Effectiveness of Auditory Training for Adult Cochlear Implant Users

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Abstract

Clinicians working with adult cochlear implant (CI) users often recommend auditory training (AT) as an intervention to improve listening abilities. Lack of robust evidence and inconsistencies in AT studies, however, limits confidence in the usefulness of this intervention. This thesis assessed the effectiveness of AT for adult CI users in the context of clinical decision-making, resource allocation and evidence-based practice in a series of three manuscripts.

First, AT practices and their associated costs were assessed using data from a survey distributed to Australian audiologists working with adult CI users (n=78, 33% response rate). Is was demonstrated that clinicians believe AT is beneficial, and adopt varied methods to deliver AT. Costs incurred for clients who receive AT were estimated to range from AUD 0 to AUD 1438.98 per program, depending on the AT method of delivery.

Second, a randomised crossover study investigated the effectiveness of a computer-based auditory training (CBAT) program, in comparison to a computer-based visual training (VT) program, on measures of listening and cognitive abilities, and self-reported communication and quality of life in 26 adult CI users. It was demonstrated that although on-task improvement occurred for both the AT and the VT programs, these improvements did not transfer to the outcome measures assessed post-training and at follow-up.

Finally, a rapid review of nine CBAT studies in adult CI users was conducted. Inconsistencies in training stimuli, outcome measures and study findings associated to risk of bias present within and across studies, indicated that current evidence provides very low confidence that AT can improve speech perception, and low confidence that it can improve cognitive abilities, self-reported listening and quality of life in adult CI users.

This thesis provides practical and up-to-date evidence about AT in adult CI users which can influence both current clinical practices and future research studies.

Statement of Originality

I state that this work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Ethics review, guidance and approval have been obtained from:

- Macquarie University Human Research Ethics Committee: 5201400407
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Abbreviations

AO	Auditory-Only
AT	Auditory Training
BKB/A	Bamford-Kowal-Bench/Australia
CBAT	Computer-Based Auditory Training
CI	Cochlear Implant
CNC	Consonant-Nucleus-Consonant
CT	Cognitive Training
FSH	Fiona Stanley Hospital
GRADE	Grading of Recommendations Assessment, Development and Evaluation
ICF	International Classification of Functioning, Disability and Health
IVA-CPT	Integrated Visual Auditory Continuous Performance Test
MQU	Macquarie University
OTC	Over-the-Counter
PICOS	Participants, Intervention, Comparator, Outcomes and Study design strategy
PRCA	Personal Report of Communication Apprehension
RST	Reading Span Test
SESMQ	Self-efficacy for Situational Communication Management Questionnaire
SMRT	Spectral-Temporally Modulated Ripple Test
SNR	Signal-to-Noise Ratio
SRT	Speech reception threshold
SSQ-12	Speech, Spatial and Qualities-12
TRT	Text-Reception-Threshold
VST	Victoria Stroop Test
VT	Visual Training

Chapter 1. Introduction

1.1 Background and rationale

Difficulties understanding speech is one of the main consequences of hearing loss and can affect participation in social, leisure and employment activities (Boothroyd 2007). Hearing technologies such as hearing aids and cochlear implants (CIs) may alleviate some of these, however only partially (c.f. Friesen et al. 2001; Hällgren et al. 2005). The acoustic amplification provided by hearing aids to the remaining cochlear hair cells can be sufficient for speech understanding for individuals with mild to severe hearing losses, but as sensory hearing loss progresses (i.e. the hair cells further degenerate or die resulting in a decrease in auditory thresholds), a CI may be recommended as a more effective option. CIs convert the acoustic signal into an electrical (channel vocoded) signal, which triggers an action potential in either the residual auditory hair cells still present on the basilar membrane for a particular frequency range, or the peripheral processes leading from that hair cell to the spiral ganglion cells, via as many as 22 electrodes placed in the cochlea (see Wilson & Dorman 2008 for a review). While this electrical signal encoding can provide speech understanding for adults with severe to profound hearing losses, the signal perceived by the brain is considerably altered in comparison to adults with normal acoustic hearing or those using hearing aids (Moore 2008). Listening with a CI therefore requires increased mental effort to recognise what is being said, and this is exacerbated in complex listening situations, for example when listening in a noisy environment such as a crowded restaurant.

Clinical audiological rehabilitation services, however, expand beyond the provision of hearing technologies and aim to support speech understanding and effective communication more broadly, in particular when clients experience limitations with hearing aids and CIs. Audiological rehabilitation may include components related to counselling on hearing loss and device management, monitoring of outcomes as well as delivery of interventions such as the teaching of communication strategies, lipreading and providing auditory training (AT; Boothroyd, 2007).

The specific provision of AT to improve individuals' listening beyond device usage gained attention in the 1940s with the beginning of the audiology profession (Jerger 2006; Kricos & McCarthy 2007; Pichora-Fuller & Levitt 2012) and was focussed on AT for hearing aid users, as CIs were not clinically available at that time. It was believed that in combination with hearing aids, AT could help World War II veterans make optimal use of their residual hearing. Mark Ross, a veteran at the time who later became an audiologist reported:

> *["For at least eight weeks and eight hours a day, I attended various kinds of "classes" and was tested and retested on a number of different hearing aids. Most of the classes, as I recall, focused on speechreading and were quite creative. These included, for example, the use of tachistoscopes (a kind of slide projector) to deliver rapid, sequential visual stimuli and other kinds of visual perceptual and memory exercises, live skits presented in a glass-enclosed room for practice in identifying both verbal and non-verbal messages, and auditory training classes, using a classic Carhart formulation to present the acoustic stimuli (that is, going from discriminating broad speech features to smaller and smaller acoustic differences)."]* (Ross 1997, reporting intervention he received in 1940s)

While the resources used in the 1940s may have become obsolete, the rationale used for the delivery of AT remains similar. It relies on the assumption that hearing devices alone cannot completely restore the auditory system's function, and that structured listening practice (i.e. training) can make individuals better listeners. This is based on the knowledge that the brain is plastic and that neurons can reorganise depending on sensory input and training (see Irvine 2018a for a review). Some of the key approaches recommended to achieve these improvements include training with verbal and non-verbal (i.e. environmental sounds) stimuli, starting with easier stimuli (such as auditory-visual) and progressing in difficulty by providing less cues to the listener (i.e. providing only auditory cues or adding background noise) (c.f. Moore & Amitay 2007; Henry et al. 2015a). While there is a general agreement that training level should be challenging, yet motivating, there is no consensus, however, on the best parameters (i.e. dosage, stimuli) that should be used when providing AT.

In the years following the implementation of AT as a rehabilitation service, several studies investigated the effects that different AT protocols could have, such as comparing the use of adaptive or constant signal-to-noise ratios (SNR; Bode & Oyer 1970), the use of open- or closed-set response alternatives (Bode & Oyer 1970), presentation of target stimuli in the auditory modality only or combined with lip-reading (Watts & Pegg 1977; Walden et al. 1981), as well as using only sentences as training stimuli or a combination of sentences and phoneme stimuli (Rubinstein & Boothroyd 1987).

Despite the several components of AT assessed, the early studies did not establish that AT was an efficacious intervention for adults with hearing loss (see Sweetow & Palmer 2005 for a review). The outcomes of AT on speech perception performance as measured in controlled settings (i.e. efficacy) as well as how these translate to real-life benefits and with other populations (i.e. effectiveness) are important to understand. These, in conjunction with measures of cost-effectiveness (i.e. cost of an intervention in relation to its outcomes) can support clinical discussions and the development of clinical guidelines related to the provision of AT (c.f. NHMRC 1999; Robey 2004). Well-developed clinical guidelines aim to improve the quality of health care by reducing the use of unnecessary, ineffective or harmful interventions (NHMRC 1999). A review from Bamford (1981) suggested that there was a disagreement amongst audiologists regarding the effectiveness of AT, and asserted that there was a lack of well-controlled studies – particularly those using no-training control groups – which meant that no clear conclusion could be drawn as to whether training improved speech understanding. Bamford (1981) also observed that the qualitative reports on the benefits of AT by rehabilitationists exceeded quantitative controlled studies and that the outcome measures used in AT studies were not reflective of real-life gains. In parallel to this debate, according to survey studies and reports, the delivery of AT began to decrease as a possible result of clinicians' increased confidence in hearing aid technology and the lack of reimbursement for AT (Schow et al. 1993; Prendergast & Kelley 2002; Jerger 2006).

Over three decades later, the debate on whether AT is an effective intervention for individuals with hearing loss remains. While several computer-based programs have been developed specifically for AT, and provide a controlled method for assessing its efficacy, a systematic review of AT studies conducted between 2004 and 2012 suggested that AT benefits were inconsistent within and across studies and did not typically generalise to untrained tasks (see Henshaw & Ferguson 2013 for a review). This, in addition to the lack of adequate scientific control found in most articles included in the review, limits the potential for these studies to guide clinical practice. A need for better controlled studies to assess the benefits of AT has been identified by both Henshaw and Ferguson (2013) and Sweetow and Palmer (2005) who reviewed the evidence of AT studies conducted between 1970 and 1996.

This need has become even more important following the passing of the Over-the-Counter Hearing Aid Act of 2017 in the United States (House of Representatives 2017). Specifically, the passing of this Act has stimulated a discussion about the relevance of the audiologist' role beyond the provision of hearing aids, generating a renewed interest in AT. Since the passing of this Act, several articles have recommended that audiologists include AT as part of their clients' rehabilitation (c.f. Tye-Murray 2016; Taylor 2017; Banks 2017; Abrams 2018), suggesting this could ensure retention of audiologists' roles as rehabilitationists (Abrams 2018) and also generate profits (Tye-Murray 2016). Moreover, current computer technology has supported an increase in the development of computer-based auditory training (CBAT) programs, which are now easily available to clients and clinicians (c.f. Olson 2015), although their effectiveness has not been rigorously evaluated to allow clients and clinicians to make evidence-informed decisions. Consequently, in CI practice, AT guidance that is not based on compelling evidence is provided to clients and clinicians (Henry et al. 2015a).

While in most cases CIs provide improvements in speech perception, there is a large inter-individual variability in outcomes. Pre-, peri- and post-operative factors such as hearing sensitivity (pure tone average thresholds of the better hearing ear), CI brand, percentage of active electrodes, use of hearing aids prior to implantation and duration of hearing loss have all been suggested to contribute to CI outcomes (Lazard et al. 2012). Disregarding the specific reasons for this variability, when using a CI, some adults will understand speech on a mobile telephone, but others may not be able to comprehend speech without lipreading (i.e. will not acquire 'good' speech recognition, at least as measured clinically; c.f. Blamey et al. 2013; Holden et al. 2013). Thus, it may be clinically intuitive to provide AT as an approach to supplement cochlear implantation, especially for those who do not achieve good outcomes. In fact, face-to-face AT was regularly delivered to adult CI users in the early days when these devices first became clinically available (c.f. Tucci et al. 1990). Further, a recently developed manual (i.e. Henry et al. 2015a) that guides clinicians on how to conduct AT with adult CI users may suggest that AT is delivered by clinicians.

AT relies on brain plasticity, and it is known that the brain remains plastic throughout the lifespan and that it can reorganise as a response to altered auditory experience (see Irvine 2018b for a review). However, while the goal of AT is to primarily improve speech perception, this is not always achieved. For instance, Holden et al. (2013) retrospectively assessed the clinical outcomes of 114 postlingually deafened adults who received AT for two years from CI switch-on. By the end of this period, individuals' speech recognition scores varied from 2.9% to 89.3% indicating that, despite undergoing a lengthy AT program, speech understanding remained low for some individuals.

Prospective AT studies conducted with adult CI users provide further indication that AT outcomes can be inconsistent. Studies which trained individuals on speech perception tasks suggest that the degree and time course of improvement varies amongst individuals (Fu et al. 2004), and that not all CI users benefit from AT (e.g. Stacey et al. 2010; Tyler et al. 2010; Oba et al. 2011; Schumann et al. 2015a). The reasons for this remain unclear, and studies often do not include broader measures beyond speech perception that could provide such knowledge (see Sweetow & Palmer 2005; Henshaw & Ferguson 2013 for a review). While speech perception is a standard outcome measure, it provides limited knowledge of individual characteristics (such as functioning and cognitive profile) and what motivates them to engage in AT (i.e. their personal goals), limiting the identification of which individuals could be more likely to benefit from AT.

Listening is a combination of auditory and cognitive processes (Arlinger et al. 2009). For example, factors such as attention and working memory have been shown to contribute to speech understanding in complex listening conditions (Rönnberg et al. 2008; Arlinger et al. 2009; Wild et al. 2012; Rönnberg et al. 2013; Pichora-Fuller et al. 2016). Similarly, phonological representation – which is deteriorated in individuals who had a long duration of auditory deprivation – is suggested to play a role in speech understanding (c.f. Lyxell et al. 1998; Lyxell et al. 2003). Complexity in listening introduced by the signal that is provided through a CI, which lacks important speech cues, demands that CI users constantly engage cognitive processes when listening. Thus, individuals' performance on listening tasks is likely to depend on the amount of cognitive 'energy' invested towards listening. The Framework for Understanding of Effortful Listening (FUEL) proposes that this investment of cognitive 'energy' is driven by reward (Pichora-Fuller et al. 2016). That is, individuals may be motivated to invest effort in a demanding listening situation if the content is interesting and motivating, however, if the content is no longer interesting, motivation declines and individuals withdraw from the task. However, even when listening is rewarding and the investment of cognitive energy is high, listening may be fatiguing leading individuals to stop engaging with the task (see Pichora-Fuller et al. 2016 for a review). Recent research in CI users suggests that this effort-reward balance and social connectedness form part of a broader conceptualisation of listening effort, which may guide decisions related to social engagement versus withdrawal (Hughes et al. 2018).

Aligned with this, it is possible that AT may reduce the amount of cognitive resources that are required for listening, thereby decreasing the effort required in a listening task (see Tremblay & Backer 2016 for a review). Further, in a study where normally hearing participants received a training task that required them to discriminate between two identical frequency tones – an impossible task – improvement was shown when individuals were tested on a frequency discrimination task where the tones differed (Amitay et al. 2006). The authors suggested that this transfer of learning may have occurred as a result of participants increased attention after engaging with the training task, demonstrating the important role of this cognitive element on learning (c.f. Amitay et al. 2006). Hence, the acknowledgement of cognitive factors in training studies may further help identify effects which are not explicitly measured via speech recognition tests, and may provide further understanding of individual variability following training. However, cognitive outcome measures have not yet been robustly examined in AT studies conducted with adult CI users. This is despite evidence from studies conducted with groups of aided and unaided hearing-impaired individuals which indicates that some AT programs can improve cognitive abilities. For example, improvements following AT have been reported for auditory working memory (Sweetow & Sabes 2006; Ferguson et al. 2014), divided attention (Ferguson et al. 2014), self-reported concentration, attention and focus in everyday listening (Ferguson & Henshaw 2015a).

Programs involving elements of both auditory and cognitive (e.g. working memory) training, such as the Listening and Communication Enhancement (LACE) proposed by Sweetow and Henderson-Sabes (2006) have initially indicated that this type of program could be effective for hearing aid users' listening and cognitive abilities. Other cognitive training programs marketed as "brain-training" have also been evaluated as an option to improve speech perception. This may have been encouraged by the mass marketing of these programs in the recent years, which suggested that cognitive training could be helpful to limit the rate of cognitive decline in older adults, although it is uncertain whether cognitive training effects occur (Lampit et al. 2014; Simons et al. 2016). For adults with an unaided hearing loss, Anderson et al. (2013a) observed a significant post-training improvement of 1.22dB in speech perception and attention in participants who practiced an auditory-cognitive module of the Brain Fitness Cognitive Training (Posit Science) for a duration of eight weeks. Importantly, Brain Fitness is a cognitive training program that uses auditory stimuli. However, in a primarily visuospatial working memory training study, using Cogmed, hearing aid users showed improvement in trained working memory tasks but not in untrained speech recognition (Ferguson & Henshaw 2015b). Oba et al. (2013) investigated the effect of a visual digit span training for adult CI users and found improvement in the visual digit span task, however only a small improvement of 0.07 to 1.11dB in speech recognition. These results suggest that evidence for the transfer of learning to untrained tasks is mixed for cognitive training programs, and may be governed by both the underpinning mechanisms of the training tasks as well as the training stimuli employed. The same is true for AT programs, whereby transfer of learning to untrained tasks does not always occur (c.f. Henshaw & Ferguson 2013).

An effective training intervention to improve speech perception in adult CI users is yet to be identified. As Pisoni et al. (2018) recently suggested: developing a novel intervention to address poor outcomes with a CI is among the three future challenges of CI research. Specifically, the authors recommended the identification of an effective intervention that leads to improvements beyond practice effects in CI users with poor speech recognition performance. Boothroyd (2010) also made specific recommendations for AT research, and suggested that studies should aim to identify which aspects of listening are targeted by AT, which specific AT protocol features are responsible for auditory learning, who is a candidate to receive AT, and whether improvements in speech perception found after AT transfer to social participation and quality of life (see Boothroyd 2010 p.608 for a review). Improved selection of outcome measures was also recommended by Henshaw and Ferguson (2013), who suggested that cognitive outcomes as well as self-report measures of listening should be addressed in future AT research.

Boothroyd (2007) proposed that audiological rehabilitation, and therefore AT, should not only lead to improvements in speech recognition, but also to confidence in communication, social participation and quality of life. Yet, self-report measures of listening and quality of life are often overlooked in AT studies. The framework provided by the International Classification of Functioning, Disability and Health (ICF; World Health Organisation 2001) proposes that functioning is a result of the interaction between individuals' health condition as well as personal and environmental factors. As indicated by Granberg et al. (2014) however, most current clinical outcome measures in audiology are biased towards measures of body function with limited available measures assessing limitations in activities and participation, or the contribution of contextual factors, such as personal factors and environmental factors. Thus, self-report measures of listening and quality of life are important to supplement behavioural measures of speech perception.

Importantly, AT should elicit perceptual learning, which refers to the practice-induced ability of improving the recognition and interpretation of sensorial information on a long-term basis (Goldstone 1998; Gold & Watanabe 2010). Perceptual learning relies on two stages of memory consolidation: (i) the first stage refers to rapid consolidation which occurs minutes after practice has ended (Dudai 2004), which is also referred as acquisition of learning (Zach et al. 2005); and (ii) the second stage refers to consolidation which may take several weeks or months to occur, which is also known as system consolidation. The latter may involve reorganisation of the brain circuits or systems that encode the memory and may spread to a new location in the brain (Dudai 2004). Although there is uncertainty as to whether the first stage characterises perceptual learning, or procedural learning (i.e. learning the task) – with studies demonstrating contradicting findings (c.f. Hawkey et al. 2004; Ortiz & Wright 2009) – an important outcome is whether learning generalises to untrained tasks and is retained over time after the training has ended.

Besides the several aspects that need to be acknowledged in AT studies, a few suggestions to improve the scientific quality of studies have also been made (c.f. Henshaw & Ferguson 2013). These include conducting studies that are randomised, blinded, with an active control group, and that include sample sizes as recommended by a power calculation. Henshaw and Ferguson (2013) further suggested consideration of factors that are relevant to training studies such as ecological validity, provision of performance feedback during AT, inclusion of follow-up assessment to assess retention of learning, and reporting of participants' adherence to AT. Additionally, reporting of findings should be transparent, including detailed reporting that could allow for adequate assessment of study quality and replicability. Following these recommendations may lead to high-level study quality, which could more reliably inform clinical practice and support shared decision-making.

Importantly, effectiveness of AT is not the only factor to be considered when clients and clinicians discuss audiological rehabilitation options. These discussions should also consider individual needs, personal goals and the cost that may be associated to AT. Cost-effectiveness analysis of interventions are relevant as they can further inform evidence-based practices, by allowing for resource allocation to be addressed in a systematic rather than intuitive manner (Eichler et al. 2004). Better understanding clinical approaches adopted in CI rehabilitation can enable such evaluations to be conducted within a clinically relevant context, which could facilitate the translation of knowledge to practice in audiology (c.f. Moodie et al. 2011).

1.2 Thesis objective

The objective of this thesis was to assess the effectiveness of AT for adult CI users, in the context of clinical decision-making, resource allocation and evidence-based practices. This was addressed by assessing current AT practices and their associated costs for clinical service providers and adult CI users; and evaluating the effectiveness of CBAT on short- and long-term, trained and untrained measures of listening and cognitive abilities and quality of life for adult CI users.

1.3 Thesis outline

Three studies have been conducted as part of this thesis.

The first study, presented in Chapter 2, aimed to describe current rehabilitation practices that CI audiologists in Australia adopt with adult CI users, and assess the cost that different AT methods incur for clinical service providers and adult CI users. This chapter describes data collected from a survey which had a 33% response rate of CI audiologists in Australia and informs on audiologists' beliefs towards AT, practices audiologists adopt in relation to AT, as well as method of delivery, stimuli and strategies used during AT. Further, a cost analysis of methods such as face-to-face, home-based, and group-based AT was conducted and the implication these costs may have for clinical service providers and adult CI users is discussed. The second study, described in Chapter 3, aimed to assess whether a computer-based speech in noise AT program leads to short- and long-term changes in trained and untrained measures of listening, cognition and quality of life. A secondary aim of the study was to assess whether directly training the underlying cognitive abilities required for speech perception in noise, using a computer-based visual training (VT) program without the auditory component, would elicit comparable outcomes as the AT program. Twenty-six adults from across three study sites participated in this study. Effects of AT in behavioural measures of listening and cognition and self-report measures of communication and quality of life were assessed.

The third study, described in Chapter 4, aimed to contextualise the findings of the study described in Chapter 3 within an up-to-date rapid systematic review of AT studies for adult CI users following on from the systematic review by Henshaw and Ferguson (2013). Nine studies were identified which assessed the effects of CBAT on speech perception, cognition, communication and/or quality of life for adult CI users. Findings are discussed in terms of evidence for on-task learning, transfer to improvements in untrained outcomes, and retention of learning as well as study quality.

Finally, Chapter 5 provides an overview of the studies that formed this thesis and discusses the implications of this research for clinical practice and future research.

Chapter 2. Auditory training for adult cochlear implant users: a survey and cost analysis study

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2.1 Abstract

Objectives: The aims of this study were to: a) describe audiologists' practices towards auditory training (AT) for adult cochlear implant (CI) users with a postlingual hearing loss; and b) assess the cost of different AT methods for clients and service providers in comparison with no AT delivery. **Design:** A survey was distributed to approximately 230 Australian CI audiologists to investigate the range, magnitude and rationale of AT practices adopted as part of rehabilitation services with adult CI users. The cost of these different AT practices was then estimated from the perspectives of both clients and service providers, and compared against no AT delivery. **Results:** Seventy-eight audiologists responded to the survey (33% response rate), of which 85.5% reported that AT is a necessary component of rehabilitation. Home-based and face-to-face were the methods most frequently adopted to deliver AT. Methods used during training, such as stimuli type, feedback and encouragement for training adherence varied across respondents. The cost analysis indicated that home-based training resulted in the lowest program costs, whereas face-to-face AT (when delivered independently from routine appointments) was the method with highest cost for clients and service providers. **Conclusions:** The type of AT, recommended frequency of sessions and overall duration of program varied widely among respondents. Costs incurred by clients depended mainly on whether the AT was home-based or clinician-led (i.e. face-to-face, group-based), program fees and travel arrangements made by clients, as well as clinicians' wages and the method chosen to deliver AT.

2.2 Introduction

Speech perception performance varies considerably in adult cochlear implant (CI) users. This variation may be influenced by factors such as duration of severe or profound hearing loss, residual hearing, and age at implantation (Lazard et al. 2012; Blamey et al. 2013; Holden et al. 2013). Even when adults reach excellent speech perception performance with their CIs (e.g. recognising 95% of sentences spoken without access to lipreading), limitations, when listening in noisy environments for example, may remain, requiring that individuals constantly invest greater mental effort than normally-hearing individuals to succeed in listening tasks (Pichora-Fuller et al. 2016; Hughes et al. 2018).

Auditory training (AT) may be recommended clinically as a means of addressing these listening limitations. AT aims to facilitate brain reorganisation by exposing individuals to sounds in a controlled learning situation, leading to improved listening abilities. In addition to reducing difficulties in speech understanding, AT is suggested to improve confidence in communication, social participation and quality of life (Boothroyd 2010). Traditionally, AT has been delivered in a face-to-face setting by a clinician, however, several other options exist, such as group or home-based training, which can also be self-delivered online (Kricos & McCarthy 2007; Olson 2015). In the context of this study, AT is defined as structured listening activities that aim to improve speech perception.

Despite being a traditional audiological intervention, no standard AT guideline exists to guide the AT protocol or regimen to follow. Research evidence indicates that results following AT vary, with individual factors (Oba et al. 2011; Sabin et al. 2013; Schumann et al. 2014) and differences in training protocols (see Wright & Sabin 2007; Wright et al. 2010; Molloy et al. 2012 for reviews) identified as possible contributors to this variability. Discrepancy in results following AT has also been found for the same AT program when evaluated in different studies (e.g. Sweetow 2008; Olson et al. 2013; Saunders et al. 2016). Henshaw and Ferguson (2013) systematically reviewed 13 AT studies – of which seven were conducted with adult CI users – and found that the quality of those ranged from very low to moderate when assessed with the 2004 Grading of Recommendations Assessment, Development and Evaluation (GRADE) Working Group guidelines, indicating that limitations in scientific rigour of AT studies did not allow for the development of clinical guidelines in relation to AT.

Better-controlled studies have been published following this systematic review, however, mainly with unaided hearing-impaired listeners or hearing aid users (e.g. Ferguson et al. 2014; Saunders et al. 2016; Whitton et al. 2017). Although these studies did not evaluate the effect of AT on CI users, findings suggested that training might only be effective for some individuals (Ferguson et al. 2014; Whitton et al. 2017), not with all protocols (Saunders et al. 2016), and that the effects may not be sustained on a long-term basis (Whitton et al. 2017). Fewer controlled studies, however, have assessed the effectiveness of AT specifically for adult CI users. Despite this, a variety of approaches have recently been evaluated to improve speech perception in adult CI users, including training with environmental sounds (Shafiro et al. 2015), psychophysical tasks (Barlow et al. 2016), melodic contours (Lo et al. 2015; Fuller et al. 2018) and music (Smith et al. 2017), as well as pitch discrimination training (Vandali et al. 2015) and speech perception training (Bernstein et al. 2014; Schumann et al. 2014; Miller et al. 2016). Findings of these studies indicate that there is no consensus about what constitutes the best approach to AT for adult CI users, as AT does not always lead to robust improvements in speech perception (Schumann et al. 2014; Barlow et al. 2016; Shafiro et al. 2015; Smith et al. 2017). This heterogeneity in study findings, in combination with the lack of empirical evidence to support AT poses a barrier for clinicians and clients to follow an evidence-informed decision when assessing whether to include AT as part of the rehabilitation program.

Early reports suggest that there has been a decrease in the clinical delivery of AT, at least for hearing aid users. A survey study conducted by Show et al. (1993) suggested that this decrease in AT delivery between 1982 and 1990 was mainly due to clinicians' increased confidence in hearing aid technology. More recent reports confirmed that AT is not routinely delivered for hearing aid users, with the main barriers being lack of clinicians' time and resources, reimbursement of services, and availability of client transport (Prendergast & Kelley 2002; Rossi-Katz & Arehart 2011). More recently however, new regulations regarding the distribution of Over-The-Counter (OTC) hearing aids (House of Representatives 2017 p.1065) have been perceived as a threat to the sustainability of hearing aid dispensing as the main profit centre for the audiology profession, thus, leading several authors to suggest the provision of AT as an alternative fee-generating service for adult hearing aid users (Tye-Murray 2016; Taylor 2017; Banks 2017; Abrams 2018). In conjunction, these suggest that the decision to deliver AT is not strongly evidence-based, but seems to revolve around developments in technology, available resources and the evolution of professional roles.

In the specialised field of CIs, however, this scenario could differ. An early study indicated that AT was an integral part of rehabilitation across 99 CI centres surveyed, where clinicians reported delivering or recommending AT to adult CI users for over 20 hours (Tucci et al. 1990). This suggests that the barriers to AT reported by hearing aid clinicians were not the same in CI centres during these same years. However, it is possible that clinicians' confidence in CI technology alone was not strong, and therefore AT was delivered to ensure optimal benefit with the device. Signal processing technology in CI has advanced since then and therefore, the importance given to provision of AT by CI audiologists could have changed. No survey studies, however, have been conducted to update the knowledge provided by Tucci et al. (1990). A survey of rehabilitation practices adopted by CI audiologists can inform whether and how AT is conducted, resources utilised and sources of evidence clinicians base their decisions on in a scenario where evidence to support AT is not robust.

