Speech perception abilities of single-sided deaf adult cochlear implant users; normal hearing ear and cochlear implanted ear.

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Final version

Date: 10-5-2021

Study: Clinical Language, Speech and Hearing Sciences, program in Clinical Health Sciences, Faculty of Medicine, Utrecht University, The Netherlands

Course: 2018-2019 KG-10 Afstudeeronderzoek (KGWL06014)

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Intended journal: Ear & Hearing

Reference style: Vancouver superscript

Number of words: 3762

Number of words abstract: 298

List of abbreviations and relevant definitions

BCD	Bone Conduction Device
CI	Cochlear Implant
CINGLE	Cochlear Implantation for siNGLE-sided deafness
CROS	Contralateral Routing of Sound
CVC	Consonant Vowel Consonant
dB	Decibel
dBA	A-weighted decibels
DIN	Digits In Noise Test
HINT	Hearing In Noise Test
HU	Hogeschool Utrecht
NH	Normal hearing
PPVT-3-NL	Peabody Picture Vocabulary Test-3-NL: a norm referenced receptive vocabulary test for children and adults aged 2-99
Rpo	Ripples per octave
SMRT	Spectral-temporally Modulated Ripple Test
SNR	Signal to Noise Ratio
SRT	Speech Reception Threshold
SSD	Single-sided deaf
UMCU	University Medical Centre Utrecht
WAIS-4-NL	Wechsler Adult Intelligence Scale IV NL

Abstract

Background: Single-sided deaf patients have one normal hearing ear and one ear with moderate to profound hearing loss. Single-sided deafness can result in two main difficulties; problems with localization and speech perception. Up until recently, a criterion for a cochlear implant was bilateral hearing loss. It is, still, difficult to predict the speech perception abilities of a single-sided deaf adult with a cochlear implant.

Aim: The aim was to find a test which provides an accurate prognosis of speech perception in adult single-sided cochlear implant users.

Method: This observational, correlational, cross-sectional study included 18 adults. The participants performed hearing in noise tests, a spectral resolution test, a vocabulary test, and a working memory test. A comparison of the mean group data is reported. Also reported are correlations between the tests and the context factors.

Results: The participants performed significantly better with their normal hearing ear compared to their cochlear implanted ear. The context factors j and k did not significantly differ. Significant high correlations were found between phonological processing and hearing in noise for the implanted ear and lexical context factor j. Significant moderate correlations were found between spectral resolution for the normal hearing ear and both the j factor for phonemes in a word and the k factor for the implanted ear. A significant low correlation was found between the k factor of the implanted ear and a hearing in noise result for the normal hearing ear.

Conclusion and Recommendations: The results put phonological processing forward as a predictor for future performance in speech perception for single-sided deaf adults with a cochlear implant. It is, however, noteworthy that this study lacks power. Future research should include more participants and divide these participants up into subgroups.

Keywords: cochlear implants, hearing in noise tests, speech perception, single-sided deaf.

Samenvatting

Achtergrond: Eenzijdig dove volwassenen hebben één normaal horend oor en één oor met gemiddeld tot erg gehoorverlies. In de huidige zorg is een criterium voor een cochleair implantaat bilateraal gehoorverlies. Het is alleen moeizaam om de spraak verstaan mogelijkheden van een eenzijdig dove volwassene met een cochleair implantaat te voorspellen.

Doel: Het doel van dit onderzoek was het vinden van een test welke een nauwkeurige prognose geeft van het spraak verstaan van eenzijdig dove volwassenen met een cochleair implantaat.

Methode: 18 participanten zijn geïncludeerd in deze observationele, correlationele, cross-sectionele studie. De participanten hebben spraak in ruis tests, een spectrale resolutie test en logopedische tests uitgevoerd. Vergelijkende groepsdata van de tests en de context factoren j en k werden beschreven. Correlaties tussen meerdere tests en de context factoren werden beschreven.

Resultaten: De participanten presteerden op alle tests significant beter met hun normaal horende oor dan met hun geïmplanteerde oor. Factoren j en k voor beide oren verschilden niet significant van elkaar. Significante hoge correlaties werden gevonden tussen fonologische verwerking en drie testresultaten van het geïmplanteerde oor. Daarnaast werden significante gemiddelde correlaties gevonden tussen spectrale resolutie van het normaal horende oor en zowel de j factor van fonemen in een woord als de k factor voor het geïmplanteerde oor. Ook de woorden in ruis resultaten voor het normaal horende oor correleerde significant met factor k voor het geïmplanteerde oor.

Conclusie en aanbevelingen: De resultaten tonen fonologisch verwerken als voorspeller voor het spraak verstaan van eenzijdig dove volwassenen met een cochleair implantaat. Wel is het van belang te melden dat deze studie weinig power heeft. Verder onderzoek zal meer participanten moeten includeren zodat deze in subgroepen onderverdeeld kunnen worden.

Trefwoorden: Spraak in ruis tests, spraak verstaan, cochleair implantaat, eenzijdig doof

Introduction

Single-sided deaf (SSD) patients have one normal hearing (NH) ear with hearing loss of $\leq$ 25dB and one ear with moderate to profound hearing loss of $\geq$70 dB[1]. About 3% to 6% of the adult population is single-sided deaf[2]. Two main forms of SSD exist; SSD from birth and sudden SSD. The causes of sudden SSD vary (eg; a tumor, trauma to the head, and Meniere's disease). SSD can result in two main difficulties in life; problems with localization and poorer speech perception[3].

NH listeners use both ears to pick up sounds around them. Interaural time and level differences make it possible for the brain to pinpoint the location of these sounds. This gives people the possibility to locate the sound without looking[4,5]. People with SSD tend to locate all sounds on the side of their NH ear[3,4,5].

Using both ears is also beneficial in distinguishing noise at separate locations from speech, which makes it possible to understand speech in noisy environments. This ability is called the cocktail party phenomenon[6]. SSD adults hear all sound monaural. The NH ear has to process both speech and masking sound. This results in difficulties in both locating the sound and segregating speech from the masking sound[3,4].

Another effect prevalent in SSD adults is the head shadow effect. A target sound is located near the impaired ear and a masking sound is located near the normal hearing ear, which results in a skewed signal-to-noise ratio (SNR). The noise will appear louder than the target sound, which will result in difficulties in perception[6].

Speech perception is primarily determined by the SNR. Plomp (1977) stated that the typical cocktail party SNR is 0dB. It was concluded that this ratio is adequate for NH listeners. For hearing impaired listeners, however, speech perception will be poor and the effort tiring[7].

Speech perception is also influenced by context[30]. An NH listener is able to understand a word without hearing all letters or a sentence without hearing all words[8].

The redundant stimuli of speech are shown using factors j and k. Factor j reports the relationship between an element (e.g. phoneme of a word or of a sentence) and a whole (a word or a sentence). Listeners are able to correctly predict a following phoneme using lexical context. This prediction rate is expressed by the j factor. Factor j can both be used for phonemes in a word or in a sentence. When a listener needs all phonemes of a word or words in a sentence to understand that word, the value of the j factor will be the same as the number of phonemes[8,9].

Factor K reports the relationship between a stimulus and its context. Listeners are able to predict a subsequent word in a sentence using semantic context. This prediction rate is expressed by the k factor. The value of the k factor will be one when the listener does not use context in listening to the sentence. When context is used, the value of k will be larger than one[8,9].

Both factors represent at what rate listeners use syntactic and lexical context before hearing the stimulus. Factors j and k can be calculated using the data from speech in noise tests using two equations; j: $Pw=P^{j}_{p}$ and k: $Pc = 1 - (1 - Pi)^{k}$. For factor j, Pw represents the probability of recognition of wholes, Pp represents the probability of recognition of the parts. For factor k, Pc represents the probability of recognition of speech elements in context, Pi represents the probability of recognition without context[8,9].

Treatment for people with single-sided deafness (SSD) has changed over the last years. Up until recently, a criterion for a cochlear implant (CI) was bilateral hearing loss[10,11,15]. This criterion has been extended, but SSD patients are, still, mainly fitted with either a Contralateral Routing of Sound (CROS) system or a Bone Conduction Device (BCD)[1,11,12,15]. Previous research has shown significant improved hearing performances in SSD patients using a CI compared to a CROS system or BCD use[11,12].

