Testing the Speech Perception and Spatial Awareness of Children with a Cochlear Implant in a Virtual Classroom Environment

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Abstract

Introduction: Speech perception in acoustically challenging environments remains challenging for children with cochlear implants. When considering the implementation of an automatic classifier system in the classroom, it becomes crucial to assess the potential advantages against possible drawbacks. Consequently, the central question centers on assessing whether the positive impact on speech perception justifies the potential negative consequences for auditory spatial awareness. In this master's thesis project a new test design was created to evaluate the speech perception and spatial awareness of children with cochlear implants in an ecologically valid classroom environment.

Methods: This master's thesis project aimed to develop a test that was both ecologically valid and reproducible, focusing on the evaluation of three distinct conditions: Autosense on, Autosense off, and a remote microphone. Eligible participants for the study included children with cochlear implants aged between 5 and 18 years. The study utilized a virtual reality classroom environment, incorporating acoustical parameters of a real classroom setting into a 12-array loudspeaker setup. Assessment of frontal speech perception in noise was done with the digits-in-noise (DIN) test, while spatial awareness was assessed through the presentation of animal stimuli from various directions. Additionally, a randomly presented ice cream truck during the session served to evaluate environmental sound awareness (ESA). A pilot study was conducted on students, adults with cochlear implants and normal hearing children to validate the test method and fine-tune the levels of spatial awareness stimuli.

Results: The pilot study validated a virtual classroom setup for speech perception and spatial awareness in children with cochlear implants. Results from 14 participants, consisting of students, normal hearing and cochlear implant individuals, were included for test validation. Initial findings showed clarity in instructions, no adverse effects with virtual reality glasses, and comparable speech-in-noise scores in individuals. Spatial awareness tasks displayed a ceiling effect, leading to adjustments in stimuli levels. Psychometric curves for spatial awareness stimuli levels varied among cochlear implant individuals, complicating the correlation between speech perception and spatial awareness. The test method proved suitable for normal hearing children, highlighting adaptability and ecological validity.

Conclusion: The results of this pilot study indicate the feasibility of the test for children with cochlear implants aged between 5 and 18 years. Regarding spatial awareness levels, it is recommended to use -5 dB and 0 dB SNR, with the goal of reducing the likelihood of floor or ceiling effects.

Abbreviations

AB = Advanced Bionics (Valencia, CA, USA)

ANSI = American National Standards Institute of Acoustics

CI = cochlear implant

DIN = digits-in-noise

ESA = environmental sound awareness

HA = hearing aid

ILD = interaural level difference

ITD = interaural time difference

LTASS = long-term average speech-spectrum

METC = Medical Ethics Assessment Committee

OS = operating system

OSC = Open Sound Control

SA = spatial awareness

SNR = signal-to-noise ratio

SRT = speech reception threshold

VR = virtual reality

Contents

1 Introduction

With the rapid advancements in technology, cochlear implants (CI) have become a groundbreaking solution for those facing severe sensorineural hearing loss. Since the introduction of cochlear implants in the 1960s, people with severe sensorineural hearing loss can partially restore their auditory experiences [1, 2]. A cochlear implant is an electronic medical device that helps individuals with severe to profound sensorineural hearing loss to (partially) perceive sounds again [3]. It consists of both external and internal components. An external microphone positioned behind the ear captures the incoming environmental sounds and conveys them to the speech processor. The speech processor converts the environmental sounds into coded signals using digital coding techniques and filtering, depending on the active program [4]. The processed signals are transmitted to the internal components using a transmitter coil. Internally, the cochlear implants consist of a receiver / stimulator and an electrode array. The receiver / stimulator converts the digital signals into electrical impulses, which are then transmitted to the electrode array. The electrical impulses that are generated by the electrode array directly stimulate the auditory nerve fibers situated in the cochlea. This bypasses the damaged natural hair cells, resulting in a restored auditory perception in individuals with severe to profound sensorineural hearing loss [3]. The internal components are implanted using a surgical procedure. A subperiosteal pocket behind the skin and above the skull is created where the receiver/stimulator package can be placed. With an micro drill the mastoid bone is drilled to reach the cochlea as final destination to place the electrode array [5].

1.1 Auditory perception

The cochlear implant was first introduced in 1957 by Djourno and Eyries [6]. Since the introduction, much improvement has been made in speech comprehension because of enhanced signal processing algorithms, improved electrode arrays and beamformers [7, 8]. Most adults with a cochlear implant experience a better auditory functioning and achieve better performance in speech recognition tests in quiet [9, 10]. However, speech recognition in acoustically challenging environments (i.e. noisy) remain challenging for cochlear implant users. It is said that three bottom up processing limitations are causing these difficulties for users in understanding speech in noisy situations. Firstly, there is the loss of audibility, in which an individual experiences reduction or impairments in their ability to hear sounds at certain frequencies. In contrast to individuals with normal hearing, CI users experience a loss of audibility, leading to a decreased quality of sound perception that may not fully replicate natural hearing. Some users may experience difficulties in perceiving certain frequencies or nuances in sound. Especially in high frequencies where speech sounds are less intense, cochlear implant users experience challenges [11]. Secondly, there is distortion in the signal processing of cochlear implants because of a loss of spectral and temporal processing sensitivity and selectivity compared to normative functionality of a healthy auditory system [12]. This loss affects the user's capacity to effectively extract speech signals in acoustically challenging environments. And lastly, there is less efficient binaural processing [13]. The spatial cues that enable CI users to segregate speech from background noise is not as good preserved as in their normal hearing equivalents. This affects the spatial benefit that CI users can have when comprehending speech. Especially unilateral cochlear implant users experience difficulties when integrating inputs from both ears to identify sound sources [14].

These mechanisms cause CI users to lag behind their normal-hearing equivalents in speech perception in noise, and in auditory spatial awareness. Auditory spatial awareness is defined as "the awareness of the presence, distribution, and interaction of sound sources in the surrounding space" [15]. This includes sound localization, acoustic signal recognition and auditory selective attention. Speech perception in noise and spatial awareness (SA) are of great importance in the development of individuals, contributing to top down processing such as language development and cognitive skills [16]. During childhood the ability to perceive and distinguish speech establishes the foundation for language acquisition. Exposure to different phonemes and the ability to discriminate between them are essential for developing language skills. Strong speech perception skills are linked to better reading and communication abilities later in life [17, 18].

Auditory spatial awareness is also vital for the development of individuals because it contributes to safety, communication, and social interactions [19]. It helps individuals to locate the source of sounds in their environment and thereby play a significant role in effective communication, facilitating more effective engagement in conservations. Spatial awareness becomes crucial in acoustically challenging environments, for example when there is background noise. Binaural hearing can help individuals segregate speech from background noise. Spatial cues such as interaural level difference (ILD), interaural time difference (ITD) and head shadow play a key role in helping the auditory system to effectively segregate signals from noise and comprehend speech [20, 21]. Both speech perception and spatial awareness also play key roles in social development [22, 23]. Effective communication relies on the ability to perceive and interpret speech accurately. Spatial awareness contributes to social interactions by enabling individuals to localize the sound source, switch attention and engage in group activities [23].

Insufficient speech perception in noise and spatial awareness adversely affect the top-down processing of cochlear implant users. Consequently, this further impedes the speech perception, as the fall back on cognitive and linguistic processes becomes unfeasible [24]. Especially young children encounter problems, attributed firstly to a higher SNR needed than adults to understand speech in noise [25]. Secondly, the ubiquity of noisy environments such as the classroom or playground amplifies the difficulties that children with cochlear implants encounter daily [26].

These mechanisms may contribute to reduced cognitive skills such as language and phonological working memory in children with cochlear implants compared to their normal hearing equivalents [27]. A noisy situation that children encounter is the classroom [28]. In the classroom several sources of noise coming from classmates or objects can cause a decrease in SNR and increase difficulties to understand speech. This can affect childrens' educational performances and social interactions [29], but also the integration of children with cochlear implants into mainstream schools [30, 31, 32]. Another problem that amplifies the difficulties for cochlear implant users are the acoustics of a mainstream school classroom. The American National Standards Institute of Acoustics (ANSI) recommends a maximum reverberation time of 0.6 seconds in an unoccupied, furnished classroom with volume under 10,000 cubic feet (283 m3) [33]. However, mainstream schools often do not meet the requirements for acoustics as described by ANSI. In conclusion, challenges remain to integrate children with cochlear implants in mainstream schools and to minimize cognitive problems and educational deficits [34] . Several programs and settings specifically designed for children to encounter these problems are developed and used in practice.

One solution for a better speech understanding in the classroom is the remote microphone which can be placed on the teacher during teacher-led instruction. Employing these systems can potentially yield an improvement of 15-20 dB compared to using a hearing aid alone [35]. Consequently, remote microphone technology emerges as the optimal solution for enhancing speech perception in noise, especially in scenarios where the primary talker (e.g. teacher) remains consistent over an extended period. However, only in 22-35% of the school time the teacher is instructing, while 34% is dedicated to group work and interactive lessons, with several sources and directions of interest [36]. The remote microphone might not provide the same advantage when placed in a group. While directional microphones may be less effective than remote microphones during frontal instruction or individual work [37], they could prove beneficial during group sessions by enhancing the signal-to-noise ratio (SNR) [38]. A directional microphone is designed to be more sensitive to sounds arriving from the front than sounds coming from behind, effectively reducing background noise [39]. Yet, challenges still emerge during group work, as children need to shift attention when someone else speaks. The effectiveness of off-axis attenuation in directional microphones becomes crucial, as too much attenuation could hinder children's ability to detect and decide if a new speaker requires attention. Hence, there are situations when the directional microphone is not beneficial and manually switching to an omnidirectional microphone mode is recommended. However, figuring out the optimal program for specific situations can be challenging for cochlear implant users [40].

Addressing the challenge of manual mode-switching, especially for children, Phonak / Advanced Bionics developed an automatic classifier system that analyzes the acoustics of the user's environment every 0.4 seconds to determine the type of listening situation. The sound processor (Sky CI M) is specifically suited for children's listening situations. Compared to the adult version, the pediatric variant aims to better classify group work as 'speech in noise' and identify yelling and shouting as unwanted noise [36]. Notably, the pediatric version activates the directional mode at lower sound levels, facilitating a quicker transition than its adult counterpart [36]. The AutoSense Sky OS 3.0 operating system is "uniquely designed with typical children's listening situations in mind, adjusting and optimizing the child's sound processor automatically wherever they go" [41]. For the environment, the classifier selects the optimal settings (i.e. noise management settings) in order to theoretically improve the hearing performance of the child [42, 43].