In a review of evidence-based health policy, Oxman et al. (2009) noted that in the face of insufficient research evidence to guide clinical practice, it is necessary to assess whether it is possible to be confident about the intervention despite the lack of evidence, and whether the intervention can be harmful, have no effect or not be worth the cost. No studies have yet reported that engaging in AT can be harmful to the individual from a listening ability perspective. However, studies have reported that some adult CI users do not benefit from AT (e.g. Oba et al. 2011; Schumann et al. 2015a). While there might be no harm in engaging in AT, even if no benefits are shown, there are costs incurred for both clients and service providers, including financial expenses and time requirements.

An economic assessment conducted by Lea (1991) indicated that adults with postlingual hearing loss would invest 30 hours of their first year of implantation in AT, followed by four hours or less in their second and third year after CI switch-on. In 1991, this amounted to AUD 2,250.00 for the first year of CI, and decreased to AUD 300.00 in the subsequent years of follow-up (Lea 1991). Considering an average annual inflation rate of 2.4% (Reserve Bank of Australia 2019), in the year 2017 these figures would be equivalent to AUD 4,220.05 and AUD 562.67 respectively. Travel cost expenses and time demanded from clients were not assessed in this evaluation, therefore costs incurred could have been even higher.

Economic evaluations aim to provide decision-makers with reliable information about the value of alternative interventions. These, in conjunction with systematic reviews, can assist clinicians when discussing alternative courses of action with their clients more confidently (Drummond et al. 2015). In settings where services are publicly funded, economic evaluations are part of the resource allocation decisions to try and maximise benefits with the funding available (Cunningham 2000).

Economic assessments often evaluate treatment costs (or allocation of resources) from a health system perspective, not including the costs or impacts that clients may incur. This may be based on assumptions that costs for clients are minimal or necessary, however this is not always the case. Focusing on “resources” and “impact on clients”, rather than treatment cost, could lead to more applicable recommendations. A better understanding of treatment options within the context of current clinical practices can also increase the potential for implementation of evidence-based recommendations.

Therefore, to provide practical and economical contexts to the discussions surrounding AT recommendations for adults CI users, the present study had two aims:

1. To describe current rehabilitation approaches employed by audiologists in Australia with adult CI users with a postlingual hearing loss;

2. To evaluate the resources required for the provision of different AT practices (individual face-to-face, home-based and group-based) in comparison to non-delivery of AT to adult CI users with a postlingual hearing loss, from the perspective of both clients and service providers.

2.3 Methods

This study consists of a survey and a cost analysis. As specified earlier, in this study, AT is defined as structured listening activities that aim to improve speech perception. Table 2.1 describes additional definitions used for this study.

Table 2.1. Rehabilitation methods evaluated and definitions adopted in this study

Method	Description
Face-to-face	Delivered individually by a professional in a clinical setting
Independent	Client travels to the clinic specifically for this intervention
Integrated	Delivered in conjunction with a routine appointment
Home-based	Self-conducted, out of a clinical setting
Group-based	Delivered by a professional to a group of 2-8 adults in a clinical setting
No AT	AT is not completed as part of rehabilitation

AT: Auditory training

Survey design and dissemination

A survey consisting of 35 (23 closed; 12 open format) questions (Appendix B) to assess clinicians' practices in relation to AT was developed on an online platform (Qualtrics 2018). Specifically, questions were designed to assess: participants' demographic data, how AT is delivered to adult CI users, the type and duration of AT, the materials clinicians use for provision of AT (i.e. exercise books, online platforms), and factors that may influence decision-making around these aspects. The survey was designed by the three first authors (MR, IB, EB), following recommendations summarised in Schaeffer and Presser (2003), which encompass using appropriate definitions and wording in questions, providing respondents with sufficient response categories, and including relevant reference periods to aid respondents in recalling information. The content of the questionnaire was based on the type of AT protocols found in the literature, training manuals, as well as the clinical experience in AT for adult CI users of the two first authors (MR and IB). The content was further refined following a pilot study conducted with three audiologists working with this population, who did not participate in the final study. Additionally, the survey flow was set to follow different paths depending on the rehabilitation methods reported by the respondents. That is, specific questions were displayed based on five different methods that clinicians could report: home-based AT, face-to-face AT, group-based AT, referral to another professional or organisation, or not conducting any AT as part of their work. If respondents reported employing more than one approach, questions corresponding to each category would be shown.

An invitation email to participate in the survey was distributed to practicing audiologists via Audiology Australia, the peak professional audiology body in the country (estimated membership: 2,300). This invitation contained a brief description of the study and a link to the online survey. Audiologists were informed that they could choose to not respond to the survey, but by responding, they consented to their anonymised responses to be used in this study. An additional generic email was sent directly to the main contact email address of the 35 Australian CI clinics, as listed on Cochlear Ltd. Australia/New Zealand's website (Cochlear Ltd. 2017). The data collection period was open for several weeks between July and August 2016. Participants were able to exit the survey and continue at any time within a 2-week period commencing at the time of their first attempt. Incomplete responses were automatically submitted to the survey database after the 2-week period had ended.

Participants

Audiologists who had provided services to adult CI recipients in Australia in the two years preceding the survey access were eligible to participate in the study. Eleven respondents who reported that none of their clients were adult CI users in the previous two years were prompted to the end of the survey and excluded from the study.

Survey analysis

Open format responses were analysed through a systematic qualitative approach (see Miles et al. 2013 for a review), using both content breakdown and deductive analysis (see Graneheim & Lundman 2004 for for detail about analysis methods adopted). Specifically, this required anonymous responses for each question to be broken down and analysed in a deductive reasoning matrix. To ensure responses were accurately interpreted, three investigators (MR, EB, IB) independently examined the responses, simplifying raw data into meaning units or key phrases within the text. Meaning units were then further categorised into codes and regrouped into emerging themes. This process was iteratively refined until the three investigators reached an agreement.

Economic evaluation framework

The economic evaluation compared the relative cost of different AT methods for adult CI users with a postlingual hearing loss against no AT delivery (i.e. AUD 0.00). This was evaluated from the perspectives of both clients and service providers. The setting of the current assessment consisted of CI clinics in Australia. In these, CI follow-up appointments are subsidised by the national health insurance scheme (i.e. Medicare), however, this does not encompass services such as AT for adults (Australian Government Department of Health 2017), which would have to be self-funded (i.e. out-of-pocket).

Survey responses were used to inform duration and frequency of AT sessions as well as overall duration of the AT program for face-to-face and home-based approaches. The likely number of sessions per month for face-to-face training that is integrated within a mapping appointment was based on data from Vaerenberg et al. (2014), which describes the average number of yearly CI mapping appointments globally. Group-based AT time investment data was based on survey responses for face-to-face training that was delivered independently, based on the assumption that clinicians would recommend a similar amount of sessions if AT was delivered to a group.

Costing was conducted for the states of New South Wales (NSW) and Victoria as these encompass 57.6% of the Australian population (ABS 2016), and also the two largest CI clinics in Australia. All the costs described in this study comprised the most up to date online resources available as of July 2017.

For clients' out-of-pocket expenses, public and private transportation modes were measured. As a reasonable estimation, the distance travelled to the clinic was limited to a minimum of 1km and a maximum of 100km, although some clients would travel for longer distances to attend a clinical appointment. Private transportation costs were estimated for private car travel and driving costs based the Australian Taxation Office rates (Australian Taxation Office 2017b). Parking was costed based on a range of options that could be available to clients – from free parking to up to 2 hours of private parking in a central region of the capital cities of NSW and Victoria. Public transport cost ranges were based on the minimum distance travelled in a pensioner concession and maximum distance travelled paying the full transportation fee. Clients' time investment (i.e. time off work) refers to work adjustments clients might have to make to attend AT sessions. This was estimated only in terms of time, not productivity.

Session fee refers to the price clients would pay for an AT program if attending face-to-face sessions or undertaking computer-based auditory training (CBAT) at home. For face-to-face AT, data was obtained through personal communications with different CI clinics, whereas the cost of CBAT packages were obtained by re-verifying companies' websites of programs described in Olson (2015).

A manual search was conducted to identify any additional CBAT programs not described in Olson (2015). Cost of packages were converted to AUD using the average currency exchange rate of USD 0.79 per unit for the financial year ending 30 June 2017 (Australian Taxation Office 2017a). Additional transaction fees were not included in costing. Costs displayed on Table 2.2 inform session fees for home-based AT.

Table 2.2. Cost of auditory training software packages

Software	Annual cost (AUD)	Source
Angel Sound	0.00	http://angelsound.tigerspeech.com/angelsound_help.html
CASPER	0.00	http://boothroyd.sdsu.edu/files/
clEAR	405.06	http://www.clearworks4ears.com
eARena	Various	Olson (2015)
LACE	100.00	http://www.neurotone.com/lace-interactive-listening-program
Listening Room	0.00	http://thelisteningroom.com/
RMQ	126.57	http://www.sensesynergy.com/readmyquips
Sensoton	113.86	http://www.sensoton.com/
Soundscape	0.00	http://www.medel.com/us/soundscape/
SPATS	189.87	Olson (2015)

Currency rate of AUD1.26 was used for conversion. CASPER: Computer-Assisted Speech Perception Testing and Training; LACE: Listening and Communication Enhancement; RMQ: Read my Quips (Complete); SPATS: Speech Perception Assessment and Training System for Hearing-impaired persons.
Note: Seeing and Hearing Speech is originally reported in Olson (2015), however this program has been discontinued (source: http://www.sens.com/products/seeing-and-hearing-speech-lessons-in-lipreading/).

Resources used by service providers were calculated by obtaining health professionals awards as well as on-costs and overhead costs. This was conducted using public health professionals awards in NSW (IRCNSW 2017) and Victoria (Victoria State Government 2017), assuming professionals are full-time employees (i.e. 38 hours per week and 52 weeks per year). Overhead and on-costs were obtained from the two largest CI clinics in the country, as reported for collaborative research purposes.

Program costs were obtained by multiplying the minimum and maximum costs of each intervention by the mean frequency of intervention and duration clinicians indicated delivering or recommending within the survey. Programs which have one-off costs for quarterly or yearly subscriptions were discussed separately.

This study was approved by Macquarie University's Human Sciences Research Ethics Sub-Committee reference number 5201400407.

2.4 Results

Participants and response rate

Seventy-eight clinical audiologists with an average of 16.6 (SD: 10.36) years of professional experience responded to the survey on AT practices with adult CI users. Of the 78 respondents, 38 completed the entire survey. At the time of survey closure, Audiology Australia indicated having approximately 2,300 registered members, of whom nearly 10% conducted work related to CIs (personal e-mail communication to authors). This figure, however, may be an over-representation as it also includes paediatric and research audiologists, who may not have met the study's participation eligibility. Based on the number of participants who started responding the survey (n=78), it is estimated that the survey had a response rate of at least 33%.

Of the 78 audiologists who responded the online survey, 38 answered to all questions, therefore the number of total responses for each question varied. While 23.1% of the 78 audiologists reported working mainly with adult CI users, 55.1% of the respondents reported that adult CI users formed only a quarter or less of their clientele. Respondents' demographics are presented in Table 2.3.

Table 2.3. Demographic data of survey participants

Descriptive	n	%
Years of Experience in Audiology	*78*	
≤5	14	17.9
>5 and ≤15	26	33.3
>15 and ≤25	22	28.2
>25	16	20.5
Age	*37*	
20-35 years	14	37.8
36-50 years	15	40.5
51-65 years	8	21.6
Gender	*38*	
Male	3	7.9
Female	35	92.1
Adult CI users clientele	*78*	
1-25%	43	55.1
26-50%	6	7.7
51-75%	11	14.1
>75%	18	23.1
Workplace size	*38*	
0-10 clinicians	14	36.8
>10 clinicians	24	63.2

AT definition

Most respondents agreed that AT refers to "structured listening activities that aim to improve speech perception" (n=49/78). Only one respondent reported not agreeing with this definition, but did not provide an alternate definition. Among the 30.8% (n=24/78) participants who partially agreed with the definition provided, it was suggested that AT extends beyond structured activities and aims to improve not only speech perception. For example, it was suggested that AT could also be a product of daily listening, focus on environmental sound awareness as well as involve strategies to build up clients' confidence.

Perceived necessity and recommendations for AT

Of the 78 respondents, 85.5% agreed to some extent that AT is necessary to improve outcomes in adult CI users with a postlingual hearing loss (Figure 2.1), and a majority reported recommending AT within their clinical practice with this population (n=59/69; Table 2.4).

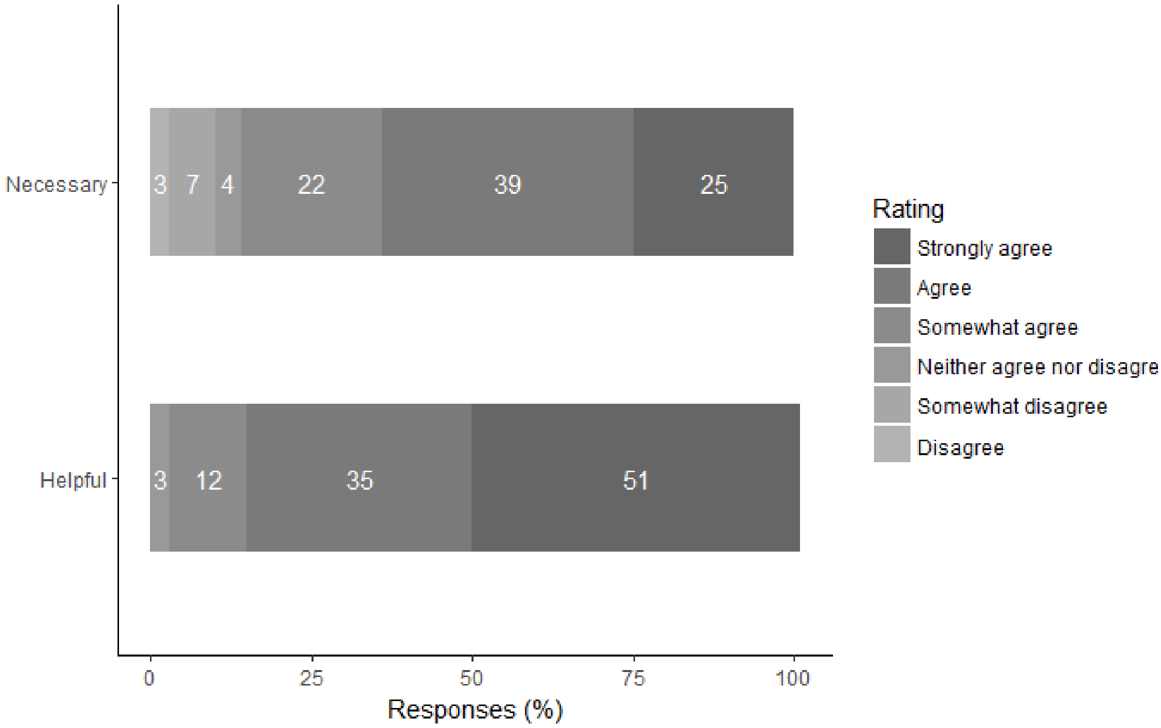

Figure 2.1. Role of auditory training in relation to improvement of speech perception outcomes in implanted adults (n=69).

Responses suggested that 53.6% (n=37/69) of clinicians, either use a combination of methods with the same client or use a range of approaches with their different clients (Table 2.4). The most common methods reported together were home-based and face-to-face AT (n=20/37). Limitation of resources, not knowing how to conduct AT, or the clinic not offering this service were reported as main reasons for referring clients to a specialised AT professional (n=18/69). Those who reported not encouraging AT did not indicate a reason for following this approach (n=4/69). Lack of research evidence around AT was not indicated by any of the respondents as a reason not to conduct or recommend AT.

The remaining survey questions aimed to address specifics of each approach employed by clinicians, therefore the following sections of this paper describe practices of clinicians who reported employing home-based and/or face-to-face AT with their clients.

Table 2.4. Clinicians approach in relation to auditory training for adult CI users

	n	%
Individual face-to-face	41	59.4
Home-based	48	69.6
Group	0	0
Referral to a specialised professional	18	26.1
Do not conduct nor refer	4	5.8

Multiple choice question.

AT focus areas, material, and delivery style

Several listening domains were reported to be part of AT, however the main focus-area was related to speech perception - with a combination of word and sentence discrimination being the most frequently reported (n= 16/34; Figure 2.2). Clinicians reported relying mostly on printed exercises, audiobooks and CBAT to facilitate AT (Figure 2.3). Additionally, over half of the respondents (n=18/34) reported using aural rehabilitation manuals, such as Cochlear Ltd.'s manual (Henry et al. 2015a), to guide AT sessions.

While 14/28 clinicians reported providing feedback after the presentation of each stimuli, 5/28 reported not providing feedback and 8/28 reported they might provide feedback after a set of trials is presented or based on the type of encouragement each client needs.

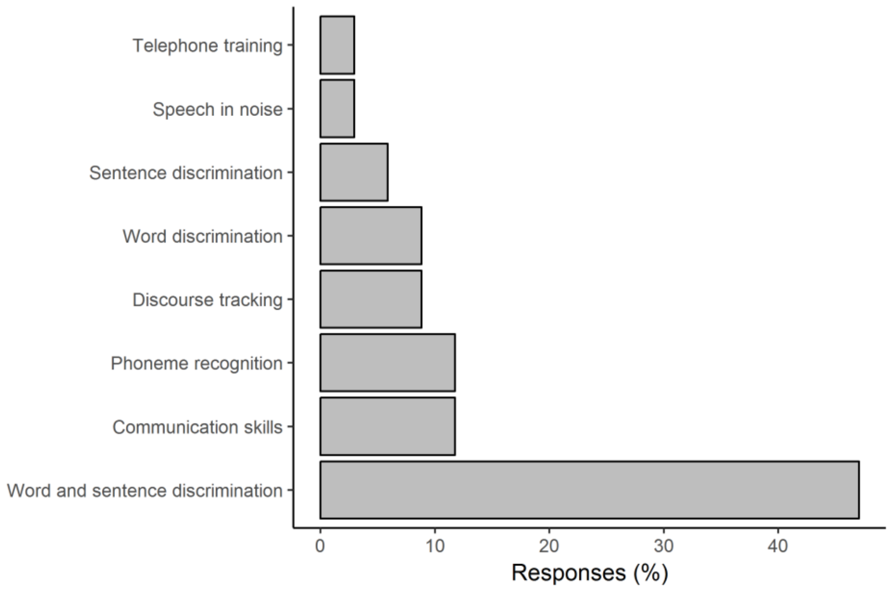

Figure 2.2. Areas that receive most focus during auditory training sessions (n=34).

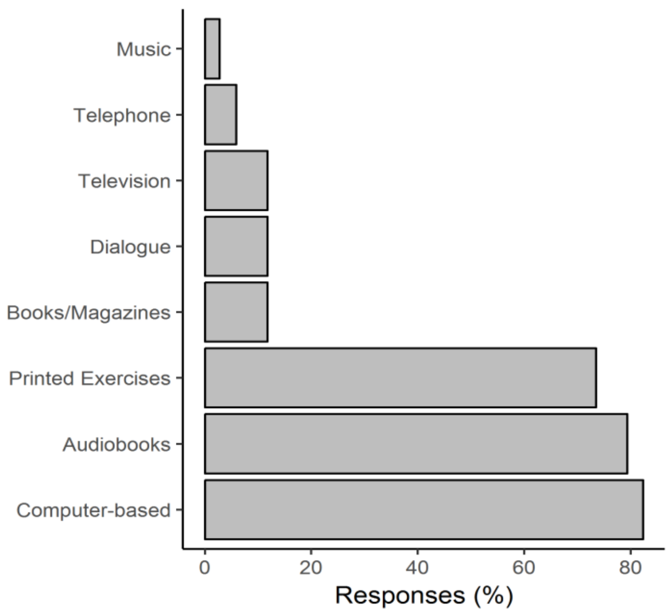

Figure 2.3. Support material used for delivery of home-based and face-to-face auditory training (n=34).

Engagement and monitoring

Clinicians reported using a range of strategies to promote adherence with the training program (Figure 2.4). Counselling, which included goal setting and discussion of expected outcomes, was the strategy mostly reported by audiologists (n=26/34). Support of clinical team members or significant others may also be enlisted to motivate clients' adherence (n=10/34). Adherence is also encouraged by discussing reassessment results with clients (n=9/34), providing educational knowledge (i.e. discussing brain plasticity; n=5/34) or making a contractual agreement (n=3/34).

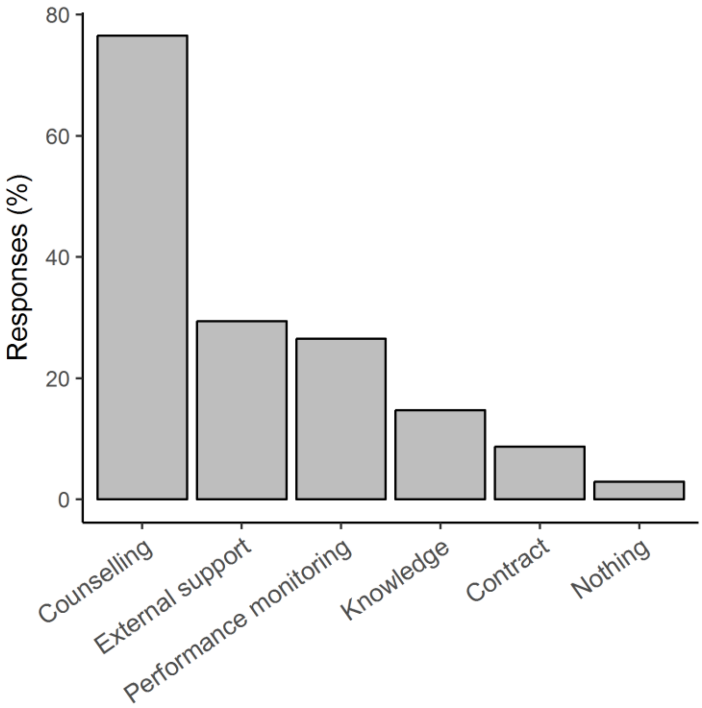

Figure 2.2. Strategies used to promote clients' compliance to the AT program (n=34).

Twenty-one out of 36 respondents indicated evaluating whether the training was beneficial to their clients. These assessments included subjective reports from the clients or significant others (n=21/36), speech recognition tests (n=20/36) and the use of functional questionnaires (n=7/36).

Recommended intensity and duration of AT

While 11/27 reported increasing the training difficulty level when their clients are scoring a specific percentage of trials correctly (i.e. 80% correct), 15/27 reported changing difficulty level based on client's performance, however not based on a specific percentage. Seven respondents indicated setting difficulty at a level that would be either comfortable or not affect their clients' motivation.

The recommended duration of AT sessions was highly variable across respondents and also between methods (Figure 2.5). Twenty-three out of 29 respondents, reported conducting face-to-face AT for less than 45 minutes per session, which could imply that AT is conducted within a CI programming appointment. Additionally, it was indicated that the overall duration of AT when delivered face-to-face ranges between one and seven months (n=29), whereas home-based AT ranges between one and 11.2 months (n=25).

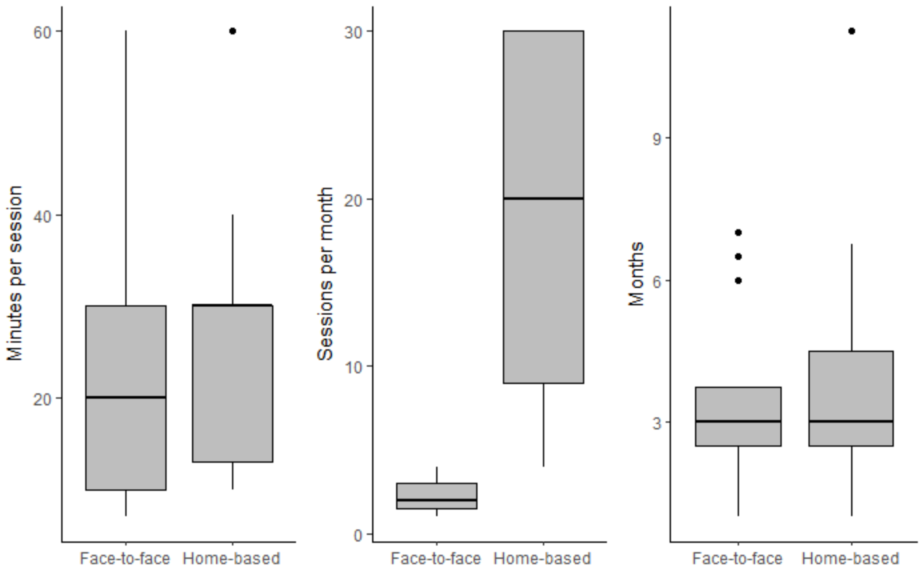

Figure 2.3. Reported duration and frequency for each AT method.

Cost of auditory training

Table 2.5 displays the range of out-of-pocket costs that different AT methods can incur for clients as indicated by the cost estimation conducted. The highest costs were associated with clinician-led AT. Face-to-face AT that was delivered as an independent clinical service incurred the highest cost for clients. Costs were lowest for AT when clinical time was shared amongst a group of clients, when AT was integrated within a routine appointment (as no extra transportation costs are incurred and session fees may be treated as part of the routine appointment), and when AT was home-based.

Table 2.5. Range of estimated costs of different AT methods for clients per session

		Face-to-face		Home-Based	Group
		Independent	Integrated		
Items	**Unit Costs**	**AUD**	**AUD**	**AUD**	**AUD**
Travel expenses					
Public Transport NSW	Various†	2.50-15.40	0.00	0.00	2.50-15.40
Public Transport Victoria	Various‡	2.05-8.20	0.00	0.00	2.05-8.20
Petrol	0.66§	0.66-66.00	0.00	0.00	0.66-66.00
Parking in NSW	59¶	0.00-59.00¶	0.00	0.00	0.00-59.00
Parking in Victoria	46¶	0.00-46.00	0.00	0.00	0.00-46.00
Session fee	Various‡‡	95.00-150.00	0.00-150.00	0.00-1.20	11.88-95.00
Total cost per AT session		**95.66-271.00**	**0.00-150.00**	**0.00-1.20**	**12.54-216.00**

† Transport for NSW (https://www.transport.nsw.gov.au/)
‡ Public Victoria Transport (https://www.ptv.vic.gov.au/)
§ Australian Taxation Office (https://www.ato.gov.au)
¶ Secure Parking (https://www.secureparking.com.au)
‡‡ Private communications with CI clinics.

Table 2.6 shows the time required by clients to undertake each AT method. Face-to-face AT that is integrated to a routine appointment required the least time from clients. In contrast, audiologists may recommend that clients practice at home daily, which could mean up to seven hours of AT, weekly. However, clients would not need to take time-off work for home-based AT, whereas a full day of work might be missed if clients attended clinician led interventions.

Table 2.6. Time investment required from clients for each intervention

	Face-to-face		Home-Based	Group
	Independent	Integrated		
Time-off work per session (hours)	2-7.5	2-7.5	0	2-7.5
Session duration (minutes)	60†	5-45†	10-60†	60
Sessions per month (n)	1-4†	0.08-0.5¶	4-30†	1-4
Duration of AT program (months)	1-7†	1-7†	1-11.25†	1-7
Total (hours of AT/program)	**1-28**	**0.006-2.6**	**0.67- 337.5**	**1-28**

†Data extracted from survey; ¶Based on number of mapping appointments reported in Vaerenberg et al. (2014). Group sessions duration and frequency assumed that clinicians would recommend an amount similar to face-to-face independent AT.

Table 2.7 displays the cost that clinician-led AT may incur for clinical service providers in comparison to home-based AT. When AT was delivered by clinicians, the cost for one hour of intervention was between AUD 93.80 and AUD 175.28 for the clinical service. The median of reported sessions per month and duration of training programs reported (Figure 2.5) was multiplied by minimum and maximum costs incurred for service providers. This indicated a full program cost between AUD 559.99 and AUD 1,046.42 for clinical service providers, if hourly appointments were conducted. Clinician-led methods included face-to-face and group-based AT, therefore, resources could be optimised if AT was delivered to a group. Home-based AT has no associated cost for service providers, providing clinicians follow-up with clients on aspects of AT during their routine appointments, rather than dedicating time to regularly check their clients home-based AT progress. A sensitivity analysis was conducted to assess the impact that transportation used by clients to attend AT could have on overall AT costs (Table 2.8). This was conducted to address the fact that costs for clinician-led methods were influenced by transportation methods used by clients, however this study did not collect information on the proportion of clients who uses each transportation method. Three case scenarios were established. 1. the base case scenario assumed 50% of clients travel on public transport with the remainder using their own car, indicating a cost range of AUD 96.47 to AUD 212.15 per session. 2. if 75% of clients use public transport to travel to the clinic, this would translate to a minimum of AUD 96.02 and maximum of AUD 184.47 per session. Finally, 3. if only 25% clients use public transport, costs range from AUD 95.71 to AUD 239.82.

