the algorithm calculates a long-term estimation of the noise level using a 1.3 s time window and an instantaneous SNR. Depending on the difference between the instantaneous SNR and the long-term average SNR, a negative gain is applied. In this study we used the Medium setting of ClearVoice, resulting in a negative gain down to -12 dB (Advanced Bionics, 2012; Buechner et al. 2010).

Study design and procedures

In this prospective efficacy study, a within-subject repeated measures design was used. A factorial design was defined with 3 two-level factors: factor TNR (on/off), factor CNR (on/off), and factor Transients (stimuli with or without transients). A full 3-factor design has $2^3 = 8$ conditions, but it was not needed to test the effect of factor TNR in combinations with stimuli without transients as the TNR algorithm will not be activated in these conditions. From the remaining six conditions, four conditions tested the different combinations of TNR and CNR for stimuli with transients. These four conditions were balanced across participants with a 4×4 Latin Square. The other two conditions tested CNR-on and CNR-off for stimuli without transients and TNR off. These two conditions were alternated in order across participants. For all six conditions, the ANL and the speech intelligibility in noise were measured. After these tests an annoyance rating and a paired-comparison rating approach was used to measure the effect of TNR and CNR on the perceived annoyance of four sounds that contained both continuous noise and transients.

The fitting parameters of the CI were set according to the programme used in daily life. If the CNR was switched on, M-levels were increased by 5% (M-levels are basic fitting parameters used to define the amount of electrical output at the most comfortable level). The increase of M-levels was done in order to increase the effect of the CNR, according to the recommendations of Advanced Bionics and previous research (Brendel et al. 2012; Dingemanse and Goedegebure 2017).

Stimuli

To test the effect of TNR, we decided to use non-artificial stimuli with pronounced transients. A variety of transient kitchen sounds were recorded near a person's ear during emptying the dishwasher in a typical home kitchen. Transients as clinking bowls, dishes, cups, spoons and other similar sounds were recorded with a sample frequency of 44.1 kHz and a bit depth of 16 bits. Since this was an efficacy study we wanted to ensure that the TNR was activated by the transients. An analysis of the fast envelope levels of the speech that was used in de speech intelligibility and ANL tests showed that transients should have a peak level of at least 22 dB above the Root Mean Square (RMS) level of the speech in order to be detected by the TNR algorithm in at least 90% of the cases. The RMS-level of speech was 70 dB (SPL), so the peak level of the transients needed to be at least 92 dB (SPL). Transients that had a lower peak level were amplified to achieve a peak level of at least 92 dB (SPL). Transients that sounded unnatural after amplification were excluded. Next it was checked for which transients the TNR was really activated, using the transients combined with the speech signal of the ANL-test (see below) as input. This was done by Advanced Bionics with a software implementation of the algorithm. Eighty-one per cent of the transients activated the TNR. In other cases most likely the rise time of the transient was too slow to reach the criterion of 20 dB/ms. Again, these transients were excluded. At the end of the procedure, there were 96 unique transients, varying in content, duration, level, frequency spectrum and experienced loudness (see Table 1 for details about levels).

Note that the transients were not necessary experienced as loud, because most transients had a short duration. The resulting transient sounds were mixed with the speech stimuli for use in the speech intelligibility test and the ANL test (see test descriptions for details).

For the paired comparisons and annoyance ratings, four stimuli were created that were combinations of transients with high peak levels and continuous noise. These stimuli differed in transient

Table 1. Stimuli and mean values of the characteristics of the transients used.

Type of stimuli	*Type of transients*	*SPL peak (dB SPL)*	*# Transients/ second*	*Rise time (μs)*	*Duration (ms)*	*Type of continuous noise*
Transients for speech-in-noise tests	Clinking dishes, glasses etc.	95	1.0	675	134	Steady-state speech noise
Transients for ANL tests	Clinking dishes, glasses etc.	95	0.5	675	134	Steady-state speech noise
Kitchen sounds and exhaust noise	Clinking dishes, glasses etc.	97	1.6	933	147	Noise of an exhaust (65 dB SPL)
Hail on car window and car noise	Hail hits on car window	97	5.2	437	38	Car noise (72 dB SPL)
Hammering and machine noise	Hammering	96	2.0	1200	195	Noise of a sewing machine (63 dB SPL)
Steps with heels and babble	Steps with heels	97	2.0	1177	198	Babble noise 100p, near continuous (67 dB SPL)

Duration is the time interval between the occurrence of transient peak level and a level 20 dB below this peak level.

characteristics and in continuous noise type and were thought to be representative for different acoustic situations in daily life. Table 1 gives a description of the type and acoustic characteristics of the transients and continuous noise. The transients and the continuous sounds were mixed to create a stimulus in which the transients were at least 22 dB above the continuous noise level in order to be detected by the TNR algorithm. Again, transients were selected from recordings without additional signal processing, except some minor gain corrections to make sure that transients were above the threshold of the TNR activation. The four signals had a duration of 5 s and the dB (RMS) level was 70 dB (SPL).