In assessing the potential advantages and drawbacks of implementing the classifier in noisy environments such as the classroom, it's essential to weigh the potential benefits against the possible risks. The improvement in speech perception, particularly from the teacher, is a noteworthy advantage that the classifier may bring. On the other hand, the potential reduction in auditory spatial awareness raises concerns. The classroom environment often demands spatial awareness for various activities and interactions. If the classifier compromises this aspect significantly, it could have adverse effects on overall learning and engagement. Therefore, the central question revolves around determining whether the positive impact on speech perception justifies the potential negative consequences for auditory spatial awareness. A comprehensive evaluation of these factors is crucial to make an informed decision about the implementation of the classifier in a classroom setting. Therefore, the Department of ENT in the Erasmus MC initiated a research project together with Advanced Bionics, that will investigate the potential benefits and clinical relevance of this new automatic classifier system in a classroom setting, also considering potentially reduced auditory spatial awareness and relevant environmental sounds. A part of the study will be executed in a virtual classroom environment in which children with CI will experience realistic situations in order to measure speech perception in noise and spatial awareness in an ecologically valid way.

2 Objectives

The research project initiated by the Department of ENT in the Erasmus MC has as primary objective:

- Gaining insight in the potential benefit and clinical relevance of the automatic classifier AutoSense Sky OS in various acoustic conditions for children using Naida CI Sky.

Secondary objectives are:

- Investigate the behavior of the AutoSense Sky OS classifier in different realistic listening situations with a technical evaluation (part 1)
- Compare the auditory functioning of children with Naida CI Sky with the AutoSense Sky OS switched on and off (part 2).

This master's thesis project will specifically focus on:

- Creating a ecologically valid classroom setting in Virtual Reality (VR).
- Design a test method that evaluates both frontal speech perception in noise and spatial awareness.
- Validate the test method on normal hearing children and adults with a cochlear implant.

3 Methods

3.1 Development of a new test method

To gain insight in the potential benefit and clinical relevance of the automatic classifier AutoSense Sky OS in a classroom setting for children using Naida CI Sky it was necessary to develop a new test design. This design aimed to evaluate the AutoSense Sky OS on both frontal speech perception and spatial awareness from various directions in a classroom setting. The trade off between the perception from the front and the spatial awareness from other directions can provide valuable insights into the feasibility of an automatic classifier system in situations that children may encounter such as a classroom. It was determined that the automatic classifier was compared to two additional CI program settings, the AutoSense off (standard parameter settings of 'calm situation') and the incorporation of a remote microphone. The main study is divided into four sessions spanning across two scheduled appointments (figure 1). The AutoSense off condition and the remote mic condition are evaluated in the first appointment with the newly designed test method. Subsequent to the first appointment, there are two instances of a 2-week take-home period for both the conditions AutoSense on and AutoSense off. Using questionnaires, both conditions are evaluated after the take-home period. It is not expected to observe learning effects, as the changes to the normal user programs are small, which also justify a period of only two weeks per condition. At the second appointment, the two conditions are evaluated in the newly designed test method. The differences in frontal perception and differences in spatial awareness between the conditions provide insights in the potential benefits and clinical relevance of the automatic classifier system. The order of the tested conditions is randomized and blinded for each participant.

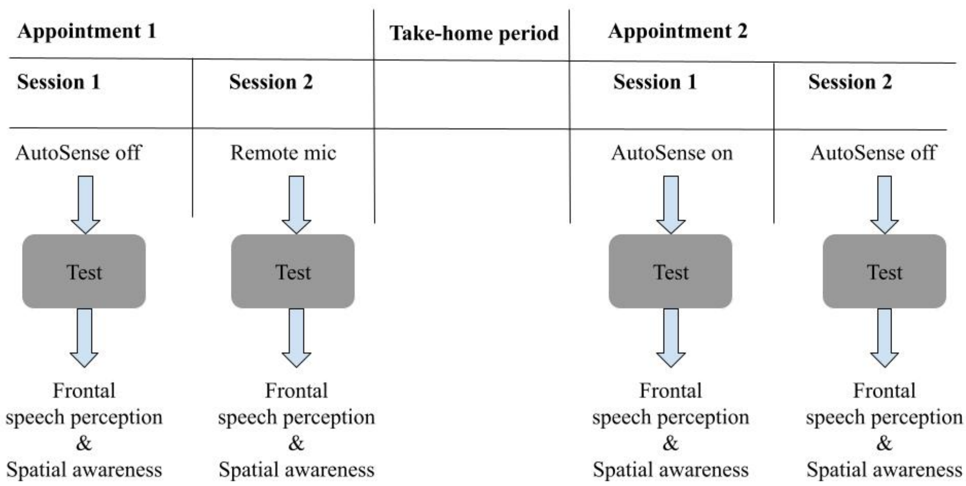


Figure 1: The study is divided in two appointments in which three CI conditions are evaluated. This master's thesis project focused on developing and validating a new test to evaluate these conditions.

The primary objective of this master's thesis project was to create a new test design in an ecologically valid virtual reality classroom setting for the comprehensive evaluation of speech perception and spatial awareness of children with cochlear implants. In the following paragraphs I elaborated upon crucial factors that were considered during the development of a test method that needs to be both reproducible and ecologically valid, focusing on:

- Study population
- Sensitivity and ecological validity
- Frontal speech perception in noise
- Spatial awareness
- Environmental awareness

3.1.1 Study population

Participants eligible for this study are children aged between 5 and 18 years with a Sky CI M cochlear implant with the AutoSense Sky Operating System (OS) of Advanced Bionics. Participants are recruited through the department of ENT in the Erasmus Medical Center in Rotterdam with the following inclusion criteria:

1. Participants have made use of cochlear implants longer than six months.
2. Speech perception in quiet $\geq$ 70% correct responses at 65 dB SPL.
3. No additional disabilities that interfere with VR evaluation

Study participants are excluded if there is a history known of vision impairments related to perception of 3D through VR glasses, or if the participant has a medical history of epilepsy. In examining this study population, it's crucial to consider factors such as attention span and adaptability, particularly among the youngest and oldest age groups. The test design needs to strike a balance, avoiding excessive length to prevent concentration from influencing speech perception and spatial awareness outcomes. At the same time, it should be sufficiently long to yield robust results from the tests. Additionally, the entertainment level of the virtual reality setting plays a key role in maintaining attention span and should be engaging and relatable across all age groups.

3.1.2 Sensitivity and ecological validity

The study design is structured as a double blinded crossover study, assessing three different CI conditions on frontal speech perception in noise and spatial awareness within a classroom setting for children with cochlear implants. Therefore, it is essential for the new test method to be reproducible and achieve a high test-retest reliability and sensitivity. This requires a controlled laboratory setting where all parameters can be controlled. However, it is also important to achieve high ecological validity, because then the results can provide insights that accurately represent real-world scenarios. Virtual reality (VR) technology has the potential to provide a realistic visual environment that can simulate that of an actual space such as a classroom while maintaining the controlled acoustic environment available in a laboratory [44]. Hence, in this master's thesis project a virtual classroom setting with realistic acoustical and virtual parameters should be created to assess the potential benefits of the AutoSense Sky OS in a classroom.

3.1.3 Frontal speech perception in noise

In this new test method, a evaluation method to assess the frontal speech perception in noise of participants should be incorporated. The evaluation method used to assess the frontal speech perception in noise can also influence the ecological validity of the test. As was described in the literature study, there are several speech in noise tests that vary in structure, complexity, level of context and presentation. Two Dutch tests that were mentioned in the retrieved articles that are already available, feasible and reliable for children were the Dutch Digits-In-Noise (DIN) test and the Oldenburg Sentence Test [45, 46]. The Dutch DIN test is easy to use, no major age related effects are observed and requires less vocabulary knowledge. However, it lacks the ecological validity that the Oldenburg Sentence Test has. Still, for a speech in noise assessment which focus mainly on the auditory aspect I would recommend the Dutch DIN test, because it is easily comparable within an individual and is already a common test in clinic for children with cochlear implants. Yet, to obtain higher ecological validity, it is recommended to replace the long-term average speech spectrum (LTASS) noise utilized in the DIN test with more authentic classroom noise.

3.1.4 Spatial awareness

Another auditory parameter evaluated in the classroom is the spatial awareness of the participant. In a classroom setting it is crucial that not only target speech from the front is evaluated, but also target / speech coming from other directions. An automatic classifier system in a cochlear implant may give the advantage to cancel noise out from various directions and only focus on target speech from the front, which might lead to a better frontal speech in noise perception. However, a disadvantage is that spatial cues are not preserved, while children with CI can still benefit from these. In particularly, the auditory selective attention and spatial awareness could be affected, because of the lack of other directional input.

As mentioned in the literature study, no existing literature is available specifically evaluating spatial awareness. Therefore, a new task has to be designed for this study to evaluate the participants' awareness of surroundings with and without the AutoSense Sky OS. Two studies can serve as a foundation for the design of the new test. Wolfe et al. (2017) investigated the net benefit in speech perception from the front compared to the back, examining with an adaptive noise management program and the basic program [47]. This trade-off between the enhanced speech perception from the front and decrement in speech from the back can be used as a foundation for the new task. Loh et al. (2022) provided groundwork for the spatial awareness stimuli coming from various directions [48]. Their study involved simultaneously presenting two stimuli from different loudspeakers to assess the auditory selective attention. In our study the focus is to evaluate the spatial awareness by observing whether the stimulus was detected when presented from a random direction. Instead of two simultaneously presenting stimuli, one single stimuli can be presented from a random direction to assess the spatial awareness.

3.1.5 Environmental sound awareness

Lastly, the incorporation of a environmental sound awareness (ESA) task is required. Environmental sounds can be defined as non-speech, non-musical sounds in the listener's surroundings that convey information about places, objects, and actions [49]. These sounds can help listeners navigate their surroundings, warn of potential dangers, and provide a sense of aesthetic satisfaction. Examples of environmental sounds in a classroom are the school bell or an alarm sound. In the new test method, a scenario should be incorporated that simulates an environmental sound. For example, a school bell is triggered on an unexpected moment to evaluate the participants' responsiveness and alertness.

3.2 Implementation of the new test method

In this master's thesis project the new test method in VR was designed and validated in a pilot study. After test validation and METC approval, the test method can be incorporated into the main study to evaluate the potential benefits of an automatic classifier system. This paragraph describes the intended test setup, technical details of the test and test methods.

3.2.1 Test setup

In this crossover study three different conditions are compared to evaluate which cochlear implant setting performed best for children in a classroom setting. Below, there is a description of the technical details for each condition.