Table 2.7. Cost of different AT methods for clinical service providers per hour of AT session

	Unit Costs	**Clinician led AUD**	**Home-Based AUD**
Audiologists' wages	Various	33.50-62.60	0.00
On-costs (30% of wages)	Various	10.05-18.78	0.00
Overhead (150% of wages)		50.25-93.90	0.00
Total		**93.80-175.28**	**0.00**

A range of costs for undertaking AT are associated with whether the clients need to travel to the clinic and the method of travel to the clinic to receive this service – including the type of transport method they use, the frequency of sessions and the duration of the training program (in addition to program fees). Multiplying the median of reported sessions per month and duration of training programs reported (Figure 2.5) by minimum and maximum costs, it is estimated that face-to-face AT program costs could range from AUD 574.00 to AUD 1,438.98 and home-based program costs could range AUD 0.00 to AUD 72.60 for clients. The latter is taking into consideration the amount of sessions recommended by clinicians who reported the survey, however if clients were to purchase a CBAT package, the minimum cost would be AUD 100.00 (see Table 2.2). If group-based training was conducted for the same amount as indicated for face-to-face training and the minimum number of participants in the group was two and maximum eight, these costs would range from AUD 71.75 to AUD 719.49 for each client for the full program.

Table 2.8. Sensitivity analysis for face-to-face auditory training

				%Public Transport				**%Public Transport**		
	min	**max**	**Min avg**	**50%**	**75%**	**25%**	**Max avg**	**50%**	**75%**	**25%**
Public Transport										
NSW	2.50	5.40	2.28	1.14	0.85	0.21	6.80	3.40	5.10	1.70
VIC	2.05	8.20						0.00		
Driving expenses	0.66	66.00	0.66	0.33	0.17	0.50	66.00	33.00	16.50	49.50
Parking										
NSW	0.00	59.00						0.00		
VIC	0.00	46.00					51.50	25.75	12.88	38.63
Session Fee	95.00	150.00	95.00	95.00	95.00	95.00	150.00	150.00	150.00	150.00
Total				**96.47**	**96.02**	**95.71**		**212.15**	**184.48**	**239.83**

Avg: average; Three case scenarios were assumed. The base case scenario assumed 50% of clients travel by public transport; scenario two assumed 75% travel to the clinic by public transport and case three assumed only 25% clients travel by public transportation.

2.5 Discussion

The aims of this study were to describe audiologists' practices towards AT for adult CI users with a postlingual hearing loss and assess the cost of different AT methods for clients and service providers in comparison with no AT delivery.

Survey results indicated that audiologists believe AT is a necessary component of CI rehabilitation, with most respondents indicating that they either conduct or recommend this intervention. When AT is not personally delivered, this is due to a lack of professional training in this area, which is in line with the findings of Prendergast & Kelley (2002) and Rossi-Katz & Arehart (2011). Clinicians compensate for this gap in service delivery by referring their clients to a colleague or recommending home-based AT. This, and the fact that only a low number of respondents reported not conducting nor recommending AT, indicates that AT is perceived as beneficial for adult CI users.

The fact that no audiologist reported the weak research evidence of AT studies as a reason for not conducting AT, suggests that clinicians are either not aware of it or do not believe that the evidence is in line with AT conducted clinically. In fact, responses from this survey indicated that AT as conducted clinically may not have the same control as when conducted for research purposes. For example, some respondents reported adjusting AT protocol on a case by case basis, such as subjectively adjusting the difficulty of the tasks and giving feedback based on clients' motivation. While motivation should be kept high to ensure that clients adhere to the training program (Henshaw et al. 2015), there is a risk of training tasks not being delivered at a level that is challenging enough to induce auditory learning. Similarly, responses relating to whether clinicians provide feedback to clients during training were inconsistent. However, it has been suggested that provision of feedback induces learning (Hervais-Adelman et al. 2008; Loebach et al. 2010) in studies with normal hearing listeners, and is consistently used in AT studies as it can allow listeners to compare wrong and correct alternatives when practicing and therefore, learn by comparing items.

Survey results also indicated that audiologists focus on several aspects of speech perception during AT, with most emphasis being given to recognition of words and sentences. Very few respondents, however, reported providing AT that uses speech in noise as stimulus. Speech perception in noise is a common complaint of CI users and the stimulus often used to assess AT in research studies (see Henshaw & Ferguson 2013 for a review).

The duration and frequency of sessions were highly variable not just between home-based and face-to-face AT, but also within face-to-face AT only. Some respondents reported delivering 10 minutes of AT every 3 months, which could indicate that AT is integrated within a routine mapping appointment. Because AT is not reimbursed by health insurance in Australia, this may be a means of ensuring this intervention is delivered at no additional costs to clients – suggesting that audiologists believe that even this reduced duration at spaced frequency can be beneficial. It is also possible that clinicians recommend home-based training in conjunction with these short face-to-face sessions.

This large variability in practice indicated by responses throughout the survey in relation to AT could be an effect of the lack of strong evidence on AT efficacy. This variation in practice does not solely exist in AT, but in various aspects of CI practice (Vaerenberg et al. 2014). Rigorously developed practice guidelines, which can be of easier access to clinicians than peer-reviewed articles are also lacking in AT. In this survey, 53% of respondents indicated referring to a widely available CI manufacturer's manual (i.e. Henry et al. 2015b) to guide AT sessions. While this manual may have been developed with the intention to provide a guidance to clinicians, its content is not based on robust evidence (c.f. Henshaw & Ferguson 2013). However, the fact that over half of respondents rely on this manual suggests that manufacturers can have a powerful influence on clinical practice. Therefore, it is important that such materials are prepared based on the best level of evidence, and that clinicians and clients are aware of the benefits and limitations of AT.

For example, the information given in this AT manual for adult CI users differs from what has been assessed by research studies. It suggests that AT should start in the weeks following switch-on of the CI (Henry et al. 2015a), despite no studies having evaluated the benefits of AT in relation to time of switch-on. This manual also recommends the development of an individualised and varied AT exercise plan led by the CI user, as opposed to a standardised AT programs that are usually evaluated for research purposes. It further encourages training with a communication partner who should adapt their speech and use motivation strategies, factors that cannot easily be considered within a randomised controlled trial (RCT). As such, it would be reasonable for clinicians to conclude that the training programs assessed within the published literature do not represent the AT they provide clinically. As indicated in this study, audiologists often use counselling strategies to ensure clients adhere to the program and feel motivated during the sessions.

In contrast, "pragmatic trials" are an option yet to be explored to assess the overall effectiveness of AT interventions as they would be used routinely in CI clinics (Helms 2002). A well-designed pragmatic trial could test the hypothesis that AT, as conducted clinically, is more beneficial than the AT currently provided in research. Because of the limited evidence to support that AT is beneficial, it is of extreme importance that outcomes of interventions are adequately measured. In this study's survey, respondents reported monitoring progress by subjective reports from clients or significant others followed by speech perception tests and only a small proportion of reported using functional questionnaires. Ideally, these would be evaluated twice before AT is delivered, and assessed again at the middle and end of the program, to ensure training effects are higher than test-retest effects and that is transferring to untrained tasks and meeting clients' goals.

Other considerations to make when deciding the rehabilitation program involve the cost that clients are willing to pay to receive AT and the time they are willing to dedicate. The cost analysis in this study showed that face-to-face training when conducted independently from routine appointments can have a cost of up to AUD 1,438.98 for clients, while if this was shared between a group, this cost would decrease at least by half. For service providers, this intervention could cost up to AUD 175.28 per hour of intervention. It is also important to consider that time off work may be necessary for some clients to attend these interventions. Productivity losses were not costed in this study, however, are also an aspect to be considered when making decisions with clients. In contrast, home-based AT costs can range from AUD 0.00 to AUD 100.00 and time off work may not be required. No costs would be incurred for clinics as well, however, even when costs for clients and clinics are AUD 0.00, there could be costs involved, such as the hosting of the AT application on an internet service provider.

The lack of evidence-based outcomes for different rehabilitation programs means that the economic evaluation in this study was limited to a cost analysis of out-of-pocket costs for clients, and could not provide recommendations on which treatment program was the most effective. Another limitation is that these costs are closely aligned with the health funding infrastructure in Australia. However, despite these limitations, this study questions the relative value of different AT programs and provides a framework for other centres to build on. Making the costs and benefits of each program more explicit to clients and clinicians can aid shared-decision making and complement recommendations from systematic reviews of AT benefits.

2.6 Conclusion

Findings of this study demonstrated that CI audiologists believe that AT is a necessary component of rehabilitation and that the majority either recommends or delivers this intervention to adult CI users. Methods that clinicians use during AT, recommended frequency of sessions and overall duration of program varied widely among respondents. Costs incurred for clients who receive AT were estimated to range from AUD 0 to AUD 1438.98 per program, depending on whether the intervention is self-conducted or led by a clinician, whether clients need to travel to the clinic to receive AT, and the transportation methods used. For clinical service providers, costs are influenced by clinicians' wages and the method chosen to deliver AT. Full program costs when training is delivered by a clinician ranged from AUD 559.99 to AUD 1,046.42 for clinical service providers.

2.7 Supporting information

Appendix B. Survey of Auditory Training Practices in Cochlear Implant Clinics in Australia

2.8 Acknowledgements

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2.9 Author contributions

IB conceived the experiment. MR, IB, EB designed and conducted the experiment and data analysis for the survey. MR, IB and VM designed and conducted the cost analysis. MR prepared the manuscript with contributions from IB, EB and VM.

Chapter 3. Effectiveness of computer-based auditory training for adult cochlear implant users: a randomised crossover study

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3.1 Abstract

Objective: To assess the effectiveness of a computer-based auditory training program compared to a computer-based visual training program at improving short- and long-term trained and untrained measures of listening and cognitive abilities and quality of life. **Design:** A multisite randomised crossover study with repeated measures was conducted. Data from 26 adult cochlear implant users were collected across three sites. Participants completed either 6 weeks of speech perception in noise training followed by 6 weeks of text recognition in noise, or vice versa. Outcome measures were administered twice before each training program, to control for test-retest effects, as well as twice after completion of each training, to assess effects immediately following training, and long-term effects after a delay period of no-training. Linear mixed-effects models were fitted to analyse whether changes on the training tasks and outcome measures occurred at post-training and whether these were higher than test-retest. **Results:** Statistically significant improvement was shown for performance during both the auditory and the visual training program, however, this on-task learning did not transfer to improvements in outcome measures tested outside the training program. **Conclusion:** Findings from this study suggest that experienced cochlear implant users do not show transfer of on-task learning to untrained listening and cognitive abilities and self-report measures of listening and quality of life after the computer-based auditory training and visual training programs used in this study.

3.2 Introduction

Auditory training (AT) aims to maximise individuals' auditory skills through structured listening practice, to ultimately enhance communication, social participation and quality of life (Boothroyd 2010). A recent survey study conducted with clinicians in cochlear implant (CI) centres indicated that face-to-face and home-based AT is often recommended for adult CI users (see Chapter 2). A cost analysis of different AT approaches conducted as part of the same study suggested that home-based AT was the method with lowest cost for both clients and clinical service providers. Computer-based auditory training (CBAT) is one option for providing home-based AT, however, its efficacy has not been rigorously evaluated.

Two systematic reviews of AT have been conducted to date, and they demonstrated that well-controlled studies assessing the efficacy of AT for individuals with hearing loss are lacking (Sweetow & Palmer 2005; Henshaw & Ferguson 2013), and that higher level evidence is needed to guide clinical practice. Recently, Pisoni et al. (2018) suggested that developing a novel intervention for individuals who do not reach optimal benefit with their CIs is among the main challenges in future CI research, as the authors indicated - little evidence exists that current CBAT programs provide benefits that are higher than practice effects. However, while developing a novel and effective intervention to address poor outcomes is important, better understanding the aspects of listening that are targeted by current AT approaches is a necessary step to improve the design of rehabilitation interventions.

Interventions that aim to improve outcomes after cochlear implantation, such as CBAT, have focused mainly on directly training individuals to listen to speech stimuli. The efficacy of these interventions is usually assessed by measuring post-training changes in trained and untrained measures of speech perception (e.g. Fu et al. 2004; Miller et al. 2008; Oba et al. 2011; Schumann et al. 2015a). Speech is also the most common stimulus and outcome measure used in clinical practice by audiologists who deliver AT to adult CI users (see Chapter 2). Although benefits have been found in some studies which used speech stimuli, variation in outcomes exists across studies, especially when assessing whether improvement on trained tasks transferred to untrained material (see Henshaw & Ferguson 2013 for a review). A few studies have also reported that some individuals do not show benefit from training (Tyler et al. 2010; Oba et al. 2011; Schumann et al. 2015a). Thus, as indicated by Boothroyd (2010), it is important to understand who is most likely to benefit from training, what aspects of listening AT is targeting and which specific features of AT protocols elicit auditory perceptual learning.

Addressing these points suggested by Boothroyd (2010) requires that investigations of AT effectiveness include outcome measures that enable researchers and clinicians to better understand individual characteristics, to provide knowledge of either how these may predict training outcome or how these are affected by training. This would involve assessments that go beyond speech perception measures, as these provide limited information of everyday functioning (Granberg et al. 2014). For instance, self-report measures of communication and quality of life could supplement speech perception measures by informing how AT affects individuals' management of communication in different situations, self-efficacy, activity and social participation.

Another important factor to consider as a contributor to auditory perceptual learning is cognition. Cognitive processes play an important role in listening (see Arlinger et al. 2009; Rönnberg et al. 2013; Pichora-Fuller et al. 2016 for reviews). Specifically, the lack of temporal fine structure cues, which are excluded from the CI signal processing strategies, contributes to difficulties CI users have when trying to understand speech in the presence of background noise (see Moore 2008; Moon & Hong 2014 for reviews). Therefore, a constant allocation of cognitive resources is required to compensate for these difficulties, with working memory, phonological representations, and attention being suggested to contribute to speech understanding performance (Rönnberg et al. 2008; Rönnberg et al. 2013; Pichora-Fuller et al. 2016). Thus, it has been suggested that AT is targeted at reducing the amount of cognitive resources individuals need to allocate during listening (Tremblay & Backer 2016), which could therefore make listening less effortful.

Although cognitive abilities have not been investigated in AT studies with adult CI users, research conducted with other populations of hearing-impaired listeners offer insight into how these may interact. For example, Sweetow and Sabes (2006) demonstrated that hearing aid users showed improvements in inhibition control in the visual Stroop test, and auditory working memory in the listening span test following auditory-cognitive training with the Listening Enhancement and Communication Enhancement (LACE) program. Ferguson et al. (2014) demonstrated that a group of unaided individuals with mild to moderate hearing loss showed improvement in divided attention measured with the Test of Everyday Attention, as well as in working memory measured with a visual letter monitoring task following four weeks of phoneme discrimination training. Such improvements in cognitive abilities, however, were not shown by Saunders et al. (2016) in new and experienced hearing aid users following training with two versions of LACE. The only measure of cognition investigated by the authors, however, was auditory working memory measured with a digit span task, which differed from the task used by Sweetow and Sabes (2006). Where possible, cognitive abilities in hearing-impaired listeners should be measured by visual tasks, to ensure that hearing loss does not lead to bias in results

A few studies have evaluated the role of cognition from a different perspective, by investigating whether directly training cognition could generalise to listening gains. Anderson et al. (2013a) demonstrated that individuals with mild to moderate hearing loss showed an improvement of 1.22 dB in speech perception in noise following a cognitive training (CT) that focused on speed of auditory processing. Although these results were statistically significant the authors indicated that this was just below the clinical significance of 1.9 dB for the specific speech perception test used in that study (i.e. QuickSIN). The findings of Anderson et al. (2013) however, were more encouraging than the results of Oba et al. (2013) who observed little to no benefit in CI users' speech perception following a non-auditory, cognitive training program using a visual digit span task. Similarly, in a study involving verbal and visuospatial working memory training with hearing aid users, no effects were seen for measures of speech perception (Ferguson & Henshaw 2015b).

While such findings could be indicative that CT is not an effective intervention to improve speech perception in noise, multiple studies in perceptual learning indicate that transfer effects are only demonstrated when the untrained outcome measures are closely related to the tasks trained (see Ahissar et al. 2009 for a review). It is therefore possible that the reason for the findings in Oba et al. (2013) and Ferguson and Henshaw (2015) was due to a limited overlap between trained and untrained tasks.

An example of a visual task that overlaps with speech perception in noise is the text reception threshold (TRT; Zekveld et al. 2007). The TRT was developed to be a visual analogue of the speech reception threshold (SRT) and measures the ability to understand text that is covered by adaptive vertical bar patterns. A 30% shared variance between the TRT and the SRT was demonstrated by Zekveld et al. (2007) in individuals with normal hearing, and a later study which developed an improved parameter, the TRT_{500}, demonstrated a shared variance of 50.5% between these two measures in normally hearing adults (Besser et al. 2012). These findings indicate that the TRT test assesses the nonauditory abilities relevant for speech perception in noise. The TRT has been suggested as a potential test used to assess the cognitive processes involved in speech recognition, such processing speed, attention and working memory, and disentangle the underlying constructs of communication issues in individuals with a hearing loss (Kramer et al. 2009). Considering the overlap between the TRT and the SRT, such paradigm could also be useful to inform whether directly training abilities that are relevant to speech perception can elicit improvement in listening and cognitive abilities and quality of life. The use of such paradigm should also enable for comparisons with AT that uses speech in noise as training stimuli.

Thus, the present study aimed to assess whether a computer-based speech in noise AT program leads to short- and long-term changes in trained and untrained measures of listening, cognition and quality of life. A secondary aim was to assess whether directly training the underlying cognitive abilities required for speech perception in noise, using a computer-based visual training (VT) program without the auditory component, would elicit comparable outcomes as the AT program.

To test this, adult CI users were enrolled in a crossover study, where both interventions were received, however in different order for each group. This allowed for comparisons between intervention and within-subject. Double baseline measures were used to account for changes in performance that would be solely due to training and not test-retest effects.

It was hypothesised that both training programs would offer larger learning effects over and above controls, who were not hypothesised to show any improvements. Furthermore, it was hypothesised that learning effect sizes on measures of listening and cognitive abilities and quality of life would be larger for AT than for VT due to the auditory component of AT. It was anticipated that immediate post-training effects would be larger than test-retest effects (i.e. double baseline), and that these would be retained longer term, although a decrease in performance was expected.

3.3 Methods

This study is reported in accordance with the Consolidated Standards of Reporting Trials (CONSORT) extension for nonpharmacologic treatments (NPTs; Boutron et al. 2017). The CONSORT-NPT is intended to standardise and improve the way trials of NPTs are reported. This study protocol was retrospectively registered with the ISRCTN trial registry (ISRCTN98523729) in September 2017, prior to the end of data collection.

This study was approved by the Human Research Ethics Committee of Macquarie University (reference number: 5201500069) and the Royal Victorian Eye and Ear Hospital (reference number: 17/1327H).

Study design and sites

A multisite randomised crossover study was conducted (see Figure 3.1). Data collection commenced at Macquarie University (MQU) in Sydney and two other sites – Fiona Stanley Hospital (FSH) audiology sector, Perth; and The HEARing Cooperative Research Centre (CRC), Melbourne – were included at a later stage to increase recruitment of participants. The sites where data collection occurred were clinical rooms within university spaces (CRC and MQU) and an audiology clinic within a hospital (FSH). MR administered data collection at the MQU site, and provided training on the study and data collection protocol to five data collectors at FSH and two data collectors at the CRC sites. Data collection was part of the Master of Audiology clinical and research training of the two data collectors at the CRC and four data collectors at FSH. The fifth data collector at FSH was a senior audiologist and researcher who also supervised the research personnel during their clinical placements at this site. In addition to the initial training provided, author MR established weekly communications with data collectors at each site to ensure the study protocol was being followed accordingly. All the programs and tools for assessment of outcome measures were installed by MR using the same equipment models which were loaned to the sites for the period of the study. Data collection forms were completed for each participant at each visit, and all digital data derived from assessments was automatically available on an online platform. Information from physical data collection forms were digitised and transferred to the same online platform.

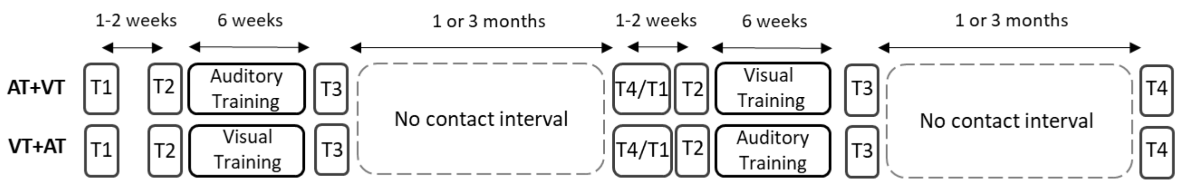


Figure 3.1. Study design. No contact interval was 3 months in one study site and 1 month in the other two sites.

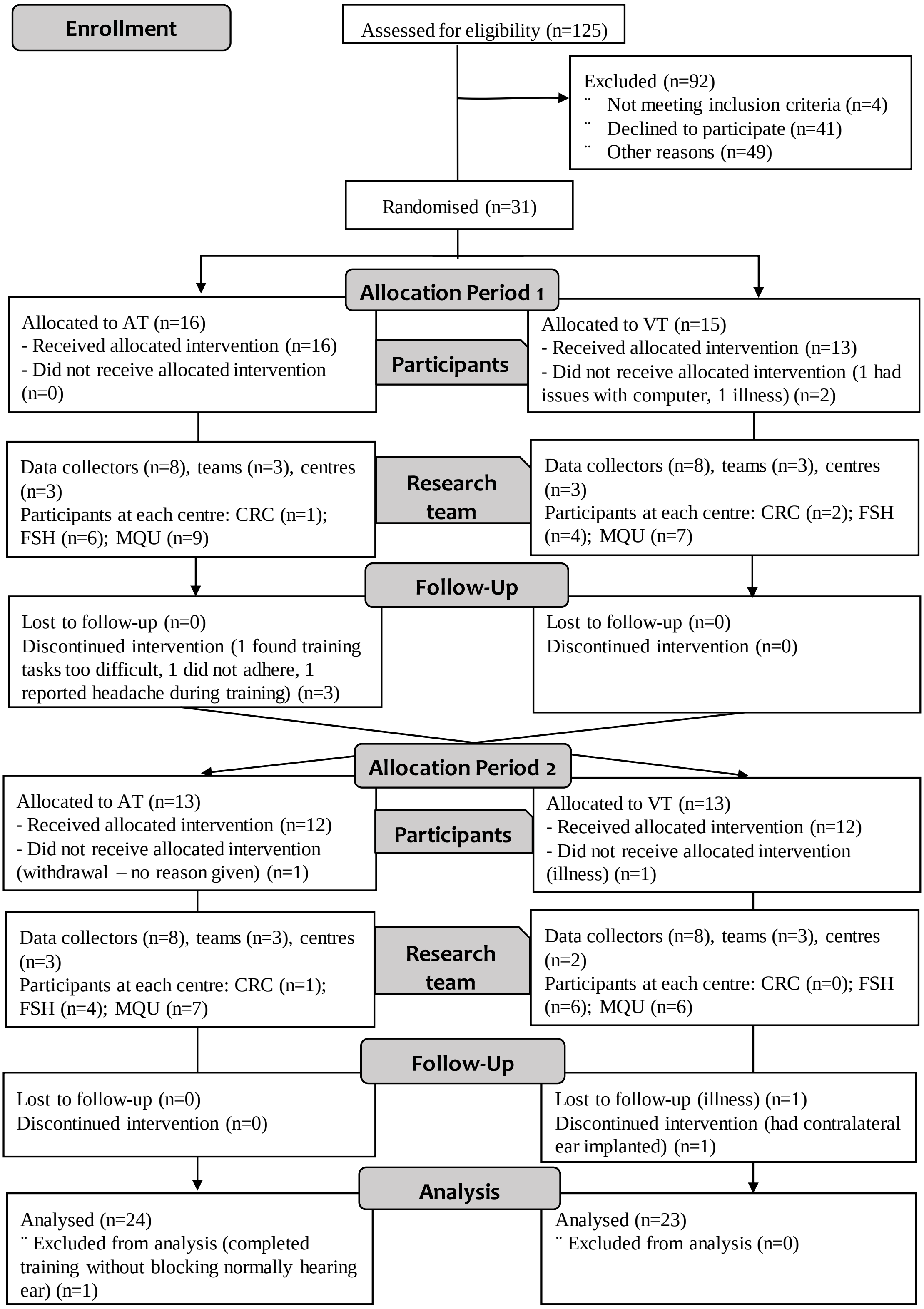
Participants

Prospective sample size estimation was conducted considering that the study used a repeated-measures crossover design (MGH Biostatistics Center 2015). The sample size calculation was based on Bamford-Kowal-Bench/Australia (BKB/A; Bench & Doyle 1979) sentences in 4-talker babble. Retrospective data were used to determine the mean change in BKB/A sentences from a larger group of CI users. Based on that analysis, a 20 percentage point difference was established to determine a clinically meaningful difference post-training (i.e. at T3). This is consistent with Thornton & Raffin (1978), which specified a difference of over 10 percentage points to be considered significant in speech discrimination tests and with and the Food and Drug Administration requirements (c.f. Centers for Medicare and Medicaid Services 2005), which described a 20 percentage point difference in open-set recognition tests to be considered a significant change in CI treatment. Thus, the power calculation indicated a requirement of 18 participants in each intervention group. This sample size implied a probability of 80% that the study would detect a treatment difference at a two-sided 0.05 significance level. Additionally, it implied that if 18 participants started and finalised both training programs, there would be 18 participants in each intervention group of this crossover study.

Potential participants were identified by collaborating organisations using their databases. Individuals were recruited via personal invitations sent by the Sydney Cochlear Implant Centre - an RIDBC service (SCIC) in Sydney, FSH in Perth, and the Royal Victorian Eye and Ear Hospital (RVEEH) in Melbourne, as well as from a database of research volunteers with the Australian Hearing Hub in Sydney. Additionally, recruitment advertisements were displayed and distributed at the abovementioned clinics and posted on social media pages of SCIC and Cochlear Ltd. The recruitment period was open from 01 March 2016 to 28 July 2017.

Adults who were uni- or bilateral CI users with at least one year of CI experience were eligible to participate in the study. One year of CI experience was selected as a criterion to ensure that any training effects were not confounded with device acclimatisation, because significant improvement in listening abilities are typical in the first year after implantation, whether or not training is provided (c.f. Blamey et al. 2013; Holden et al. 2013). Adults needed to be competent English speakers to perform tasks, able to use a computer and not present significant neurological or cognitive impairment, as assessed by the Mini-Cog test (Borson et al. 2003), or significant visual impairment (assessed by an on-screen letter monitoring test). Those who met the eligibility criteria and signed the participant information and consent form received a participant identification code.

Data from 26 participants were included, however five of these participants had their data analysed only for one intervention arm of the study due to withdrawing from the study before completing the second intervention or failing to comply with the required listening mode during training (Figure 3.2). In one case, a participant completed both training programs but became ill before



FSH: Fiona Stanley Hospital; CRC: HEARing Cooperative Research Centre; MQU: Macquarie University

Figure 3.2. Participant flow diagram.

attending the post-training session for the second training (VT) program and withdrew from the study. Therefore, this participant had their performance over the course of the training program analysed, but not for the outcome measures related to the VT arm.

Randomisation, concealment of allocation, and blinding

Ideally, participants would have been allocated into groups through a stratified randomisation method, which would allow for a better balance in demographics between groups. Time restrictions in the current study, however, did not enable for the recruitment phase to be completed before the beginning of data collection and therefore each site was provided with a group allocation list, which was pre-generated in Randomization.com (http://www.randomization.com). Author MR was responsible for generating the allocation sequence, and assigning participants to interventions, whereas participants were enrolled in the study by the data collectors at each site. Neither participants or data collectors were blinded, however participants were informed of the intervention they would be receiving first only at the end of the second study visit (T2).

Procedures

Data collection occurred between 10 September 2016 and 01 March 2018. Baseline measures were obtained twice before the start of each training, to account for test-retest effects. Even before the second training was received, this double baseline was important to control for any test-retest effects that could have occurred following a period of no-training. Due to data collection timing logistics, the training retention period was shortened at FSH and the CRC testing sites, as shown in Figure 3.1 (interval between T3 and T4).

The order in which tests were presented for each participant at each testing session was randomised to avoid fatigue effects interfering in the test results. Each testing session lasted between 1h30min and 2h. Participants were given a break in the middle of each session.

Participants were instructed not to have their CIs programmed between T1 and T3, to avoid introduction of factors that could be confounded with training effects.

Participants received a compensation of AUD 40.00 for each assessment visit they attended at the study sites.

Visit 1 (T1): Participants were given detailed information about the study, asked to read and sign the PICF to confirm they agreed with the study procedures. Screening tests were administered and participants' hearing history and demographic information were collected. If the participant met the inclusion criteria, the first baseline measures were collected.

Visit 2 (T2): Participants performed the evaluations in the test battery, and only at the end of this session, they were informed of the training program they would be receiving first. Participants created an account protected with password to use the program and were instructed about how to login and use the program.