Speech-in-noise test

Speech intelligibility in noise was measured with Dutch female-spoken, unrelated sentences in steady-state speech spectrum noise (Versfeld et al. 2000). The noise started three seconds before the speech to activate the CNR and ended 0.5 s after the speech. For the speech-in-noise conditions with transients, a modified version of the speech tracks was made by applying four transients to each list item. For each list item the four transients were randomly selected from the set of 96 transients (see previous paragraph). Two of the four transients were added in the 3-s interval of noise before the start of the sentence, with a randomly chosen delay with the constraint that the first transient was within the first half of the interval and the second transient in the second half. This was done to include the possibility that the noise estimation of CNR ClearVoice was influenced by the transients. The other two transients were added in the sentence interval, also with a randomly chosen delay and the constraint that the first transient was within the first half of the sentence and the second transient in the second half. The peak levels of the transients were at least 22 dB above the RMS-level of the speech to make sure that the TNR was activated. The presentation level of the sentences was fixed at 70 dB (SPL). This speech level is often reached in noisy situations (Pearsons, Bennett, and Fidell 1977). The Speech Reception Threshold in noise without transients (SRTn) was measured twice with an adaptive procedure targeting at 50% of words understood correctly, using 26 sentences. The first measurement was a practice run.

For the six different test conditions in the experiment, the speech and noise had a fixed SNR based on the individual SRTn +2 dB. The 2 dB was added because a drop in intelligibility due to the transients was expected and the test should not be too difficult for participants. Furthermore, floor and ceiling effects should be prevented for. Participants were asked to repeat as many words as they could from the sentence. The per cent of correct words per sentence list of 18 sentences was scored.

Acceptable noise level test

The ANL was tested with the same speech and noise material as the speech intelligibility in noise test. The sentences were connected with intervals of 500 ms of silence between them and played as running speech at 70 dB SPL in all ANL measurements. The task was to select the maximum background noise level (BNL) that the participant was willing to accept while following the speech. The listeners were given oral and written instructions, which were Dutch translations of the instructions provided by Nabelek et al. (2006). For each ANL measurement the BNL procedure was repeated three times and the mean value was used to calculate the ANL as the difference of the speech level and the mean BNL. Before the measurements, participants were made familiar with the BNL procedure in a practice condition.

For the measurement conditions with transients, the transients were added to the speech at a rate of 0.5 Hz. This low rate was chosen to prevent the speech from becoming unintelligible most of the time, due to the transients. The peak levels of the transients were set at least 22 dB above the RMS-level of the speech, to make sure that the TNR was activated. Note that the transient levels were not changed in the BNL procedure, only the level of the continuous noise was adjusted, as we wanted to be sure to stay in the active range of the TNR.

Paired comparisons and annoyance rating

A paired-comparison rating approach was used to measure the effect of TNR and CNR on the perceived annoyance of four sounds that consisted of both continuous noise and transients. For each sound, a participant compared three CI programmes with noise reduction (TNR only, CNR only, TNR and CNR simultaneously) to a reference condition without noise reduction (TNR-off and CNR-off). A two-interval, seven-alternative forced choice paradigm was used, with seven possible answers on an ordinal scale, ranging from ''A is much less annoying'' to ''B is much less annoying''. The answers were transformed to numbers ranging from −3 to 3. The seven choice categories and the transformation to numbers were in accordance with the Comparison Category Rating method described in ITU-T P. 800 Annex E.1 (ITU-T P.800 1996). The participants could listen to both fragments of sound as many times as they want

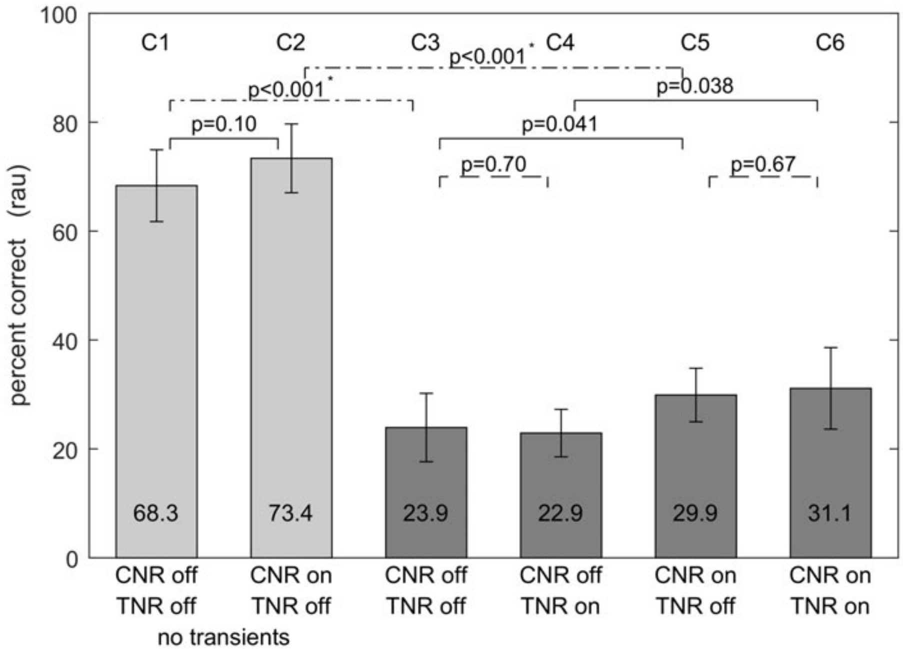

Figure 1. Mean and 95% confidence intervals of per cent correct scores for the speech intelligibility in noise test for six conditions. The two light grey bars on the left show speech scores for speech without transients. The four dark grey bars show speech scores values for speech with transients. The annotations C1–C6 give the condition numbering. Several test conditions were compared and uncorrected *p*-values were shown. Asterisks denote that a difference is significant after correction for multiple comparisons. Dashed lines show the significance of differences due to TNR, solid lines show the significance of CNR effects, and dash-dotted lines show the significance of the effect of transients.

before they completed their rating. They were asked to listen to the whole sound and to rate it in the end.