Condition A: AutoSense on
Autosense Sky OS is the operating system of the Advanced Bionics cochlear implant that enabled the automatic classifier of the speech processor. The speech processor used Phonak's / AB Autosense system, which is an automatic classification system to identify external sounds and re-optimize the settings every 0.4 seconds for the environment in which the person is located. This is done by amplifying the relevant (speech) signal and suppressing disturbing sounds, which improves functioning with the CI. The Advanced Bionics classification system has been specially developed for sound situations in which children often find themselves.

Condition B: AutoSense off
In the AutoSense off condition, the Autosense Sky OS system is deactivated. This means that cochlear implants switches to a 'calm situation' program. In this state, the microphone mode becomes omnidirectional, capturing sounds from all directions.

Condition C: Remote microphone
In this condition, the Advanced Bionics' remote microphone Roger^{TM} device was added to the loudspeaker setup. A remote microphone served as an additional input audio device to enhance speech perception, particularly in challenging acoustic environments such as a classroom. It captured and transmitted the input signals from the remote microphone directly to the processor of the cochlear implant, thereby enhancing signal clarity and decreasing the impact of environmental noise. The remote microphone was positioned remotely from the cochlear implant processor and was typically placed in proximity to the sound source of interest. It was determined that in a classroom setting, the sound source of interest was the teacher. Hence, the remote microphone was placed on the teacher's shirt neckline in virtual reality. A virtual microphone (that simulated the remote microphone) was implemented in Tascar [50], transmitting the analog signal to the Roger docking station through sound card audio input. In the virtual reality laboratory setting, the remote microphone was technically implemented in the loudspeaker setup without reverberation and reflections.

Loudspeaker setup
The speech perception in noise and spatial awareness were assessed using a 12 loudspeaker array with 30 degrees distance in between and placed at head level 1 meter from the participant. The reverberation

time was implemented in the loudspeaker output using convolution. The loudspeaker system was controlled with Tascar software, which was connected to the main Matlab script using Open Sound Control (OSC). Loudspeakers were calibrated with a decibel meter positioned at the participant's location in the center of the loudspeaker arrangement. The classroom noise file was played through the loudspeakers and was adjusted to achieve a level of 65 dB SPL, as measured by the decibel meter. Moreover, DIN triplets and spatial awareness stimuli were calibrated in Matlab, with a decibel meter placed on the participant's location as the reference.

Figure 2: 12-array loudspeaker setup with 30 degrees distance in between.

Virtual acoustical environment

A classroom setting was simulated using virtual reality (VR), incorporating the loudspeaker setup to create audiovisual integration. Audio components were derived from recordings obtained in a real classroom during a working session of a fourth grade cohort. An omnidirectional Ambisonics microphone was positioned near the participant's intended table in the test, capturing a 30-minute session. The recording was then post-processed to a classroom noise fragment of 2 minutes with an LAeq weighted average of 65 dB SPL. The aim of the post-processed recording was to mimic a multi-talker background noise in which no individual conversations could be identified. Furthermore, additional point sources were introduced into the classroom setting to replicate sounds such as door openings and pen scribbling.

The reverberation time was calculated using room impulse responses recorded in an empty classroom. A reverberation time of 0.41 seconds was derived from the measurements. By optimizing all recorded impulse responses, it was determined which settings for gain, absorption and damping matched the measured reverberation. It was found that different combinations of gain, absorption and damping could achieve the same reverberation time T60. Despite achieving the same T60, each combination resulted in a distinct sound output. Therefore, an acoustically expert meticulously assessed three different combinations by listening in the intended setup, selecting the one with the best ecologically validity.

Virtual visual environment

For the visual part of the classroom setting, the dimensions of the classroom and associated attributes were measured to implement in the virtual reality environment. The environment was created in Unreal Engine 4, a real-time 3D creation tool for immersive experiences. The participant was placed at a table in the center of the classroom at 2 meter from the teacher (see figure 3. This placement ensured the perception of not only direct sound, but also the incorporation of reflections. Reflections of the wall and tables were included in the loudspeaker setup. A teacher was placed in front of the classroom and 29 classmates were placed on the remaining seats. Five classmates were selected as a potential sound source for the spatial awareness stimuli. These classmates were sophisticatedly designed in MetaHuman with the capability of speech. Speech was animated through live recordings made in Faceware Studio. The remaining classmates were created in MakeHuman with reduced abilities to minimize the computational demands during the rendering process.

The visual setup utilized an HTC Vive Pro head-mounted display and the participant was provided with two physical remote controls which were also visualized in VR. Response times upon pressing the button on the back of the remote were recorded in the datalogging and used for further analysis. A jitter of 4 milliseconds was computed between Unreal Engine and Tascar's datalogging, which was well below typical reaction times of approximately 250 ms. This ensured an accurate measurement of the reaction time.

3.2.2 Test methods

To assess speech perception, the digits-in-noise (DIN) test was used, while a new test was developed to evaluate spatial awareness.

DIN test

The frontal speech in noise perception was evaluated with the digits-in-noise (DIN) test. The DIN test utilized a set of 120 unique digit triplet combinations constructed from the digits 0 to 9 uttered by a male speaker and separated by silent intervals. Typically, the stimulus signal was mixed with stationary long-term average speech spectrum (LTASS) masking noise. However, for this study the stationary LTASS noise was replaced by classroom babble noise in order to comply for ecological validity of the test. The DIN triplets were separated from the LTASS noise and calibrated again, after which MATLAB controlled the loudness steps. The recorded classroom noise was adjusted and compressed to minimize great variabilities. After adjustments, a variability analysis was executed in MATLAB to check for variabilities in the classroom noise signal.

The child's task was to repeat all three digits correctly after each presented triplet. The speech reception threshold was determined by varying the SNR adaptively according to the correctness of the response following the standard one-up down procedure with a step size of 2 dB. When the first triplet was not correctly identified, it was repeated with an increase of 4 dB until a correct response was obtained. Only when the first triplet was repeated consistently, a second triplet was presented. The DIN SRT was calculated by taking the average of the trials 5 to 24. Each participant was exposed to a random list containing 24 triplets for each condition. The DIN triplets were presented at 0 degrees azimuth to mimic a teacher. Classroom noise was continuously presented from all directions to mimic classmates. In VR, the teacher was standing at a distance of 2 metres from the participant.

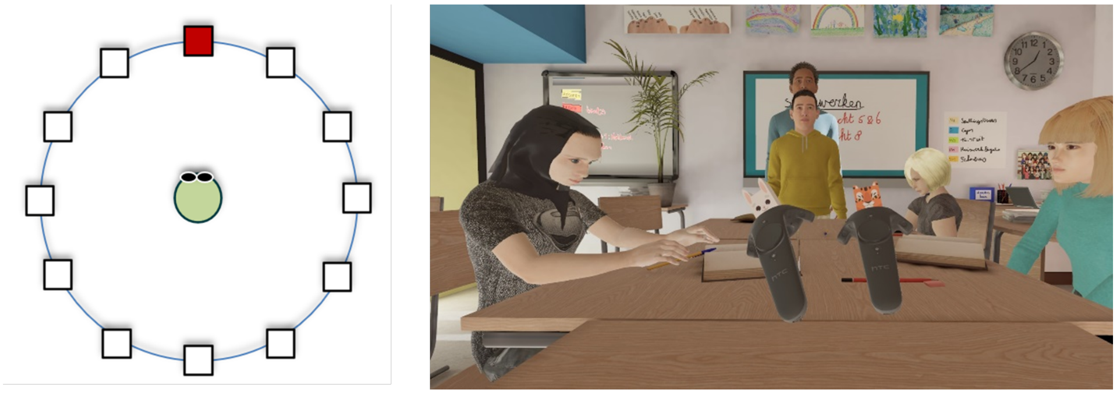


Figure 3: The setup for the DIN test. The DIN triplets were presented from 0 degrees azimuth representing a teacher in VR. In the VR environment, the teacher's mouth uttered incomprehensible triplets.

Spatial awareness task

To obtain ecologically valid outcomes of the cochlear implant performances it was not only important to evaluate the speech from the front, but also the spatial awareness from other directions. Therefore, a new task was specifically designed for this study based on studies of Wolfe et al. and Loh et al. [47, 48]. In this task, one stimulus signal was randomly presented from a loudspeaker. The child's task was to identify which animal was presented using two remote controls, also presented in the virtual reality environment. The stimulus signal consisted of a two-syllable animal name, either "konijn" (rabbit) or "tijger" (tiger). Animals were chosen because of universality and reproducibility of the test. The stimuli were delivered by a female child speaker positioned at 0, +-90, +-120 or 180 degrees, representing classmates (figure 4). Each angle and stimulus level featured presentations of the two items (tiger or rabbit), resulting in a total of 24 items per condition, akin to the number of items for the DIN test. The outcome measure for the spatial awareness task comprised the identification scores of target words. These scores could be categorized into two percentages: the percentage of observed stimuli and the percentage of correctly identified stimuli. The percentage of observed stimuli served as an indicator of the participants' spatial awareness, while the accuracy of providing correct responses indicated the speech perception from different directions. Additionally, response times were obtained from the remote controls.

Because no SNR levels were known in existing literature for this spatial awareness task, it was determined that in this pilot study the SNR levels were established and evaluated for the study. Accordingly, SNR levels of 5 and 10 dB SNR were designated for normal hearing children and 0 and 5 dB SNR for CI children. After the pilot study a critical assessment was undertaken to evaluate the SNR levels for the main study, with the specific attention to the potential presence of a ceiling effect.

Figure 4: The setup for the SA test. The animal stimuli ('konijn' or 'rabbit') were presented from 0, ±90, ±120 and 180 degrees azimuth. Stimuli were presented by classmates in VR.

Figure 5: The setup for the environmental sound awareness test. The sound was presented from 90 degrees azimuth animal stimuli. Participants could achieve a visual reward when looking in the right direction.

Environmental sound awareness

To evaluate the environmental sound awareness of each condition, a bell of an ice cream truck was presented once during each session. Randomly between the 10th and 30th trial a 3 second fragment of an ice cream bell was played from 270 degrees (right from participant). Reflections and reverberation of the bell sound were included in the loudspeaker setup. As a reward for looking in the right direction, an ice cream was placed in the virtual classroom at 270 degrees (figure 5). The investigator recorded their observations in an input dialog for later assessment. Furthermore, head movements served as outcome measure for environmental awareness.