It can, however, be difficult for SSD adults to get used to hearing with a CI. The brain has to process two different types of input, due to the NH ear providing normal input. Another problem is the use of interaural time differences. The processor of a CI has a different processing time than an ear. The interpretation of the interaural time will differ between the CI and the NH ear. Due to this, an SSD adult has to relearn how to locate sound and perceive speech in noise[13-15].

Currently, an SSD adult is tested for medical viability for a unilateral CI, but it remains difficult to predict the benefits from this implant. Not all SSD adults are able to relearn locating sound and perceiving speech in noise[11-15]. It is, however, unclear which factors (eg age, duration of deafness, etiology, language abilities, etc…) influence this.

Important is pinpointing an objective test which can provide an accurate prognosis of the speech perception abilities of SSD adults with a unilateral CI. Objective test results will provide researchers with a better understanding into the influencing factors for SSD adults implanted with a CI, which could provide a baseline for further research.

Aim

The aim of this study was to find a test which provides an accurate prognosis of speech perception in adult single-sided deaf cochlear implant users, using data gathered from their normal hearing ear.

This aim can be specified using the following question: To what extent do results of hearing in noise tests, spectral resolution tests, language ability tests, and phonological processing tests correlate with the speech perception scores of adult single-sided cochlear implant users?

Method

Design

This study used an observational, correlational, cross-sectional design; 1) observational: no intervention took place during this study, 2) correlational: relationships were assessed without manipulation of the variables, and 3) cross-sectional: the participants were tested at one moment in time to assess a possible correlation between the test results[16].

Participants were recruited and tested between June 2019 and November 2019. Recruitment and testing took place at the University Medical Center Utrecht, Utrecht (UMCU). Possible participants that met the inclusion criteria were tested in one session.

A flowchart of the design can be found in figure 1 below.

Population and domain

The study population entailed post lingually SSD adults (age ≥ 18 years) with a unilateral CI. Inclusion criteria were: adults (ages ≥ 18 years), post lingually unilateral deaf or unilateral severely hearing impaired, and CI implanted on the impaired ear with a maximum period of 10 years SSD.

Exclusion criteria were: medical conditions that influence the language development, cognitive disabilities, and learning disabilities. These conditions and disabilities could have an effect on speech recognition[17,18].

Data collection

All Participants took part in the CINGLE[1] study of the UMC Utrecht. The additional testing was conducted following their checkup for the CINGLE study in a session of one hour at the UMC Utrecht. Multiple tests were conducted; hearing in noise tests, a spectral resolution test, a vocabulary test, and a working memory test.

All hearing in noise tests were, separately, conducted on the normal ear and the implanted ear. The implanted ear was disabled by removing the CI and covering the implanted ear with a one sided ear protector. The normal ear was attenuated using an earplug and the one sided ear protector. Each session started with testing the participant’s normal ear, to ensure that the participant understood the tests.

The tests were conducted using a Yamaha model MSP5 Studio speaker, a laptop, and an ESI U24XL sound card. The speaker was placed on a stand at ear level when the participant is seated. The participant was seated one meter from the speaker in a soundproof room. The

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[1] The CINGLE study is an ongoing study at the UMC Utrecht into new treatment options for single-sided deaf patients. The treatment focuses on a cochlear implant (umcutrecht, 2020).

volume of the masking noise was always set at 60dBA. The volume of the different speech materials was set with an up-down procedure according to Plomp and Mimpen[19.]

Speech in noise tests

During the first part of the session, three speech in noise tests were conducted; a Consonant-Vowel-Consonant (CVC) in noise test, a Digits In Noise (DIN) test, and a sentences in noise test (in this paper called the Hearing sentences In Noise Test (HINT)).[20-22, 26-28]. The CVC, DIN, and HINT were chosen, because they most accurately simulate speech perception in daily life. The CVC test consisted of 24 sense-words per list, the DIN test consisted of 27 items of three numbers per list and the HINT consisted of 13 sentences per list. The participant was instructed, at the beginning of these three lists, to repeat each item to their best ability[19]. In the CVC test every correct word and phoneme, in the DIN list every correct number, and in the HINT every correct word and sentence was counted. With the CVC, DIN, and HINT test we measure the SNR for 50% word, digits or sentences correct. These tests were repeated if the standard deviation was larger than 2.5 to ensure test-retest reliability[20-22]. Additionally in the CVC test every correct phoneme as a function of presented SNR is counted, and in the HINT test every word as a function of presented SNR is counted. The raw data was fit to determine the performance intensity functions. These functions were used to calculate context factors j and k. The context factors j and k were not calculated for the DIN test, since no context is used in the repetition of series of numbers[9,22].

Spectral Ripple Test

The Spectral-temporally Modulated Ripple Test (SMRT) measured the spectral resolution using a three-interval forced choice procedure. It has been proven that spectral resolution has an effect on speech perception[29]. The participant hears three stimuli of which one had a lower ripple per octave (rpo) density. Subsequently, the participants were asked to choose which of the stimuli was different. This test was not repeated[20].

Vocabulary test and working memory test

In addition to the hearing tests, two speech language pathology tests were conducted; the PPVT-3-NL, and one subtest of the WAIS-4-NL. The subtest of the WAIS-4-NL tests working memory[23-25].

The PPVT-3-NL is a vocabulary test for all ages. The participant is shown four pictures and asked to choose the corresponding picture to a specific word[23].

The working memory subtest of the WAIS-4-NL consists of number series which the participant has to repeat either in the same order or in reverse. The amount of numbers in the series increase as the test proceeds[24,25].

Data analysis

The quantitative data was statistically analyzed using IBM SPSS Statistics for Windows 10 version 23.0. All analyses were interpreted using a significance level of 0.05.

This study focuses on finding a correlation between the test results of the normal ear and the test results of the implanted ear. First, the differences between the normal ear and the implanted ear were analyzed using a One-way ANOVA. Subsequently, scatterplots were used to determine possible correlations between the test results. Finally, the Pearson Correlation was used to definitively determine correlations between the test results.

Ethical Issues

The current study is part of a previously approved study (CINGLE). This CINGLE study was approved by the Medical Ethical Committee of the UMCU. Informed consent was given when participants entered the CINGLE study.

Results

Participants

In total, 18 SSD CI users participated in this study. The baseline characteristics of these participants can be found in table 1 below. No distinction was made between the side of implantation. Ages of the participants varied from 21 years old until 77 years old (mean age = 57.8). The duration of CI use varied from 3 months to 5 years and one month. The genders were evenly divided with 9 male participants and 9 female participants.

All participants completed the full set of tests. The power of this study is quite small with 18 participants. This is evident in the results. This study will, however, be continued at the UMCU.

Descriptives

Speech language pathology tests

The mean Q-score of the PPVT-3-NL test was 99.89 WQ (sd=15.9), with a range from 61 to 122. The mean score of the WAIS-4-NL was 101 (sd=5.1), with a range from 93 to 112. All results can be found in table 2 below.

Speech in noise tests

The results of the speech in noise tests varied greatly. Most participants performed better on the speech in noise tests with their normal ear versus their implanted ear. This is shown in figure 2 below. A statistically significant difference was found between the NH ear and the CI ear for all hearing in noise tests. One participant, however, performed better with their implanted ear on multiple tests. All results can be found in table 3a and in figure 3 below.

CVC in noise

The mean SRT score of the CVC in noise test for the NH ear was -3.7dB (sd= 1.8) and a range from -9.0dB to -1.3dB. The mean SRT score of the CVC in noise test for the implanted ear was 3.0dB (sd= 4.4) and a range from -4.0dB to 11.2dB. The difference between the NH ear and the implanted ear for the CVC in noise test was significant ($F(1,34) = 31.584$, $p = .000$).

DIN

The mean SRT score of the DIN test for the NH ear was -7.5dB (sd= 1.0) and a range from -9.0dB to -5.5dB. The mean SRT score of the DIN test for the implanted ear was -3.9dB (sd= 1.8) and a range from -6.9dB to 0.2dB. The difference between the NH ear and the implanted ear for the DIN test was significant ($F(1,34) = 47.327$, $p = .000$).

HINT

The mean SRT score of the HINT test for the NH ear was -3.3dB (sd= 1.4) and a range from -5.8dB to -1.0dB. The mean SRT score of the HINT test for the implanted ear was 3.1 dB (sd=

3.6) and a range from -1.4dB to 10.6dB. The difference between the NH ear and the implanted ear for the HINT was significant (F(1,34) = 44.749 p = .000).