Visits 3 and 4 (T3), and 6 and 7 (T4): Measures in the test battery were performed to assess for short- and long-term effects of training. Visit T4 acted as both long-term follow-up for the first training and the first baseline measurement preceding the second training.

Visit 5 (T2): Testing was administered and at the end of this visit, participants were instructed about how to use the second training program.

Training periods: Participants were instructed to contact the site data collectors if they were experiencing any issues with the program. Author MR monitored participants' adherence to the training programs once a week and if any inconsistencies in adherence were identified, participants were contacted by data collectors at each site and encouraged to continue training.

Interventions

Participants were asked to complete two 6-week blocks of individual computer-based training programs at their home: a verbal auditory training (AT) and a verbal written-based visual training (VT). For each training block, participants were requested to use the program five times per week. Because there is no agreement in the literature in regards to the best regimen to be adopted for training (see Henshaw & Ferguson 2013 for reported frequency and duration of AT programs), this study adopted a regimen that appeared sufficient to generate potential perceptual learning, while being reasonably limited to increase the potential for adherence of participants to the program. A computer-based delivery mode with remote monitoring was chosen to increase the potential to recruit a sufficient number of participants in the study (i.e. no travels involved).

Both training programs consisted of tasks that required recognition of words and sentences under masked conditions. In the AT this consisted of listening to target stimuli with a 4-talker babble and identifying what was heard, whereas in the VT it consisted of reading target stimuli that were masked by a series of bars, adapted from the TRT_{500} (Besser et al. 2012).

The order in which training programs were completed depended on the group the participants had been allocated to.

Some of the participants recruited used a hearing aid in their non-implanted ear, which has the potential to lead to more variable hearing abilities over time in comparison to ears using cochlear implants. To limit this variability, and focus the experiment on training with cochlear implants, participants were instructed to use the AT program wearing their CI(s) but not wearing a hearing aid.

For the AT program, participants were requested to adjust their computer volume to a comfortable level.

Development of training programs

A review of existing training programs was conducted to evaluate the possibilities of using programs already available at the time this study was designed. The limits identified in existing programs included not being able to choose the specific tasks participants could have access to (such as words and sentence stimuli only), stimuli recorded in non-Australian English and different program design and layout between VT and AT programs, which could have added biases related to motivation when comparing the effects of the two programs.

Therefore, two training programs were specifically developed for this study (see Appendix C; Toybox Labs 2016). The layout of both programs was identical (Figure 3.3), with the client side of the software packages developed in C++ for Windows platform (2003 and higher) and the server side where participants' data was stored and secured running on Amazon Web Services, and accessible only to program developers and investigators. Additional program characteristics included the possibility to lock the access to each program by the administrator remotely, allowing users to have access to only one, both or any of the programs.

Participants were requested to create an account when they started the study and had to log into the program every training session to have their results recorded. Participants had access to the number of correct trials they obtained at the end of each module, whereas investigators had access to participants' scores, time taken and level of difficulty participants started and finished each module for each session. Additionally, at the beginning of each training session, participants were asked to indicate how many hours they slept in the previous night as well as how they were feeling at time of the session (a five-point Likert scale with smileys ranging from "very happy" to "very sad"), which were also saved to their session results. These were collected to measure whether mood and sleep could affect training outcomes, as suggested in the perceptual learning literature (c.f. Censor et al. 2006).

Development of training stimuli

Recording and editing of auditory stimuli

Sentence and word lists were recorded by a female and a male speaker in an acoustically treated recording booth. Speakers were professional Australian voice actors aged 30. Mono sound recordings were obtained at 16 bit, 48kHz sampling rate, and high passed filtered at 40Hz, using an AKG C535 condenser microphone and a PreSonus StudioLive 16.4.2 and digitally transferred onto ProTools 12.5. The stimuli were manually segmented into individual .wav files, and a silent interval was set 2ms before each stimulus onset.

Additionally, a 4-talker babble track was extracted from a standard Australian speech perception test and segmented into 22 different tracks, and equalised to the target stimuli level. Eighteen additional levels with a 2dB difference between levels were then created for each of the 22 tracks, totalising 19 different masking levels. Thus, for each difficulty level in the AT program, 22 different segments of 4-talker babble could be presented to participants, to avoid acclimatisation to the masking noise.

The level of all tracks, including the masking track, was equalised in MATLAB 9.0, by calculating the root mean square (RMS) and maximum value from all the sound files.

Sentences

Sentence material was extracted from Harvard/IEEE sentences (Egan 1948; IEEE 1969) and spelling and pronunciation were adapted to Australian English. This corpus was used to avoid similarity to material commonly used in clinical assessments, such as the Australian Sentence Test in Noise (Dawson et al. 2013), BKB/A sentences (Bench & Doyle 1979) and City University of New York sentences (Boothroyd et al. 1985), and to replicate material used in previous AT studies (Fu et al. 2005; Fu & Galvin 2007; Fu & Galvin 2008). The 72 Harvard/IEEE sentence lists were split in half, with the first 36 lists used in AT program and the remaining used in the VT program.

For the AT, sentences were grouped according to their length and initial phoneme of the first sentences (trials). When the sentence started with an article, the initial phoneme of the second word was considered. This totalised in 360 sentences and 2430 different trials (Table 3.1). For the

Table 3.1. Number and length of sentences in the submodules for the auditory and the visual training programs

Submodule	Sentence length (words per sentence)	Number of sentences	
		Auditory Training	**Visual Training**
1	5-6	30	36
2	7-8	230	303
3	9-10-11	100	119
Total		**360**	**358**

VT, sentences were grouped according to their length and initial grapheme. Two sentences containing 12 words were excluded due to lack of enough sentences to form a trial, thus, the total number of stimuli for this module was 358 sentences, which resulted in 2208 different trials (Table 3.1).

Words

Material for the initial and final consonant discrimination modules was extracted from the Maryland Consonant-Nucleus-Consonant (CNC) word list (Causey et al. 1984). Non-words, names and words that are not classified as CNC in Australian English (i.e. /far/, /jar/; see Cox 2012 for a review) were excluded from the list and additional words were included where applicable. The final word list material consisted of 986 words and was used for both AT and VT programs.

For the AT, words were distributed in a phonetic matrix according to their place and manner of articulation in Australian English. Based on initial and final phoneme contrasts, two modules were created. Only words that had at least two additional group contrasts were used as stimuli in each module (i.e. */pool/* was used in the initial consonants module, where */tool/*, */cool/* and other words were available, however it could not be used in the final consonants module, where only one word */pooch/* was available). The 'initial consonant' module consisted of 418 different stimuli and 2319 possible trials, in which words differed only in their initial phoneme (i.e. /*geek/*, */seek/, /cheek/*), whereas the 'final consonant' module consisted of 311 different stimuli and 1272 possible trials, in which words differed in their final phoneme only (i.e. /*dog/, /doll/, /dot/).* The phonetic matrix was verified for accuracy by a linguist.

For the VT, words were grouped according to their middle and final graphemes, to create the 'initial letters' module, where words differed only by their initial grapheme, totalising 320 different stimuli and 1736 different trials. Middle and initial graphemes were used to develop the 'final letters' module, where words differed only in their final grapheme, also resulting in 148 different stimuli and 509 trials.

Masking

As previously specified, masking consisted of 4-talker babble. For the VT, parameters were set according to the TRT_{500} described in Besser et al. (2012) and masking stimuli was based on the original publication of the TRT (Zekveld et al. 2007) following personal communication with Zekveld. A box measuring 22 pixels was created and filled in black and white according to each difficulty percentage level. The percentage of white (unmasked) colour determined task difficulty. Multiple boxes were placed side by side until the target stimuli were covered.

Training protocol

Each training program consisted of three modules, with 25 trials each, organised in recognition of initial consonant (module 1), sentences (module 2) and final consonant (module 3). Training difficulty was modulated by an adaptive protocol. To avoid that participants were exposed to the same stimuli every session, seed randomisation was used for presentation of target stimuli.

For the AT, a 4-talker babble was presented first and 1000ms later the audio of the target stimulus was presented. Three response alternatives appeared on the screen 500ms after stimulus presentation ceased and the participants' task was to choose the correct alternative. Stimuli presentation in the VT followed the protocol described for the TRT_{500} in Besser et al. (2012), where once the stimulus had fully appeared, it remained on the screen for 500ms. The stimuli reading speed, however, was defined based on an estimation of between word interval in the audio files used in the AT. For this, the black bars appeared first on screen, 1500ms later the target stimulus was presented in a word-by-word fashion – in the case of the sentence module – with an interval of 400ms between each word. After that, three alternatives were presented on the screen, and participants had to choose the correct alternative. Figure 3.3 displays trial sequence used in both training programs.

For both programs, if the correct alternative was selected, positive visual feedback was given by a small green tick being shown on the screen accompanied by a high pitch sound, and the next trial would begin. If an incorrect alternative was selected, a small cross accompanied by a low pitch sound was presented and a new screen with both the chosen and the correct alternative were presented for comparison. In the AT program, participants were allowed to replay both alternatives as many times as they wanted. The difficulty level was adjusted by a change in the masking stimuli which would be increased each time three trials were correctly identified or decreased each time one trial was incorrectly identified (3-up, 1-down). In the AT this corresponded to a 2dB change in the masking noise, whereas in the VT this corresponded to a change of 6 percentage points in the width of the masking bars. The difficulty level used in the last trials of each module was recorded and the following training session would start with this same level. Difficulty level was independent among modules, that is, an increase in difficulty on the initial consonant module would not affect the difficulty level on sentence recognition or final consonant and vice-versa.

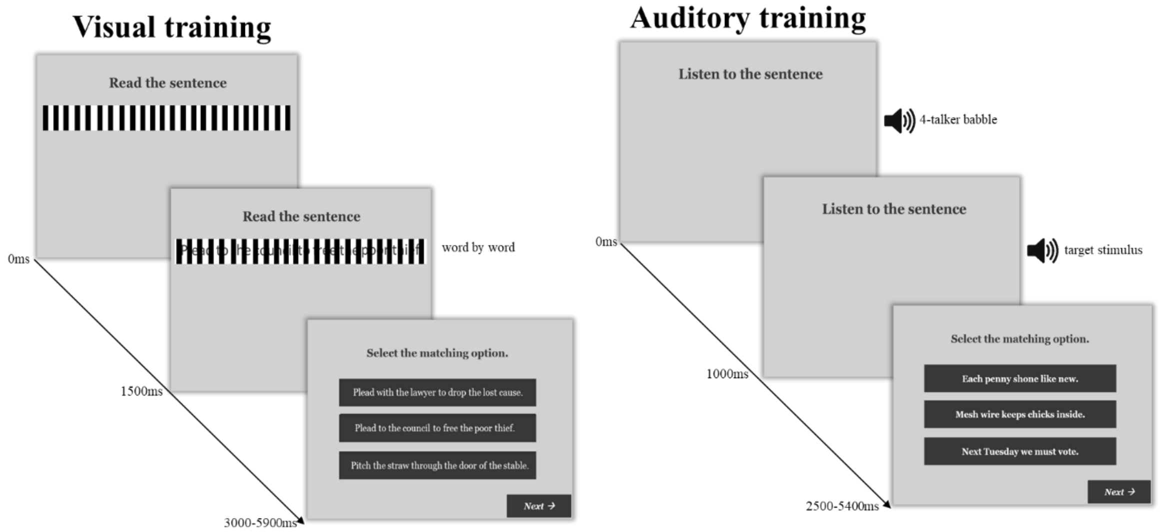


Figure 3.3. Example of trial sequence used in the sentence module of each training program. A consequent trial was presented if the correct alternative was selected. If an incorrect alternative was selected, the following screen contained feedback to participants.

For the sentence module in both programs, there were different submodules based on sentence length (Table 3.1). Participants would progress to the following submodule once they had correctly identified 80% of the total stimuli in a submodule. Submodule progression was independent of masking progression, that is masking level could increase, however, participant could continue training in the same sentence length submodule if an 80% correct response rate was not achieved.

Session completion was achieved once the three modules in the program were completed (i.e. 75 stimuli presented). If the three modules were not completed and participants attempted to close the session a message would be displayed enquiring whether they were certain they wanted to escape the program and that their session would not be uploaded to the server. Results were only saved if participants completed the three modules. Similarly, if the program was opened for a second time on the same day, a message would be displayed informing that the training session for that day had already been completed. If the program was opened for a third time, participants would not be able to access the training tasks. Participants were given access to the training programs only for the period they were using each of them, with access being blocked to the program they were not using at the time or to both program during the no-training period. These series of approaches were taken because it was desired that all participants were equally exposed to the same amount of trials during the training phase.

Outcome measures

The outcome test battery was designed to evaluate whether training led to improvements in listening and cognitive abilities and quality of life. Speech understanding in noise assessed with BKB/A sentences was selected as the primary outcome measure, as understanding speech in noisy environments is amongst the most common complaints of adults with a hearing loss. This was also the measure most related to training (i.e. masked verbal information), and thus, for which most benefit was expected following training. Secondary outcome measures included measures of listening and cognitive abilities and quality of life. Some CI users may have difficulties in understanding segments of speech even in quiet environments, and therefore, the effect of training on perception of monosyllabic words in quiet was also investigated. Similarly, poor spectral resolution may limit listeners' understanding in complex listening situations (Aronoff & Landsberger 2013), therefore, this was an important outcome to investigate.

Outcome measures of cognitive abilities have also been assessed as cognition plays an important role in listening. Prior studies have suggested that AT may have effects on abilities such as working memory, processing speed, and attention (c.f. Sweetow & Sabes 2007; Anderson et al. 2013a; Ferguson et al. 2014; Ferguson & Henshaw 2015a). Phonological representations have not yet been assessed in AT studies, however, in conjunction with the cognitive abilities mentioned before, this has been suggested to contribute to the ease of listening understanding (Rönnberg et al. 2008; Rönnberg et al. 2013; Pichora-Fuller et al. 2016), and may be a relevant factor to investigate.

Self-reported measures of communication and quality of life provide a means of assessing real-world performance. Although it has been suggested that word and sentence-based training should have positive effects on communication, social participation and quality of life (Boothroyd 2007), this relationship has not been well established in the literature. In addition to assessing AT effects on self-perceived qualities of listening, this study also aimed to assess its effects on how individuals feel in different listening situations, by assessing communication self-efficacy and communication apprehension. These can also provide information about social participation prior to and following AT. General quality of life questionnaires were selected to investigate whether AT had any impact on activities of daily living and health-related quality of life.

All behavioural tests were conducted in a sound-treated booth. Stimuli were delivered at 65dB HL through a loudspeaker positioned 0º azimuth to the participant at a distance of 1 metre. Tests of speech understanding in noise, quiet and spectral resolution were delivered in the same mode as participants completed the training at home (i.e. CI only in case participants were hearing aid users). Self-report measures were obtained through an online platform out of the laboratory (Qualtrics 2018).

Speech understanding in noise: Six lists of *BKB/A sentences* (Bench & Doyle, 1979) spoken by an Australian-English female speaker were presented to participants in two different conditions. Each BKB/A list consists of 16 sentences and is scored on the number of words correctly repeated out of 50 key words. To avoid ceiling effects, two difficulty conditions were assessed at each timepoint. All participants were tested at baseline with three sentence lists in 4-talker babble at +10dB HL SNR. If participants scored <50% of the key words correctly, three lists at +20dB HL

SNR were presented. If ≥50% were scored correctly, three lists at 0dB HL SNR were presented. These two conditions were determined at the first study visit and consistently used throughout the remaining visits. For each participant, lists to be presented at each session were predefined to avoid exposure to the same lists on consecutive sessions – that is, participants would only be presented with a repeated list from visit 4 (T4) onwards. Sentences were different from those used in the training programs. Participants were given small breaks between the presentation of each list. Participants' responses were videorecorded for offline verification of scoring. Scores on the three lists presented for each condition were averaged and presented as percentage correct.

Word recognition in quiet: *CNC word lists* consisting of 50 recorded words spoken by an Australian female speaker were presented in quiet. This test was based on the original CNC test, and is consistent with the frequency of occurrence of phonemes in conversational Australian English. Scoring was based on the percentage of words correctly identified. One list was presented to participants at each timepoint and participants were not exposed to repeated lists overtime. Of the words used, 559 (56.7%) differed from those used in the training programs. Responses for this test were also videorecorded for offline verification of scoring.

Spectral resolution: This was assessed with the *spectral-temporally modulated ripple test* (SMRT, Aronoff & Landsberger 2013). This test consisted of a three interval, forced choice, adaptive task, where three sounds were presented, and the participant had to select on a computer screen the one that sounded different. Thresholds were scored based on the average of the last six reversals and are presented as ripples per octave.

Visual and auditory attention: The *Integrated Visual Auditory Continuous Performance Test (IVA-CPT)* was used to assess focused, sustained, divided, and alternating visual and auditory attention. This test requires participants to click the mouse when a determined target is seen or heard and not to click when seeing or hearing a non-target item. Performance was measured by reaction time and number of hits (i.e. accuracy) for target and non-target items.

Additionally, the *Victoria Stroop Test* (VST, Spreen & Strauss 1998) was used for assessment of sustained attention and inhibition control. The *VST* is a short version of the Stroop Colour-Word Test (Stroop 1935), and consists of three tasks. It requires participants to correctly identify the colours of dots seen on the screen, the colour in which words are printed and lastly the colour in which colour-names are printed. The average reaction time for the colour-names task divided by the reaction time for the dots task is presented with lower reaction times indicating better inhibition control.

Phonological representations: This were assessed with the *rhyme judgement test* (Ausmeel 1988) which consists in determining whether two words displayed simultaneously on a computer screen rhyme or not. Scores were calculated by reaction time and percentage of trials scored correctly.

Verbal working memory: this was assessed with the *reading span test* (RST, Baddeley et al. 1985). This task involves identifying whether a sentence presented visually via a computer screen makes sense or not (assuming comprehension of the sentences), and recall of either the first or the final words of the sentences that are visually presented in blocks of 3, 4, and 5 sentences at a time. Scores were calculated by percentage of items recalled throughout the test.

Self-report listening: This was assessed with the *Speech, spatial and qualities-12* (SSQ-12; Noble et al. 2013)**,** a 12-item questionnaire that measures auditory disability and handicap and assesses four major factors: speech hearing, spatial hearing, qualities of hearing, and listening effort. These are assessed through a 0-10 scale, with the higher end of the scale reflecting better scores

Communication apprehension: This assessed with the *Personal Report of Communication Apprehension* (PRCA-24; McCroskey et al. 1985), a 24-item scale, to assess communication in four contexts: public, small groups, meetings and interpersonal encounters. Scores range between 24 and 120, with scores from 24-55, 55-83, and 83-120 indicating low, moderate and high level of communication apprehension respectively.

Communication self-efficacy: The *Self-efficacy for Situational Communication Management Questionnaire* (SESMQ; Jennings et al. 2013)**,** a scale containing 20 everyday situations was used to assesses confidence in management of communication situations in simple and complex noisy environments. Rating scale ranges from 0 (not confident at all) to 10 (very confident). Total score ranges from 0 to 200 with higher scores indicating greater self-efficacy.

Quality of life: This was assessed with the *Quality of Life Scale* (Burckhardt & Anderson 2003), which consists of a 16-item questionnaire that measures quality of life through a 7-point satisfaction scale. Scores can range from 16 to 112 with higher scores indicating greater quality of life.

The *SF-36* (Ware & Sherbourne 2015), a 36-item questionnaire which focus on eight health concepts, was used to assess health-related quality of life. It comprises questions related to activity limitations due to physical or emotional health problems. For this study, only five areas of the SF-36 were assessed: general health, vitality, social functioning, emotional role limitation and mental health. Scores range from 1 to 100 with higher scores indicating greater health-related quality of life.

Data analysis

Statistical analysis was conducted in R (R Core Team 2018) using the lme4 package (Bates et al. 2015). Linear mixed-effects models were created to evaluate the effect of each training, and how this varied within groups. This allowed to account for inherent individual variability as well as how factors influenced results at each timepoint of interest. By accounting for these, it is expected to reduce error in the models used and increase the ability to detect effects of training. Final models used to analyse each outcome measures were decided following exploratory modelling. In each analysis, the best-fitting model was used, which was evaluated by the lowest Akaike information criterion (AIC) when comparing models (Akaike 1974). P-values were obtained by using lmerTest package (Kuznetsova et al. 2017) and significance was set at $p<0.05$. The complete outputs of models fitted are contained in Appendix C.

Participant differences

Differences between training allocation groups at the first baseline are described by mean and standard deviation and tested with t-Student test for normal distributed data. Non-parametric Kruskal-Wallis test was conducted for continuous non-normal distributed data and these are described by median, lower and upper quartiles. Categorical data are described by frequency and tested with Chi-squared test (Table 3.2).

On-task learning

Analysis of performance during completion of training programs was conducted by using log data of participants in each program. On-task improvement was assessed by comparing the last level of difficulty (i.e. SNR, TRT) participants were presented at each session, for each module. Analyses were conducted separately for each program as the dependent variable was different for each of these (i.e. dB SNR and TRT %). The linear mixed effects models used to evaluate on-task improvement on both AT and VT included the interaction between onset of hearing loss (pre- vs. postlingual) and session, and training allocation order as fixed factors. To account for within group variance across sessions, participants were included as random effect, and session was included as random slope in both models. In the case where participants completed more than 30 training sessions, the additional sessions were excluded from the analyses. This was conducted to assess how much learning occurred within the period participants were requested to train for, and ensure data analysis was balanced. The total amount of sessions completed, however, was included as a factor in the analysis of outcome measures (off-task learning). Because the literature suggests that the rapid initial learning may represent procedural (i.e. participants adapting to the task itself) but not stimulus learning (Ortiz & Wright 2009), a sensitivity analysis, in which the first 5 training sessions were not considered was conducted. Further, to allow for interpretation of whether any summation effects that any learning acquired during the first training could have on performance in the second training program, analysis of was also conducted by assessing intervention outcome when for the first period of the study only.

Outcome measures (transfer of learning)

The effect of training on outcome measures collected at each timepoint was analysed by assessing whether changes occurred in post-training (T3) in relation to performance at the second baseline (T2), and whether this were retained at follow-up (T4). This enabled to assess procedural learning due to test-retest (T1-T2), which could not have been assessed if post-training changes were considered in relation to the average of T1 and T2. Similarly, if the first baseline (T1) was used as reference in the analysis, this would not enable to assess whether training effects were higher than test-retest effects (T1-T2). For this analysis, participants were combined by intervention received (i.e. not training allocation order).

To assess whether performance in measures of auditory and cognitive abilities changed as an effect of training, linear mixed effects models were fitted. Fixed factors included age, onset of hearing loss, duration of hearing loss (calculated from onset of hearing loss) in the ear with shorter time of auditory deprivation, CI experience (if bilateral, the duration of experience in the latest implanted ear was considered), training order (i.e. group allocation), as well as the interactions between timepoint and type of training, and amount of training sessions completed and timepoint. For speech perception measures, the interaction between timepoint and working memory capacity (i.e. performance in the RST) was also analysed, as this has been previously suggested to support listening (c.f. Rudner et al. 2011). The models included participants as random factors, with random slopes for timepoints, which enabled to account for individual differences and how these varied between timepoints. The limited variance in self-report data did not allow for the models to converge, and therefore, models used to analyse these outcome measures did not have random slopes. Exploratory modelling indicated that time of follow-up (i.e. 1 or 3 months) did not contribute to results at T4, and therefore, were not included in the final models, however, descriptive for groups who received according to time at follow-up is shown in Appendix C. Similarly, although training order was considered as a fixed factor in the models, data analysis was also conducted considering only the first period of the study. The same models described above were used in this analysis, however, with no random slopes, as the number of participants in each group was reduced. These are not discussed within this chapter, however are presented in Appendix C.

3.4 Results

Demographics

Overall, allocation of participants into study groups was balanced for demographics (Table 3.2), except for the number of participants with prelingual hearing loss, which were allocated to the same group. As the randomisation list was pre-generated, this could not have been foreseen. A significant difference between groups however was found for performance in words in quiet and quality of life at baseline (AT+VT: median=24.0; VT+AT: median 58.0, p=0.045) and quality of life (AT+VT: mean=48.3; VT+AT: median 37.9, p=0.035) at baseline.

Table 3.2. Demographic information of participants, depending on order of training allocation

	All	AT+VT	VT+AT	p-value
Age (SD), years	63.23 (10.76)	62.23 (12.34)	64.23 (9.33)	0.646
Sex (female:male)	13:13	6:7	7:6	1
Onset (postlingual:prelingual)	22:4	9:4	13:0	0.096
CI experience [quartiles], years	4.00 [3.00;6.00]	4.00 [3.00;7.00]	3.00 [3.00;5.00]	0.392
N	26	13	13	

AT: auditory training; VT: visual training; SD: standard deviation; CI experience in the latest implanted ear was considered in case of bilateral implantation. t-Student test performed for age, Kruskal-Wallis test performed for CI experience; Chi-squared test perform for sex and onset of hearing loss.

Adherence and time taken on training programs

Adherence to the training programs was assessed by looking at number of sessions completed by all participants involved in the study, including those who withdrew or were excluded at a later phase of the study. Of the 24 participants who completed the AT program, 17 (70.8%) completed or more 30 sessions, 6 (25%) completed between 26 and 29 sessions and 1 (4.1%) completed 20 sessions. Of the three participants who withdrew from the study before completing the AT program, number of sessions completed was 0, 1, 7 and 13. Of the 24 participants who completed the VT, 14 (58.3%) completed 30 sessions or more, 8 (33%) completed between 26 and 29 sessions and 2 (8.3%) completed between 20 and 25 sessions. The two participants who withdrew from the study did not complete any training sessions (Figure 3.1).

Participants took on average 12.8 (3.1) minutes and 9.5 (2.5) minutes to complete individual AT and VT sessions respectively, which equalled 384 minutes of AT and 285 minutes of VT in total.

On-task performance

Learning was shown for all AT and VT tasks trained (Figure 3.4). As demonstrated in table 3.3, largest improvements occurred for initial (β= –0.15, *SE*= 0.03, p<0.001) and final consonants (β= –0.11, *SE*= 0.03, p<0.01) in comparison to sentences (β= –0.03, *SE*= 0.01, p= 0.04) in the AT program. A sensitivity analysis was conducted, by removing the first week of training, to assess whether effects would be maintained after participants adapted to the training task (Table 3.4). Even when the first week of training was removed from the analysis, improvements were still present, with slopes similar to the analysis which contained all six weeks of training. Although in the sensitivity analysis improvement in sentences module was no longer significant, however, the effect size remained the same (β= –0.03). Improvement was also shown for all VT tasks, however, this was smaller for both the initial and final consonant modules, and no longer significant for final consonants when the first week of training was excluded from the analysis (Table 3.4). In general, participants with a prelingual hearing loss showed significantly higher SNRs in the AT than participants with a postlingual hearing loss for all tasks. As shown by the interaction (Session X Onset hearing loss) in tables 3.3 and 3.4, however, prelingually deafened participants presented a similar or slightly steeper slope of improvement over the course of AT than postlingually deafened participants, which was significant for the sentences module (β= –0.09, *SE*= 0.03, p<0.008). This also occurred for the initial consonant and sentence modules in the VT program, although effects were not significant. The order in which participants received training was not a significant predictor of on-task learning for either the AT or VT programs, indicating that training learning on one modality did not diminished or contributed to performance on the second training. However, analysis of on-task performance was conducted for each training group separately according to the order training was received, and on-task learning was also demonstrated (Appendix C).