Combined test method

To acclimatize the participant to the test protocol, it was determined to include two training sessions during the first appointment. The first training session consisted of five digits-in-noise (DIN) triplets presented adaptively. In the second training session, an additional five stimuli regarding spatial awareness were introduced. Following the training sessions, the testing phase for a particular condition commenced, as shown in figure 6. For each condition, both the DIN test and Spatial awareness test were run simultaneously, with a randomization determining whether a DIN test item or a Spatial Awareness item was presented. It was decided to limit the consecutive presentation of a DIN item or spatial awareness item to a maximum of four times. Moreover, the order of the tested conditions were also randomized for each participant.

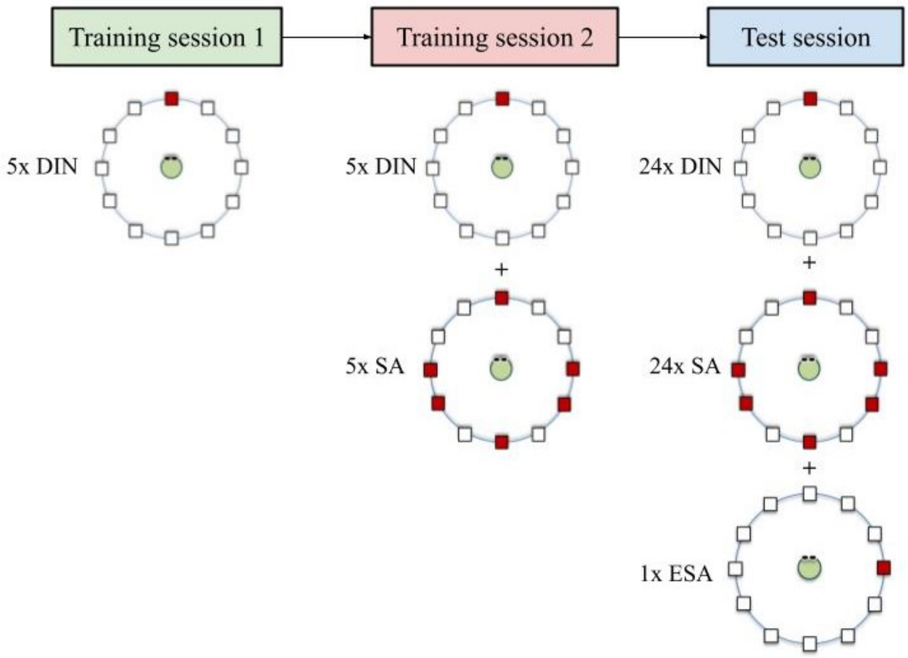


Figure 6: The combined test setup. In the test session 24 DIN triplets, 24 SA stimuli and 1 environmental sound were presented randomly to the participant.

3.2.3 Pilot study

Given the absence of established values for the spatial awareness task, it was decided to conduct a pilot study. This was intended to validate the test setup and refine the parameters employed for the spatial awareness task. Students, normal hearing children and adults with a cochlear implant were enrolled for this pilot study. For the cochlear implant individuals the specific inclusion criteria comprised individuals in their 4th adjustment or beyond and preferably, with a speech perception in quiet exceeding 80%. Patients were excluded if the investigator assessed that their technical proficiency was not sufficient enough to comprehend the VR (remotes).

One single session consisting of two training sessions and one test session were conducted on the participants. Similar to the main study, the DIN test and spatial awareness task were randomly presented to the participants. Different stimulus levels were introduced during the session to determine the optimal values for the spatial awareness task. In cochlear implant adult it was determined to derive psychometric curves to find optimal values for the spatial awareness stimuli. Stimulus levels of -5, 0, 5 and 10 dB SNR were chosen, each presented three times from 90 degrees and 270 degrees. Afterwards, a psychometric curve was generated from the % spatial awareness (SA) identification scores. Outcomes of these psychometric curves were used to determine two values to present the spatial awareness stimuli. Furthermore, possible relations between the DIN outcome and spatial awareness outcomes were evaluated. The findings from the pilot study were presented and extensively discussed in this master's thesis project with the aim of gaining insights and refining the test methodology.

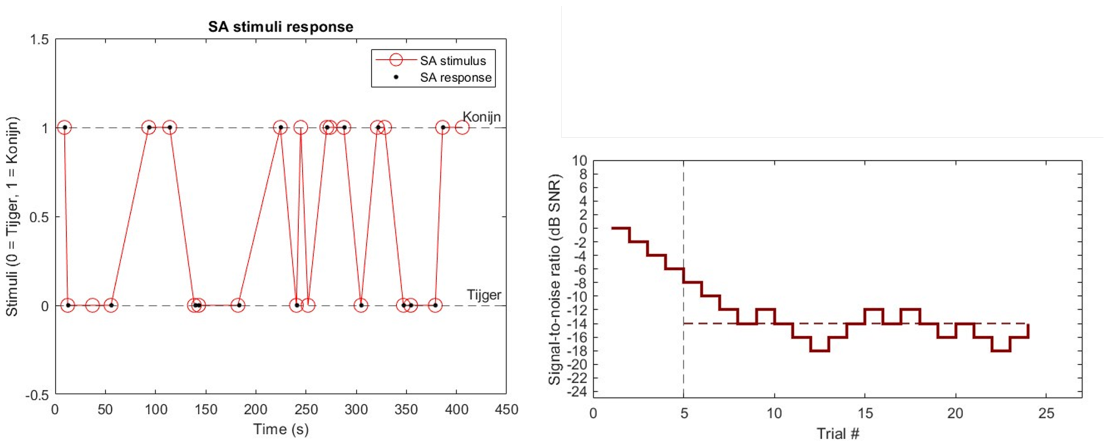
4 Results

The results section in this thesis presented the findings of the pilot study. The results were divided into three measured groups: Students, adults with cochlear implants and normal-hearing children.

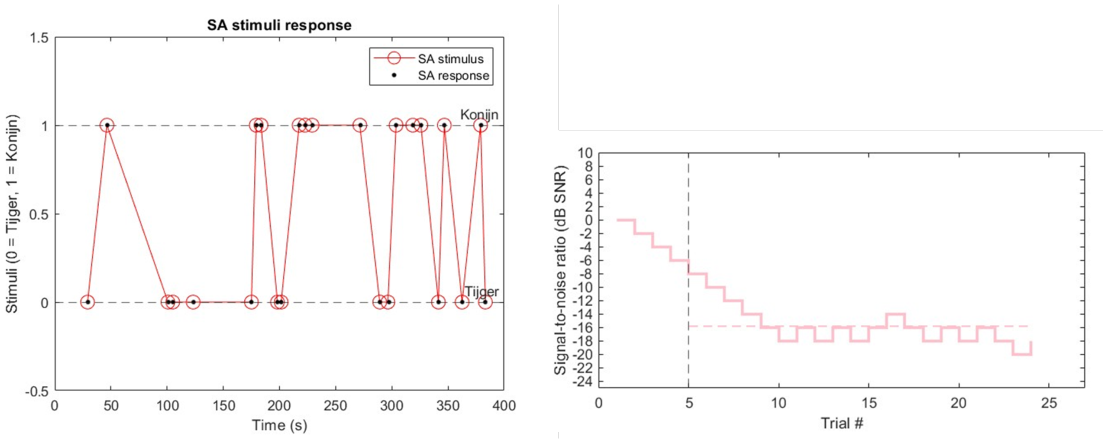
4.1 Test validation on students

Firstly, the designed test setup was assessed on two students. In an empty virtual classroom the DIN triplets (24 trials) and spatial awareness task (24 trials) were randomly presented to the students. Spatial awareness stimuli were presented at -5 and -10 dB SNR.

Student 1 achieved an average DIN SRT of -14 dB SNR, with spatial awareness (SA) identification scores of 83% at -5 dB SNR and 67% at -10 dB SNR (figure 7a. Student 2 achieved an average DIN SRT of -15.8 dB SNR, and achieved a perfect SA identification score of 100% at both SNR levels, as shown in figure 7b.



(a) Student 1



(b) Student 2

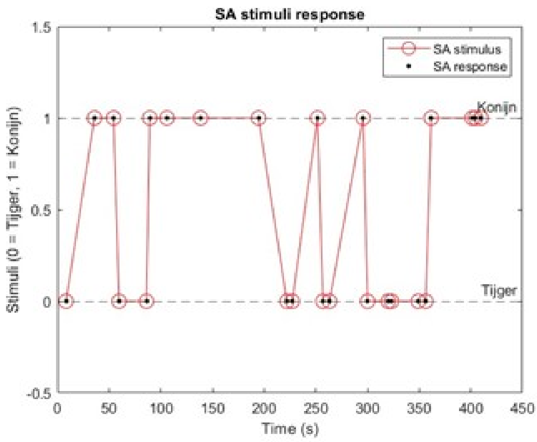
Figure 7: On the left: spatial awareness stimuli responses of two students. If the red circle contained a black dot, the animal stimuli was observed by the student. On the right side, the signal-to-noise ratios of each DIN trial.

4.2 Test validation on adults with cochlear implants

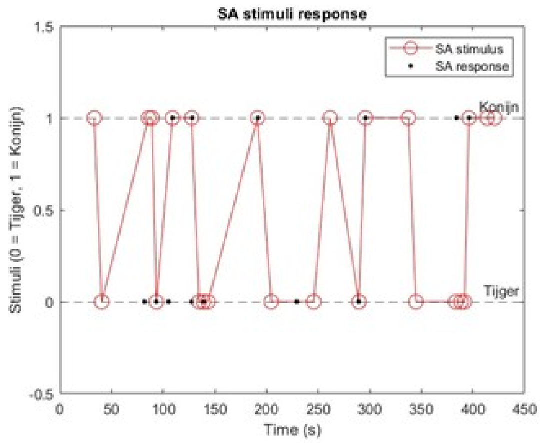
Three adults with a cochlear implant (CI) met the inclusion criteria and underwent testing within the experimental setup, assessing spatial awareness levels at 5 and 10 dB SNR. One subject was excluded due to a wrong interpretation of the spatial awareness task and time limitations.

Adult 2 was a young adult with a cochlear implant on the left side with an average DIN SRT score of 1.8 dB SNR, together with an SA identification score of 100% at stimuli levels of 5 and 10 dB SNR, shown in figure 8a.

Adult 3 was a participant with a cochlear implant on the right side, and achieved an average DIN SRT score of -2.8 dB SNR with SA identification scores of 33% at 5 dB SNR and 42% at 10 dB SNR (figure 8b).