SMRT

Most participants performed better on the SMRT with their NH ear versus their CI ear. A statistically significant difference was found between the NH ear and the CI ear for the SMRT. The results can be found in table 3a and figure 4 below. The results show a wide variation in the ability to hear a difference in spectral resolution. This is shown in figure 5 below.

The mean score of the SMRT for the NH ear was 5.9rpo (sd=1.7) and a range from 1.47rpo to 8.01rpo. The mean score of the SMRT for the CI ear was 2.9rpo (sd=1.8) and a range from 0.00rpo to 5.87rpo. Participant number 6 could not hear a difference with his CI in spectral resolution in the first three test items, which resulted in a score of 0.00rpo. The difference between the NH ear and implanted ear for SMRT was significant (F(1,34) = 31.911, p ≤ .001).

J&k factors

The factors j and k were calculated using the raw data of the speech in noise tests. No statistically significant differences were found for the context factors; j(CVC): F(1,34) =0.000, p = 0.997, j(HINT): F(1,34) = 0.405 , p = 0.529, k: F=(1,34) = 2.731, p = 0.108. The group results are shown in table 3b and figure 6 and 7 below.

Correlations

Correlations were calculated for all tests between both ears and within each ear. All the results of the hearing tests (CVC in noise, DIN, HINT, SMRT) for the implanted ear correlated significantly with each other.

The WAIS-4-NL test showed multiple significant correlations with test results from the implanted ear. The WAIS test correlated significantly with the SMRT for the implanted ear (Rs= .758, p= 0.000), with the CVC in noise results for the implanted ear (Rs= -.508, p= 0.031), and with the j factor calculated from the HINT results of the implanted ear (Rs= -.539, p=0.021). These correlations are shown in figures 8 to 10 below.

The j factor calculated from the HINT of the implanted ear correlated significantly with the SMRT for the NH ear (Rs = -.532, p = 0.023). The k factor of the implanted ear correlated both with the CVC in noise for the NH ear (Rs = .469, p = 0.050) and with the SMRT for the NH ear (Rs = -.517, p = 0.028). These correlations are shown in figures 11 to 13 below.

Discussion

The aim of this study was to find a test which provides a prognosis of speech perception in adult single-sided deaf CI users. This aim was studied using hearing in noise tests (CVC in noise, HINT, DIN), a spectral resolution test (SMRT), and speech language pathology tests (PPVT-3-NL, WAIS-4-NL)[21-28]. The main research question was: To what extent do results of hearing in noise tests, language ability tests and phonological processing tests correlate the speech perception scores of adult single-sided deaf cochlear implant users?

The mean results showed that the participants performed better on the hearing tests with their NH ear versus their CI ear. The j and k factors showed that all participants used context factors similarly using their NH ear or their CI ear.

Low, moderate, and high correlation were found between the tests. The WAIS-4-NL test showed correlations with multiple tests. The correlation between the results of the WAIS-4-NL and the results of the SMRT of the NH ear was high. A moderate correlation was found between the results of the WAIS-4-NL and the results of the CVC in noise test of the CI ear, and the results of the WAIS-4-NL and the results of the j factor of the HINT of the CI ear. Two other correlations were moderate; the correlation between the results of the SMRT of the NH ear and the factor k results of the CI ear, and the correlation between the results of the SMRT of the NH ear and the results of the j factor of the CVC in noise test of the CI ear. One correlation was low; the correlation between the results of the CVC in noise test of the NH ear and the factor k results of the CI ear.

The correlations with the WAIS-4-NL test showed that phonological processing influences speech perception of the CI ear. The WAIS-4-NL is a working memory test which shows that speech perception is better in adults with a better working memory. The more phonemes or words someone can retain, the faster someone will recognize that word or sentence. This finding can also be linked to the use of context. Phonological processing influences the context used for words and phonemes in sentences (factor j). Using the retained phonemes or words to recognize words or sentences faster helps people perceive speech. An advantage to the WAIS-4-NL test is that it does not rely on hearing. The test is executed using both ears with no regard to the ability of those ears, which results in a suitable test for SSD adults.

It is, however, noteworthy that the distribution of the results of the WAIS-4-NL test was small which could be the underlying reason for the correlations. The power of the found correlations is also quite small as only 18 participants were included in this study. The moderate correlation between the SMRT of the NH ear and both the j factor of the HINT of the NH ear and the k factor of the implanted ear showed that spectral resolution significantly correlates with the use of context both within words (j-factor) as within sentences (k-factor). The low correlation between the results of the CVC in noise test for the NH ear and the k factor of the implanted ear signifies that when a participant performed well on the CVC in noise test with their NH ear, they also used context more when listening to sentences in noise with their CI. These results unfortunately do not offer an outcome in the search for an objective test to predict cochlear implant use by SSD adults.

It is difficult to claim that the aim of this study was reached. Only 18 participants could be included in the timespan of this study. The main difficulty with this study was the heterogenous group. Most notably the difference in age range (21 years old until 77 years old) and CI use (3 months until 5+ years). These shortcomings effect the power of this study.

Another shortcoming is the use of the k factor. A moderate and a low significant correlation were found for the k factor of the CI ear. It is, however, questionable if these correlations are actually significant and reliable. The Dutch HINT provides a non-reliable k factor. The sentences used in the Dutch version of the HINT vary in word length (6 to 10 syllables), whereas the English version used by Boothroyd (1988) has a set of 4 syllables for every sentence[9,28]. Furthermore, the SRT for the CVC words is close to the SRT for words in sentences. This results in the k factor being less reliable in comparison to the k factor in the study of Boothroyd (1988). Further research is needed to determine how the SRT data of this method can be used to calculate the k-factor between words in isolation and words in Dutch sentences.

The current study chose to perform the tests in a certain order where the participant always started with their normal hearing ear. It would be interesting to see if starting with the implanted ear provides different results.

This study has chosen for a certain set of tests to be executed, these are not all possible tests that could be influential in speech perception.

Further research is also needed with a bigger participant group. A bigger participant group would result in more power to the study and the findings. A bigger participant group would also enable the group to be split into subgroups. These subgroups could, at least, be divided into age and longevity of CI use. Results of such studies could be more substantial.

In conclusion, this study showed a correlation between phonological processing and spectral resolution, speech in noise, and lexical context (factor j). The study put the WAIS-4-NL forward as a possible predicting test for future speech perception abilities in SSD adults using a CI.

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Tables

Table 1 Demographics

Subject	Sex	Age	CI side	Etiology	CI use in years
1	M	42	AD	Unknown	4;1
2	M	66	AS	Sudden Deafness	2;0
3	F	55	AD	Labyrinthitis	0;7
4	F	51	AD	Labyrinthitis	0;8
5	M	69	AS	M. Menière	0;3
6	F	60	AS	Latrogenic	5;1
7	F	49	AS	Sudden deafness	3;1
8	F	59	AS	Sudden deafness	2;9
9	F	59	AS	Sudden deafness	5;1
10	M	68	AD	Sudden deafness	3;1
11	M	51	AS	M. Menière	4;2
12	M	72	AS	Labyrinthitis	5;1
13	M	65	AD	Sudden deafness	5;1
14	F	76	AS	Labyrinthitis	4;1
15	M	65	AD	Sudden deafness	2;1
16	M	56	AS	Sudden Deafness	2;1
17	F	20	AS	Sudden deafness	2;1
18	F	50	AD	Sudden deafness	1;1

Table 2: Mean results PPVT-3-NL & WAIS-4-NL

Descriptive Statistics

	N	Minimum	Maximum	Mean		Std. Deviation
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic
PPVT-3-NL	18	61,00	122.00	99.8889	3.75028	15.91111
WAIS-4-NL	18	93,00	112.00	101.2778	1.19313	5.06203
Valid N (listwise)	18					

Table 3a Results

PP Number	CVC NH	CVC CI	HINT NH	HINT CI	SMRT NH	SMRT CI	DIN NH	DIN CI	Peabody	WAIS
1	-2,3	-2,1	-3	-1	7,9	1,933	-7,8	-4,4	107	99
2	-3,4	2,3	-2,6	4,6	5,8	2,5	-7,6	-5,1	120	103
3	-4,4	4	-2,2	9,8	7,233	2,3	-7,8	-3	97	99
4	-4,8	1,9	-2,6	5,8	4,833	1,9	-8,8	-3,8	90	103
5	-4,8	-3,8	-2,2	-0,2	6,633	4	-8,8	-6,9	102	105
6	-3	6,5	-5,4	1,8	4,4	0	-7	-4,6	122	97