Table 3.3. Estimates for on-task performance during the 6 weeks of each training program

	N	**Initial consonants** Estimate (SE)	**Final consonants** Estimate (SE)	**Sentences** Estimate (SE)
Auditory Training	*24*			
(Intercept)		13.92 (0.94)***	13.47 (1.03)***	3.47 (0.98)**
Session		- 0.16 (0.03)***	- 0.12 (0.03)***	- 0.03 (0.02)
Onset HL (Prelingual)		4.02 (1.36)**	3.67 (1.59)*	5.37 (1.38)***
Training order (VT+AT)		- 1.09 (1.14)	-1.11 (1.20)	-0.54 (1.19)
Session x Onset HL (Prelingual)		- 0.02 (0.07)	0.03 (0.07)	- 0.09 (0.04)*
Visual Training	*24*			
(Intercept)		42.63 (1.59)***	42.66 (2.32)***	36.57 (1.47)***
Session		- 0.20 (0.05)***	- 0.15 (0.08)	- 0.12 (0.03)**
Onset HL (Prelingual)		0.81 (3.29)	- 4.42 (4.87)	0.79 (2.89)
Training order (VT+AT)		0.04 (1.79)	-0.85 (2.23)	0.57 (1.95)
Session x Onset HL (Prelingual)		- 0.11 (0.11)	0.20 (0.19)	- 0.07 (0.08)

HL: Hearing loss; VT+AT: Visual training received in the first period and auditory training received in the second period of the study. Onset HL postlingual and training order AT+VT are in the intercept.
*Significance codes: *** p< 0.001; **p< 0.01; *p< 0.5*

Table 3.4. Estimates for on-task performance with data from the first week of each training program removed from analysis

	N	**Initial consonants** Estimate (SE)	**Final consonants** Estimate (SE)	**Sentences** Estimate (SE)
Auditory Training	*24*			
(Intercept)		13.73(1.05)***	13.28 (0.89)***	3.51 (0.96)**
Session		- 0.15 (0.03)***	- 0.11 (0.03)**	- 0.03 (0.01)*
Onset HL (Prelingual)		3.00 (1.56)*	4.53 (1.32)**	5.32 (1.33)***
Training order (VT+AT)		-1.15 (1.27)	-0.93 (1.06)	-0.54 (1.15)
Session x Onset HL (Prelingual)		- 0.02 (0.07)	-0.012 (0.07)	- 0.09 (0.03)**
Visual Training	*24*			
(Intercept)		43.26 (1. 54)***	43.67 (2.09)***	36.69 (1.47)***
Session		- 0.24 (0.04)***	- 0.20 (0.07)*	- 0.13 (0.03)***
Onset HL (Prelingual)		1.49 (3.14)	-2.63 (4.33)	0.21 (2.93)
Training order (VT+AT)		0.04 (1.82)	-0.88 (2.2)	0.78 (1.95)
Session x Onset HL (Prelingual)		-0.15 (0.10)	0.10 (0.16)	- 0.04 (0.07)

HL: Hearing loss; VT+AT: Visual training received in the first period and auditory training received in the second period of the study. Onset HL postlingual and training order AT+VT are in the intercept.
Significance codes: *** p< 0.001; **p< 0.01; *p< 0.5

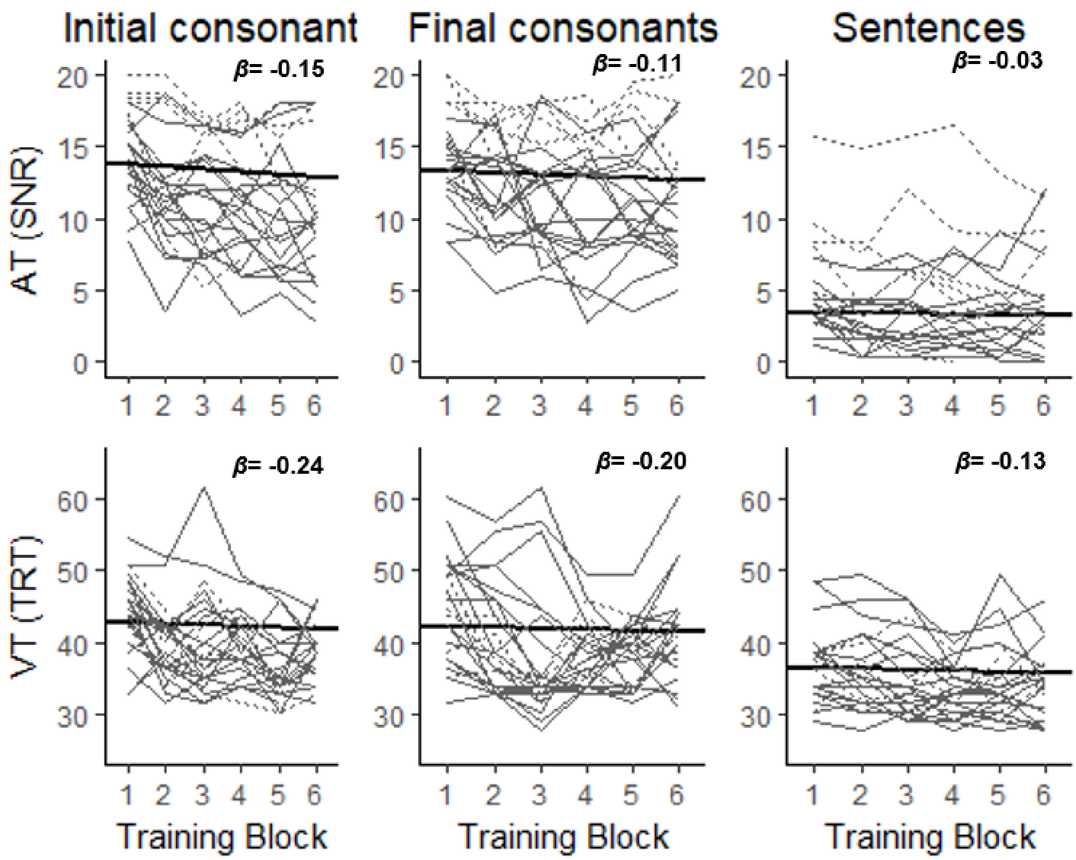


Figure 3.4. Individual training slopes for all participants (n=26). Dashed lines represent participants with prelingual hearing loss. Bold line represents regression line extracted from fitted models, with estimates presented for each training module.

Outcome measures (transfer of learning)

Individual and group performance observed for the AT and VT at each timepoint for each outcome measure described below are displayed in figures 3.5 to 3.9. Tables 3.5 to 3.8 display a summary of the results of linear mixed model analyses. Complete outputs with both random and fixed effects are shown in Appendix C.

Speech understanding in noise: No significant difference was found at post-training or follow-up results in this measure for either AT nor VT when this were analysed by condition (Easier or Harder), neither when analysed by SNR (i.e. 20dB, 10dB, 0dB). Estimates for post-training (T3) and follow-up (T4) higher than test-retest is some instances, however, with large standard errors and therefore not significant (see table 3.5). For example, this was found for both AT and VT in the easier condition of BKB sentences, however, only by approximately 2 percentage points if compared with T1 were participants showed higher scores (i.e. T3-T1).

Word recognition in quiet: No significant changes in CNC word scores were found following AT nor VT. The highest performance in CNC words occurred only for the AT group at follow-up (T4), however, as indicated by the model this equalled only 2.21 percentage points improvement in relation to the second (T2), and better, baseline (β= 2.21; *SE*= 8.07; *p*=0.78).

Spectral resolution: No significant difference was found for spectral resolution overtime for both AT and VT (Figure 3.6).

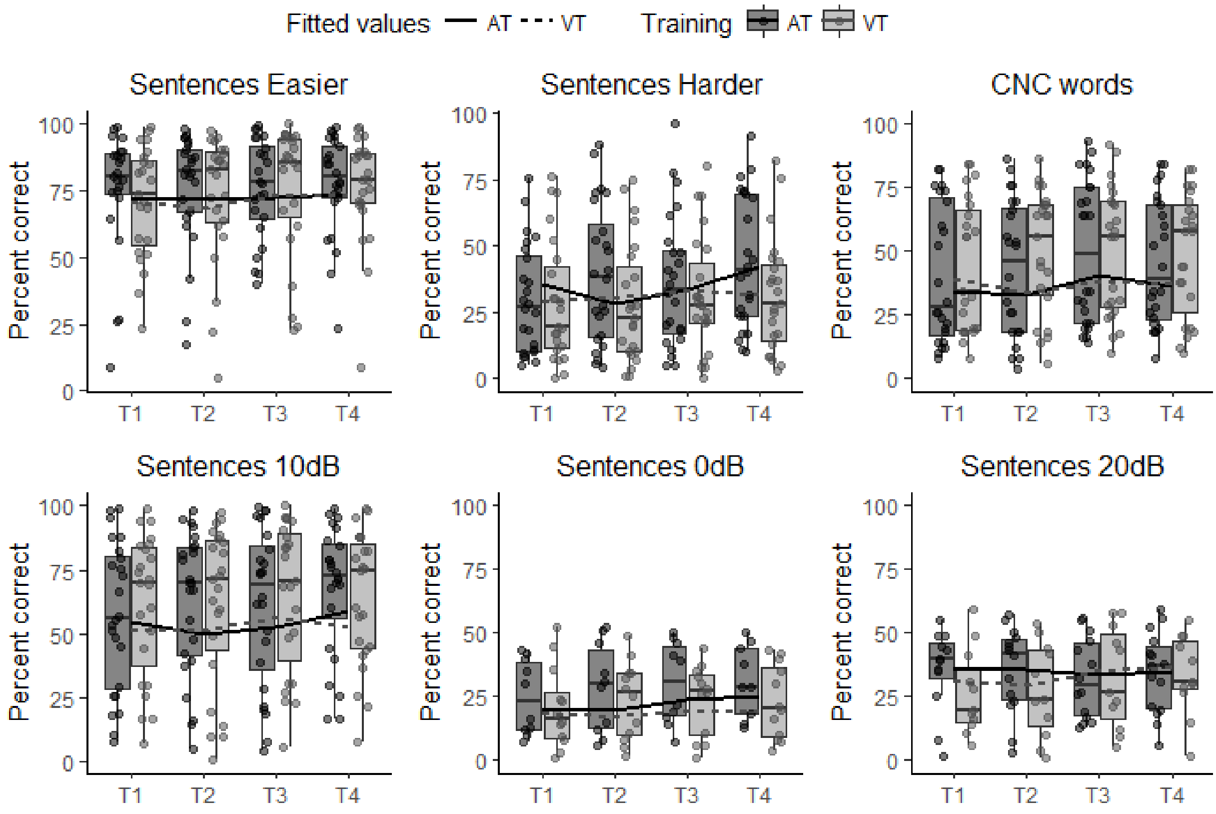


Figure 3.5. Boxplots and dots represent raw data for all participants (n=26) of untrained auditory abilities. Dashed lines represent regression line extracted from fitted models.

Table 3.3. Fixed effect estimates of auditory and visual training groups for measures of auditory abilities (untrained)

	Speech in noise (condition)		Speech in noise (SNR)			Word recognition	Spectral resolution
	Easier	**Harder**	**10dB**	**20dB**	**0dB**		
	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)
(Intercept)	69.90 (25.82)	42.93 (32.23)	41.77 (30.85)	30.74 (28.80)	140.86 (51.96)*	6.22 (25.76)	2.93 (1.45)
T1	13.80 (19.88)	-33.63 (22.07)	-25.49 (22.32)	15.83 (22.39)	-23.84 (19.61)	-6.20 (8.07)	-0.37 (0.28)
T3	15.74 (19.61)	-4.83 (20.96)	-2.96 (21.20)	6.23 (23.75)	-1.02 (17.72)	-1.09 (7.44)	0.12 (0. 29)
T4	4.30 (20.26)	12.89 (21.69)	-3.20 (21.72)	9.46 (23.97)	0.55 (19.50)	2.21 (8.07)	-0.27 (0.29)
T1 x Training (VT)	-0.99 (4.88)	9.14 (5.21)	5.08 (5.21)	-1.09 (4.94)	-0.68 (4.66)	-3.82 (4.17)	0.22 (0.40)
T3 x Training (VT)	2.57 (4.84)	6.72 (5.17)	6.54 (5.18)	6.72 (4.87)	-2.93 (4.55)	-7.79 (4.16)	-0.23 (0.40)
T4 x Training (VT)	1.46 (4.87)	-3.90 (5.20)	-3.27 (5.20)	6.44 (4.87)	-3.88 (4.70)	-4.19 (4.19)	0.45 (0.40)
N	25	25	25	15	11	25	26

Participants were tested in an easier and harder SNR condition. Analysis was conducted by condition and also by SNR received in each condition.
Second baseline and auditory training are on the intercept. Shaded values show differences that were greater at post-training (T3) or follow-up (T4) than for test-retest (T1-T2).
*p< 0.05

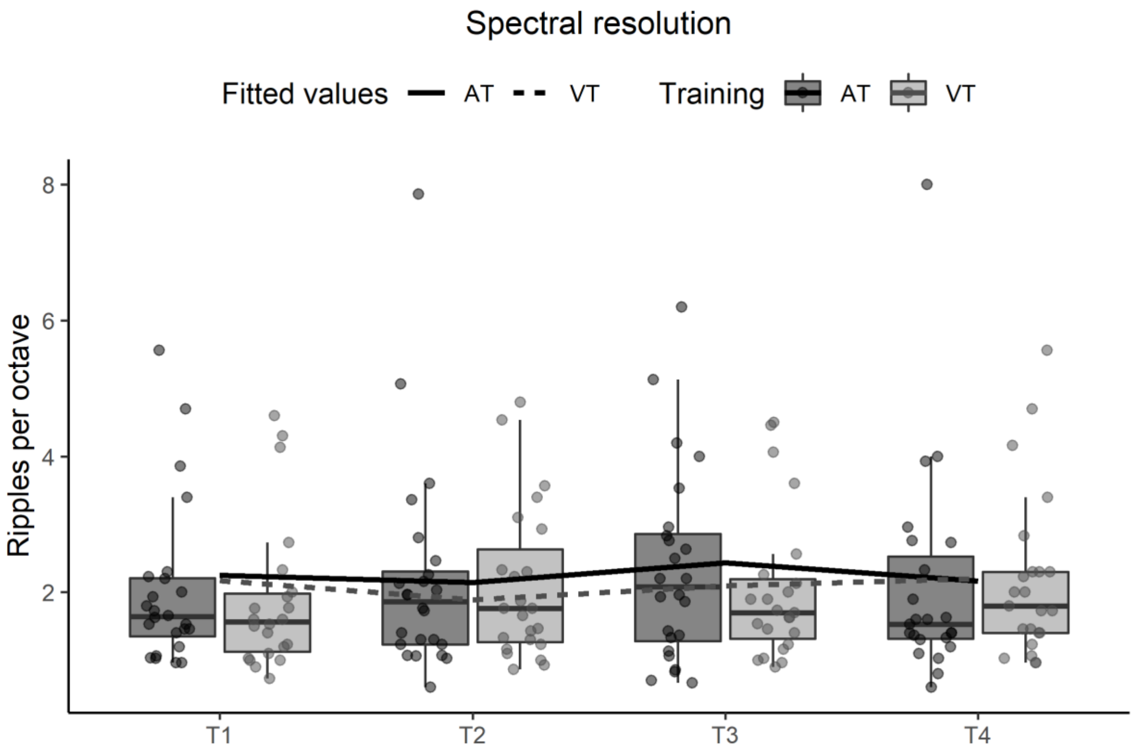


Figure 3.6. Boxplots and dots represent raw data for all participants (n=26) of untrained spectral resolution. Dashed lines represent regression line extracted from fitted models.

Visual and auditory attention: No significant difference was found for the visual attention task in the IVA-CPT for either training group. However, a significantly worse performance was found in the auditory attention task at T1, T3 and T4 for the VT group. However, because results at T3 (β= 34.94; *SE*= 16.90; *p*=0.04) and T4 (β= 39.65; *SE*= 17.18; *p*=0.02) were similar to T1 (β= 34.54; *SE*= 17.17; *p*=0.0464), these results cannot be interpreted as a decrease in auditory attention performance following the VT (Table 3.6).

Inhibition control: No significant differences were found for this measure, although estimates for fixed effects modelled indicated a higher performance for both AT and VT groups at T3 (Table 3.6).

Phonological representations: The highest change in reaction time for this measure occurred from the first (T1) to the second baseline (T2; β= –517.74; *SE*= 240.63; *p*=0.03) for both AT and VT. This however was not accompanied efficiency, as in T1, where participants showed a larger average reaction time was also the timepoint where participants made more mistakes on the rhyme judgement task (*β*= –10.66; *SE*= 17.17; *p*=0.0464). The highest percentage correct score at this task occurred at T3 (12.92 percentage points higher than T2), however with worse reaction time than T2 (Table 3.6).

Verbal working memory: Training did not affect performance on the visual working memory task. Where improvements in relation to T2 were shown, these were not higher than test-retest. Age was shown to negatively contribute to performance on this task (*β*= –0.88; *SE*= 0.24; *p*=0.001).

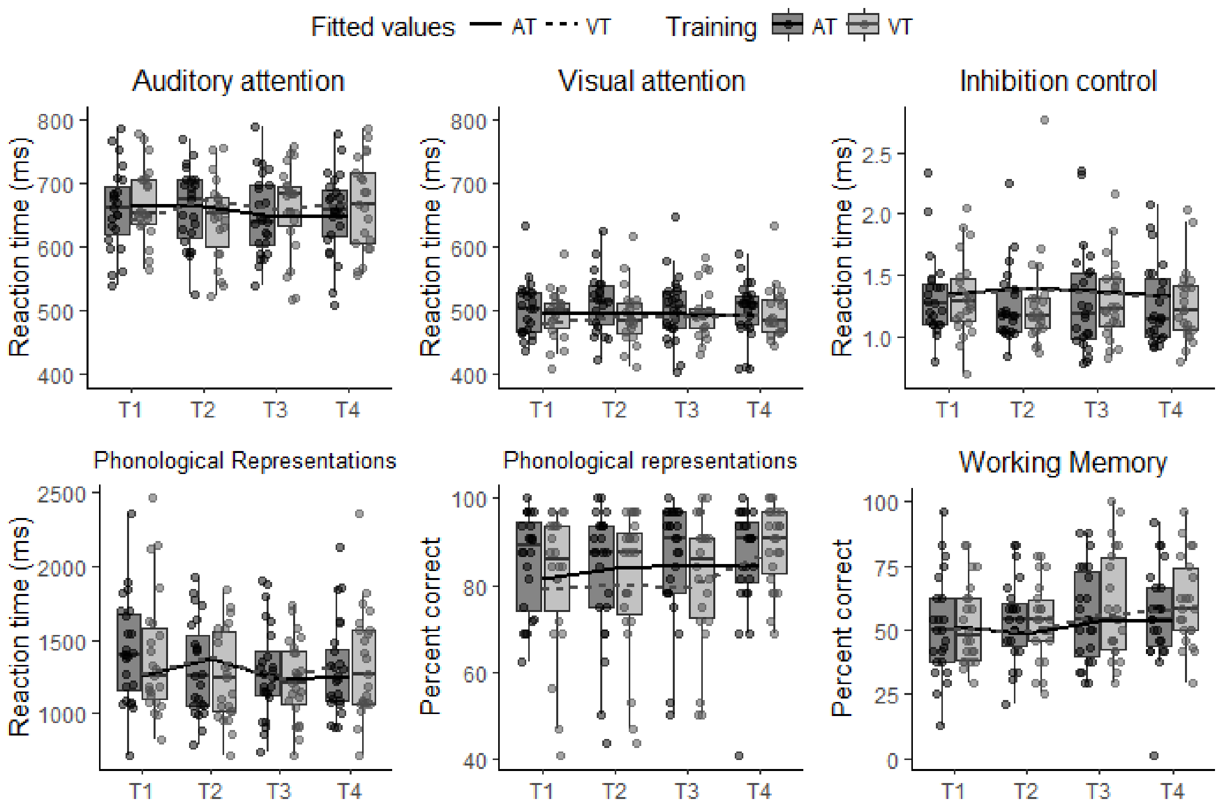


Figure 3.7. Boxplots and dots represent raw data for all participants (n=26) of untrained cognitive abilities. Dashed lines represent regression line extracted from fitted models.

Table 3.4. Fixed effect estimates of auditory and visual training groups for measures of cognitive abilities (untrained)

	Visual attention (ms)	**Auditory attention (ms)**	**Inhibition control (ms)**	**Phonological Representations (ms)**	**Phonological Representations (% correct)**	**Working Memory (% correct)**
	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)
(Intercept)	507.46 (51.99)***	677.49 (73.56)***	0.56 (0.44)	815.16 (364.53)*	102.59 (13.77)***	112.97 (18.29)***
T1	-45.58 (31.04)	69.48 (55.04)	0.04 (0.30)	517.74 (240.63)*	-10.66 (16.22)	-11.95 (13.35)
T3	-30.47 (31.40)	-60.82 (53.95)	-0.24 (0.29)	134.86 (221.99)	23.58 (15.28)	4.99 (13.31)
T4	-53.17 (31.12)	-64.10 (55.82)	-0.03 (0.30)	-13.20 (221.14)	2.59 (15.43)	0.05 (14.34)
T1 x Training (VT)	11.40 (9.72)	34.54 (17.17)*	-0.004 (0.09)	-0.66 (66.60)	-1.65 (4.75)	2.20 (4.28)
T3 x Training (VT)	9.46 (9.59)	34.94 (16.90)*	0.004 (0.09)	-17.54 (65.83)	-2.94 (4.71)	3.47 (4.28)
T4 x Training (VT)	16.88 (9.69)	39.66 (17.18)*	0.003 (0.09)	87.14 (65.79)	4.90 (4.70)	5.43 (4.32)
N	26	26	26	26	26	26

Visual and auditory attention refer to the reaction time in the IVA-CPT. Inhibition cotnrol was assessed with the VST, by assessing reaction time for colours divided by reaction time for words. Second baseline and auditory training are on the intercept. Shaded values show differences that were greater at post-training (T3) or follow-up (T4) than for test-retest (T1-T2).
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

Self-report listening, communication apprehension and self-efficacy: As shown in table 3.7, no significant differences were found for these measures overtime.

Table 3.5. Fixed effect estimates of auditory and visual training groups for self-perceived listening and communication abilities

	Self-report listening (1-10)	**Communication Apprehension (24-120)**	**Self-efficacy (0-200)**
	Estimate (SE)	Estimate (SE)	Estimate (SE)
(Intercept)	3.63 (1.79)	71.27 (23.11)**	124.92 (45.82)*
T1	-0.012 (0.79)	2.03 (8.90)	17.68 (26.29)
T3	0.17 (0.08)	2.86 (8.89)	-6.56 (26.29)
T4	0.43 (0.25)	-0.84 (9.03)	5.71 (26.80)
T1 x Training (VT)	-0.82 (0.25)	-1.61 (2.78)	2.48 (8.26)
T3 x Training (VT)	0.23 (0.25)	-1.61 (2.80)	-9.62 (8.26)
T4 x Training (VT)	0.32 (0.26)	2.87 (2.88)	2.52 (8.56)
N	26	26	26

Second baseline and auditory training are on the intercept. Shaded values show differences that were greater at post-training (T3) or follow-up (T4) than for test-retest (T1-T2).
*** p< 0.001; **p< 0.01; *p< 0.05

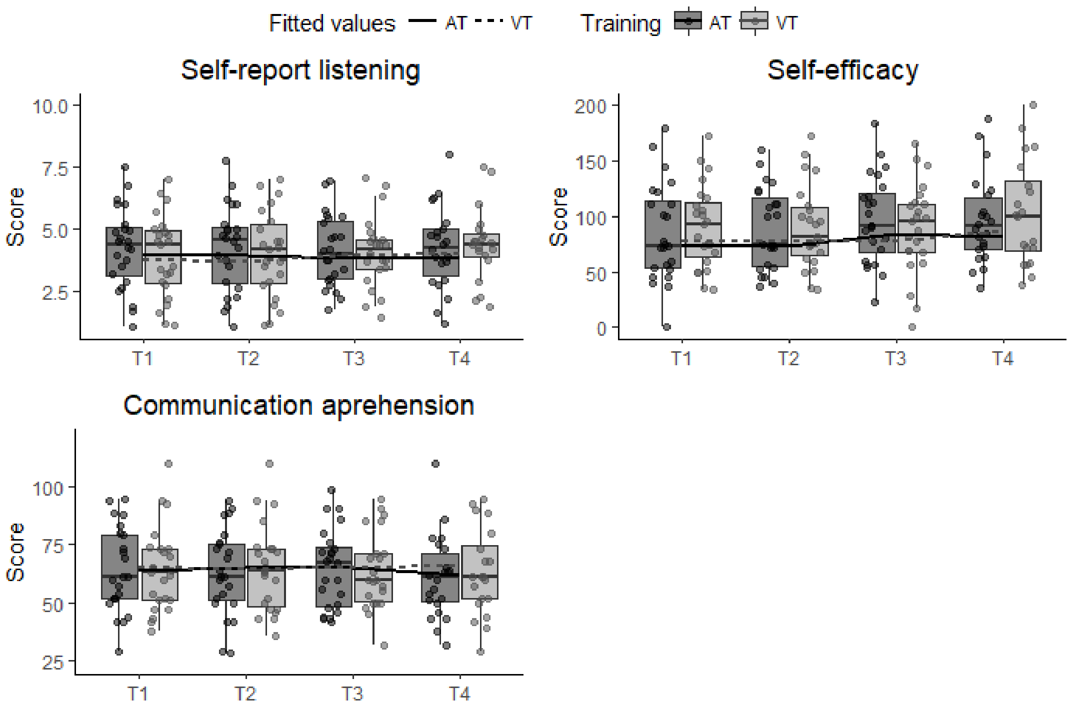


Figure 3.8. Boxplots and dots represent raw data for all participants (n=26) of perceived communication. Dashed lines represent regression line extracted from

Quality of life: Overall, participants showed high scores in the quality of life scale and the SF-36, with lower scores for the sections of general health and vitality. A significant negative difference, however, was found for the VT group in general health at post-training (T3) and follow-up (T4). When a secondary analysis was conducted, including age at baseline as an interaction with timepoint and training type, age was found to be a significant contributor to scores. A significant difference was also found for vitality at follow-up, with the AT group showing lower scores at this timepoint. Similarly, when age was controlled in the analysis of self-report vitality, the significant difference at follow-up was no longer demonstrated. No significant differences were found with the general quality of life.

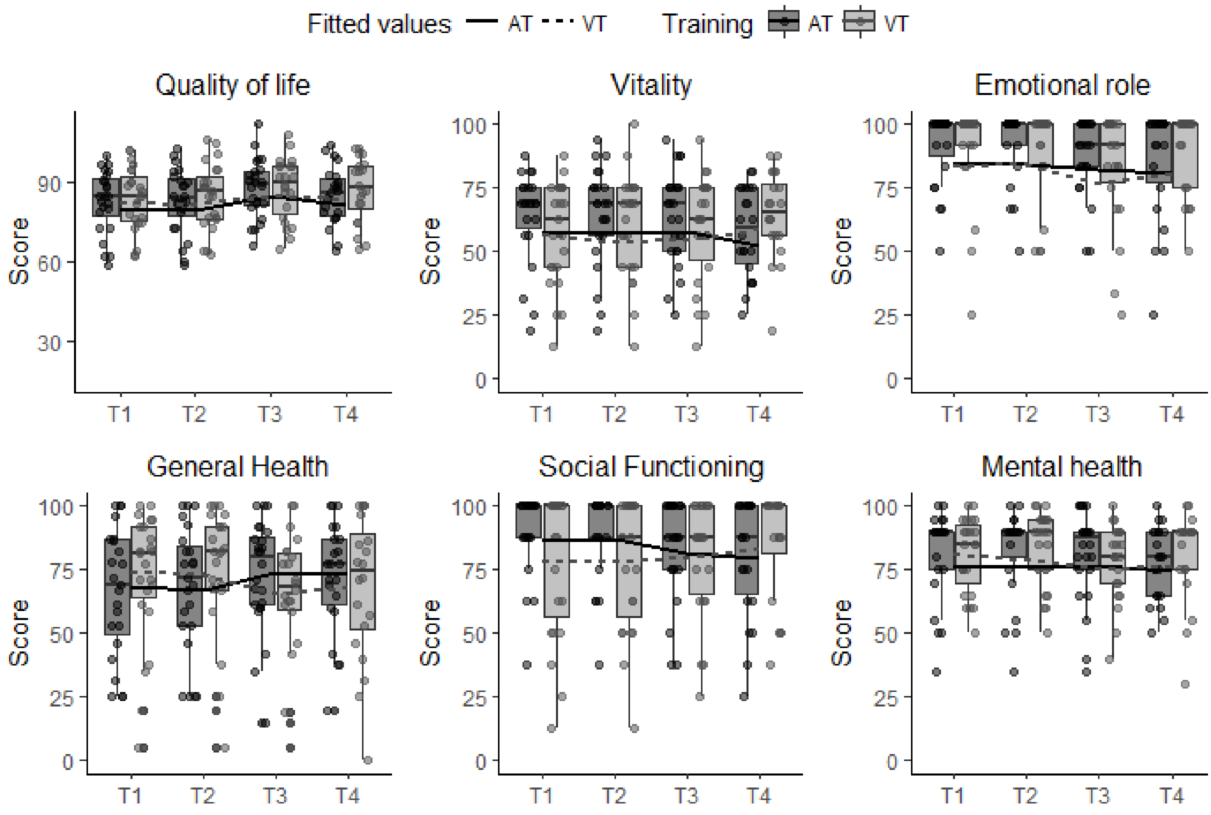


Figure 3.9. Boxplots and dots represent raw data for quality of life. Dashed lines represent regression line extracted from fitted models.