(a) Adult 2



(b) Adult 3

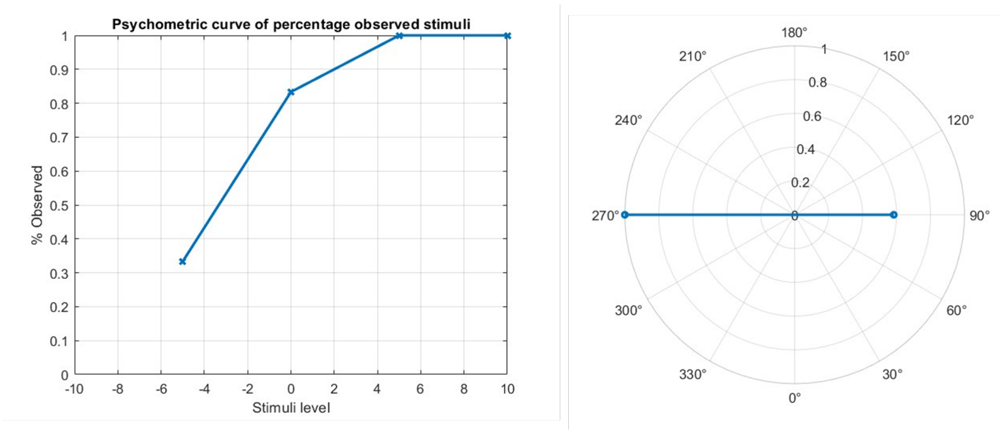
Figure 8: The spatial awareness stimuli responses at 5 and 10 dB SNR of two adults with a cochlear implant. In adult 2, all stimuli were observed, while in adult 3 an average of 37% was observed.

To gain more knowledge about accurate values for the spatial awareness stimuli, it was decided to derive psychometric curves at -5, 0, 5 and 10 dB SNR. The presentation angles were reduced to 90 degrees (left) and 270 degrees (right). Three additional adults with a cochlear implant were included in the pilot study. Adult 4 had a bimodal cochlear implant with the CI left, adult 5 had an unilateral cochlear implant on the left side, and adult 6 had an unilateral cochlear implant on the right side. All three participants had 100% scores at 10 dB SNR levels of the spatial awareness stimuli.

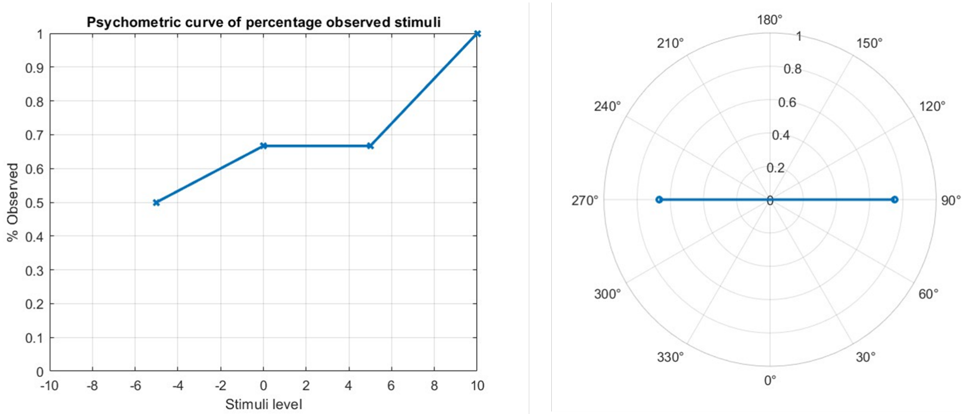
Adult 4 also had a 100% SA identification score at 5 dB SNR. The SA identification score decreased from 100% to 83% at 0 dB SNR and to 33% at -5 dB SNR. Additionally, more stimuli on the hearing aid side (right) were observed by the participant (figure 9a). The average DIN SRT score of adult 4 was -2.8 dB SRT.

Adult 5 had a different progression at the same stimuli levels (figure 9b). The psychometric curve of adult 5 decreased to a minimum of 50% at the lowest stimuli level of -5 dB SNR. No differences between the stimuli side were observed. Adult 5 achieved an average DIN SRT score of 1.7 dB SRT.

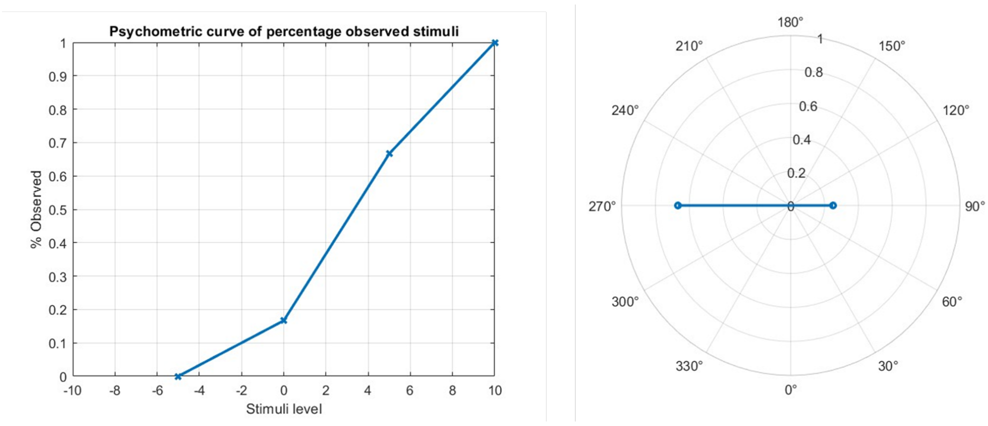
Adult 6 had a steep psychometric curve at -5, 0, 5 and 10 dB SNR levels (figure 9c). At -5 dB SNR, no spatial awareness stimuli were observed by the participant, while at 10 dB SNR a perfect SA identification score of 100% was observed. The participant observed more stimuli presented from the cochlear implant side (right). The participant obtained an average DIN SRT score of 0.1 dB SRT.



(a) Adult 4: CI on the left, HA on the right. Average DIN SRT score of -2.8 dB SNR.



(b) Adult 5: CI on the left. Average DIN SRT score 1.7 dB SRT.



(c) Adult 6: CI on the right. Average DIN SRT score of 0.1 dB SRT.

Figure 9: Psychometric curves were generated from the spatial awareness task involving three adults with a cochlear implant. Polar plots illustrate the observed proportion of animal stimuli at various angles. Notably, the participant was directed towards 0 degrees azimuth.

4.3 Test validation on NH children

The experimental setup was validated on normal hearing children who were acquainted within the ENT department. Critical considerations in these tests included the attention span of the children, the adaptability for both the youngest and oldest age groups, and the incorporation of an environmental awareness task. Seven children were included aged from 7 to 14 years. A 4-year old child was excluded as the task proved to be too challenging for their age group. Training session 2 was shortened from 5 trials DIN and 5 trials SA to 3 DIN and 3 SA, prioritizing a more concentrated effort on the subsequent test session. The main test session lasted approximately seven minutes. Spatial awareness stimuli were presented at levels of -10 and -15 dB SNR.

All seven children had DIN SRT scores in the range of -15 dB SRT. The DIN trials of the participants are displayed in figure 11 together with the DIN trials of the CI participants. The average DIN SRT of the normal hearing children was -15.2 dB compared to an average DIN SRT of -0.5 dB SNR in the CI adults.

As shown in table 1, the SA identification scores at -10 and -15 dB SNR varied among the participants. Child no. 6 did not observe any spatial awareness stimuli at these levels. This could be attributed to a lack of concentration and talking during the session, leading to the inability to perceive the subtle stimuli. Polar plots were generated to visualize variations in SA identification scores from each angle. As shown in figure 10, child 2 had a lower SA identification score on the right side and from the front than on the left side. Furthermore, SA identification scores of child 2 did not match the (relatively good) average DIN SRT score of -14 dB SNR.

The school bell sound was presented in three children, however no response was observed. In four children the ice cream truck sound was presented from 270 degrees (right). Two children responded to the sound and received a visual reward.

Table 1: Seven normal-hearing children were included in this pilot study. The average DIN SRT scores and SA identification scores at -10 dB SNR and -15 dB SNR are displayed.

No.	**DIN SRT (dB SRT)**	**Identification score at -10 dB SNR**	**Identification score at -15 dB SNR**
1	-16.2	92%	75%
2	-14.0	83%	25%
3	-15.6	100%	50%
4	-16.2	100%	75%
5	-16.6	92%	75%
6	-14.4	0%	0%
7	-13.2	42%	33%

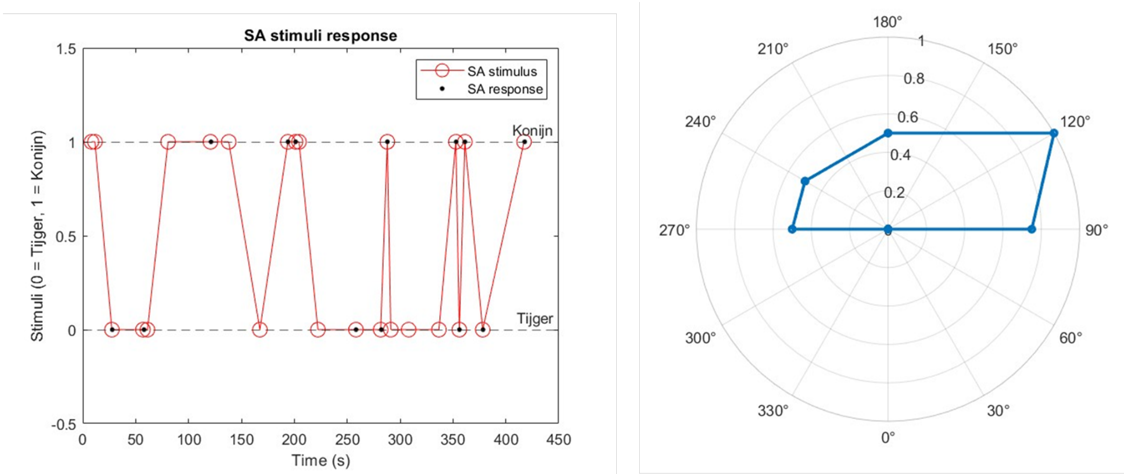


Figure 10: Child 2 exhibited unilateral hearing loss on the right side which was observed in a decreased spatial awareness at 240 and 270 degrees.