7	-5	0	-2,2	-0,6	5,1	3,633	-6,3	-5,9	76	97
8	-2,1	2,1	-5	1,8	8,033	4,533	-8	-2,7	80	107
9	-1	3,2	-3	-1,4	4,767	5,167	-7,6	-6,5	105	107
10	-9,1	-2,7	-5	-1,4	6,2	5,867	-7,6	-6,9	110	105
11	-3,6	0	-4,2	-1	7,6	4,933	-6,5	-4,4	115	112
12	-6,3	3,4	-3,8	4,6	6,533	1,433	-9	-2,9	91	95
13	-2,9	4,2	-3	3	3,1	0,967	-6,9	-3,8	98	93
14	-1,3	5	-4,6	4,2	7,333	1,733	-5,5	-2,9	105	103
15	-2,1	11,2	-1,4	5,8	1,467	0,9	-7	-1,5	106	95
16	-2,9	5,1	-5,8	4,2	5,667	2,6	-6,5	-5	97	99
17	-3,2	-4	-1	1,8	5,933	2,367	-7,4	-2,1	116	105
18	-3,6	10,3	-1,8	10,6	6,6	1,533	-8,4	0,2	61	99

Table 3b Results factor j & k

PP Number	CVC J NH	CVC J CI	Sentence J NH	Sentence J CI	k NH	k CI
1	1,8506212	1,73321	2,041078116	3,1324617	2,244187	16,55905
2	1,6372068	1,910821	6,687733212	2,683673593	2,302457	1,172792
3	1,840035	2,262575	2,193589532	4,185023078	1,499822	1
4	2,0536247	1,502188	5,014574428	5,427981772	2,442215	1
5	1,9956536	2,043955	1,336670746	3,254604038	2,352644	1
6	1,5871452	1,543448	3,766907009	4,139554625	2,125444	16,57903
7	2,1238437	2,494613	2,107763073	4,83386602	1,585889	3,745797
8	2,3933193	1,864184	2,107763073	2,157575944	3,678351	2,526742
9	1,742022	2,877833	8,343423861	2,60347312	14,38397	15,2213
10	1,7408029	2,033948	1,70493342	2,76836345	1	1,747059
11	1,8956	1,597918	1,807214493	1,288413483	2,04974	2,665878
12	2,5664019	2,457206	5,107963573	3,369548243	2,249086	2,283786
13	2,4941371	2,251219	8,841488372	4,258033546	1,653385	4,466055
14	3,2233531	1,7	1,5	2,6	4,986359	7,7
15	2,7208226	3,2	4,2	2,5	2,074585	26,9
16	2,3590004	2,9	1,2	3,2	3,521589	3
17	2,0349005	2,1	2,4	2	1,237658	1
18	1,8036073	1,6	3,2	2,1	2,369482	1,9

Table 4 Correlations

Correlations

		SMRT_NH	SMRT_CI	CVC_in_noise_NH	CVC_in_noise_CI	DIN_NH	DIN_CI	HINT_NH	HINT_CI
SMRT_NH	Pearson Correlation	1	,392	-,099	-,402	-,159	-,025	-,272	-,097

	Sig. (2-tailed)		,107	,696	,098	,529	,923	,274	,703
	N	18	18	18	18	18	18	18	18
SMRT_CI	Pearson Correlation	,392	1	-,352	-,559*	-,030	-,571*	-,182	-,581*
	Sig. (2-tailed)	,107		,153	,016	,905	,013	,470	,011
	N	18	18	18	18	18	18	18	18
CVC_in_noise_NH	Pearson Correlation	-,099	-,352	1	,361	,399	,360	,058	,114
	Sig. (2-tailed)	,696	,153		,141	,101	,142	,821	,651
	N	18	18	18	18	18	18	18	18
CVC_in_noise_CI	Pearson Correlation	-,402	-,559*	,361	1	,137	,588*	,009	,743**
	Sig. (2-tailed)	,098	,016	,141		,588	,010	,972	,000
	N	18	18	18	18	18	18	18	18
DIN_NH	Pearson Correlation	-,159	-,030	,399	,137	1	-,075	-,295	-,209
	Sig. (2-tailed)	,529	,905	,101	,588		,767	,234	,405
	N	18	18	18	18	18	18	18	18
DIN_CI	Pearson Correlation	-,025	-,571*	,360	,588*	-,075	1	,313	,728**
	Sig. (2-tailed)	,923	,013	,142	,010	,767		,206	,001
	N	18	18	18	18	18	18	18	18
HINT_NH	Pearson Correlation	-,272	-,182	,058	,009	-,295	,313	1	,279
	Sig. (2-tailed)	,274	,470	,821	,972	,234	,206		,263
	N	18	18	18	18	18	18	18	18
HINT_CI	Pearson Correlation	-,097	-,581*	,114	,743**	-,209	,728**	,279	1
	Sig. (2-tailed)	,703	,011	,651	,000	,405	,001	,263	
	N	18	18	18	18	18	18	18	18
PPVT_III	Pearson Correlation	-,128	,003	,084	-,291	,281	-,380	-,167	-,410
	Sig. (2-tailed)	,612	,992	,741	,242	,258	,119	,508	,091
	N	18	18	18	18	18	18	18	18
WAIS	Pearson Correlation	,521*	,758**	-,010	-,508*	-,016	-,289	-,154	-,419
	Sig. (2-tailed)	,027	,000	,968	,031	,948	,245	,542	,083
	N	18	18	18	18	18	18	18	18

CVC_NH_J	Pearson Correlation	-,136	-,279	,311	,260	,359	,360	-,112	,180
	Sig. (2-tailed)	,591	,262	,209	,298	,144	,143	,658	,474
	N	18	18	18	18	18	18	18	18
CVC_CI_J	Pearson Correlation	-,532*	,063	,056	,249	,150	-,114	,160	-,015
	Sig. (2-tailed)	,023	,805	,825	,319	,553	,652	,527	,954
	N	18	18	18	18	18	18	18	18
ZIN_NH_J	Pearson Correlation	-,562*	-,222	,155	,246	-,170	-,024	,220	,077
	Sig. (2-tailed)	,015	,377	,540	,325	,501	,925	,381	,761
	N	18	18	18	18	18	18	18	18
ZIN_CI_J	Pearson Correlation	-,328	-,350	-,245	,053	-,134	-,245	,057	,138
	Sig. (2-tailed)	,184	,154	,326	,833	,596	,327	,822	,585
	N	18	18	18	18	18	18	18	18
K_NH	Pearson Correlation	-,057	,324	,382	,100	,056	-,252	-,100	-,234
	Sig. (2-tailed)	,823	,190	,118	,692	,825	,313	,693	,350
	N	18	18	18	18	18	18	18	18
K_CI	Pearson Correlation	-,517*	-,323	,469*	,386	,256	,080	,044	-,139
	Sig. (2-tailed)	,028	,191	,050	,113	,305	,751	,861	,582
	N	18	18	18	18	18	18	18	18

Correlations

		PPVT_III	WAIS	CVC_NH_J	CVC_CI_J	ZIN_NH_J	ZIN_CI_J	K_NH	K_CI
SMRT_NH	Pearson Correlation	-,128	,521*	-,136	-,532*	-,562*	-,328	-,057	-,517*
	Sig. (2-tailed)	,612	,027	,591	,023	,015	,184	,823	,028
	N	18	18	18	18	18	18	18	18
SMRT_CI	Pearson Correlation	,003	,758**	-,279	,063	-,222	-,350	,324	-,323
	Sig. (2-tailed)	,992	,000	,262	,805	,377	,154	,190	,191
	N	18	18	18	18	18	18	18	18
CVC_in_noise_NH	Pearson Correlation	,084	-,010	,311	,056	,155	-,245	,382	,469*