Table 3.6. Fixed effect estimates of auditory and visual training groups for self-report measures of quality of life

	Quality of life (16-112)	**Health related quality of life (0-100)**				
		General Health	Vitality	Social Functioning	Emotional role limitation	Mental health
	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)	Estimate (SE)
(Intercept)	75.51 (14.03)***	44.29 (31.99)***	35.54 (22.56)***	80.35 (28.00)**	56.93 (18.24)**	28.59 (17.50)
T1	-2.33 (6.60)	1.50 (16.39)	-0.95 (11.92)	-0.39 (18.59)	5.36 (17.71)	7.59 (12.41)
T3	9.65 (6.63)	29.92 (16.38)	-4.63 (11.91)	-22.57 (18.58)	-5.95 (17.69)	2.64 (12.40)
T4	0.03 (6.72)	13.77 (16.63)	3.15 (12.09)	2.62 (18.86)	12.03 (17.95)	19.50 (12.58)
T1 x Training (VT)	-0.51 (2.09)	0.18 (5.13)	-2.42 (3.73)	-1.02 (5.82)	2.27 (5.55)	-1.85 (3.88)
T3 x Training (VT)	-2.31 (2.10)	-14.56 (5.13)**	-2.33 (3.75)	6.19 (5.85)	-3.76 (5.57)	-6.80 (3.90)
T4 x Training (VT)	-0.18 (2.16)	-11.46 (5.30)*	7.42 (3.86)	11.70 (6.02)	1.82 (5.72)	-2.86 (4.01)
N	26	26	26	26	26	26

Second baseline and auditory training are on the intercept.

*** $p< 0.001$; ** $p< 0.01$; * $p< 0.05$

3.5 Discussion

The aim of the present study was to assess whether a computer-based speech in noise AT program leads to short- and long-term changes in trained and untrained measures of listening, cognition and quality of life. A secondary aim was to assess whether directly training the underlying cognitive abilities required for speech perception in noise, using a computer-based visual training (VT) program without the auditory component, would elicit comparable outcomes as the AT program.

It was demonstrated that on-task improvement occurred for all tasks trained in both the AT and VT programs. Even when the rapid learning from the first week of training for each program was excluded from the analysis, training effects were demonstrated for both the AT and VT, although no longer significant for the final consonant module in the VT program. In particular, participants with a prelingual hearing loss, demonstrated a significant steeper learning slope for sentences in noise in the AT, suggesting that this group of individuals might benefit more from this type of training. Training order, did not contribute to on-task learning for either of the training programs. This differs from the findings of Bernstein et al. (2014), which indicated that CI users with a prelingual hearing loss showed greater improvement in an auditory-visual training (AV; i.e. auditory nonsense words combined with lipreading) if an auditory-only (AO) training was received first, and lower improvement in AO performance if the AV was received first, which they interpreted as learning acquired in the first program contributing to enhanced performance in the second program. The visual stimuli used by Bernstein et al. (2014) however, were of a different nature (i.e. lipreading) than the visual stimuli used in this study.

In the present study, despite the on-task learning demonstrated for both the AT and VT programs, there was no evidence for the transfer (generalisation) of learning to untrained outcome measures. In general, larger improvements occurred for outcomes between baselines (T1, T2) than at post-training (T3) or follow-up (T4), suggesting that test-retest effects were superior to any training-related transfer effects. For example, a statistically significant difference was shown for the auditory attention task for the VT group pre- to post-training (T3), however, the change from the first (T1) to the second baseline (T2) was also statistically significant and with a similar effect size (β = 34.94ms for T2-T3 and β = 31.54ms for T1-T2).

For quality of life, statistically significant improvements were shown for sections of 'general health' and 'vitality' within the SF-36. However, when age at baseline was included as an interaction term in the model, it indicated that the reported decrease in general health and vitality was in fact an effect of age, with participants in this group ranging from 42 to 84 years old. Age also contributed to performance in the visual working memory task at baseline, with older participants scoring lower on this task, as established in the literature (Wingfield et al. 1988).

Considering the similarity between the speech materials that were trained and those that were included in the (untrained) outcome measures, transfer of learning might be expected at least to the untrained recognition of sentences in 4-talker babble masking. In the present study, there was no evidence for transfer of on-task learning to untrained measures of speech in noise. However, previous studies suggest that even when trained and untrained material are very similar in nature (i.e. speech), transfer of on-task improvement remains uncertain. For example, Miller et al. (2008) demonstrated that training with syllables did not transfer to improvement in recognition of sentences in noise, and Stacey et al. (2010) indicated that training with words did not transfer to improvement in recognition of words nor sentences. Other studies, however, which used monosyllabic words, digits or nonsense words as training stimuli showed that CI users demonstrated improvement in recognition of sentences in noise (i.e. Fu et al. 2005; Oba et al. 2011; Schumann et al. 2014).

In this study, learning was shown to be specific to trained tasks. Adherence to both training programs was good overall, and the amount of training sessions completed by participants was included as a fixed effect in the analysis, therefore, it is unlikely that this lack of generalisation occurred because participants did not adhere to the training program. One possible interpretation for the findings in this study is that transfer did not occur because different procedures were used for training and testing. For instance, AT with both monosyllabic and sentence stimuli occurred in adaptive SNR, while testing occurred in quiet for words and fixed SNRs for sentences. The perceptual learning literature suggests that learning for low and high noise conditions rely on different mechanisms (see Dosher & Lu 2007 for a review), and importantly these will place different demands on cognitive processes (Heinrich et al. 2015).

Similarly, the task used for VT may not have been cognitively demanding, as despite the on-task improvement shown, transfer to untrained measures did not occur. While in this study the TRT_{500} was used as stimuli due to its relationship with the SRT, other versions of the TRT exist that have been suggested to demand more working memory and speed of processing (c.f. Besser et al. 2013).

This study contributes to the discussion of effectiveness of AT in a scenario where findings of studies have been mixed (see Henshaw & Ferguson 2013 for a review). Importantly, the inclusion of a second baseline (T2) in the study design allowed to observe that changes in outcome that are due to procedural learning (i.e. test-retest) may be larger than changes following AT. This finding highlights the importance of controlling for procedural learning in training studies. Additionally, this study further demonstrates that training that focuses solely on speech perception may elicit on-task learning, but this may not generalise. Similarly, it demonstrates that training with a visual task that is associated with recognition of speech in noise also elicits on-task learning but is not sufficient to provide improvements on untrained measures. Nevertheless, programs that combine both auditory and cognitive training may have the potential to improve auditory and cognitive performance. For example, improvement in auditory and cognitive abilities has been shown in studies with unaided hearing-impaired adults (Anderson et al. 2013a) and hearing aid users (Sweetow & Sabes 2006) following auditory-cognitive training, however, further evidence is required given that a recent study demonstrated that these improvements may not occur (i.e. Saunders et al. 2016). This is yet to be robustly examined in a CI population.

Limitations of the current study included the imbalanced distribution of prelingually deafened CI users, which were all randomly allocated to the same group, and thus led to the VT+AT group to have higher performance for most tasks. While such distribution was not ideal, training order was not shown to be a factor that contributed to performance on training nor in outcome measures. As the main goal of this study was to look at change in pre- to post-training performance rather than the comparison between AT and VT, once data from both allocation groups was combined disparities in distribution were no longer seen.

The present study required a considerable amount of coordination within and across sites, resources and time investment. Although measures were adopted to minimise the risks of bias in the study, several difficulties were encountered. For example, although recruitment was open for several months, an insufficient number of participants demonstrated interest in participating in the study before the date data collection was scheduled to start. As time restrictions were imposed by the project's timeframe, this meant that recruitment continued while data collection was ongoing. Due to this, it was not possible to conduct a stratified randomisation of participants into groups, which led to an imbalance of participant demographics between groups. Two extra sites (CRC and FSH) were later included as a measure to maximise recruitment of participants, however the time restrictions compromised the timing of the retention assessment (T4). While measures were taken in the statistical analyses to account for this population and design imbalance, these methodological limitations could be avoided in the future if recruitment was finalised before data collection. Data has also been reported separately for the first intervention period of the study, and also for different follow-up periods (Appendix C).

3.6 Conclusion

Although significant on-task improvements were shown for both AT and VT in this group of experienced CI users, neither resulted in transfer to improvements in outcome measures of listening and cognition that were not trained. These findings indicate that careful consideration should be made before adult CI users engage in AT that uses only speech in noise stimuli, as used in this study. Despite this, the current study did not indicate that training led to negative effects in these domains. Thus, this should be considered in addition to possible cost and time investment required for participation in AT programs.

3.7 Supporting information

Appendix C.

Auditory and visual training programs

Detailed demographics of study participants.

Separate analysis of first intervention period.

Complete output of linear mixed models applied in statistical analyses.

3.8 Acknowledgements

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The authors declare no conflicts of interest.

Parts of this work were presented at the Cognitive Hearing Science for Communication Conference, Linköping, June 2017 and at the Audiology Australia National Conference, Sydney, May 2018.

3.9 Author contributions

MR, IB and CM conceived and designed the experiment. MR conducted the experiment and data analysis. MR prepared the manuscript with contributions from IB and CM.

Chapter 4. Effectiveness of computer-based auditory training for adult cochlear implant users: a rapid review of the evidence

Mariana Reis

4.1 Abstract

Objectives: The objective of the present systematic review was to assess the effectiveness of computer-based auditory training (CBAT) for adult CI users. Specific aims included assessing whether there is evidence to support that CBAT leads to improvements in trained and untrained measures of speech understanding, cognitive abilities, self-reported listening and communication and quality of life in adult CI users; and whether any post-training improvements were maintained following a period of no training. **Design:** A systematic search of 14 databases, key journals and snowballing of included articles identified 4748 studies, of which nine met the eligibility criteria of this review. Data extracted from studies was conducted by the author independently and is described in terms of participants, intervention, comparison, outcome measures and study designs. **Results:** CBAT resulted in on-task learning for at least one trained measure within each of the nine studies. On-task learning generalised to improvements in untrained measures of speech perception in some studies (4/9 studies), but not to cognitive abilities, (0/1 studies), self-reported listening and communication (0/1 studies) nor quality of life (0/1 studies), where measured. Follow-up assessments were not always conducted. Where follow-ups did occur (4/9 studies), on-task learning was maintained in one study one-week post-training and improvements in performance for an untrained measure of speech perception was retained in another study six months post-training. **Conclusion:** Only one study demonstrated that transfer of learning to an untrained task of speech perception was maintained long-term. Limitations in design of studies and inconsistencies in findings across studies, reduce the confidence in the estimation of effects

reported. Further high-quality evidence is required to inform whether CBAT is an effective intervention for adult CI users. Future studies should consider the role of cognition, assessment of self-reported measures of listening and quality of life, and reduce the risk of bias by conducting randomised controlled studies, and when possible researcher and/or participant blinded, and with follow-up measures to assess retention of any improvements.

4.2 Introduction

The main goal of cochlear implantation is to improve auditory skills in hearing-impaired individuals who do not benefit from alternative interventions, such as hearing aids. However, due to a number of possible factors, outcomes vary widely across cochlear implant (CI) users (see Lazard et al. 2012; Blamey et al. 2013; Holden et al. 2013 for reviews). The variation is such that while some individuals will be able to have a conversation using the telephone, others will rely on lipreading to aid speech understanding. However, even when individuals achieve good outcomes with a CI, difficulties may exist when listening takes place in environments with background noise, such as in a cafeteria, or in settings where multiple talkers take part in the discussion, such as a social gathering.

Importantly, speech understanding requires matching the incoming auditory input provided through the CI with the individual's phonological and semantic representations as stored in their long-term memory. When the clarity of this signal is affected, by CI signal processing strategies for example, a higher amount of cognitive resources is required to successfully understand speech (see Rönnberg et al. 2013 for a review). In addition to the CI signal itself, speech understanding may be further affected by characteristics of the acoustic environment (i.e. background noise), the talker (i.e. accented speech), and the listener (i.e. working memory capacity) (Peelle 2018). These increased cognitive demands result in an elevated amount of effort invested in listening (Rönnberg et al. 2013; Pichora-Fuller et al. 2016).

Auditory training (AT) has been suggested as a potential intervention to improve auditory skills (Boothroyd 2010) and increase the ease of listening (Kuchinsky et al. 2014; Tremblay & Backer 2016). These may relate to improvements in speech understanding, cognitive skills, and self-reported measures of listening and quality of life. Overall, AT may increase the attention an individual can allocate to the structure of spoken language (Moberly et al. 2016) or reduce the amount of cognitive processes required for listening (Tremblay & Backer 2016). Computer-based auditory training (CBAT) programs are an easily accessible and low-cost intervention option for individuals who aim to improve their listening abilities, and are often recommended for adult CI users (see chapter 2). However, the most recent systematic review of CBAT studies conducted by Henshaw and Ferguson (2013) demonstrated that the evidence to support these programs as an effective intervention for individuals with a hearing loss was lacking and could not reliably guide clinical practice. Additionally, although some CBAT protocols elicit on-task learning, this may not transfer to untrained tasks, reducing its potential for real-life gains (see Henshaw & Ferguson 2013 for a review).

In that same publication, Henshaw and Ferguson (2013) made a series of recommendations to improve future efficacy studies of CBAT. These included *increasing the level of evidence*, by improving quality design (i.e. avoiding risk of bias in studies, considering inclusion of follow-up assessments) and reporting of studies (i.e. by following guidelines when summarising findings); *improving selection of outcomes* in studies, such as considering the magnitude of effects for selected outcomes to represent clinically significant differences, combining behavioural outcomes with self-reported measures of listening, including cognitive outcomes in studies as these may be abilities that improve following CBAT (c.f. Sweetow & Sabes 2006); *standardising outcome measures* to enable comparison across studies, and, identifying who is a *candidate* to receive AT given the variance in outcome found within studies. These recommendations are important as they aim to increase the reliability and applicability of research conclusions, which guide the development of evidence-based practices.

Based on this, the objective of the present review was to assess the evidence for the effectiveness of CBAT for adult CI users published since the 2013 review (published after 1st December 2012. Specific questions were:

1. Does evidence exist to support that CBAT leads to improvement in trained and untrained measures of speech understanding, cognitive abilities, self-reported listening and communication and quality of life in adult CI users?

2. If improvements occur, are these retained following a period of no training?

4.3 Methods

This rapid review is reported in accordance with the Preferred Reporting Items for Systematic Reviews (PRISMA; Moher et al. 2009).

Protocol and registration

The current study consists of a rapid review of the literature, with studies selected as part of a larger systematic review, which has been registered with PROSPERO International prospective register of systematic reviews (CRD42017076817) and is available online from: http://www.crd.york.ac.uk/PROSPERO/display_record.php?ID=CRD42017076817. While the registered systematic review reports assessment of CBAT for individuals with unaided hearing loss, hearing aid users, and CI users, the rapid review reported in this chapter assesses CBAT studies conducted with adult CI users. Rapid reviews are a type of knowledge synthesis in which steps of a systematic review are streamlined or accelerated to produce evidence in a shortened timeframe (Tricco et al. 2017). In the current rapid review all the steps related to search of studies, title and abstract screening, and full-text screening were conducted by two reviewers (HH, MR) of the systematic review team (CRD42017076817) independently. However, the synthesis and interpretation of results has been conducted only by the author of this chapter.

Eligibility criteria

Studies published in English were included in this review based on the Participants, Intervention, Comparator, Outcomes and Study design strategy (PICOS) as outlined in table 4.1. Only primary data available from December 2012 were included, as records published prior to this date would have been included in the previous systematic review by Henshaw and Ferguson (2013). When studies were identified via searches in clinical trial registries, these were included if a complete report of the results was available.

Table 4.1. PICOS eligibility criteria

Participants	Adults (18+ years) with hearing loss, who use cochlear implant(s)
Intervention	Active, individual, computer-based auditory training
Comparator	Comparison with a control group or repeated measures (pre- and post-training comparisons)
Outcomes	One or more measures relating to speech perception, cognition, communication or quality of life
Study design	Randomised control trials, non-randomised control trials, cohort studies or repeated measures (pre-and post-training comparison)

Information sources

Searches were conducted by the two first investigators in the systematic review team in 14 electronic databases in January 2018, to capture published articles and ongoing trials. These included Ovid MEDLINE, Ovid EMBASE, The Cochrane Library (Cochrane Database of Systematic Reviews, Cochrane Central Register of Controlled Trials (CENTRAL), Cochrane Methodology Register), ClinicalTrials.gov, International Standard Registered Clinical/social study Number (ISRCTN) registry, Health Technology Assessment Database, PsycINFO, Applied Social Sciences Index and Abstracts (ASSIA), Cumulative Index to Nursing and Allied Health (CINAHL), Scopus, PubMed, Web of Science (Science and Social Science Citation Index), World Health Organisation International Clinical Trials Registry Platform (WHO ICTRP), and Latin American and Caribbean Health Sciences Literature (LILACS). An example search strategy is presented in Appendix D. Additionally, snowballing from selected articles' author names and reference lists was conducted to identify any studies that could have been missing from the initial search. Hand-searches of the last six months publications from key audiology journals were also undertaken in June 2018 to ensure any eligible, but recently published articles were identified.

Study selection

Studies returned from the searches were imported into Covidence (Veritas Health Innovation 2018) for screening by title and abstract, and full-text-screening. Screening was conducted independently by the first two authors (HH, MR) in the systematic review team (see CRD42017076817 for team members). Where any conflicts regarding inclusion of studies arose, these were discussed by the four investigators in the review team.

Data collection process and data items

Data to be extracted was predetermined within a data extraction form, and amended for each study as necessary. Data extraction for this chapter was conducted independently by the author of this chapter, and included details of study design, participants, intervention and comparisons and outcomes. Outcomes collected included only the outcomes of interest for this review (i.e. measures of speech perception, cognition, communication and quality of life), rather than all outcome measures assessed within each study.

Risk of bias in individual studies

Risk of bias was assessed in accordance with the Cochrane Handbook for Systematic Review of Interventions (Handbook 2008) by the author of this chapter. For Reis et al. (Chapter 3), risk of bias assessment was conducted by the first author (HH) in the systematic review team (CRD42017076817). Sequence generation, allocation concealment, blinding of participants and study personnel, blinding of outcome assessors, incomplete outcome data, selective outcome reporting and other sources of bias were considered in the assessment.

Summary measures

Results from studies were summarised in terms of PICOS criteria. When a study included multiple intervention conditions, only data related to CBAT was included for the purpose of this review. Similarly, when different population groups were assessed (i.e. normally hearing individuals), only data related to the CI users group was collected. Outcome data preferably included pre- and post-training means and standard deviations, however, when these were not available, other test statistics were collected (i.e. difference between pre- and post-training means, standard errors, p-values). Analysis included calculation of standardised mean difference (SMD; calculated as Hedges' g with 95% confidence interval) of change from pre- to each post-training assessment. Hedges' g (Hedges 1981) is an estimation of SMD with a correction for small sample sizes. Hedges' g values <0.30 were considered small, 0.30–0.60 were considered moderate, and >0.60 were considered large effect sizes. Because a meta-analysis of results was not conducted as part of the current study, Hedges' g was calculated for each outcome measure within studies independently (i.e. results were not pooled for each outcome of interest). For studies using crossover designs, only the results from the first intervention period of the study were summarised, to avoid the introduction of possible carry-over effects.

Risk of bias and certainty assessment across studies

The 2016 Grading of Recommendations Assessment, Development and Evaluation (GRADE) working group guidelines were used to assess the certainty of evidence across studies. Risk of bias across studies was assessed in GRADEpro following guideline from Ryan and Hill (2016).

4.4 Results

Study selection

In total, the database searches returned 4747 records including papers, reviews, conference abstracts, theses and registered clinical trials of which 2671 remained after removal of duplicates. One additional study was identified through the additional journal searches. Of the 2077 studies screened by title and abstract, 194 studies were retrieved for full text evaluation. Of these, 185 were excluded due to reason displayed in Figure 4.1. Nine studies met the eligibility criteria for the review.

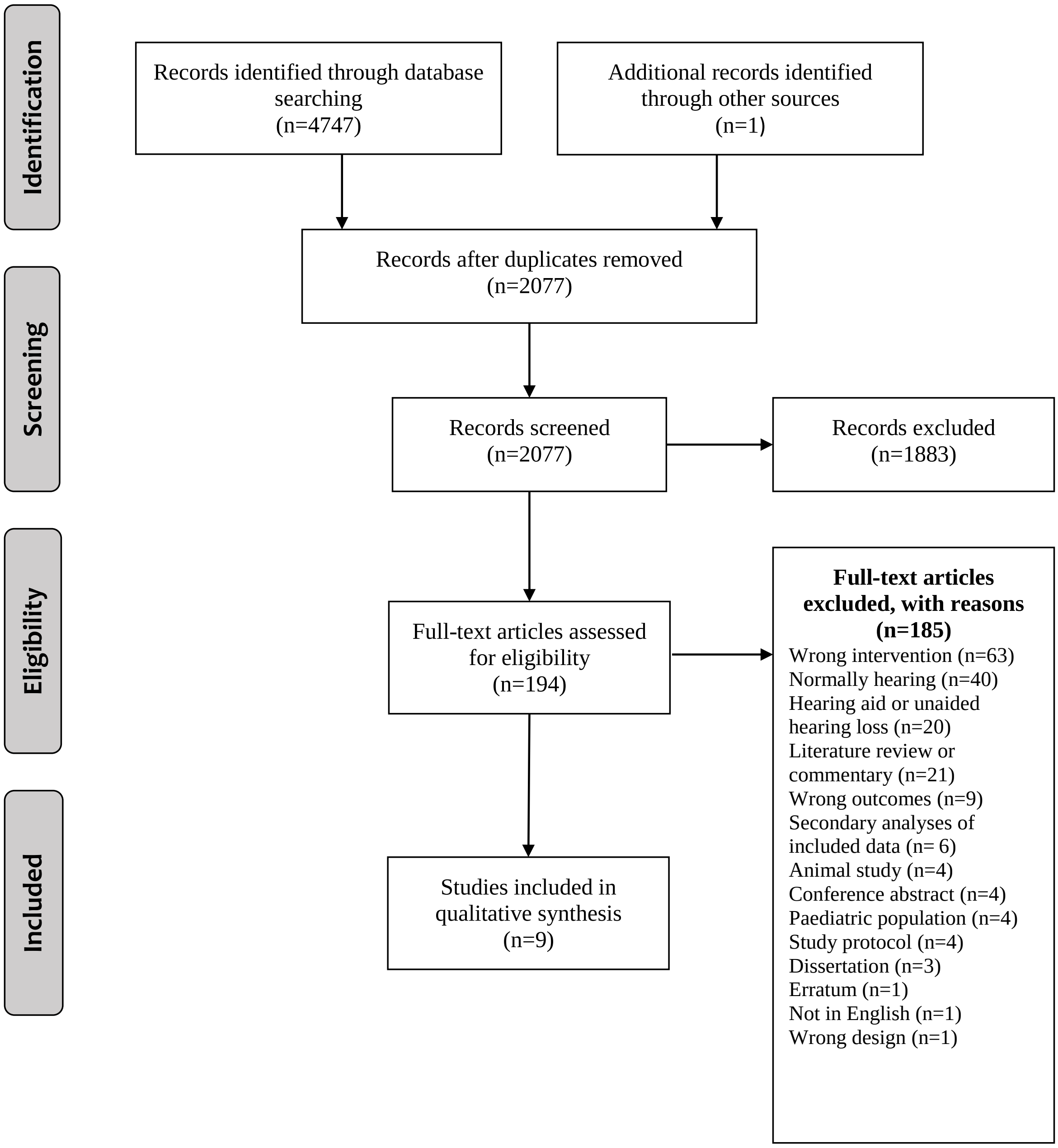

Figure 4.1. Flow diagram of study selection.

Study characteristics

Data extracted are presented in terms of PICOS, and training study relevant information, such as on-task learning, transfer of learning, adherence to training and follow-up results. Information relating to participants, intervention received, and comparators is summarised in table 4.2.

Participants

Participant samples included adult CI users with prelingual hearing loss (Bernstein et al. 2014), postlingual hearing loss (Lo et al. 2015; Shafiro et al. 2015; Miller et al. 2016; Smith et al. 2017; Fuller et al. 2018) or both (Schumann et al. 2015b; Barlow et al. 2016). Experience with device at the beginning of the AT ranged from less than a year (Bernstein et al. 2014; Smith et al. 2017) to 25 years (Reis et al. Chapter 3), with median CI experience of 6.2 (mean = 8, SD = 6.42) years across studies. Bernstein et al. (2014) did not provide exact duration of CI experience for the two participants with less than a year of experience in their study, and Smith et al. (2017) reported that the participant with least device experience in their study was using their CI for three months. Participants' mode of listening varied across studies, which included unilateral, bilateral CI users as well as bimodal listeners (see Table 4.2).

Mean age across studies ranged from 37.1 (Bernstein et al. 2014) to 69.1 years (Fuller et al. 2018), and median age across studies was 60.5 years (mean = 59.82, SD = 10.59). Participant sample sizes ranged from n=10 (Barlow et al. 2016) to n=28 (Bernstein et al. 2014), with a median sample size of 19 (mean = 19.44, SD = 6.48). Females formed the majority of the sample in most studies, except in Bernstein et al. (2014) where males were majority and Reis et al. (Chapter 3) where sex distribution was equal. Barlow et al. (2016) and Fuller et al. (2018) did not report sex of participants.

Intervention

The intervention in each study was CBAT, which required active engagement from participants and was individually delivered. Training was home-based in five studies (Lo et al. 2015; Shafiro et al. 2015; Barlow et al. 2016; Smith et al. 2017; Reis et al. Chapter 3) with the remaining being conducted in the laboratory (Bernstein et al. 2014; Miller et al. 2016; Fuller et al. 2018; Schumann et al. 2015b).

Four studies used speech material for the training stimuli, such as phonemes (Miller et al. 2016), non-sense consonant-vowel-consonant (CVC) and vowel-consonant-vowel (VCV) (Schumann et al. 2015b), non-sense consonant-vowel-consonant-vowel-consonant (CVCVC) (Bernstein et al. 2014), words and sentences (Reis et al. Chapter 3). Training stimuli used in the remaining studies included environmental sounds (Shafiro et al. 2015), psychophysical stimuli (Barlow et al. 2016), melodic patterns (Lo et al. 2015; Smith et al. 2017; Fuller et al. 2018), pitch and timbre (Smith et al. 2017). Bernstein et al. (2014) evaluated CVCVC words presented in conjunction with lipreading and without lipreading. Smith et al. (2017) evaluated the HearTunes (Rehab) package, which included pitch and timbre discrimination and musical patterns identification which focused on training listeners selective, divided and alternating attention.

Training session duration was only reported in terms of the recommended duration in most studies, except for Reis et al. (Chapter 3) which reported actual session duration as extracted from the training program's datalogging capability. This datalogging however, included only sessions up to the recommended training program end-point, as in cases where participants used the training program for longer, data from additional training sessions was not included in the analysis. Bernstein (2014) and Smith (2017) did not report session duration, and Miller et al. (2016) indicated that although two hours were recommended, duration varied across participants and exact session duration was not reported. Overall, session duration ranged from 12.8 minutes (Reis et al. Chapter 3) to 2 hours (Miller et al. 2016; Fuller et al. 2018). Frequency of training ranged from twice per week (Bernstein et al. 2014; Miller et al. 2016) to seven times per week (Barlow et al. 2016). Training duration ranged from 2 days (Bernstein et al. 2014) to 6 weeks (Lo et al. 2015; Fuller et al. 2018).