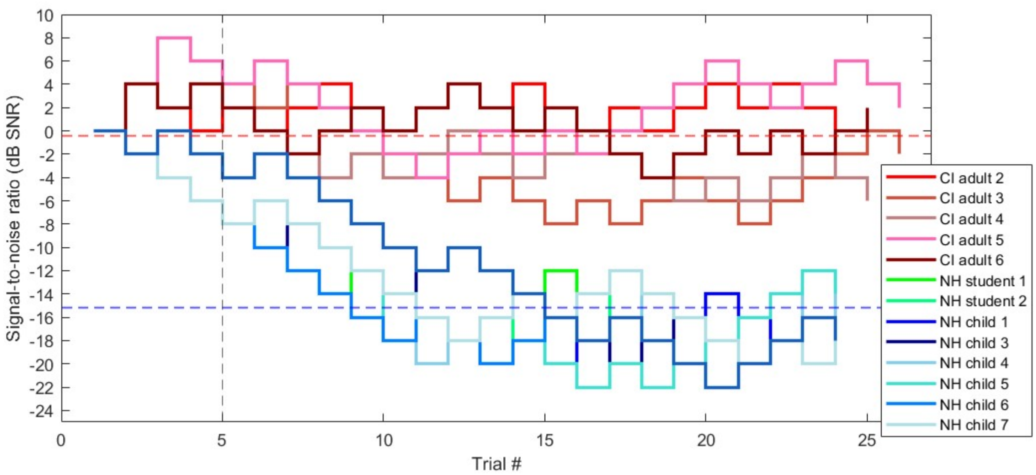


Figure 11: All DIN trials of the included participants. In red: the participants with a cochlear implant with an average DIN SRT score of -0.5 dB SNR. In blue: the normal hearing participants with an average DIN SRT score of -15.2 dB SNR.

5 Discussion

This pilot study aimed to validate the test setup created for the evaluation of speech perception in noise and spatial awareness in a virtual classroom setting in children with cochlear implants. The outcomes of this pilot study helped to optimize the test and perform reliable and reproducible measurements on children with cochlear implants. This paragraph discussed the outcomes of the pilot study, extracting essential information crucial for conducting a reproducible and ecologically valid test in the main study.

5.1 Results pilot

A total of 14 participants were enrolled in the pilot study, serving various purposes. Both normal hearing and cochlear implant individuals were included in this pilot study. At first, two students were included to assess the test setup while the virtual classroom was still empty without animations and attributes. Instructions for the participants were easily to follow and the purpose of the remote controls were clear. No side effects in the use of the virtual reality glasses were observed. The DIN test (assessing speech in noise) was conducted in conjunction with the spatial awareness task (levels of 0 and 5 dB SNR). The students' average DIN SRT scores were -14.0 and -15.8 dB SNR respectively. Comparing these DIN SRT scores to normal hearing DIN SRT scores found in literature, it corresponds to the average DIN SRT scores found in a study conducted by Wilson et al. involving normal hearing young adults [51].

The results of the spatial awareness task revealed a ceiling effect, as all spatial awareness stimuli were accurately identified by the students. Additionally, for two adults with cochlear implants, 5 and 10 dB SNR levels were employed for the spatial awareness stimuli. In this case as well, a ceiling effect was observed in one of the adults. Therefore, it was determined to evaluate the next participants in this pilot study with multiple stimuli levels to obtain psychometric curves. The stimuli levels were determined on -5, 0, 5 and 10 dB SNR and presentation angles were reduced to 90 and 270 degrees. The aim was to find out realistic values for spatial awareness stimuli to evaluate CI users in a virtual classroom. Furthermore, a possible relationship between the DIN outcome and spatial awareness stimuli levels were investigated.

Three participants with a cochlear implant were included and the psychometric curves were derived from the test, each following a distinct trajectory. In adult 4 a ceiling effect was observed from 5 dB SNR, while adult 5 had a more stable psychometric curve and adult 6 a more steep curve (figure [fig no]).These psychometric curves with SA identification scores at different levels did not link directly with the average DIN SRT outcomes of the participants. Adult 5 achieved comparable SA identification scores on both sides as shown in the polar plot, despite having only one cochlear implant (on the left side). This suggest that adult 5 has an effective spatial hearing. In addition, the stability of the psychometric curve was notable, particularly at low levels of -5 and 0 dB SNR. With an average DIN SRT of 1.7 dB SRT, it indicates that stimuli presented from various directions were detected with comparable accuracy to the DIN triplets from the front, and possible providing insights into the participant's level of spatial hearing. Adult 6 on the other hand had a strong inclination towards the side of the cochlear implant (figure . . .). In combination with a steep psychometric curve this suggests less effective spatial hearing, and hence a decreased spatial awareness. Adult 6 achieved an average DIN SRT of 0.1 dB SRT while achieving a SA identification score of 17% at 0 dB SNR , indicating that the ability to perceive speech from the front was relatively strong compared to other directions. Establishing a clear connection between the DIN scores and the spatial awareness scores proved challenging, given the individual variability among participants.

In the main study differences between the three programs (Autosense on, Autosense off and remote microphone) in DIN score and SA identification scores will be evaluated within each subject. The spatial awareness task will employ only two stimuli levels to obtain more consistent data collection per presentation angle. It is essential to identify two appropriate levels that are applicable to all included participants. Crucially, the goal is to ensure that differences in SA identification scores between the conditions are observable. This means avoiding both ceiling and floor effects across all participants during the test. A recommended SA identification score of 50% might facilitate the observation of improvements and deteriorations between the three conditions within the subject. However, the psychometric curves obtained in this pilot study showed variability among subjects in SA identification scores and uncertainty when identifying stimuli, possibly linked to the level of spatial hearing. Selecting two fixed stimuli levels for all participants is therefore challenging due to potential variations in the level of spatial hearing among CI participants. The three psychometric curves of CI adults showed that stimuli levels between -5 and 5 might be appropriate levels, depending on the level of spatial hearing of the participant. However, it is expected in the main study that there will be primarily bilateral cochlear implant users, reflecting the prevailing bilateral approach in children with severe hearing loss nowadays in the Netherlands [52]. This suggests a commendable level of spatial hearing in these children, hence tending towards stimuli levels of -5 and 0 dB SNR.

5.2 Normal hearing children

Normal hearing children were included to validate the test setup. Critical considerations during these tests that were taken into regard were the attention span of the children, the adaptability for both the youngest and oldest age groups, and the incorporation of an environmental awareness task. Seven children were included aged between 7 and 14. The spatial awareness levels were determined on -10 and -15 dB SNR. Six different presentation angles were included so that all directions could be evaluated. Additionally, the environmental awareness task was included in this stage in which an ice cream truck sound was played randomly during the test.

The findings showed that the test was appropriate for children. Regarding the attention span, a single test session lasted approximately seven minutes, which was a manageable duration for all normal hearing children. Nevertheless, two children displayed a lack of concentration and talked during the session. Consequently, both children exhibited low SA identification scores, with one failing to observe any spatial awareness stimuli. For the main study it should be taken into regard to provide instruction to focus on the animal stimuli and DIN triplet while refraining from talking. In order to enhance and optimize attention span during the test session, the training sessions were shortened. The children exhibited a quicker learning curve than anticipated, and no discernible learning effects were observed during the main test session.

Furthermore, it should be taken into regard that participants in the main study will need to undergo the test twice (for both conditions). Additionally, children with cochlear implants might be more susceptible to the loud classroom babble noise, potentially leading to an overstimulation. Therefore, we recommend to take a long break in between the two sessions. In the main study, children aged between 5 and 18 years qualify for inclusion. Consequently, it is important that the virtual test setup suits the entertainment and engagement levels of both the youngest and oldest age group. In the pilot we included children aged from 7 to 14 years. Feedback from all participants indicated that they found the test enjoyable and relatable.

Moreover, no major fluctuations in DIN levels in the final trials were observed among normal hearing children, indicating consistent effort and concentration throughout the test. There was one child who exhibited unilateral hearing loss on the right side which could also be observed in the spatial awareness task, as shown in the polar plot in figure 10. This indicated that the test setup was sensitive enough to detect such differences. Additionally, the environmental awareness task was introduced for the first time in normal hearing children. Initially, a 3 second fragment of a school bell was incorporated in the virtual classroom setup. However, no significant responses were observed in three normal hearing children. Consequently, it was decided to replace the environmental awareness stimuli sound with a less conventional one, where a response was reciprocated with a visual reward in the form of an ice cream. In two of the four children there was an active response on the ice cream truck sound. The remaining two individuals perceived the sound, but did not respond with a head movement in the right direction. It is expected that such occurrences may be more frequent in children with cochlear implants, given the advantage that has in localizing sounds.

5.3 Validation of combined speech perception and spatial awareness

To evaluate speech in noise in a classroom setting the digits-in-noise (DIN) test was chosen. In contrast to sentence tests, the DIN test does not achieve a comparable level of ecological validity. However, it does not rely on the top down processing of children, it is relatively easy for children of all ages, and children are often familiar with the DIN, as it is a clinical validated test in the Netherlands [45, 53]. These advantages make it a relatively straightforward test to assess differences in speech in noise within individuals. The DIN test used recorded classroom noise instead of LTASS noise.

If the change in noise type had any effect on the average DIN SRT outcome, it could not directly be compared in the pilot study, because all participants had no history of clinical DIN tests. However, two young adults (22 & 23 yrs) with an unilateral cochlear implant had an average DIN SRT score of 1.8 and 0.1 dB, which was comparable to the outcomes of unilateral CI children in the study of Vroegop et al. [45]. Another important note during the pilot study were fluctuations in the DIN SRT levels, as shown in figure [fig no]. Although a variability analysis helped minimize variability in the classroom babble noise, there were instances were certain DIN triplets could be presented at a more optimal moment than others.
Another factor contributing to these fluctuations could be that the adults with cochlear implant, measured in this pilot, were assessed in an empty classroom. This may have led to concentration problems and reduced effort during the sessions. In the main study participants aged between 5-18 years are more likely to have a history of clinical DIN tests, hence we can use the clinical data to explore potential variations in DIN SRT outcomes. Nevertheless, it is important to note that for this study only intra-subject variability is evaluated as a primary outcome.

To assess spatial awareness, a task was custom-designed for this study based on the articles of Wolfe et al. and Loh et al. Because of the absence of prior literature on this specific spatial awareness task, the primary aim of this pilot study was to validate the newly developed task [47, 48]. The results demonstrated its reproducibility and suitability for children of all ages, and was sensitive for directionality. Moreover, with the incorporation of classroom babble noise, reverberation and visual integration of a real classroom, it achieved a high level of ecological validity within a controlled laboratory environment. Yet, the question pertains to the task's sensitivity in detecting any differences between the Autosense programme and the calm program (Autosense off). To uphold ecological validity, short stimuli comprising a single word and two syllables were utilized. It is questionable whether these short stimuli can effectively activate the Autosense program and prompt a switch to a more suitable setting for spatial awareness. Nevertheless, we think this approach aligns with an high ecological validity observed in a real classroom.