	Sig. (2-tailed)	,741	,968	,209	,825	,540	,326	,118	,050
	N	18	18	18	18	18	18	18	18
CVC_in_noise_CI	Pearson Correlation	-,291	-,508*	,260	,249	,246	,053	,100	,386
	Sig. (2-tailed)	,242	,031	,298	,319	,325	,833	,692	,113
	N	18	18	18	18	18	18	18	18
DIN_NH	Pearson Correlation	,281	-,016	,359	,150	-,170	-,134	,056	,256
	Sig. (2-tailed)	,258	,948	,144	,553	,501	,596	,825	,305
	N	18	18	18	18	18	18	18	18
DIN_CI	Pearson Correlation	-,380	-,289	,360	-,114	-,024	-,245	-,252	,080
	Sig. (2-tailed)	,119	,245	,143	,652	,925	,327	,313	,751
	N	18	18	18	18	18	18	18	18
HINT_NH	Pearson Correlation	-,167	-,154	-,112	,160	,220	,057	-,100	,044
	Sig. (2-tailed)	,508	,542	,658	,527	,381	,822	,693	,861
	N	18	18	18	18	18	18	18	18
HINT_CI	Pearson Correlation	-,410	-,419	,180	-,015	,077	,138	-,234	-,139
	Sig. (2-tailed)	,091	,083	,474	,954	,761	,585	,350	,582
	N	18	18	18	18	18	18	18	18
PPVT_III	Pearson Correlation	1	,245	-,188	-,030	,087	-,196	,027	,296
	Sig. (2-tailed)		,327	,455	,907	,731	,437	,915	,233
	N	18	18	18	18	18	18	18	18
WAIS	Pearson Correlation	,245	1	-,275	-,338	-,264	-,539*	,312	-,305
	Sig. (2-tailed)	,327		,270	,170	,289	,021	,207	,218
	N	18	18	18	18	18	18	18	18
CVC_NH_J	Pearson Correlation	-,188	-,275	1	,284	-,076	-,037	-,015	,133
	Sig. (2-tailed)	,455	,270		,254	,763	,885	,952	,599
	N	18	18	18	18	18	18	18	18
CVC_CI_J	Pearson Correlation	-,030	-,338	,284	1	,222	,010	,319	,357
	Sig. (2-tailed)	,907	,170	,254		,375	,967	,197	,146
	N	18	18	18	18	18	18	18	18

ZIN_NH_J	Pearson Correlation	,087	-,264	-,076	,222	1	,213	,415	,192
	Sig. (2-tailed)	,731	,289	,763	,375		,395	,087	,446
	N	18	18	18	18	18	18	18	18
ZIN_CI_J	Pearson Correlation	-,196	-,539*	-,037	,010	,213	1	-,175	-,067
	Sig. (2-tailed)	,437	,021	,885	,967	,395		,487	,791
	N	18	18	18	18	18	18	18	18
K_NH	Pearson Correlation	,027	,312	-,015	,319	,415	-,175	1	,303
	Sig. (2-tailed)	,915	,207	,952	,197	,087	,487		,222
	N	18	18	18	18	18	18	18	18
K_CI	Pearson Correlation	,296	-,305	,133	,357	,192	-,067	,303	1
	Sig. (2-tailed)	,233	,218	,599	,146	,446	,791	,222	
	N	18	18	18	18	18	18	18	18

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Figures

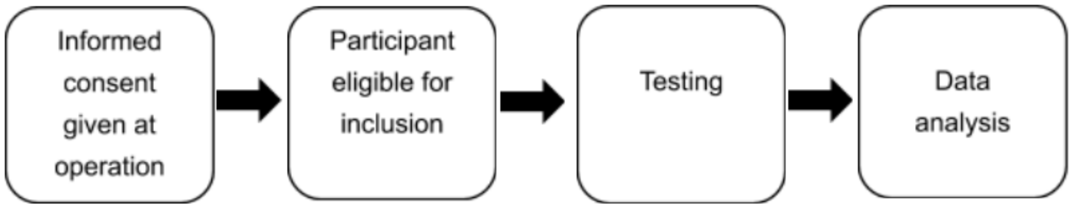

Figure 1: Flow chart of study design

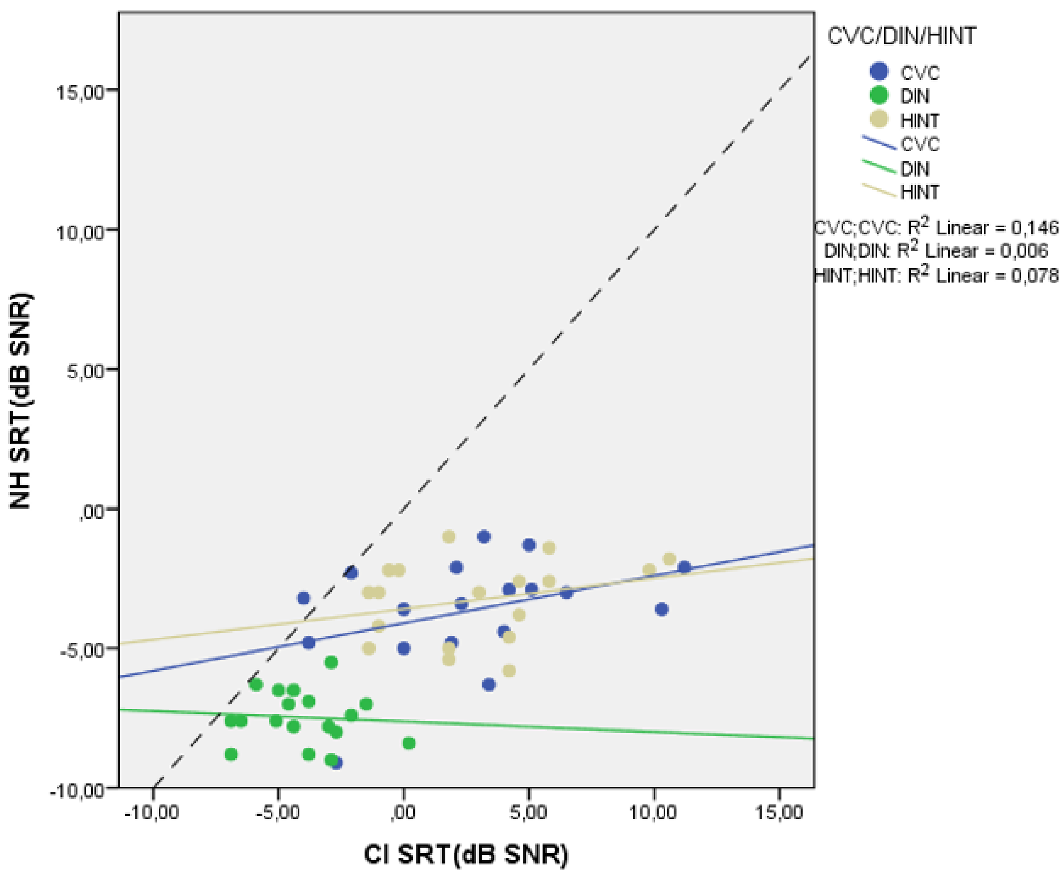

Figure 2: SRT (dB SNR) results of the normal hearing (NH) ear as a function of Cochlear Implanted (CI) ear. Primary SRT results of the CVC in noise, DIN, and HINT test in dB SNR. The blue line represents the regression line for the CVC in noise results. The green line represents the regression line for the DIN results. The beige line represents the regression line for the HINT results. The dashed line represents the diagonal.

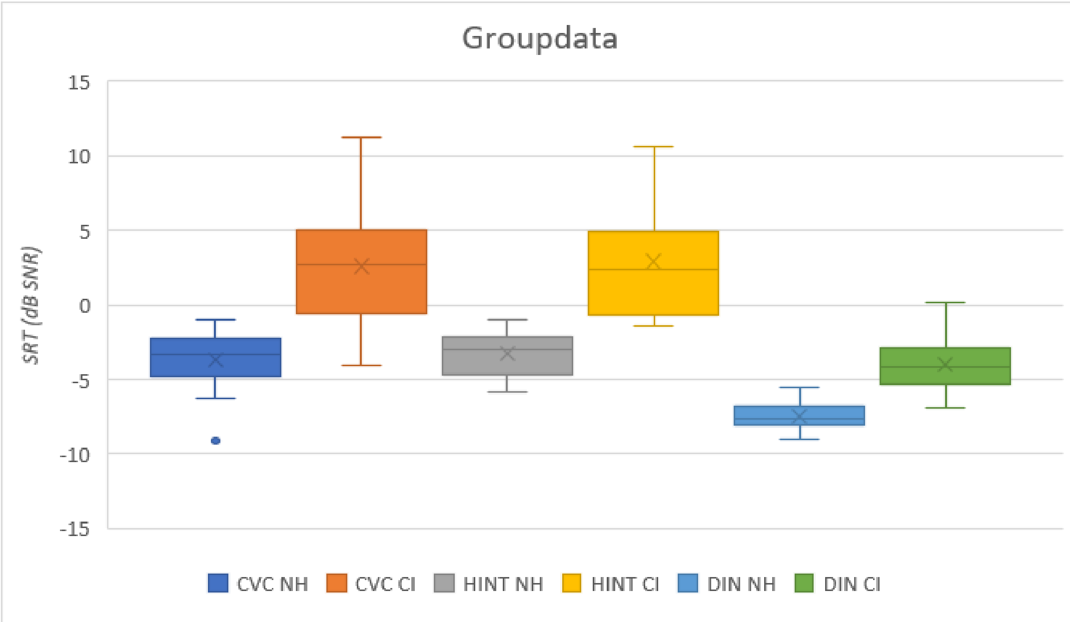

Figure 3: Group data CVC-in-noise, DIN, HINT (SRT (dB SNR)). 18 participants per test. Dark blue represents the results of the CVC-in-noise test for the NH ear. Orange represents the results of the CVC-in-noise test for the CI ear. Grey represents the results of the HINT test for the NH ear. Yellow represents the results of the HINT test for the CI ear. Light blue represents the results of the DIN test for the NH ear. Green represents the results of the DIN test for the CI ear.