Comparator

Studies that included control groups or comparison from pre- to post-training were considered in this review. Two studies included a no-intervention control group (Schumann et al. 2015a; Miller et al. 2016). Fuller et al. (2018) compared the CBAT intervention with a music therapy intervention

Table 4.2. Descriptive summary of extracted data from the nine included studies

Study	Design	Participants				Training			Control type
[training delivery]		N	Mean Age	Percent Female	Onset of hearing loss and device experience	Stimuli	Frequency and duration	Adherence	
Bernstein (2014) {Experiment 1} [Laboratory]	Non-randomised crossover design	28	37.1	46.4	All prelingually deafened. 3 bilateral CI, 25 not specified. CI Experience = 0-17 years, mean = 6.2 years.	Paired-associates. Non-sense CVCVC words presented in the auditory mode only followed by training in the audio-visual mode (AO-AV) or vice-versa (i.e. AV-AO).	Session duration not reported. 7-block sessions per day for 2 days.	NR	
Lo (2015) [Home]	Repeated measures, with parallel group	16	58	68.8	All postlingually deafened. 10 bilateral CI; 3 unilateral CI, 3 CI+HA. CI Experience = 1-20 years, mean = 9 years.		15-30 minutes per session. 4 sessions per week for 6 weeks.		Acitve (12 normally hearing listeners)
		Interval=8	59.4	87.5	6 bilateral CI; 1 unilateral CI; 1 CI+HA. CI Experience = 1-20 years, mean = 10.4 years.	Melodic contours with note duration fixed at 250ms and adaptive interval size (1 to 7 semitones).		MCTP (Interval): 100%	
		Duration=8	56.6	50.0	4 bilateral CI; 2 unilateral CI; 2 CI+HA. CI Experience = 1-19 years, mean = 8.7 years.	Melodic contours with interval size fixed at 5 semitones and adaptive note duration (450-50ms).		MCTP (Duration): 62.5% (5/8). 25% (2/8) completed 4 weeks of training. Adherence unknown for 1/8 (data logs corrupted).	
Schumann (2015) [Laboratory]	Randomised controlled trial	27	60.5	66.7	25 postlingually and 2 prelingually deafened. 10 bilateral CI; 17 unilateral CI. CI Experience = 2-9 years, mean = 4.4 years				Passive
		CBAT=15	60	73.3	13 postlingually and 2 prelingually deafened. 7 bilateral CI; 8 unilateral CI. CI Experience = 2-7 years, mean = 4.2 years.	Nonsense syllables: Phoneme discrimination task	45-60 minutes per session. 2 sessions per week for 3 weeks.	100%	
Shafiro (2015) [Home]	Repeated measures	14	63	64.3	All postlingually deafened adults. Listening mode not reported. CI Experience = 1-8 years; mean = 5 years.	Environmental sounds (adjusted to individuals pre-test performance - i.e. stimuli trained consisted of sounds identified with accuracy of 50% or less at pre-test)	40-60 minutes per session. 4 sessions per week for 1 week.	NR	Within-participant

Table 4.2. (continued)

Study	Design	Participants				Training			Control type
[training delivery]		N	Mean Age	Percent Female	Onset of hearing loss and device experience	Stimuli	Frequency and duration	Adherence	
Barlow (2016) [Home]	Repeated measures	10	55.3	NR	4 postlingually and 6 prelingually deafened adults. Listening mode not reported. CI Experience = 1.7 - 4.3 years, mean = 3.01 years	Temporal (gap-in-noise; temporal modulation transfer function; iterated rippled noise) & Spectral (frequency discrimination; spectral rippled noise) psychophysical tasks:	Approximately 1 hour per session. 7 sessions per week for 1 week.	100%	Within-participant
Miller (2016) [Home]	Non-randomised pseudocontrolled trial	14	60.8	71.4	All postlingually deafened. 9 bilateral CI; 5 non-specified if unilateral or bimodal. CI Experience = 0.7-22.8 years, mean = 7.5 years.		Recommended 2 hours, but reported to differ dramatically across participants. 2 sessions per week for 2 weeks.		Passive
		CBAT=9	58.2	77.8	5 bilateral CI; 4 non-specified. CI Experience = 0.7-22.8 years, mean = 8 years.	Phoneme discrimination (/ba/, /da/, /wa/, and /ja/ productions spoken by 4 female and 4 male)		100%	
Smith (2017) [Laboratory]	Repeated measures	21	56.7	66.7	Postlingually deafened adults; CI Experience = 3 months - 13 years, mean = 24.5 months	HearTunes (Rehab) - Musical patterns, pitch, timbre.	3.5h per week for four weeks. Frequency Not reported..	NR	
Fuller (2018) [Laboratory]	Randomised controlled trial	19	69.1	NR	All postlingually deafened adults. 1 bilateral CI, 13 unilateral CI, 5 CI + HA. CI Experience = 3 - 13 years, mean = 6.3 years.			NR	Active (2 groups)
		CBAT=6	73	NR	6 unilateral CI. CI Experience = 3 - 12 years, mean = 6.3 years.	Melodic contour training, instrumental or daily sound identification.	2 hours per session. 6 sessions per week for 6 weeks.		
Reis (Chapter 3) [Home]	Randomised controlled trial with crossover design	26	63.2	50	22 postlingually and 4 prelingually deafened adults. 8 bilateral CI, 8 unilateral CI, 8 CI+HA. CI Experience = 1-25 years, mean = 6.11 years.	AT: Words and sentences in adaptive 4-TB.	12.8 minutes per session. 5 times per week for 6 weeks.	70.8% completed requested 30 sessions. 25% completed between 26 and 29 sessions and 4.1% completed 20 sessions. Participants who withdrew from the study completed 0, 1, 7 and 13 sessions.	Within-participant & Active

Data from normally hearing participants and control interventions are omitted from this table.
CBAT: Computer-based auditory training; CI: Cochlear implant; HA: Hearing aid; TB:talker babble; SNR: signal-to-noise ratio; AO:auditory-only; AV:auditory-visual; MCTP: Melodic Contour Training Program; AT: Auditory training; VT: Visual training.
AuSTIN: Australian Sentence Test in Noise; BKB/A: Bamford-Kowal-Bench/Australia; CNC: consonant-nucleus-consonant; CVC: consonant-vowel-consonant; CVCVC: consonant-vowel-consonant-vowel-consonant; IEEE: IEEE sentences; IVA-CPT: Integrated visual auditory - continuous performance test; VCV: vowel-consonant-vowel; LNT: Lexical neighborhood test; NCIQ: Nijmegen Cochlear Implant Questionnaire; PEPS-C: Profiling Elements of Prosody in Speech-Communication; PRCA-24: Personal report of communication apprehension; QOLS: Quality of life; RST: Reading span test; SESMQ: Self-efficacy for situational communication management questionnaire; SF-36: Short-Form 36; SPIN-R: Speech-in-noise Revised; SSQ-12: Speech, spatial and qualities; VST: Victoria Stroop Test.

al. (Chapter 3) compared CBAT to a visual training program and also to differences seen in relation to baseline measures conducted at two timepoints (test-retest), and Bernstein et al. (2014) a group of individuals who received CBAT combined with lipreading and then CBAT only in the auditory modality (AV-AO), with a group who received the same interventions in the opposite order (AO-AV). Lo et al. (2015) included a control group of normally hearing adults. The remaining studies assessed post-training changes in relation to single (Smith et al. 2017) or double baselines (Shafiro et al. 2015; Barlow et al. 2016) only.

Outcome measures

Measures used to assess training outcomes included validated speech perception tests, such as the Australian Sentence Test in Noise (Dawson et al. 2013; Lo et al. 2015), the Goettingen sentence test (Kollmeier & Wesselkamp 1997; Schumann et al. 2015a), the Revised Speech-in-Noise test (Elliott 1995; Shafiro et al. 2015), the Lexical Neighborhood Test (Kirk 1998; Barlow et al. 2016), IEEE sentences (IEEE 1969; used by Smith et al. 2017), Bamford-Kowal-Bench/Australia sentences (BKB/A; Bench & Doyle 1979), consonant-vowel-consonant words (Bosmana & Smoorenburg 1995; Fuller et al. 2018) and the consonant-nucleus-consonant test (Peterson & Lehiste 1962), which was the only measure used in more than one study (Shafiro et al. 2015; Reis et al. Chapter 3). Two studies did not include validated speech perception tests, however they assessed benefit by measuring changes with the same trained material, spoken by different speakers (Miller et al. 2016) or with lists that were not used during the training (Bernstein et al. 2014). Lo et al. (2015) assessed question/statement prosody (i.e. intonation) with the turn-end subtest of the Profiling Elements of Prosody in Speech-Communication (Peppé & McCann 2003) and Fuller et al. (2018) included measures of vocal emotion identification (Gilbers et al. 2015).

The study by Reis et al. (Chapter 3) was the only study to include behavioural measures of cognition, including attention, as measured with the Integrated Visual Auditory-Continuous Performance Test and the Victoria Stroop Test (VST; Spreen & Strauss 1998), verbal working memory, assessed with the reading span test (RST, Baddeley et al. 1985), and phonological representations assessed with the rhyme judgement test (Ausmeel 1988).

Reis et al. (Chapter 3) was also the only study to assess self-reported measures of listening and communication with the Speech, Spatial and Qualities of Hearing questionnaire (SSQ-12; Noble et al. 2013), the Personal Report of Communication Apprehension (PRCA-24; McCroskey et al. 1985), and the Self-Efficacy for Situational Communication Management questionnaire (SESMQ; Jennings et al. 2013).

Quality of life measures were assessed by Fuller et al. (Fuller et al. 2018) with the Nijmegen Cochlear Implant questionnaire (Hinderink et al. 2000) and by Reis et al. (Chapter 3) with the Quality of Life Scale (QOLS; Burckhardt & Anderson 2003) and the Short-Form36 (SF-36; Ware & Sherbourne 2015).

Study designs

There were four repeated-measures designs (Lo et al. 2015; Shafiro et al. 2015; Barlow et al. 2016; Smith et al. 2017) - one also included a parallel group (Lo et al. 2015), three randomised controlled designs (Schumann et al. 2015a; Fuller et al. 2018) - Reis et al. (Chapter 3) used a crossover design, Bernstein et al. used a non-randomised controlled design (Bernstein et al. 2014) and Miller et al used a non-randomised pseudo-controlled design (Miller et al. 2016).

On-task learning

On-task learning was defined as any improvement on a task or stimulus that was directly trained, and measured by data extracted from the training program used or assessed using identical stimuli (i.e. same list and talker). Overall, studies reported significant on-task learning for trained tasks. However, Smith et al. (2017) found limited on-task learning on trained tasks with the HearTunes (Rehab) for participants with high musical ability. Fuller et al. (Fuller et al. 2018) reported on-task improvements only for a subset of trained tasks, which were assessed before and after training. Bernstein et al. (Bernstein et al. 2014) presented on-task improvement for groups AV-AO and AO-

AV separately only for the first period of the study, as this were measured with AO stimuli outside the training program itself, results are only reported for the AO-AV group which showed a decrease of 1.8% points in performance in comparison to their results in the single day of AO training.

Generalisation of on-task learning

Generalisation of learning was considered as any improvement shown in stimuli or tasks that were not directly trained. These included measures using tasks of the same nature, however with different material used (i.e. different lists of words used for training and testing).

Speech perception

Eight studies reported measures of untrained speech perception, however, generalisation did not occur in all studies and not for all measures assessed within studies (see Table 4.3). Improvement for stimuli that were the same as those used in the training, but spoken by different talkers such as in Miller et al. (2016), were considered on-task learning and not generalisation. Similarly, Reis et al. (Chapter 3) reported an overlap of 43.3% between the CNC words used in two training modules and those used to measure outcome before and after training.

Of the four studies which directly trained speech perception (Bernstein et al. 2014; Miller et al. 2016; Schumann et al. 2015b), significant improvement on untrained tasks was reported only by Schumann et. al (2015a). This occurred for the recognition of sentences in speech-shaped noise (SSN) at +5dB SNR (mean= 10% points, p=0.01), but not for the 0dB SNR condition. Bernstein et al. (Bernstein et al. 2014) did not report statistical analysis for the 3.4% points mean improvement following training. Reis et al. (Chapter 3) did not find significant improvement in performance post-training, despite the overlap of 43.3% in CNC word material used for training and testing, and the on-task improvement found for identification of CNC words in noise.

Of the five studies which did not use speech material as training stimuli, three demonstrated some form of on-task learning generalisation. Barlow et al. (2016) found improvement for monosyllabic but not multisyllabic words in the LNT. The authors indicated moderate effect sizes for the perception of easy (Cohen's d=0.27) and hard (Cohen's d=0.30) monosyllabic words. While Fuller et al. (2018) did not find improvement on untrained tasks following training with melodic contours, Lo et al. (2015) showed that their participants, who also trained with melodic contours, significantly improved in consonant discrimination in quiet and in a question-statement identification task. However, the control group used in this study consisted of normally hearing listeners and thus post-training effects were made in comparison to a single baseline measure, not enabling to compare if improvements were an effect of training. The same occurs in Smith et al. (2017) who found a significant post-training improvement in the perception of IEEE sentences in quiet (15% points, $p<0.05$) and in noise (23% points, $p<0.05$) in a cohort of participants who were classified as having low musical ability, however they did not control for procedural learning in their study design. Shafiro et al. (2015) found no generalisation of environmental sounds on-task learning to speech perception.

Individual level data presented by Schumann et al. (2015a) suggested that not all participants demonstrated benefit after training. Similarly, data from Reis et al. (Chapter 3), suggested that some individuals demonstrated improvement in speech perception when assessed with BKB sentences in noise.

Cognition

Only Reis et al. (Chapter 3) included cognitive outcome measures, where no significant post-training improvements were found (see table 4.4).

Self-reported communication

Reis et al. (Chapter 3) did not find significant post-training differences for the SSQ-12, PRCA-24 or SESMQ (see table 4.4).

Self-reported quality of life

Fuller et al. (2018) did not find a significant improvement for quality of life measured with the NCIQ. Reis et al. (Chapter 3) also did not find significant differences post-training for the QOLS and the SF-36 (see table 4.4).

Table 4.3. Outcomes in untrained measures of listening and calculated Hedges' g effect sizes*

Study	Training Stimulus	Outcome	Outcome measure	Post-training	Follow-up
Bernstein (2014) {Experiment 1}	Nonsense words	Speech-in-quiet	(Q) CVCVC - closed-set	Data not reported for each intervention separately	n/a
Lo (2015)	Melodic contours	Speech-in-quiet	(Q) Consonant Discrimination	**Interval: 0.77 (0.14, 1.60)** **Duration: 0.10 (-0.51, 0.74)**	n/a
		Speech-in-noise	(4TB) Consonant Discrimination	Interval: 0.25 (-0.35,0.92) Duration: -0.02 (-0.64, 0.60)	n/a
		Speech-in-noise	(4TB) AuSTIN	Interval: 0.26 (-0.34, 0.93) Duration: 0.20 (-0.41, 0.85)	n/a
		Speech-in-quiet	(Q) PEPS-C	**Interval: 0.30 (-0.30, 0.98)** **Duration: 0.79 (0.15, 1.61)**	n/a
Schumann (2015)	Nonsense syllables	Speech-in-noise	(SSN) Goettingen sentences 5dB SNR	**0.52 (-0.07, 0.87)**	**0.40 (-0.05, 0.89)**
		Speech-in-noise	(SSN) Goettingen sentences 0dB SNR	0.38 (0.07, 1.04)	0.34 (-0.11, 0.83)
Shafiro (2015)	Environmental sounds	Speech-in-quiet	(Q) CNC Words	0.11 (-0.36, 0.58)	0.20 (-0.27, 0.68)
		Speech-in-noise	(12TB) SPIN-R	0.11 (-0.36, 0.59)	0.05 (-0.42, 0.52)
Barlow (2016)	Temporal and spectral stimuli	Speech-in quiet	(Q) LNT in quiet	-0.02 (-0.87, 0.83)	n/a
		Speech-in-noise	(Q) LNT in 8TB	0.45 (-0.41, 1.39)	n/a
Smith (2017)	HearTunes (Rehab)	Speech-in quiet	(Q) IEEE Sentences	**LMA: 0.91 (-0.1, 1.98)** HMA: 0.16 (-0.69, 1.03)	0.24 (-0.56, 1.08) -0.13 (-0.99, 0.71)
		Speech-in-noise	(Multi-TB) IEEE Sentences	**LMA: 1.20 (0.18, 2.41)** HMA: 0.23 (-0.61, 1.12)	0.69 (-0.17, 1.67) 0.33 (-0.51, 1.24)
Fuller (2018)	Melodic contours	Speech-in-quiet	(Q) CVC	-0.01 (-0.81, 0.79)	n/a
		Speech-in-noise	(SSN) CVC	0.01 (-0.79, 0.81)	n/a
		Speech-in-quiet	(Q) Dutch sentences	-0.43 (-1.27, 0.41)	n/a
		Speech-in-noise	(SSN) Dutch sentences	0.43 (-0.41, 1.27)	n/a
		Speech-in-quiet	(Q) Vocal emotion identification	-0.99 (-1.96, -0.01)	n/a
Reis (Chapter 3)	Words and sentences	Speech-in quiet	(Q) CNC Words	0.17 (-0.56,0.93)	0.16 (-0.57, 0.91)
		Speech-in-noise	(4TB) BKB/A sentences (easier SNR)	-0.18 (-0.95, 0.56)	-0.22 (-0.99, 0.52)
		Speech-in-noise	(4TB) BKB/A sentences (harder SNR)	-0.23 (-1.01, 0.5)	0.10 (-0.65, 0.85)

Q: Quiet; SNR: signal-to-noise ratio; SSN: Speech shaped noise; TB:talker babble; AuSTIN: Australian Sentence Test in Noise; *BKB/A:* Bamford-Kowal-Bench/Australia; *CNC* : consonant-nucleus-consonant; *CVC:* consonant-vowel-consonant; *CVCVC:* consonant-vowel-consonant-vowel-consonant; HMA: High musical ability subgroup; *IEEE:* IEEE sentences; *LNT:* Lexical neighborhood test; *PEPS-C:* Profiling Elements of Prosody in Speech-Communication; *SPIN-R:* Speech-in-noise Revised; *LMA:* Low musical ability subgroup; **Note:** Bernstein (2014) did not provide results for each intervention separately; Miller et. al (2016) did not include untrained material and therefore is not reported in this table. *Effect sizes in bold indicate that the study authors reported this outcome as statistically significant.

Retention of learning

Retention of learning was defined as the maintenance of improvement assessed following a period where no training was received, where a significant difference was shown in relation to the pre-training assessment or where no significant difference was demonstrated from post-training to follow-up. Follow-up assessments were reported by four of the nine studies assessed in this review (Schumann et al. 2015a; Shafiro et al. 2015; Smith et al. 2017; Reis et al. Chapter 3). Time of follow-up ranged from 1 week (Shafiro et al. 2015) to 6 months (Schumann et al. 2015a; Smith et al. 2017) post-training.

Retention of on-task learning

On-task learning retention occurred in Shafiro et al. (2015), which found that improvement for environmental sounds were retained at 1 week post-training. Retention of generalised improvements in untrained outcomes Schumann et al. (2015a) reported retention of improvement six months post-training. The authors reported 8.4% points (p=0.014) change in comparison to baseline and 1.6% points lower than immediate post-training results.

Table 4.4. Calculated Hedges' g effect sizes for cognition, self-reported communication and quality of life outcomes

Study	Domain	Outcome	Post-training	Follow-up
Fuller (2018)	Self-reported quality of life	Hearing specific quality of life	-0.69 (-1.74, 0.10)	n/a
Reis (Chapter 3)	Cognition	Phonological representations	-0.22 (-0.73, 0.26)	0 (-0.49, 0.49)
		Inhibition control	0.13 (-0.35, 0.63)	-0.08 (-0.57, 0.4)
		Visual Attention	-0.1 (-0.6, 0.38)	-0.25 (-0.76, 0.23)
		Working memory	0.3 (-0.17, 0.82)	0.33 (-0.15, 0.85)
			0.12 (-0.36, 0.62)	0.12 (-0.36, 0.62)
	Self-reported communication	Perceived listening		
		Self-efficacy in communication	0.35 (-0.13, 0.87)	0.34 (-0.14, 0.87)
		Communication Apprehension	-0.01 (-0.49, 0.48)	-0.17 (-0.67, 0.31)
	Self-reported quality of life	Quality of life (general)	0.23 (-0.25, 0.74)	0.13 (-0.35, 0.63)
		General Health	0.3 (-0.18, 0.81)	0.72 (0.22, 1.33)
		Mental Health	0 (-0.48, 0.49)	-0.14 (-0.64, 0.34)
		Emotional role	-0.14 (-0.64, 0.34)	-0.25 (-0.76, 0.23)
		Social Functioning	-0.15 (-0.64, 0.33)	-0.47 (-1.02, 0.01)
		Vitality	0.43 (-0.06, 0.97)	-0.08 (-0.57, 0.4)

*Effect sizes in bold indicate that the study authors reported this outcome as statistically significant.

Adherence to training

Adherence was defined as the percentage of participants completing the requested training duration in each study. This was reported in five of the nine studies assessed. Schumann et al. (2015a), Barlow et al. (2016) and Miller et al. (2016) reported 100% adherence to the training program. Lo et al. (2015) reported 100% adherence to the MCTP (Interval) and 62.5% adherence to the MCTP (Duration) with the remaining 25% (2/8) participants completing 4/6 weeks of the requested training period and one participant (12.5%) for whom adherence information was not available due to program datalogging information being corrupted. Reis et al. (Chapter 3) reported 70.8% (17/24) participants completed the requested 30 sessions of training, while 25% (6/24) completed between 26 and 29 sessions, and 4.1% (1/24) completed only 20 sessions.

Risk of bias within studies

Results for risk of bias assessment are displayed in table 4.5. Of the five studies which included a control group, only Reis et al. (Chapter 3) reported generating random lists to allocate participants into groups, Bernstein et al. (Bernstein et al. 2014) and Miller et al. (2016) conducted non-randomised control studies, with the two remaining studies not reporting how randomisation was conducted (Fuller et al. 2018; Schumann et al. 2015b). Lo et al. (2015) assessed more than one intervention, however did not report how randomisation was conducted. Risk of bias due to unclear reporting or lack of allocation concealment, blinding of participants or outcome assessors was present across these six studies which evaluated more than one intervention (Bernstein et al. 2014; Lo et al. 2015; Miller et al. 2016; Fuller et al. 2018; Schumann et al. 2015b). Smith et al. (2017) and Lo et al. (2015) did not include any method to control for procedural learning and for this reason were rated high for other sources of bias.

Table 4.5. Risk of bias assessment for individual studies

	Sequence Generation	Allocation Concealment	Blinding of participants and personnel	Blinding of outcome assessors	Incomplete outcome data	Selective outcome reporting	Other sources of bias
Bernstein (2014)	High	High	Unclear	Unclear	Low	Low	Low
Lo (2015)	Unclear	Unclear	High	High	Low	Low	High
Schumann (2015)	Unclear	Unclear	High	High	Low	Low	Low
Shafiro (2015)	NA	NA	NA	NA	Low	Low	Low
Barlow (2016)	NA	NA	NA	NA	Low	Low	Low
Miller (2016)	High	High	High	High	Low	Low	Low
Smith (2017)	NA	NA	NA	NA	Low	Low	High
Fuller (2018)	Unclear	Unclear	High	High	Low	Low	Low
Reis (Chapter 3)	Low	High	High	High	Low	Low	Low

Certainty of evidence

The GRADE assessment (table 4.5) indicated that certainty of evidence for outcomes assessed in this review ranged from very low to low. Because this review included several study designs, assessment was conducted separately for RCTs and non-RCT studies. Certainty of evidence was very low for speech perception outcomes and low for cognition, self-reported communication and quality of life.

Table 4.6. Certainty of evidence across studies

Certainty assessment							Summary of findings
№ of participants (studies)	**Risk of bias**	**Inconsistency**	**Indirectness**	**Imprecision**	**Publication bias**	**Overall certainty of evidence**	**Impact**
Speech perception (follow-up: range 1 weeks to 6 months)							
131 (6 observational studies)	serious [a]	very serious [b]	very serious [c]	serious [b,c]	none	⊕◯◯◯ VERY LOW	Limited number of participants, lack of control, inconsistencies in results within and across studies, and risk of bias in studies do not provide certainty that CBAT affects speech perception.
Speech perception (follow-up: range 1 months to 6 months)							
67 (3 RCTs)	serious [d]	serious [e]	not serious	serious [f]	none	⊕◯◯◯ VERY LOW	Limited number of participants, inconsistencies in results within and across studies, and risk of bias in studies do not provide certainty that CBAT affects speech perception.
Cognition (follow-up: range 1 months to 3 months)							
34 (1 RCT)	serious [d]	not serious	not serious	serious [f]	none	⊕⊕◯◯ LOW	Limited number of participants to estimate the effect of CBAT on cognition.
Self-reported communication (follow-up: range 1 months to 3 months)							
34 (1 RCT)	serious [d]	not serious	not serious	serious [f]	none	⊕⊕◯◯ LOW	Limited number of participants to estimate the effectiveness of CBAT for self-reported measures of communication.
Quality of life (follow up: range 1 months to 3 months)							
53 (2 RCTs)	serious [d]	not serious	not serious	serious [f]	none	⊕⊕◯◯ LOW	Limited number of participants to estimate the effect of CBAT on quality of life.

a. Lack of control group or test-retest assessment; b. Heterogeneity in studies design, type of intervention and outcome measures across studies. Variability in results within studies; c. Limited sample sizes, lack of follow-up assessments in 4/6 studies, comparison to normally hearing listeners or lack of control; d. Sequence generation unclear, unclear or no allocation concealment, no blinding of participants or outcomes assessors; e. Heterogeneity in type of intervention assessed. Improvements shown in only 1/3 studies; f. Insufficient number of participants to allow for assessment of precision.

4.5 Discussion

The objective of this rapid systematic review was to assess the effectiveness of CBAT for adult CI users in studies published between December 2012 and June 2018. Specific aims were to examine whether evidence exists to support that CBAT leads to improvement in trained and untrained measures of speech understanding, cognitive abilities, self-reported listening and communication, and quality of life in adult CI users, and whether any post-training improvements are retained following a period of no training.

The nine studies assessed in this review indicated that improvements occurred for at least one task that was trained (i.e. on-task learning). However, transfer of on-task learning to untrained measures was mixed across and within studies. Of the four studies which demonstrated that transfer of learning occurred for measures of speech perception (Lo et al. 2015; Schumann et al. 2015a; Barlow et al. 2016; Smith et al. 2017), only one (Schumann et al. 2015a) demonstrated that these were retained long-term. Smith et al. (2017) indicated that only a subset of participants showed improvement post-training, however these were not retained at follow-up. Lo et al. (2015) and Barlow et al. (2016) found that transfer occurred for some outcome measures but did not assess the retention of improvement. Also of interest to this review was whether CBAT leads to improvement in cognitive abilities and self-reported measures of communication and quality of life. Only one study assessed measures of cognition (Reis et al. Chapter 3) and two assessed self-reported measures of communication and quality of life (Fuller et al. 2018), however transfer was not found for any of these areas.

Retention of learning is an important aspect to assess effectiveness of CBAT protocols. Only four studies included follow-up assessments (Schumann et al. 2015a; Shafiro et al. 2015; Smith et al. 2017), ranging from one week to six months post-training. Shafiro et al. (2015) demonstrated that on-task learning was retained one week following completion a 1-week CBAT program, and Schumann et al. (2015a) demonstrated that improvement on an untrained task was retained 6 months from the end of a 3-week training program. Another important aspect of training studies, is whether individuals adhere to the regimen, however only four studies reported this information (Lo et al. 2015; Barlow et al. 2016; Miller et al. 2016).

Training stimuli, training protocols, and outcome measures varied widely across studies. In the case where training stimulus was common between studies, the outcome measures differed (Lo et al. 2015; Fuller et al. 2018), and where outcome measures were common, training stimulus differed (i.e. Shafiro et al. 2015; Reis et al. Chapter 3). Training stimulus included speech perception material (Bernstein et al. 2014; Schumann et al. 2015a; Miller et al. 2016), music patterns (Lo et al. 2015; Smith et al. 2017; Fuller et al. 2018), temporal and spectral frequencies (Barlow et al. 2016) and environmental sounds (Shafiro et al. 2015). All these stimuli reflect the areas of difficulty CI users have due to characteristics of the signal conveyed by the CI (c.f. Moore 2008). Speech perception outcome measures used in studies varied in target stimulus and masking noise used. One of the recommendations made by Henshaw and Ferguson (2013) was that outcome measures should be standardised to enable comparison between studies and identification of an effective AT protocol. The minimum reporting standards for adult cochlear implantation have recently been revised, and suggest that speech perception outcome assessment in the clinic and in research should include CNC words in quiet, and AzBio or BKB sentences in quiet and noise (Adunka et al. 2018), to allow for comparison of future studies. These standards however do not recommend the type of masking noise that should be used for testing. The type of masking used in testing, however, has been indicated to recruit different cognitive processes and may be an important aspect to consider when selecting outcomes measures in studies (see Heinrich et al. 2015 for a review).

Similarly, although only two studies assessed quality of life, measures used differed between studies. While general health-related quality of life questionnaires, such as the SF-36 used by Reis et al. (Chapter 3) enable broader comparisons of the intervention impact on costs and health outcomes across different areas of healthcare using quality-adjusted life years (QALYs), the use of condition-specific quality of life questionnaires, such as the NCIQ used by Fuller et al. (2018)

may be more sensitive to rehabilitation interventions such as CBAT (Loeffler et al. 2010; Whitehead & Ali 2010).

The studies assessed in the present systematic review provided very low certainty that CBAT is an effective intervention to improve speech perception and low certainty that CBAT if effective to improve cognitive abilities, self-reported communication and quality of life in adult CI users. The low quality of evidence was mainly due to study designs limitations in controlling for procedural learning, lack of blinding, small sample sizes, lack of follow-up assessments, and lack of clear reporting to assess risk of bias in studies. Moreover, inconsistencies in findings across studies did not enable for precise conclusions about the effectiveness of CBAT for adult CI users.

The limitations in studies assessed in this rapid systematic review are similar to those indicated by Henshaw and Ferguson (2013) in their systematic review. It indicates that recommendations made by the authors were not adopted in several studies. Those recommendations, which included increasing the level of evidence, appropriately selecting and standardising outcome measures, and identifying who is a candidate for AT remain relevant when assessing effectiveness of CBAT protocols. Studies in CBAT for adult CI users remain necessary to reliably guide evidence-based practices. Ideally, double-blinded randomised controlled trials with follow-up assessments should be conducted to increase the level of evidence in CBAT. Self-reported measures of listening are also an important factor to consider as these can potentially provide an indication of AT effects on functioning when combined with behavioural measures. Finally, despite the increased importance cognition has gained in the field of hearing research in the recent years, only the study in this thesis (Chapter 3) investigated how cognitive abilities interact with auditory learning. Despite the study of Smith et al. (2017) reporting that one of the training modules used in the CBAT assessed in their study having a target on attention, no measures of cognition were used in that study. Future CBAT studies should consider not only the incorporation of outcome measures of cognition, but also the combination of auditory-cognitive training programs for CI users, as these may potentially improve perception and processing of speech in the brain (Anderson et al. 2013a).