In addition, an absolute rating task was used to investigate the degree of annoyance participants experienced in response to the four stimuli used in the paired-comparison task. We asked the participants to rate the experienced annoyance on an 11-point ordinal scale. The scale was labelled as ''not at all annoying'' at 0, ''slightly annoying'' at 2.5, ''moderately annoying'' at 5, ''quite annoying'' at 7.5, and ''very annoying'' at 10, following Keidser et al. (2007).

Equipment

Transient stimuli were recorded with a Samson Q1U microphone and the audio editor Audacity (2013) was used for stimulus preparation. All testing was performed in a sound-treated room. Participants sat one metre in front of a Westra Lab 251 loudspeaker (Westra Elektroakustik GmbH, Germany) that was connected to a Roland Octa-capture soundcard (model UA-1010, Roland Corporation, Los Angeles, CA), and a computer. Stimuli were presented in a custom application (*cf*. Dingemanse and Goedegebure 2017) running in Matlab (MathWorks, v9.0.0). In the ANL test, participants adjusted the sound level of the noise stimuli using the up and down keys of a keyboard. The step size for the intensity adjustment for the ANL task was 2 dB per button press. All participants were tested with the same new Naida Q70 processor and a new T-mic (Advanced Bionics, Stäfa, Switzerland).

Data analysis

A priori power analysis using the G*Power software (Faul et al. 2009) indicated that a sample of 16 people would be needed to detect a clinically significant ANL difference $\geq$3 dB (Olsen and Brännström 2014) and a clinically significant difference of 10% points in the word score on a speech intelligibility-in-noise test with 80% power and alpha at 0.05.

Speech performance scores were transformed to rationalised arcsine unit (rau) scores in order to make them suitable for statistical analysis according to (Studebaker 1985). In cases of multiple comparisons, we used the Benjamini–Hochberg method to control the false discovery rate at level 0.05 (Benjamini and Hochberg 1995).

Repeated measures analysis of variance (RMANOVA) was used to analyse the ANL and speech intelligibility in noise tests. For the analysis of the paired comparisons a one-sample Wilcoxon Signed Rank test was used. For the absolute annoyance ratings a Friedman test was used to detect if ratings were significantly different between sounds. Data interpretation and analysis were performed with SPSS (IBM, Version 23, Chicago, IL).

Results

Speech intelligibility in noise

A normality check of the transformed per cent correct data revealed normally distributed data for all conditions. The individualised SNR ranged from 2.4 to 18.7 dB. Figure 1 shows the speech scores for the six conditions and the significance levels of relevant differences between conditions. It is evident that speech scores decreased markedly with 44% points on average due to the addition of transients. The application of CNR lead to a small increase in speech scores (6.4% points on average), but the TNR did not alter

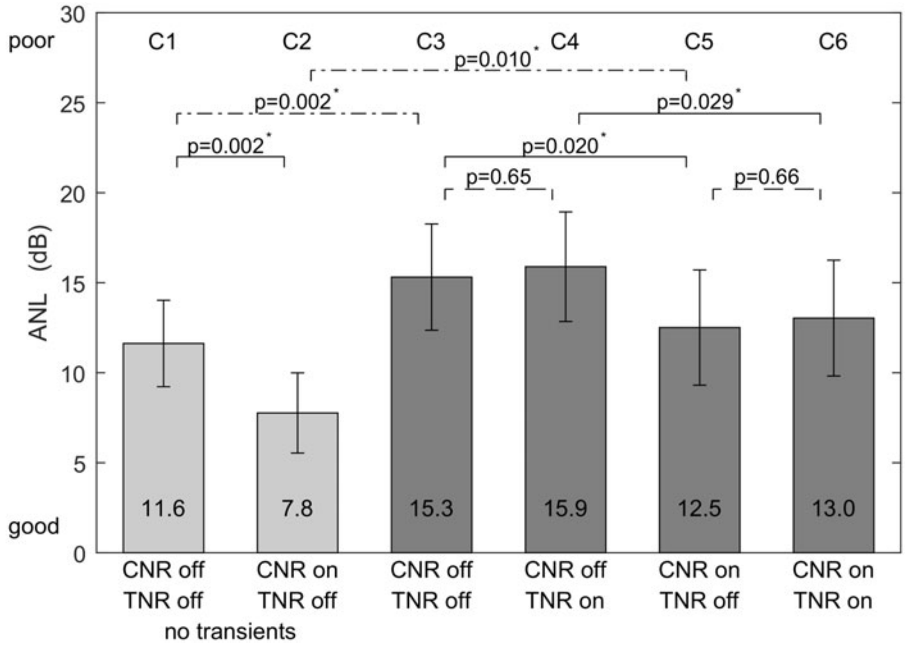

Figure 2. Mean and 95% confidence intervals of ANL values. The two light grey bars on the left show ANL values for speech without transients. The four dark grey bars show ANL values for speech with transients. The annotations C1–C6 give the condition numbering. Several test conditions were compared and uncorrected *p*-values were shown. Asterisks denote that a difference is significant after correction for multiple comparisons. Dashed lines show the significance of differences due to TNR, solid lines show the significance of CNR effects, and dash-dotted lines show the significance of the effect of transients.

the speech scores. A repeated measures ANOVA with the factors Transients and CNR (conditions C1, C2, C3, C5) showed a significant effect of the Transients factor [$F(1,15) = 191.5$, MSE = 30889.0, $p < 0.001$, $\eta^2_p = 0.93$] and a significant effect of the CNR factor [$F(1,15) = 6.8$, MSE = 483.1, $p = 0.02$, $\eta^2_p = 0.31$]. The interaction of both factors was not significant [$F(1,15) = 0.07$, MSE = 3.6, $p = 0.80$, $\eta^2_p = 0.005$].