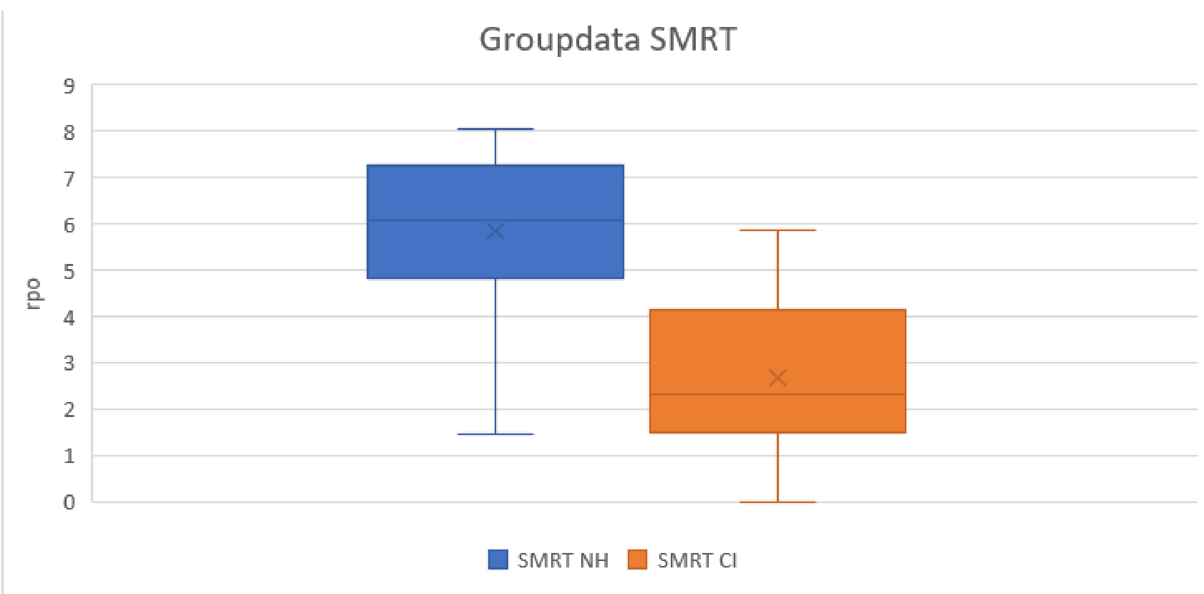

Figure 4: Group data SMRT results. 18 participants per test. Blue represents the results of the SMRT of the NH ear in rpo. Orange represents the results of the SMRT of the CI ear in rpo.

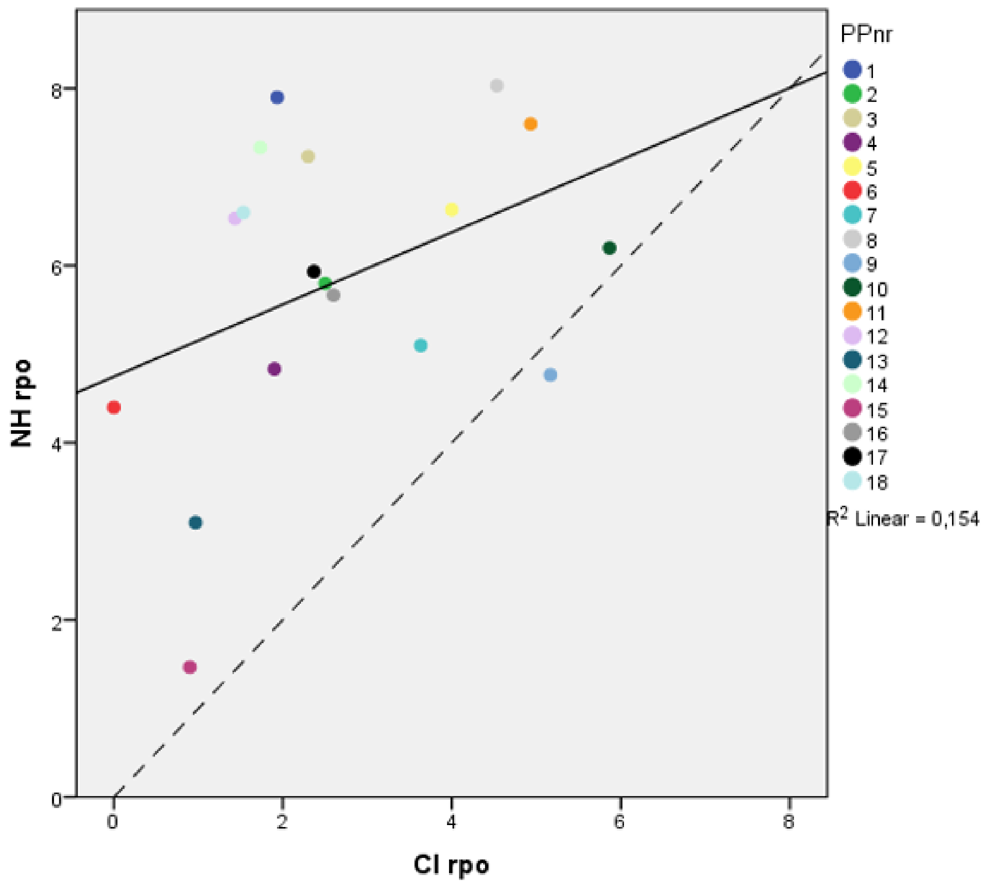

Figure 5: Primary results of the SMRT for both ears in rpo. The continuous line represents the regression line for the SMRT results. Each color represents a different participant. The dashed line represents the diagonal.

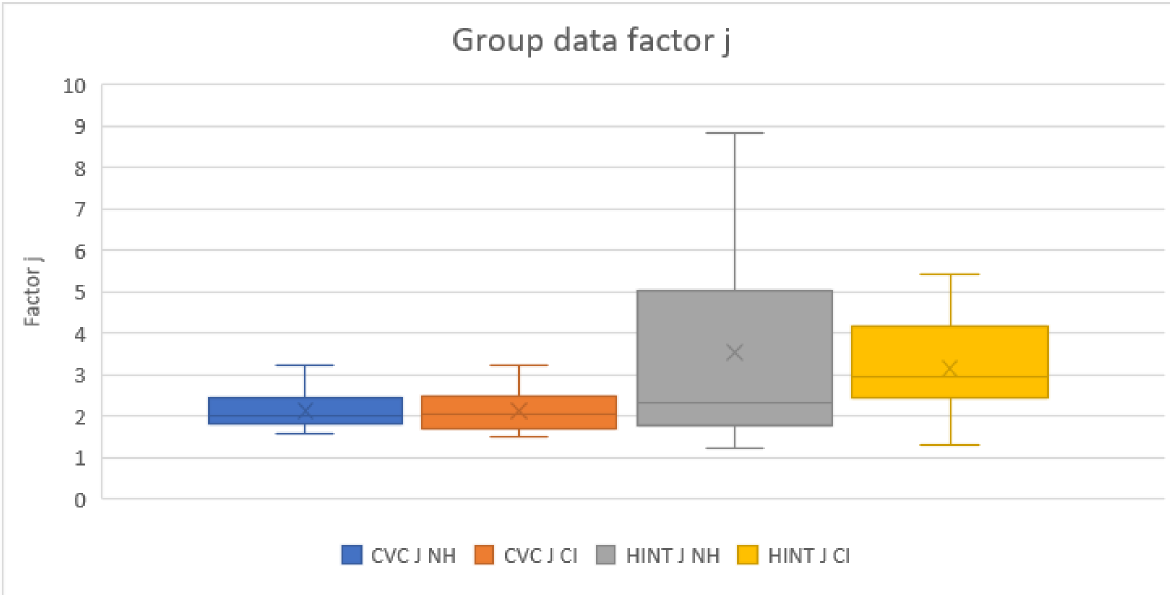

Figure 6: Group data factor j. 18 participants per test. Blue represents the j factor for the CVC in noise of the NH ear. Orange represents the j factor for the CVC in noise for the CI ear. Grey represents the j factor for the HINT of the NH ear. Yellow represents the j factor for the HINT of the CI ear.