6 Conclusion

This pilot study showed that the test is feasible for children with cochlear implants aged from 5 to 18 years. For spatial awareness levels we suggest utilizing levels of -5 and 0 dB SNR, aiming to minimize the likelihood of floor or ceiling effects among bilateral cochlear implant individuals.

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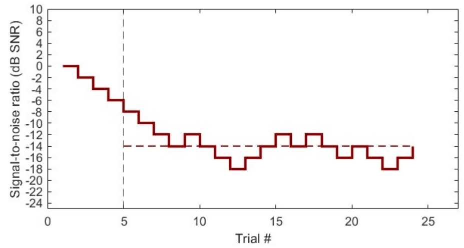
A Appendix

A.1 Student 1



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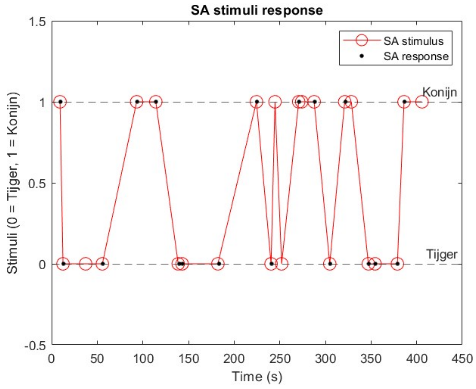

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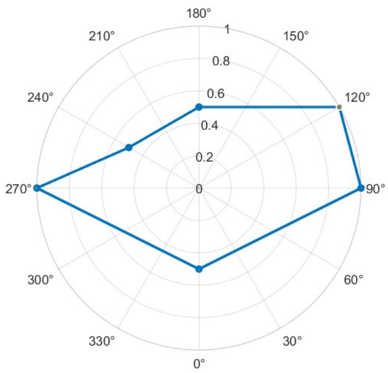

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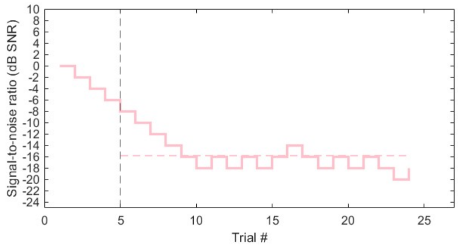

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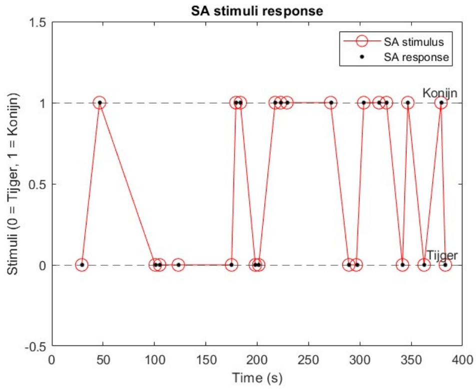

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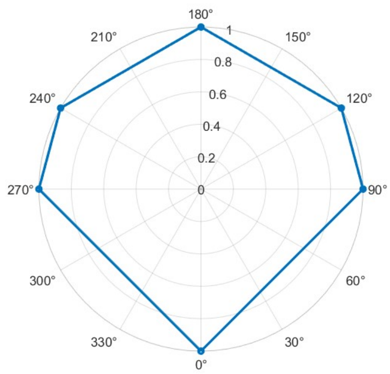

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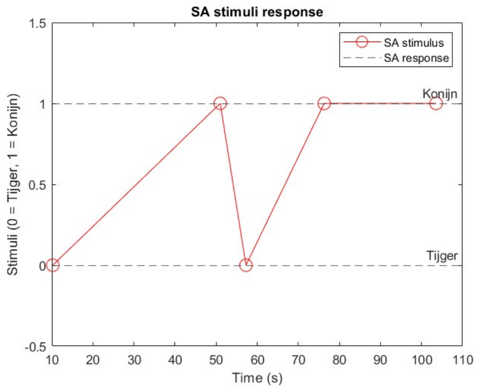

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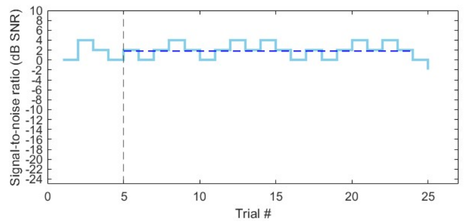

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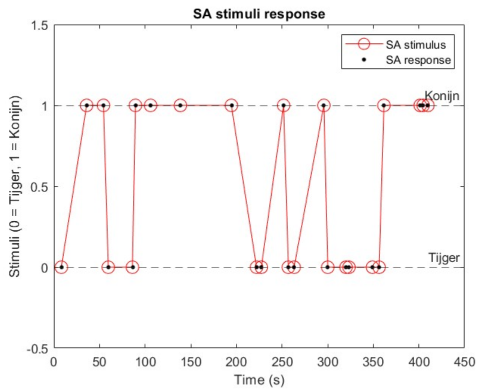

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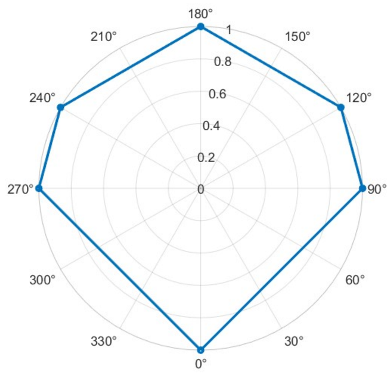

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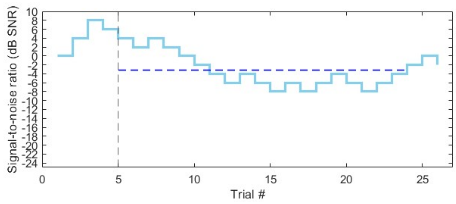

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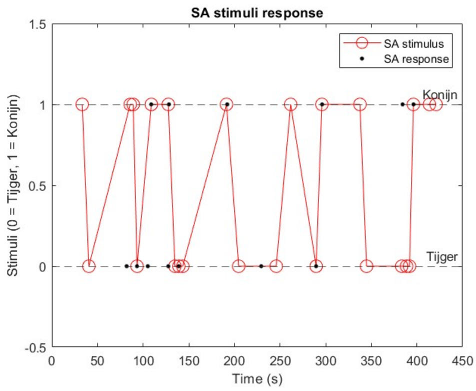

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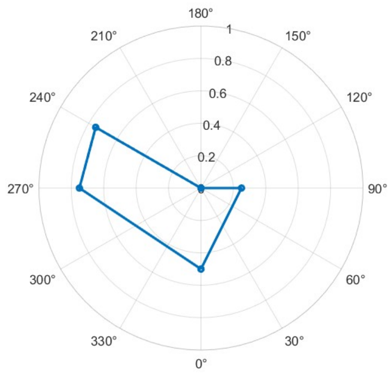

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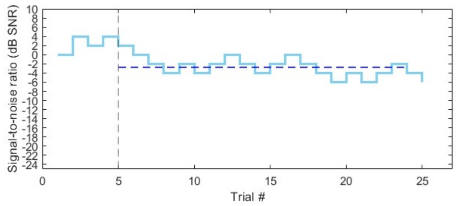
A.6 Adult 4



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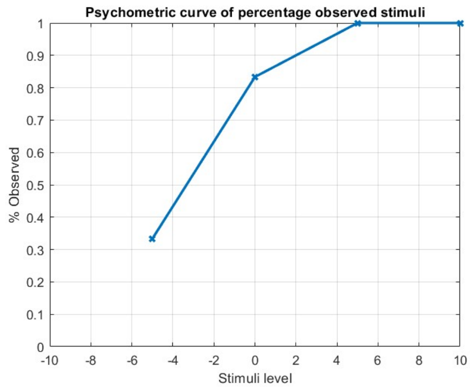

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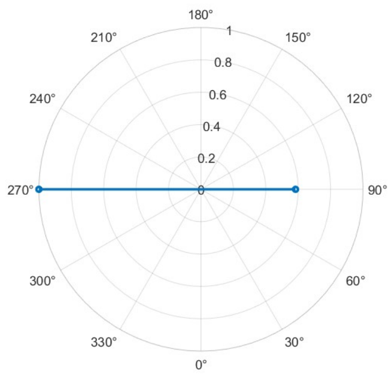

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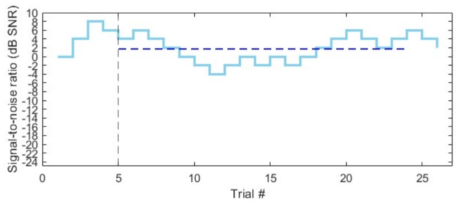

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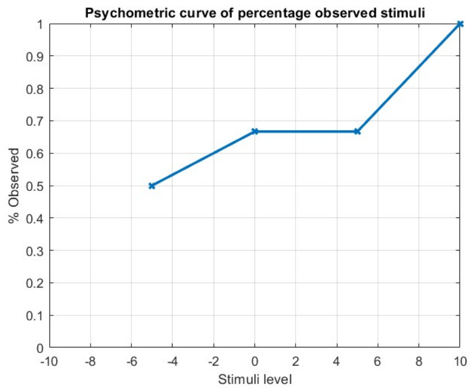

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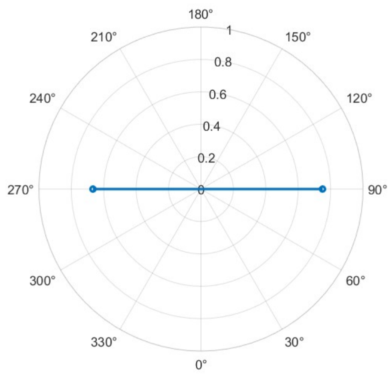

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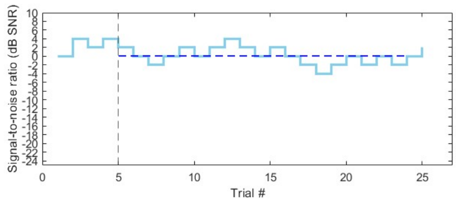

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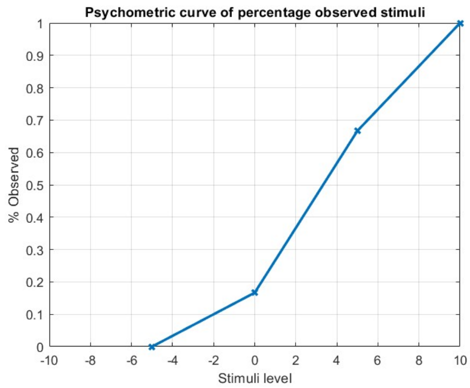