The effect of TNR, CNR, and the combined effect of TNR and CNR were analysed with a second repeated measures ANOVA with the factors TNR and CNR (conditions C3, C4, C5, C6). A significant effect was found for the CNR factor [$F(1,15) = 7.8$, MSE = 805.0, $p = 0.013$, $\eta^2_p = 0.34$], but no significant effect was found for the TNR factor [$F(1,15) = 0.003$, MSE = 0.15, $p = 0.96$, $\eta^2_p < 0.001$] and the interaction of both factors [$F(1,15) = 0.35$, MSE = 20.2, $p = 0.57$, $\eta^2_p = 0.022$].

Acceptable noise level

A normality check revealed that the ANL data is normally distributed for each condition. Figure 2 presents the group mean ANL values for the six conditions and the significance levels of relevant differences between conditions.

Figure 2 shows that in the conditions that have transients added to the speech, the noise tolerance was significantly worsened compared to the conditions without transients (ΔANL = 4.5 dB on average). Switching on TNR did not significantly affect the noise tolerance. Use of the CNR significantly improved the ANL value with 2.8 dB on average if transients were present and 3.9 dB if transients were absent. A repeated measures ANOVA with the factors Transients and CNR (conditions C1, C2, C3, C5) showed a significant effect of the Transients factor [$F(1,15) = 12.0$, MSE = 318.5, $p = 0.003$, $\eta^2_p = 0.44$] and a significant effect of the CNR factor [$F(1,15) = 15.1$, MSE = 181.5, $p = 0.001$, $\eta^2_p = 0.50$]. The interaction of both factors was not significant [$F(1,15) = 0.93$, MSE = 5.1, $p = 0.35$, $\eta^2_p = 0.059$].

The effect of TNR and the combined effect of TNR and CNR (conditions C3, C4, C5, C6) were analysed with a second repeated measures ANOVA with the factors TNR and CNR. This analysis showed no significant effect of the TNR factor [$F(1,15) = 0.49$, MSE = 2.1, $p = 0.50$, $\eta^2_p = 0.032$] and a significant effect of the CNR factor [$F(1,15) = 8.8$, MSE = 124.2, $p = 0.010$, $\eta^2_p = 0.37$]. The interaction of both factors was not significant [$F(1,15) = 0.001$, MSE = 0.004, $p = 0.98$, $\eta^2_p < 0.001$].

Substantial differences were found in the noise tolerance levels (ANL-values) between the different CI-users. The reference ANL values (for CNR-off, TNR-off and no transients) ranged from 5.3 to 20 dB. No significant correlation was found between the ANL (reference condition C1) and the median annoyance score.

Paired comparisons and annoyance ratings

Figure 3 shows the mean quantified rating score in all three conditions for each sound apart and for the average over all sounds. Statistical analysis was performed for the ratings averaged over all the sounds. The programme with TNR-on and CNR-off was rated as less annoying than the reference condition (TNR-off; CNR-off) for all sounds. This mean rating ranged between −1.75 and 0 with a median of −0.75. A Wilcoxon signed-rank test showed a statistically significant difference between the median rating and the test value of 0, $z = -3.3$, $p = 0.001$ and a large effect size of $r = -0.8$.

The rating for the TNR-off CNR-on programme ranged between −2.25 and 2 with a median of 0.25. However, the Wilcoxon signed-rank test showed no statistically significant difference between the median rating and the test value of 0, $z = 1.58$, $p = 0.11$, $r = 0.4$.