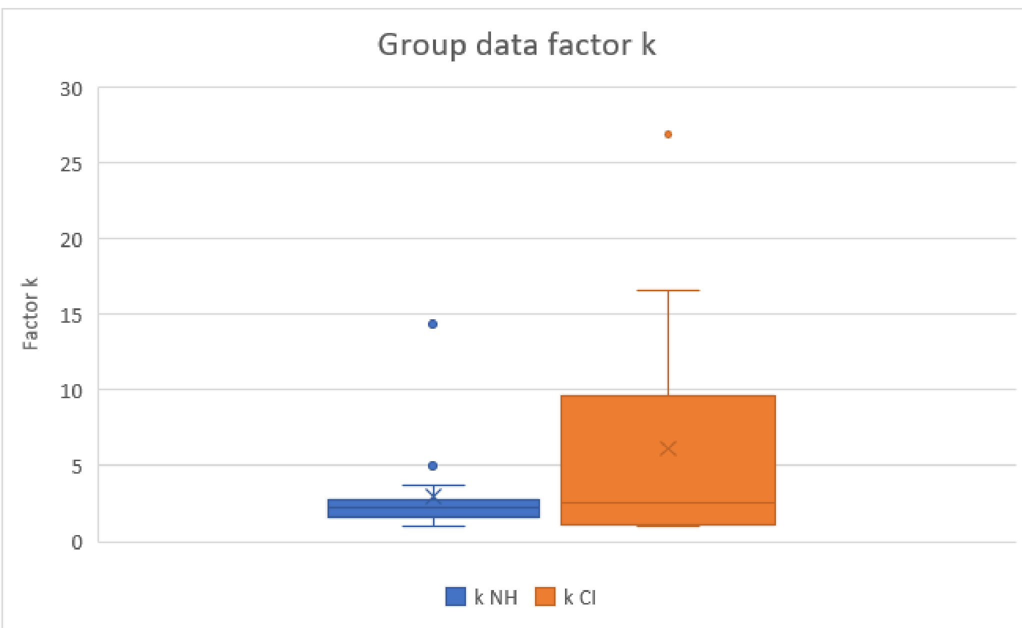

Figure 7: Group data factor k. 18 participants per test. Blue represents the k factor for the NH ear. Orange represents the k factor for the CI ear. The dots in both groups represent outliers.

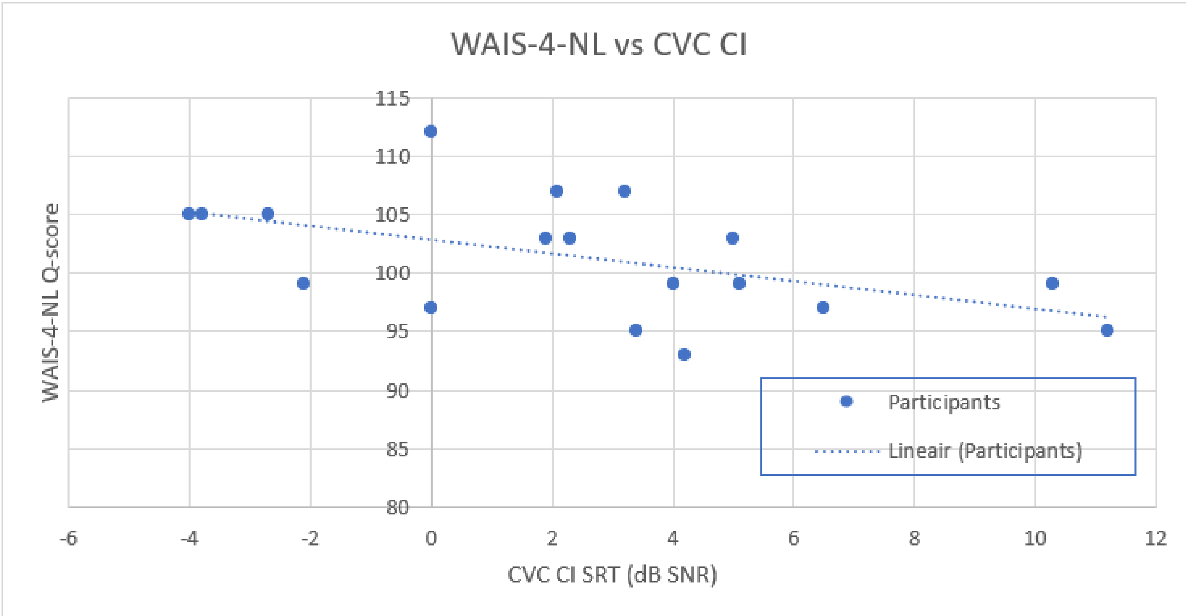

Figure 8: WAIS-4-NL vs CVC CI. The dots represent participants. Also shown is a negative trendline.

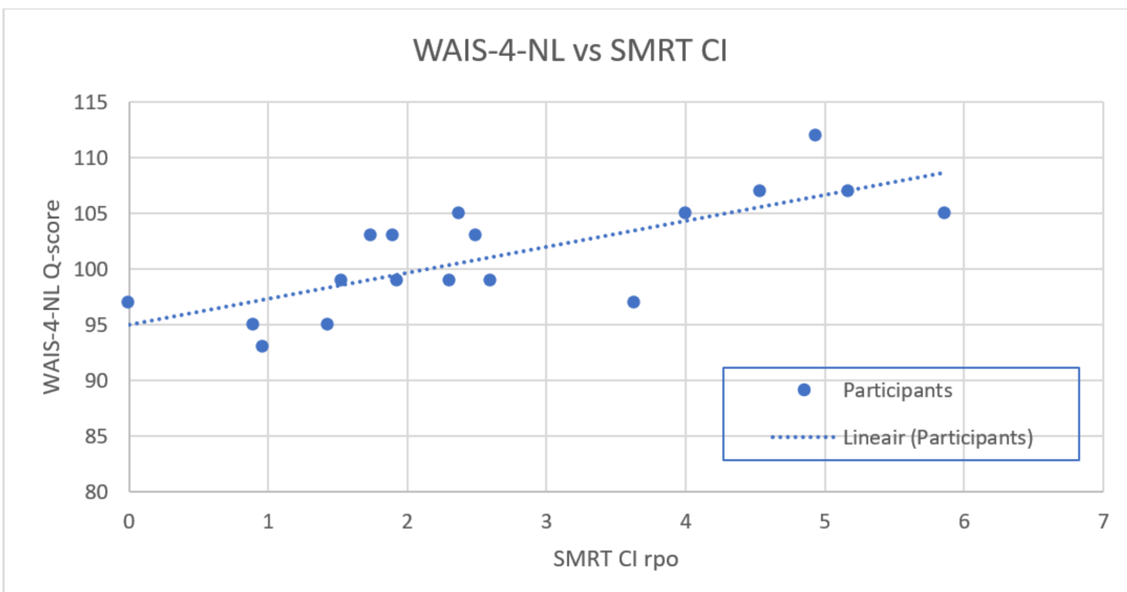

Figure 9: WAIS-4-NL vs SMRT CI. The dots represent participants. Also shown is a positive trendline.