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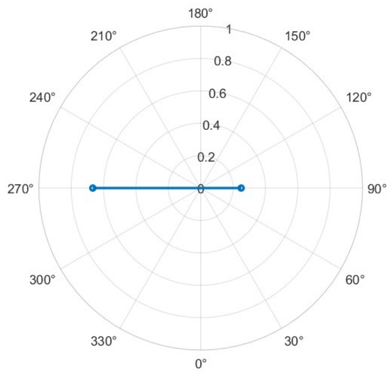
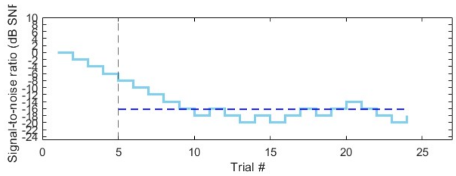


Figure 33

A.9 Child 1



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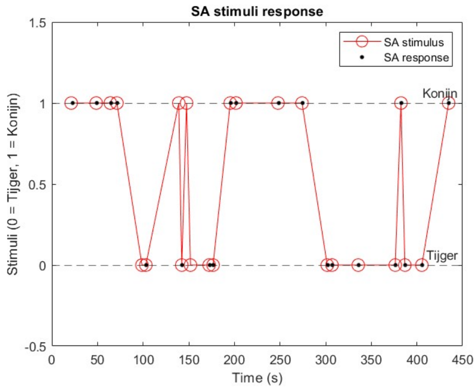

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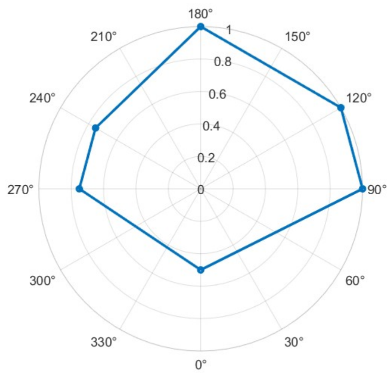

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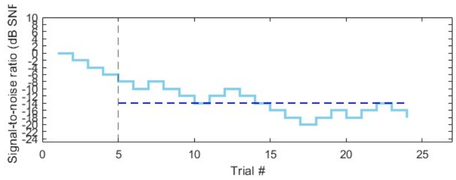
A.10 Child 2



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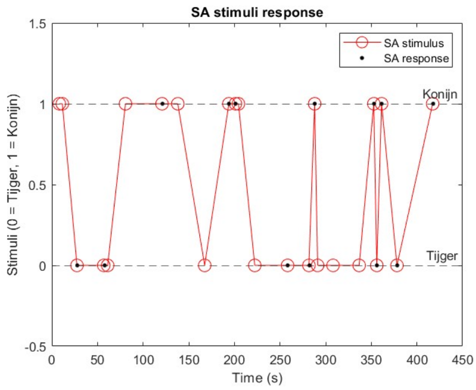

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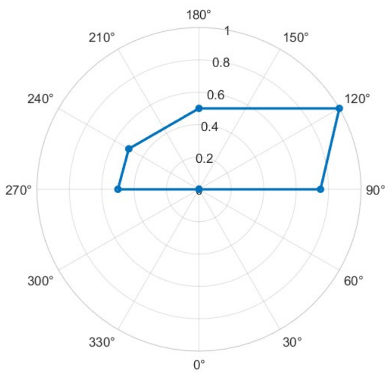

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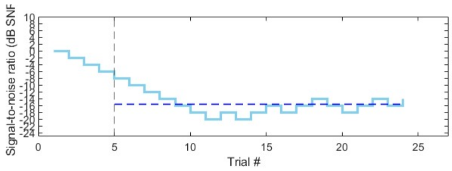

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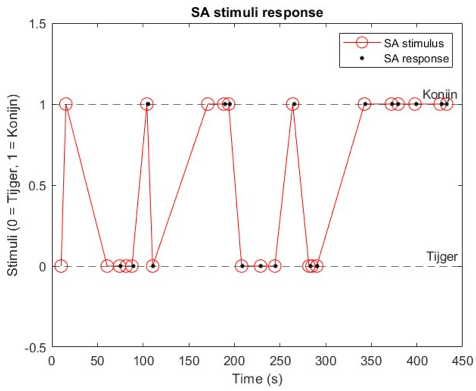

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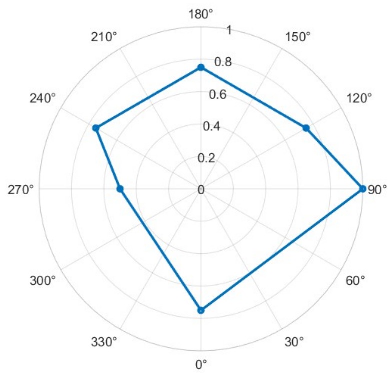

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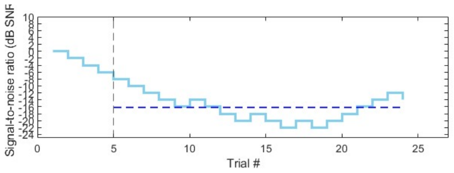

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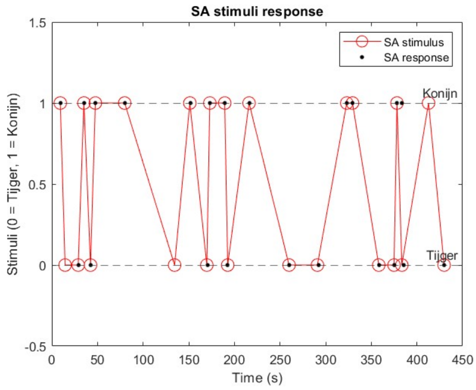

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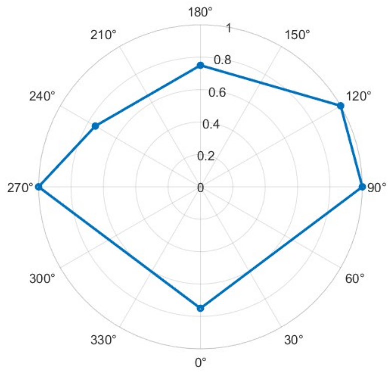

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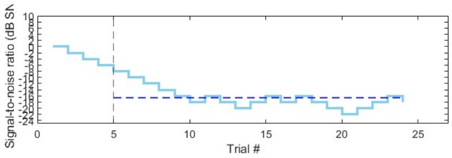

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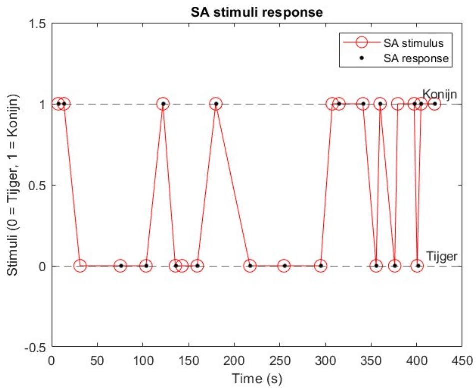

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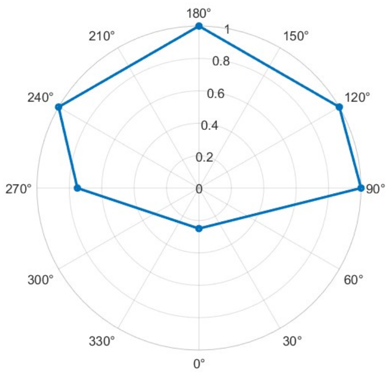

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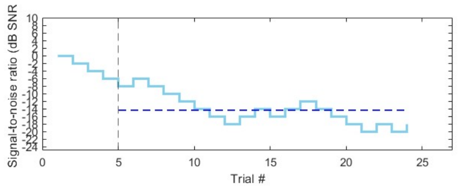

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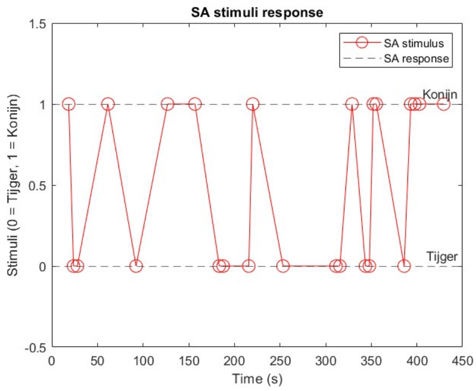

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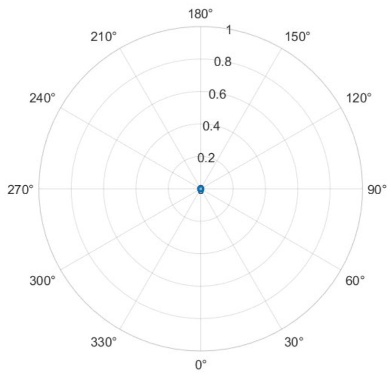

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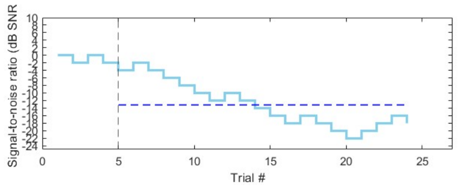

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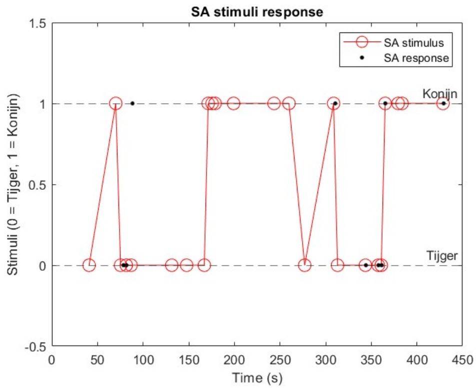

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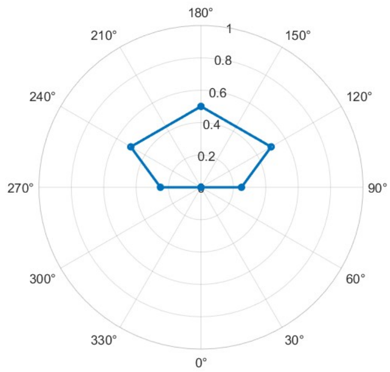

Figure 54