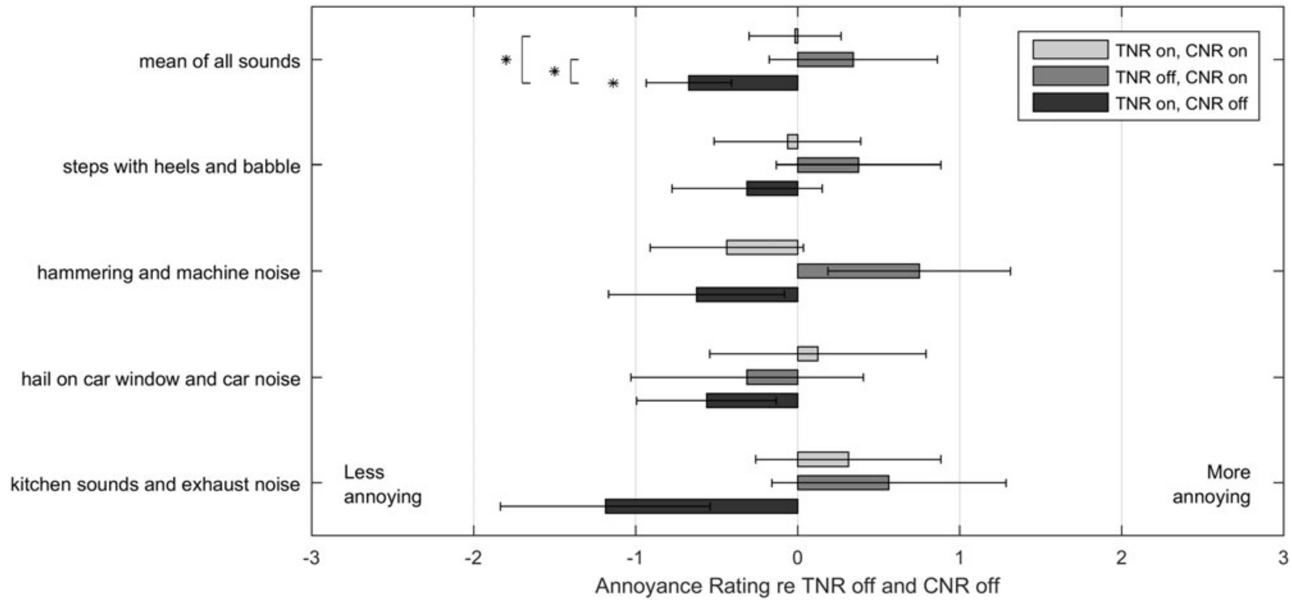

Figure 3. Mean and 95% confidence intervals of the relative annoyance rating scores, derived from the paired-comparison data, for four different sounds. Each bar indicates the relative annoyance for a sound and test condition compared with the reference condition with TNR-off and CNR-off. For the mean of all sounds, asterisks indicate differences that were significant on the $p < 0.05$ level.

With the combination of TNR-on and CNR-on the annoyance perception was not different from the reference condition on average, with a median rating of 0 and a range from -1 to 0.75 (Wilcoxon signed-rank test, $z = -0.11$, $p = 0.92$, $r = -0.03$).

When the three conditions were compared with each other, the rating of (TNR-off, CNR-on) was significantly higher than the rating of (TNR-on, CNR-off) (Wilcoxon signed-rank test, $z = -2.87$, $p = 0.002$, $r = -0.5$). The rating of (TNR-on, CNR-on) was also significantly higher than the rating of (TNR-on, CNR-off) (Wilcoxon signed-rank test, $z = -2.86$, $p = 0.003$, $r = -0.5$). The difference between the rating of (TNR-on, CNR-on) and (TNR-off, CNR-on) was nearly significant (Wilcoxon signed-rank test, $z = -1.77$, $p = 0.08$, $r = -0.3$). Overall, the participants rated use of TNR in the direction of less annoyance and use of CNR in the direction of more annoyance.

In the absolute annoyance rating task, the sounds were rated as moderately annoying on average. The kitchen sound was rated as most annoying (Median = 5, IQR = 3–6.5), the heels in babble as least annoying (Median = 3.5, IQR = 2–6). The ''hail on car window and car noise'' sound had a median rating of 4 (IQR = 2.5–6) and the ''hammering and machine noise'' sound had a median rating of 4.5 (IQR = 3–7). A Friedman test revealed a near significant effect of type of sound on annoyance [$\chi^2(3, N = 16) = 6.89$, $p < 0.073$]. Ratings differed greatly between CI users with a range from 0 (not at all annoying) to 10 (very annoying). Additionally, we analysed if higher annoyance ratings were correlated with a bigger effect of TNR-on in the paired comparisons test, but no significant correlation was found.

Discussion

Effects of transients and need for TNR

The current study has shown that transient sounds may be perceived as moderately annoying and substantially degrade speech understanding in CI users, so there is a need for TNR in CI-processors. First, we found an average annoyance rating in CI recipients for transient sounds of 4.5 (moderate annoyance) on an 11-point scale, which is lower than the reported annoyance scores of 6.3 for average to loud transient sounds in new wearers of hearing aids (Hernandez, Chalupper, and Powers 2006). An explanation for this difference may be that the participants of this study were experienced CI users, who were more used to hearing average to loud sounds than new wearers of hearing aids. Furthermore, the AGC of the CI-processor used had a fast compressor with a compression ratio of 12 above 71 dB SPL, which prevents sounds becoming too loud. In hearing aids, compression ratios are much lower and consequently high input levels may cause more annoyance. Still, in CI users, TNR may be helpful to reduce the perceived level of annoyance of transient sounds.

Second, the presence of high level transients caused a large decrease in speech intelligibility in noise. Activation of the AGC may be the main explanation of this result. The transients in our experiment had durations that were long enough to activate the fast compressor (attack time 3 ms). The fast compressor has a release time of 80 ms and affected at least one word in the sentences. Due to the high transient peak levels and the high ''transient-to-speech-ratio'' of at least 22 dB in our experiment, the AGC attenuated the speech level to just below 50 dB SPL. At this speech level, average speech intelligibility in noise for CI users is relatively low at 20%, according to Boyle, Nunn, and O'Connor (2013). Our results differ from the findings of Stobich, Zierhofer, and Hochmair (1999) who reported word scores between 50 and 60% for speech with a transient and different AGC configurations. However, they used only one transient at the beginning of the sentence, a ''transient-to-speech-ratio'' of 15 dB and a compression ratio of 3 or 6.