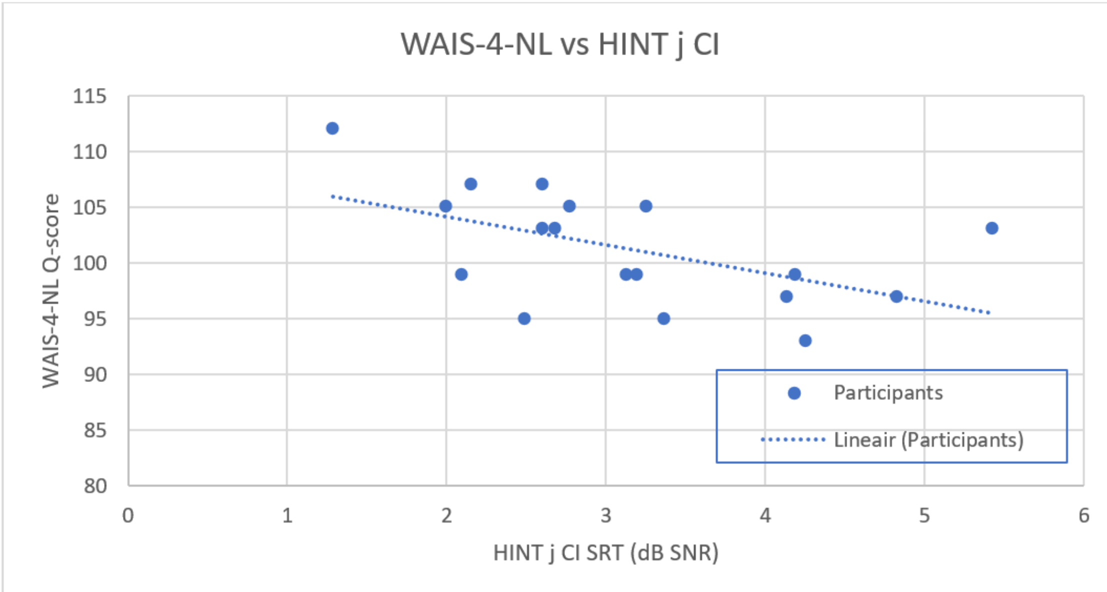

Figure 10: WAIS-4-NL vs HINT j CI. The dots represent participants. Also shown is a negative trendline.

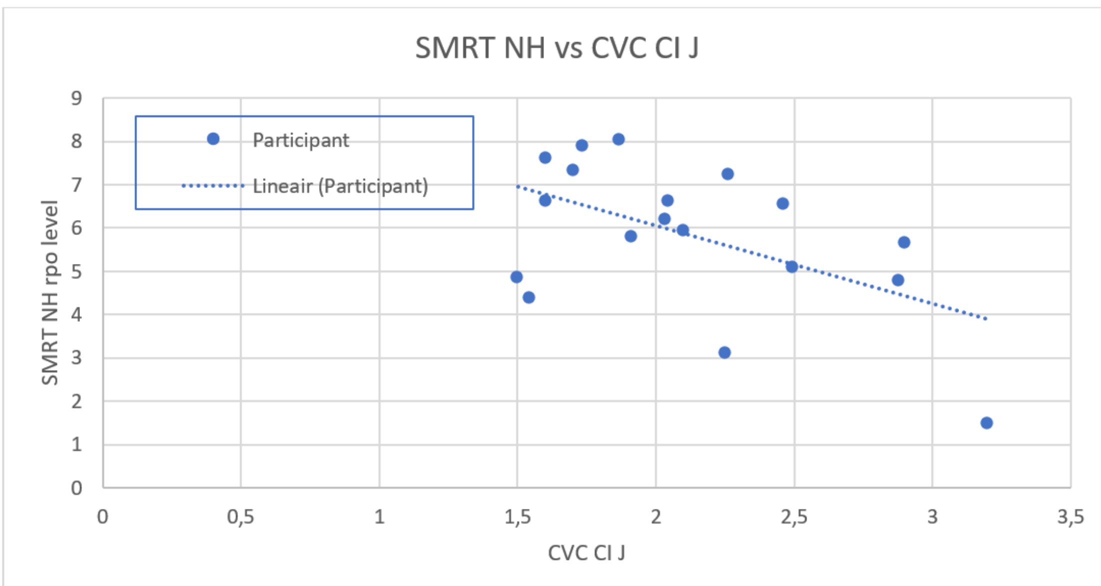

Figure 11: SMRT NH vs CVC j CI. The dots represent participants. Also shown is a negative trendline.

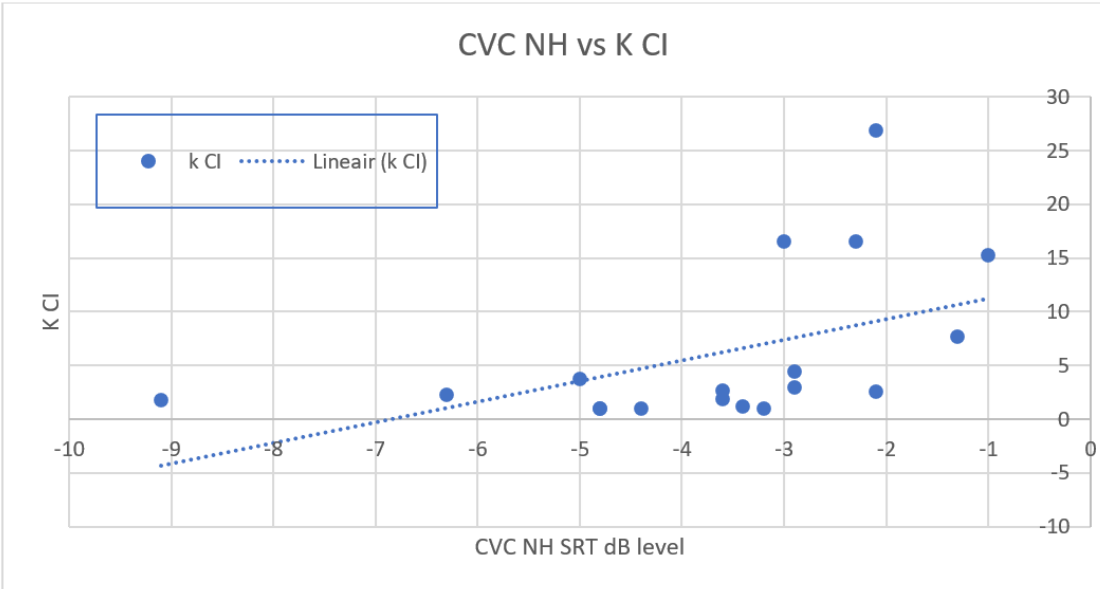

Figure 12: CVC NH vs k CI. The dots represent participants. Also shown is a positive trendline.

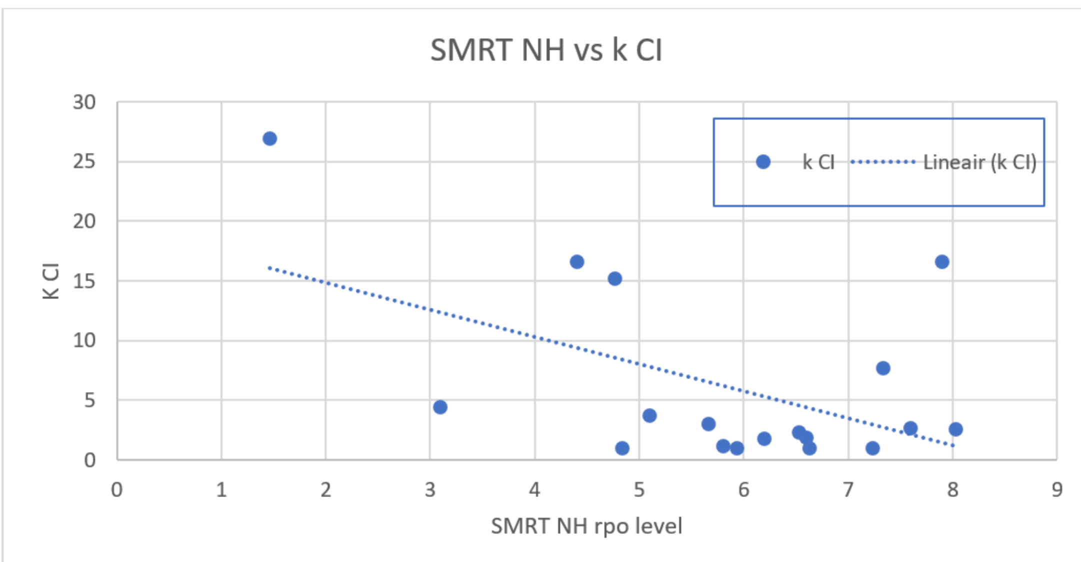

Figure 13: SMRT NH vs k CI. The dots represent participants. Also shown is a negative trendline.