Another reason that may have contributed to the drop in intelligibility could be the masking of the speech signal by the transients. It is likely that forward masking occurred besides simultaneous masking, because the transient levels were much louder than the speech level. The recovery of masking in CI users is thought to be a process in the central auditory system (Dingemanse, Frijns, and Briaire 2006; Lee, Friedland, and Runge 2012; Shannon, 1990). The time required for recovery of masking is highly variable between CI users and ranges between 100 ms and more than 1 s making it likely that forward masking played a role, at least for some patients.

The finding that transients were highly disruptive for speech perception is clinically important. Many of the participants reported that they experience a comparable disrupting effect of transient sounds when listening to speech in daily life. This emphasises the need for an effective TNR algorithm in CI processors that is able to (partly) compensate for the detrimental effect of transients on speech.

Third, the presence of transients caused a moderate decrease in noise tolerance (increase of ANL). It is most likely that reduced speech intelligibility played an important role in the observed decrease in noise tolerance. The ANL test has an instruction that contains the words ''while following the story'', indicating that intelligibility of the speech is required in the ANL test. Although the rate of transients was half of that in the speech-in-noise test, transients made parts of the speech unintelligible, which made it more difficult to follow the speech. Therefore, there was less room for adding noise that further reduces speech intelligibility. In addition, the combination of transients and noise may be less tolerable than noise alone.

Effects of TNR

This study has shown that application of TNR can lead to significantly reduced perceived annoyance for mixtures of natural transient sounds with high peak levels and continuous noises. This finding is in accordance with the intended effect of the algorithm and confirms the efficacy of the algorithm. The amount of annoyance reduction was −0.75 on average compared to the condition without TNR, which should be interpreted as slightly better, according to the Comparison Category Rating scale described in ITU-T P. 800 Annex E.1 (ITU-T P.800 1996). This is only a small improvement, but it is relative to the moderate annoyance without TNR. A small improvement still can contribute to improved listening comfort in daily practice. Perceived annoyance of transients substantially differed between individual CI users. This means that some users did not profit from TNR as they hardly perceived the transients as annoying, while the other CI-users that do need TNR may have profited substantially.

Although TNR was able to reduce perceived annoyance, the application of TNR had no significant effect on noise tolerance or speech intelligibility in noise in this study. This is in contrast with Dyballa et al. (2015) who reported a small but significant improvement of 0.4 dB in SRTn for speech intelligibility in dish-clinking transient noise, using a comparable TNR algorithm. They used a speech material that was easier to recognise, which consisted of 50 words that participants knew from training. Possibly this made their test more sensitive to small changes. In agreement with the results of this study, Keidser et al. (2007) reported that the TNR had no significant effect on speech recognition in background noise in hearing aid users. Furthermore, the lack of an effect for noise tolerance and speech intelligibility in noise in this study may be due to the short duration of the signal reduction by the TNR compared to the duration of the transients. If a transient is detected, TNR attenuates the signal by 14 or 20 dB, but within 5 ms this attenuation is reduced to about 5 dB, because of the short time constant and the exponential reduction of the TNR attenuation. Therefore, the effect of the AGC and the amount of masking would be largely the same for the TNR-on and TNR-off conditions. An improvement in the TNR algorithm could be made so that the attenuation reduction follows the decrease in level of the fast signal envelope that is used in the algorithm. This may prevent activation of the AGC, which has a longer release time than the TNR algorithm. As a result, transients may be less detrimental for speech intelligibility. Using a shorter release time of the AGC could be another option to reduce the detrimental effect of transients on speech perception.

Interaction of TNR and CNR

The combined application of TNR and CNR did not result in a cumulated improvement of speech intelligibility in noise for CI-users. This is in accordance with the absence of an effect of TNR alone. Furthermore, the effect of CNR was not influenced by the application of TNR. An possible explanation for this finding is that on the moment of a transient, speech intelligibility is disturbed, regardless of the effect of TNR on the CNR.

In the paired-comparison experiment, participants perceived more annoyance on average (although not significant) with CNR on compared with the reference condition (CNR-off, TNR-off) in noisy backgrounds that contained transient sounds. This is most likely due to an increase in M-levels of 5% in the CNR-on programmes. The combined application of TNR and CNR resulted in an equal annoyance perception for the conditions (TNR-on, CNR-on) and (TNR-off, CNR-off), indicating that the increased annoyance that arose from the increased M-levels was compensated for by the use of TNR. This shows that TNR may be helpful in combination with CNR, as it prevents CI-users from substantially turning down the volume due to annoyance to transient sounds.

These findings suggest to apply CNR and TNR together with a 5% M-level increase in a clinical used speech in noise programme, to optimise both speech understanding and listening comfort in noise.

General discussion and conclusions

This study was designed as an efficacy study to investigate the effect of a TNR algorithm and its necessity by investigating the annoyance and detrimental effect of the transients that were reduced by the TNR. The large disturbing effect of transients on speech intelligibility in noise and the positive effect of TNR on noise annoyance we found in our study shows that it is worthwhile to further study the perception of transient sounds and effects of TNR in CI users. A limitation of this study is that only transients with high peak levels were used. This is only a subset of transients that occur in daily life. It is expected that transients with lower peak levels are less annoying and less detrimental for speech perception. Future studies should investigate the effect of transients on speech in quiet and noise at several speech levels and several ''transient-to-speech'' ratios to get more insight in the detrimental effects of transients on speech perception in CI users. They should also investigate more in general how transients are perceived by CI-users, and what factors may improve the listening conditions in the presence of transients. Furthermore, it should be noted that CI users may prefer to perceive some transients, like transients in music or in alarm signals. Also, transients may be important cues in sound perception and TNR should not disrupt these cues. Ultimately, field studies should be used, investigating both disrupting and positive effects of transients and possible improvements or negative side effects of TNR. Smart algorithms based on sound environment classification would be a desirable development.

Another limitation of this study is that we included good performers only (CVC scores $\geq$70%). The effect of the CNR and TNR algorithms is not necessarily the same for CI users with less benefit of the CI. These CI users complain more often that sounds are too loud or too disturbing, so there is more room for improvement, at least for listening comfort. On the other hand, the effect of TNR may be too small to really cause a significant shift in listening comfort and performance as noisy conditions remain extremely challenging for this group of CI users

We conclude that the investigated TNR algorithm in a CI processor was effective in reducing annoyance from transient sounds with high peak levels, without causing a negative effect on speech understanding. However, TNR was not able to compensate for the large decrease in speech understanding caused by transient sounds. TNR did not reduce the beneficial effect of CNR on speech intelligibility in noise, but no cumulated improvement was found either. Both types of noise reduction serve different goals and work independently, so they can be easily combined in one CI system.

Acknowledgements

The authors gratefully acknowledge the participants and they thank Phillipp Hehrmann for analysis of the signals with respect of TNR activation and Martina Brendel for her helpful comments. Portions of the data were presented at the 14th International Conference on Cochlear Implants (CI2016), May 11–14, 2016, Toronto.

Declaration of interest: This work was supported by Advanced Bionics.

ORCID

J. Gertjan Dingemanse http://orcid.org/0000-0001-8837-3474

References

Advanced Bionics. 2012. *ClearVoice. Technical Facts*. Valencia, CA: Advanced Bionics.

Audacity. 2013. Audacity (Version 2.0.3) [Computer Program]. http://audacity.sourceforge.net/ [Downloaded 4 March 2013].

Benjamini, Y., and Y. Hochberg. 1995. ‘‘Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing.’’ *Journal of the Royal Statistical Society. Series B (Methodological)* 57 (1): 289–300. doi:10.2307/2346101.

Bosman, A. J., and G. F. Smoorenburg. 1995. ‘‘Intelligibility of Dutch CVC Syllables and Sentences for Listeners with Normal Hearing and with Three Types of Hearing Impairment.’’ *International Journal of Audiology* 34 (5): 260–284. doi:10.3109/00206099509071918.

Boyle, P. J., A. Büchner, M. A. Stone, T. Lenarz, and B. C. J. Moore. 2009. ‘‘Comparison of Dual-Time-Constant and Fast-Acting Automatic Gain Control (AGC) Systems in Cochlear Implants.’’ *International Journal of Audiology* 48 (4): 211–221. doi:10.1080/14992020802581982.

Boyle, P. J., T. B. Nunn, A. F. O'Connor, and B. C. Moore. 2013. ‘‘STARR: A Speech Test for Evaluation of the Effectiveness of Auditory Prostheses Under Realistic Conditions.’’ *Ear & Hearing* 34 (2): 203–212. doi:10.1097/AUD.0b013e31826a8e82.

Brendel, M., T. Rottmann, C. Frohne-Buechner, A. Buechner, and T. Lenarz. 2012. ‘‘Benefit of the Noise Reduction Algorithm ClearVoice for Experienced Cochlear Implant Users.’’ Paper Presented at the *12th International Conference on Cochlear Implants and Other Implantable Auditory Technologies*, Baltimore, USA.

Buechner, A., M. Brendel, H. Saalfeld, L. Litvak, C. Frohne-Buechner, and T. Lenarz. 2010. ‘‘Results of a Pilot Study with a Signal Enhancement Algorithm for HiRes 120 Cochlear Implant Users.’’ *Otology & Neurotology* 31 (9): 1386–1390.

DiGiovanni, J. J., E. A. Davlin, and N. K. Nagaraj. 2011. ‘‘Effects of Transient Noise Reduction Algorithms on Speech Intelligibility and Ratings of Hearing Aid Users.’’ *American Journal of Audiology* 20 (2): 140–150. doi:10.1044/1059-0889(2011/10-0007).

Dingemanse, J. G., J. H. Frijns, and J. J. Briaire. 2006. ‘‘Psychophysical Assessment of Spatial Spread of Excitation in Electrical Hearing with Single and Dual Electrode Contact Maskers.’’ *Ear and Hearing* 27 (6): 645–657. doi:10.1097/01.aud.0000246683.29611.1b.

Dingemanse, J. G., and A. Goedegebure. 2017. ‘‘Optimising the Effect of Noise Reduction Algorithm ClearVoice in Cochlear Implant Users by Increasing the Maximum Comfort Levels.’’ *International Journal of Audiology*. Advance online publication. doi:10.1080/14992027.2017.1390267.

Dyballa, K.-H., P. Hehrmann, V. Hamacher, W. Nogueira, T. Lenarz, and A. Büchner. 2015. ‘‘Evaluation of a Transient Noise Reduction Algorithm in Cochlear Implant Users.’’ *Audiology Research* 5 (2): 116. doi:10.4081/audiores.2015.116.

Faul, F., E. Erdfelder, A. Buchner, and A.-G. Lang. 2009. ‘‘Statistical Power Analyses Using G* Power 3.1: Tests for Correlation and Regression Analyses.’’ *Behavior Research Methods* 41 (4): 1149–1160. doi:10.3758/BRM.41.4.1149.

Hernandez, A., J. Chalupper, and T. Powers. 2006. ‘‘An Assessment of Everyday Noises and Their Annoyance.’’ *Hearing Review* 13, 16.

ITU-T P.800. 1996. Methods for Subjective Determination of Transmission Quality. International Telecommunications Union, Telecommunications Standardization Sector, Annex E.1, p. 24.

Keidser, G., A. O'Brien, M. Latzel, and E. Convery. 2007. ‘‘Evaluation of a Noise−Reduction Algorithm that Targets Non−Speech Transient Sounds.’’ *The Hearing Journal* 60 (2): 29–32. doi:10.1097/01.HJ.0000285643.45157.35.

Khing, P. P., B. A. Swanson, and E. Ambikairajah. 2013. ‘‘The Effect of Automatic Gain Control Structure and Release Time on Cochlear Implant Speech Intelligibility.’’ *PLoS One* 8 (11): e82263. doi:10.1371/journal.pone.0082263.

Korhonen, P., F. Kuk, C. Lau, D. Keenan, J. Schumacher, and J. Nielsen. 2013. ‘‘Effects of a Transient Noise Reduction Algorithm on Speech Understanding, Subjective Preference, and Preferred Gain.’’ *Journal of the American Academy of Audiology* 24 (9): 845–858. doi:10.3766/jaaa.24.9.8.

Lee, E. R., D. R. Friedland, and C. L. Runge. 2012. ‘‘Recovery from Forward Masking in Elderly Cochlear Implant Users.’’ *Otology & Neurotology* 33 (3), 355–363. doi:10.1097/MAO.0b013e318248ede5.

Liu, H., H. Zhang, R. A. Bentler, D. Han, and L. Zhang. 2012. Evaluation of a Transient Noise Reduction Strategy for Hearing Aids. *Journal of the American Academy of Audiology* 23 (8): 606–615. doi:10.3766/jaaa.23.8.4.

Mauger, S. J., K. Arora, and P. W. Dawson. 2012. ‘‘Cochlear Implant Optimized Noise Reduction.’’ *Journal of Neural Engineering* 9 (6): 065007. doi:10.1088/1741-2560/9/6/065007.

Mertens, G., A. Kleine Punte, M. De Bodt, and P. Van de Heyning. 2015. ‘‘Sound Quality in Adult Cochlear Implant Recipients Using the HISQUI19.’’ *Acta Oto-Laryngologica* 135 (10): 1138–1145. doi:10.3109/00016489.2015.1066934.

Moore, B. C., B. R. Glasberg, and M. A. Stone. 1991. ‘‘Optimization of a Slow-Acting Automatic Gain Control System for Use in Hearing Aids.’’ *British Journal of Audiology* 25 (3): 171–182. doi:10.3109/03005369109079851.

Nabelek, A. K., M. C. Freyaldenhoven, J. W. Tampas, S. B. Burchfiel, and R. A. Muenchen. 2006. ‘‘Acceptable Noise Level as a Predictor of

Hearing Aid Use.'' *Journal of the American Academy of Audiology* 17 (9): 626–639. doi:10.3766/jaaa.17.9.2.

Olsen, S. Ø., and K. J. Brännström. 2014. ''Does the Acceptable Noise Level (ANL) Predict Hearing-Aid Use?'' *International Journal of Audiology* 53 (1): 2–20. doi:10.3109/14992027.2013.839887.

Pearsons, K. S., R. L. Bennett, and S. Fidell. 1977. *Speech Levels in Various Noise Environments*. Washington, DC: U.S. Environmental Protection Agency.

Shannon, R. V. 1990. ''Forward Masking in Patients with Cochlear Implants.'' *The Journal of the Acoustical Society of America* 88 (2): 741–744. doi:10.1121/1.399777.

Stobich, B., C. M. Zierhofer, and E. S. Hochmair. 1999. ''Influence of Automatic Gain Control Parameter Settings on Speech Understanding of Cochlear Implant Users Employing the Continuous Interleaved Sampling Strategy.'' *Ear and Hearing* 20 (2): 104–116. doi:10.1097/00003446-199904000-00002.

Stone, M.A., B. C. J. Moore, J. I. Alcántara, and B. R. Glasberg. 1999. ''Comparison of Different Forms of Compression Using Wearable Digital Hearing Aids.'' *The Journal of the Acoustical Society of America* 106 (6): 3603–3619. doi:10.1121/1.428213.

Studebaker, G. A. 1985. ''A ''Rationalized'' Arcsine Transform.'' *Journal of Speech and Hearing Research* 28 (3): 455–462. doi:10.1044/jshr.2803.455.

Vaerenberg, B., P. J. Govaerts, T. Stainsby, P. Nopp, A. Gault, and D. Gnansia. 2014. ''A Uniform Graphical Representation of Intensity Coding in Current-Generation Cochlear Implant Systems.'' *Ear and Hearing* 35 (5): 533–543. doi:10.1097/AUD.0000000000000039.

Versfeld, N. J., L. Daalder, J. M. Festen, and T. Houtgast. 2000. ''Method for the Selection of Sentence Materials for Efficient Measurement of the Speech Reception Threshold.'' *The Journal of the Acoustical Society of America* 107 (3): 1671–1684. doi:10.1121/1.428451.