Limitations

Although the process of searching and screening studies was conducted with the whole team for the systematic review registered with PROSPERO (CRD42017076817), the data and summary of findings for the results presented in this chapter were extracted and reported independently by only one investigator, which could have introduced researcher bias. This report of the data, however, will form part of a broader high-quality systematic review and meta-analysis for publication, which also includes participants using hearing aids, where data will be independently extracted and all team members will discuss any conflicts and contribute to the reporting of results. This systematic review, however, is beyond the scope of the current thesis, which focuses on adults using CIs.

4.6 Conclusion

Current evidence provides very low certainty that CBAT improves speech perception, and low certainty that it improves cognition, communication and quality of life for adult CI users. Only one study demonstrated that transfer of learning to an untrained task of speech perception was maintained long-term. Limitations in design of studies and inconsistencies in findings across studies, reduce the confidence in the estimation of effects reported. Further high-quality evidence is required to inform whether CBAT is an effective intervention for adult CI users. Future studies should consider the role of cognition, assessment of self-reported measures of listening and quality of life, and reduce the risk of bias by conducting randomised controlled studies, and when possible use researcher and/or participant blinding, and with follow-up measures to assess retention of any improvements.

4.7 Supporting information

Appendix D. Example of terms used to search records in Pubmed.

4.8 Acknowledgements

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Chapter 5. Final considerations

5.1 General summary and discussion

This thesis investigated whether auditory training (AT) was beneficial for adult cochlear implant (CI) users within the context of clinical decision-making, resource allocation and evidence-based practices. Previous research has suggested that AT leads to inconsistent outcomes among CI users, and is supported by very low to moderate quality evidence (Sweetow & Palmer 2005; Henshaw & Ferguson 2013). The three studies presented in this thesis sought to further understand the context and benefits of AT by:

a. describing current rehabilitation practices adopted in Australian CI centres (Chapter 2);
b. assessing the cost of different rehabilitation approaches for adult CI users and clinical service providers (Chapter 2);
c. evaluating the effectiveness of a computer-based auditory training (CBAT) on short- and long-term, trained and untrained measures of listening and cognitive abilities and quality of life for adult CI users (Chapters 3 & 4).
d. evaluating whether AT would be comparable to benefits obtained following a non-auditory verbal training, using a visual training paradigm (Chapter 3).

The knowledge gained from these three studies is relevant to adult CI users, clinicians, and service providers when considering the role of rehabilitation interventions following cochlear implantation.

The first key finding of this thesis comes from the study presented in Chapter 2, which demonstrated that despite the lack of robust evidence demonstrating its benefits to speech perception, AT is valued by CI audiologists as an important component of CI rehabilitation. This study indicated that clinicians seek different methods to ensure that clients receive AT, such as including AT within routine appointments, recommending home-based AT or referring clients to a rehabilitationist when their clinic does not offer this type of service. The cost analysis presented within that chapter indicated that it is primarily the methods used to deliver AT to clients that affect the cost AT incurs for both clients and clinical service providers. That study further allowed identification of approaches valued by audiologists and indicated that current rehabilitation practices are not guided by high-quality evidence. This highlighted the importance of investigating the effectiveness of AT for adult CI users in a controlled study which was presented in Chapter 3.

The study in Chapter 3 was also encouraged by the need to increase the quality of AT studies to guide clinical practice (Henshaw & Ferguson 2013), and by the need to better understand aspects that are targeted by AT protocols (Boothroyd 2010). The CBAT program assessed in this study used training stimuli (i.e. speech) that are often used by clinicians (as reported in Chapter 2), and demonstrated that although on-task improvement was found after training, this did not transfer to speech perception tasks assessed outside the training program. Previous research suggested that AT could have an important role in improving cognitive abilities that contribute to listening (Kuchinsky et al. 2014; Pichora-Fuller et al. 2016). No significant improvements, however, were shown for measures of cognitive abilities, self-report listening and communication, or quality of life. The visual training used to test the hypothesis that directly training cognitive abilities recruited during listening could lead to improved outcomes also did not show any improvements in aspects of speech understanding, cognition and quality of life. These findings suggest that the training program used in this thesis, which is similar to AT regularly recommended in clinical settings, did not target the underpinning mechanisms of speech understanding that are important for functional real-world listening, nor did it affect the individuals' perceived performance gains in the real world.

The study in Chapter 3 further demonstrated that in general, changes in performance that occurred from test-retest prior to training (i.e. using a double baseline measure approach), were greater than changes found from pre- to post-training. This is an important aspect to consider, as training protocols cannot be qualified as being effective if they do not elicit improvements greater than those acquired by the simple fact of being exposed to a procedure twice. This factor however, is often overlooked in clinical practice and the clinician's perception of training benefits could be a representation of this. Thus, the inclusion of double baselines measured in the clinic before the beginning of AT is recommended to measure true effects of training.

To further assess the research questions of Chapter 3 and contextualise findings within the recently published literature, a rapid review of the evidence was conducted, and presented in Chapter 4. Main findings showed that despite on-task learning being found in all of the nine studies reviewed, only four studies showed transfer to untrained measures of speech perception, and only one study demonstrated that this was maintained long-term. Only the study described in Chapter 3 reported assessing outcome measures of cognition and self-report listening, while quality of life was assessed by a second study in that review. Similar to common clinical AT practices, Chapter 4 highlighted that research study designs, which would be expected to include more stringent control parameters than clinical practice, also often do not include more than one baseline to control for test-retest effects. A number of studies also did not include any method to control for procedural learning, such as including a control group. The inconsistencies in findings within and across studies, as well as studies characterised by several risks of bias, demonstrated that the evidence currently available in the literature provides very low confidence that AT improves speech perception, and low confidence that AT improves cognitive abilities, self-reported listening and quality of life. Importantly, Chapter 4 demonstrated that several AT approaches (i.e. psychophysical, melodic contours, pitch training) are being investigated as a means of improving speech perception in adult CI users.

The knowledge derived from Chapters 3 and 4 can assist clinicians when providing clients with realistic expectations about CI rehabilitation options, and when considering assessment of AT outcomes in the clinic. Despite the lack of strong evidence to support AT, clients' should be provided with up-to-date reliable information about the benefits of different interventions so they can make informed-decisions, aligned with their personal goals and preferences. The knowledge provided by the cost analysis in Chapter 2, may further guide clients and clinicians in rehabilitation decisions. These studies should also assist clinical managers when deciding on the provision of rehabilitation programs as part of clinical services.

5.2 Limitations of this work, and future research

This thesis provides useful evidence to address part of the knowledge gap that exists in AT research for adult CI users and raises several new questions. One of these questions relates to the stimuli and tasks used during the training programs. It has been demonstrated that programs which use auditory-cognitive tasks, rather than auditory only or cognitive only tasks have the potential to improve speech understanding and cognitive abilities (Sweetow & Sabes 2006; Anderson et al. 2013b), as well as how the brain processes speech cues in hearing aid users (Anderson et al. 2013a). This type of training is yet a topic to be investigated for adult CI users.

Further, while the AT stimuli used in Chapter 3 aimed to address speech perception under noisy conditions, the type of masking used during training consisted of an adaptive 4-talker babble noise. This type of noise and signal-to-noise ratios, however, may not be representative of noises individuals are exposed to in their daily life. The target stimuli used during AT consisted of speech material that was professionally recorded, whereby factors such as articulation, voice quality and intonation would be controlled for and as such, would not be reflective of real-world communication. If the reasoning behind transfer of learning is that an overlap needs to exist between the trained stimuli and the outcome measures (c.f. Ahissar & Hochstein 1997; Ahissar et al. 2009), perhaps future studies should investigate whether training under realistic acoustic environments (see Westermann & Buchholz 2015; Culling 2016 for examples) leads to real-world gains.

Similarly, investigating AT as conducted clinically was beyond the scope of this study. However, it would be possible that training as conducted face-to-face by a clinician leads to more benefits than computer-based AT that is conducted individually, due to possible motivational aspects related with seeing a clinician regularly. Future research could explore the cost-effectiveness of AT that is completed individually at home in comparison to AT that is delivered face-to-face.

While this thesis investigated AT within three contexts (i.e. clinical decision making, resource allocation and evidence-based practice), the viewpoint of clients who deliberately seek or are undergoing AT was not investigated. Assessing their perception could help further understand the collateral benefits clients may obtain when engaging in such rehabilitation programs. For example, while no change may be found in measures of speech understanding, cognitive abilities or quality of life, AT may contribute to enhancing other aspects that were not measured within this thesis, such as providing a feeling of self-empowerment, self-efficacy or greater knowledge and control over one's own communication abilities and limitations (Henshaw et al. 2015).

Another interesting area for discussion is whether undergoing AT from time of CI switch-on could provide further improvement in auditory abilities as compared with AT that is delivered after individuals reach CI asymptote performance in speech perception tests. The challenge imposed by this, however is that controlling for CI acclimatisation would be challenging, and would require comparison with a control group that does not receive this potentially beneficial AT intervention. Furthermore this would be confounded by the fact that this population is characterised by large inter-individual variation in outcomes during the first weeks following the switch-on of the CI.

The studies in this thesis demonstrated that variation exists in clinical practice and research studies. These include methods and materials used for outcome assessments as well as approaches and stimuli used for AT. Such variations may be because an effective AT approach is yet to be identified (Pisoni et al. 2018). Similarly, study designs which enable researchers to evaluate effects of AT in a controlled manner and appropriate outcome measures are important for advancements in the field. For example, speech perception tests impose different auditory and cognitive demands and may represent different aspects of self-reported listening (Heinrich et al. 2015). Similarly, it has been suggested that hearing-specific measures of quality of life may be more sensitive to changes occurring after hearing interventions (Abrams et al. 2005). The standardisation of tests used to assess AT outcomes is yet to be further explored in the field.

The identification of effective training tasks and stimuli remains a challenge in auditory perceptual learning, but also in other areas, such as visual perception learning (Sagi 2011; Censor et al. 2016). While these two areas share similarities (Ahissar et al. 2009), a framework that has not yet been explored is the task decomposition (Coffey & Herholz 2013), which could further the understanding of common aspects of learning in areas using different training models in studies of neuroplasticity. Finding meaningful comparisons between different areas could potentially improve the knowledge of auditory perceptual learning and enhance the design of future training protocols.

Overall, current knowledge derived from AT research is insufficient to assert whether AT is an effective intervention for adult CI users. While this may change as more high-quality AT studies are published, several difficulties exist when conducting such studies. Training studies, as any longitudinal study of intervention, demand a high investment of time and energy from both the research team and participants who commit to protocols of long duration. For instance, the study presented in Chapter 3 required an extensive amount of coordination, time investment and resources. These included the setup of the experiment at each site, the development of a training platform that would be ideal for the study, the reimbursement of participants' time and travel expenses, as well as the resources utilised at each testing. Ideally, training studies should also use double-blinding. While it may be difficult to blind participants depending on the intervention being assessed, additional resources are required for blinding of research personnel. Thus, although there is awareness that studies should have adequate scientific control, some of the recommendations to avoid bias can be difficult to follow when resources are limited. In conjunction to these difficulties in generating high-quality evidence, lies the fact that training studies demand a longitudinal design. Therefore, as these take longer to be completed, the number of studies conducted in this field will probably be lower than in fields which can utilise cross-sectional designs. This imposes an extra barrier in the generation of knowledge in the field of AT.

Additionally, difficulties may also be present in the recruitment of participants for AT studies. As demonstrated in Chapter 4, studies often present results for relatively small sample sizes. While the CI population is very specific, it may also be difficult for individuals to commit to long duration studies that require multiple visits to the laboratory. Implementing remote assessments within studies could possibly assist with this. Additionally, a collaboration between clinics and research centres could improve both the recruitment of participation for studies of this nature as well as knowledge translation.

5.3 Conclusions

This thesis provides practical knowledge about current clinical practices in CI rehabilitation and cost associated to different AT methods; effectiveness of verbal-based AT compared to VT for listening, cognition and quality of life outcomes in adult CI users; and provides a review of the most up to date research evidence in this field. The work presented in this thesis demonstrated that the role of AT in CI rehabilitation practice is varied and widespread, however this is not guided by robust evidence of AT effectiveness. This variation in practice is associated with different costs for clients and clinical service providers. When considering AT as part of a rehabilitation program, clients and clinical service providers should consider evidence-based practices, individuals' personal goals and costs associated to different interventions. Future research should focus on identifying optimal stimuli for AT programs and examining these in high-quality longitudinal studies.

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Appendix A. Ethics approval letters

Macquarie University Human Research Ethics Committee: 5201400407

APPROVED

MACQUARIE University

Human Research Ethics Committee

REQUEST FOR AMENDMENT FORM

Please complete this form for all amendments/modifications including extensions to approved ethics projects.

For quick and efficient review of your amendment, please provide sufficient information in this document to allow the amendment to be reviewed as a standalone document (i.e. it does not require the Ethics Secretariat or HREC reviewing the original application).

Please attach tracked and clean copies of all amended documents to the amendment request. Documents could include participant information and consent forms (PICF), advertising material, surveys, interview questions, verbal scripts, support letters from external organizations.

Submitting this form:

HREC approved applications: Please send this form to ethics.secretariat@mq.edu.au.

Faculty/School-approved applications:
Please send this form to the ethics subcommittee administrator of the relevant Faculty/School
Faculty of Human Sciences: fhs.ethics@mq.edu.au
Faculty of Science and Engineering: sci.ethics@mq.edu.au
Faculty of Arts: artsro@mq.edu.au
Faculty of Business and Economics: fbe-ethics@mq.edu.au
MGSM: ethics@mgsm.edu.au
PACE: pace.ethics@mq.edu.au
Faculty of Medicine and Health Sciences: ethics.secretariat@mq.edu.au.

Handwritten forms will not be accepted.

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1. **Human Research Ethics Committee Reference No: Ref: 5201400407**

2. **Chief Investigator/Supervisor: Isabelle Boisvert**

   Faculty: Human Sciences

   Department: Linguistics

   Email: isabelle.boisvert@mq.edu.au

   Date of amendment: 03/06/2016

Macquarie University Human Research Ethics Committee: 5201500069

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1 April 2015

Associate Professor Catherine McMahon
Department of Linguistics
Faculty of Human Sciences

Dear Associate Professor McMahon

Reference No: 5201500069

Title: *Effectiveness of computer-based auditory and cognitive trainings in cochlear implant recipients*

Thank you for submitting the above application for ethical and scientific review. Your application was considered by the Macquarie University Human Research Ethics Committee (HREC (Medical Sciences)) at its meeting on 26 February 2015 at which further information was requested to be reviewed by the Ethics Secretariat.

The requested information was received with correspondence on 23 March 2015.

I am pleased to advise that ethical and scientific approval has been granted for this project to be conducted at:

- Macquarie University

This research meets the requirements set out in the *National Statement on Ethical Conduct in Human Research* (2007 – Updated March 2014) (the *National Statement*).

This letter constitutes ethical and scientific approval only.

Standard Conditions of Approval:

1. Continuing compliance with the requirements of the *National Statement*, which is available at the following website:

http://www.nhmrc.gov.au/book/national-statement-ethical-conduct-human-research

2. This approval is valid for five (5) years, subject to the submission of annual reports. Please submit your reports on the anniversary of the approval for this protocol.

3. All adverse events, including events which might affect the continued ethical and scientific acceptability of the project, must be reported to the HREC within 72 hours.

4. Proposed changes to the protocol must be submitted to the Committee for approval before implementation.

It is the responsibility of the Chief investigator to retain a copy of all documentation related to this project and to forward a copy of this approval letter to all personnel listed on the project.

Should you have any queries regarding your project, please contact the Ethics Secretariat on 9850 4194 or by email ethics.secretariat@mq.edu.au

The HREC (Medical Sciences) Terms of Reference and Standard Operating Procedures are available from the Research Office website at:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics

The HREC (Medical Sciences) wishes you every success in your research.

Yours sincerely

Professor Tony Eyers
Chair, Macquarie University Human Research Ethics Committee (Medical Sciences)

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) *National Statement on Ethical Conduct in Human Research* (2007) and the *CPMP/ICH Note for Guidance on Good Clinical Practice.*

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HREC Number:	**17/1327H**
Project Title:	**Effectiveness of computer-based training for cochlear implant recipients**
Principal Investigator:	**Professor Robert Cowan**

I acknowledge receipt of the revised Participant Information & Consent Form. I am pleased to inform you that the above project has now received ethical approval from the Eye and Ear HREC, is consistent with the National Statement and satisfies the Eye and Ear research governance requirements.

The HREC approval date is 17 May 2017, the HREC Number is 17/1327H, and approval is valid for five years.

This research may now commence at the Eye and Ear.

The following documents have been approved:

- Module One Application Form, dated 3 Apr 2017
- Participant Information and Consent Form, v2.0 dated 4 May 2017

The Royal Victorian Eye and Ear Hospital HREC is constituted and operates in accordance with the National Health and Medical Research Council (NHMRC) National Statement on Ethical Conduct in Human Research (2007 and as updated) and in accordance with the Note for Guidance on Good Clinical Practice (CPMP/ICH/135/95) and the Health Privacy Principles in the Health Records Act 2001(Vic) and Section 95A of the Privacy Act 1988.

In order to comply with the National Statement and Good Clinical Practice requirements you are required to:

- submit an annual progress report for the duration of the project
- submit a comprehensive final report upon project completion
- notify the Secretariat of the project start date at the Eye and Ear
- submit all proposed amendments to the project
- submit any adverse event reports involving Eye and Ear patients
- report any unexpected developments in the project with ethical implications
- notify any changes of project Principal and all other Investigators
- advise if the project is completed prior to the anticipated date or is withdrawn

- preserve the confidentiality of information and records about research participants and only use information for the purpose specified in the approved protocol

Please note that any researcher named in the application did not participate in deliberations or decision making for this project.

Please use the HREC number in all future correspondence with the HREC Secretariat.

On behalf of the Committee, I wish you every success with your project.

Yours sincerely

Kerryn Baker
Secretary
Human Research Ethics Committee

17 May 2017

Appendix B. Supporting Information for Chapter 2

Survey of Auditory Training Practices in Cochlear Implant Clinics in Australia

You are invited to participate in a research project in which you are required to complete a short questionnaire.

Title: Auditory training for adult cochlear implant users in Australia

This study aims to gain insight into the range of auditory training practices employed by professionals in Australia who work with adult cochlear implant users. The questionnaire will focus on the types, duration, and focus areas of the training conducted.

Procedures: You are asked to respond to a questionnaire that will take approximately 15 minutes or less. This questionnaire is conducted via an online Qualtrics-created survey. No risk is expected to be related to this study.

Confidentiality: All data gathered is de-identified, will be kept confidential, and will only be reported in an aggregate format (by reporting combined results). No individual or clinic will be identifiable. All depersonalised questionnaires will be concealed, and no one other than researchers listed below will have access to them.

Participation: Participation in this research study is completely voluntary. You have the right to withdraw at any time or refuse to participate.

Researchers involved in this study:

Ms Emma Beedell (emma.beedell@students.mq.edu.au)

Dr Isabelle Boisvert (isabelle.boisvert@mq.edu.au)

Ms Mariana Reis (mariana.reis@students.mq.edu.au)

A summary of the results of the data can be made available to you on request by contacting the investigators.

Ethical guidance for this study is provided by Macquarie University Human Sciences Ethics Committee Ref: 5201400407.

Questions or feedback about this study can be sent to: isabelle.boisvert@mq.edu.au

1 Do you agree to participate?

Yes

No

2 What is your profession?

Audiologist

Speech & Language Pathologist

Habilitationist (Teacher of the Deaf, etc.)

Other, please specify... ____________________

3 How many years of experience do you have in this profession?

4 Please indicate approximately what percentage of your clients within the last 2 years have been adult cochlear implant users?

0%

1-25 %

26-50%

51-75%

>75%

5 The term 'auditory training' in the context of adult cochlear implant users, can be defined as 'structured listening activities that aim to improve speech perception.' Would you agree with this definition?

Yes

No

Mostly

6 What definition would you give for auditory training when applied to adult cochlear implant users?

7 Please indicate how strongly you agree with this statement: "Auditory training helps improve outcomes in adult CI users with postlingual hearing loss"

Strongly agree

Agree

Somewhat agree

Neither agree nor disagree

Somewhat disagree

Disagree

Strongly disagree

8 Please indicate how strongly you agree with this statement: "Auditory training is necessary to improve outcomes in adult CI users with postlingual hearing loss"

Strongly agree

Agree

Somewhat agree

Neither agree nor disagree

Somewhat disagree

Disagree

Strongly disagree

9 As part of your work with adult cochlear implant users, do you conduct or recommend auditory training? (select all that apply)

I conduct individual face-to-face auditory training

I conduct group auditory training sessions

I refer my clients to another professional for auditory training

I recommend home-based auditory training exercises (ex.: audio-books, online programs)

I do not conduct or recommend specific auditory training beyond encouraging daily listening activities

10 How did you gain your knowledge about individual or group auditory training for post lingual cochlear implant users? (select all that apply)

Learned from supervisor(s) or colleague(s)

Attended training course(s) or professional development event(s)

Self-taught with manuals, online guidance, and/or journal articles

Knowledge learned during my degree

Other, please explain: ____________________

11 Compared to auditory training conducted for adults with postlingual hearing loss, does the following differ in relation to auditory training for adults with prelingual hearing loss?

Length of session	Shorter for prelingual	Shorter for postlingual	Same
Duration of training program	Shorter for prelingual	Shorter for postlingual	Same
Type of training conducted		Same	Different

11 Could you please describe the main differences in the type of auditory training you conduct for prelingual compared to postlingual hearing loss clients?

12 Compared to auditory training for adult clients with a bilateral postlingual hearing loss who use a unilateral cochlear implant, is auditory training conducted differently for the following clients? For example: training in noise, binaural training, hearing aid on or off, direct audio input, earplug in other ear?

	Please describe any differences - in comparison to unilateral CI users
Bimodal (CI+HA)	
Bilateral Implants	
Single-sided deafness	

13 How do you promote compliance to the training program?

14 Please indicate the typical duration and frequency of auditory training with your clients with postlingual hearing loss (please use 0 if not applicable).

	Individual face-to-face training	Group training	Home-based training
Minutes per session			
Sessions per month			
Overall duration (weeks)			

15 Please indicate the areas that you primarily focus on during auditory training for postlingually deafened adults (select all that apply):

frequency and/or temporal discrimination

music perception e.g. rhythm

word and/or sentence discrimination

phoneme/vowel or consonant recognition

connected discourse tracking

communication skills eg. pragmatics, question and answer

training in noise

lip-reading

voice quality eg. gender and/or emotion

telephone training

environmental sounds

other ____________________

16 In your experience, what is the area most focused on in auditory training for adult postlingual cochlear implant users?

17 How do you decide the difficulty level of each training session? For example, when to move from closed set to open set stimuli.

18 Do you provide feedback after presentation of each stimuli?

Yes

No

It depends. Please explain ____________________

19 What kind of resources would you utilise during an adult post lingual auditory training session? For example, do you use a specific program or exercise book.

20 How confident are you that the materials mentioned above are effective for auditory training?

21 In additional to the standard testing sessions conducted at your clinic to monitor client progress, are there any other measures you use specifically to evaluate training benefit?

Yes

No

Sometimes

21 Could you please specify the tests you use to evaluate auditory training benefit? Please include the frequency with which you use these tests and the information you believe they provide.

22 Please consider the influence of the following in regard to the auditory training you conduct or recommend. Please drag them to rank from most likely to influence to least likely to influence.

______ colleagues/ word of mouth

______ personal experience

______ evidence from literature

______ outcome measures conducted in your clinic

______ clinic guidelines

______ client reports

______ internet

______ knowledge learned during your degree

23 To whom do you refer your adult clients for auditory training? (Please select all that are relevant)

Audiologist

Speech & Language Pathologist

Habilitationist (Teacher of the Deaf, etc.)

Other, please specify... ____________________

24 For what type of training do you typically refer your adult postlingual clients? Please select all that apply.

Group training sessions

Face-to-face individual auditory training

Both

Other. Please specify. ____________________

25 What is the average duration of the auditory training program for your adult clients? Please use (?) if unknown.

	Training program
Minutes per session Sessions per month Overall duration (weeks)	

26 Please explain the value you believe auditory training brings to adult clients with postlingual hearing loss?

27 Could you say that you notice an improvement in the performance of your adult clients with postlingual hearing loss following auditory training?

Yes

No, not really

Sometimes

27 Could you please explain how you measure outcomes from auditory training?

27 Could you please explain any instances in which you notice a difference and how you measure this?

28 Please indicate what types of resources you recommend for home based auditory training for adult postlingual clients

computer-based training programs

audio books

printed exercises

Other. Please specify... ____________________

29 Could you say that you notice an improvement in your adult clients' performance following home-based auditory training exercises?

Yes

No, not really

Sometimes

29 Could you please explain how you measure outcomes from home-based auditory training?

29 Could you please explain any instances in which you do notice a difference and how you measure this?

30 The reasons I personally do not conduct auditory training include: (please select all that are relevant)

Limited by resources (e.g. time, available funding)

There is a dedicated clinician in my clinic who conducts auditory training

My clinic does not offer auditory training to clients

I do not know how to conduct auditory training

I have not seen any benefits come from auditory training in my professional experience

Research I have read has not shown great benefit in conducting auditory training

I do not need to conduct auditory training as I refer my clients to someone else

I do not think my clients need auditory training because they already have good speech perception skills

I recommend home-based auditory training

Other. Please explain: ____________________

31 What is the highest level of education you have completed?

Certificate IV

Graduate Diploma

Bachelor Degree

Post graduate Diploma

Masters Degree

Doctoral degree

Other ____________________

32 What is your gender?

Male

Female

33 What is your age?

34 Please indicate how many clinicians are in your workplace? If your clinic is part of a larger company, please answer in relation to the overall body.

Less than 10 clinicians

More than 10 clinicians

I'm not sure

35 Please indicate in what type of facility you conduct auditory training?

Hospital

Private clinic

Sub branch of a larger private clinic

ENT surgery

Public clinic

Sub branch of a larger public clinic

I'm not sure

Other ____________________

Appendix C. Supporting Information for Chapter 3

Training programs can be accessed in: https://bit.ly/2FVYz2h

Table 1 Detailed demographics of study participants

ID	Age (years)	Onset HL	Aetiology		Device		CI Experience		Allocation	Site
			Right	**Left**	**Right**	**Left**	**Right**	**Left**		
1	42	Post	Ototoxic	Ototoxic	Nucleus 6	Nucleus 6	15	9	VT+AT	MQU
2	75	Pre	Measles	Measles	Nucleus 6	Nucleus 5	8	7	AT+VT	MQU
3	58	Post	Unknown	Unknown	Nucleus 5	Nucleus 5	5	17	VT+AT	MQU
4	74	Post	Ménière's	Ménière's	Nucleus 5	Hearing aid	3		VT+AT	MQU
5	68	Post	Unknown	Unknown	Hearing aid	Nucleus 6		4	VT+AT	MQU
6	76	Post	Genetic	Genetic	Nucleus 6	Nucleus 6	6	3	VT+AT	MQU
7	61	Post	Genetic	Genetic	Hearing aid	Nucleus 6		3	VT+AT	MQU
8	81	Post	Unknown	Unknown	Hearing aid	Nucleus 5		4	AT+VT	MQU
9	61	Post		Meningitis	Unaided	Nucleus 6		4	AT+VT	MQU
10	58	Post	ANSD	ANSD	Nucleus 6	Nucleus 6	11	8	AT+VT	MQU
11	72	Post	Unknown	Unknown	Nucleus 6	Hearing aid	2		AT+VT	MQU
12	62	Post	Genetic	Genetic	Sonnet	Sonnet	7	6	VT+AT	MQU
13	65	Pre	Rubella	Rubella	Unaided	Nucleus 6		25	AT+VT	MQU
14	57	Post		Ménière's	Unaided	Rondo		2	VT+AT	FSH
15	56	Pre	Genetic	Genetic	Sonnet	Unaided	6		AT+VT	FSH
16	64	Post	Ménière's	Ménière's	Hearing aid	Opus 2		3	VT+AT	FSH
17	73	Post		Unknown	Unaided	Sonnet		2	VT+AT	FSH
18	53	Pre	Rubella	Rubella	Sonnet	Opus 2	1	3	AT+VT	FSH
19	48	Post	Unknown	Unknown	Opus 2	Unaided	3		AT+VT	FSH
20	55	Post	Unknown	Unknown	Unaided	Opus 2		4	AT+VT	FSH
21	56	Post	Meningitis	Meningitis	Rondo	Rondo	4	4	AT+VT	FSH
22	73	Post	Presbycusis	Presbycusis	Hearing aid	Sonnet		1	VT+AT	FSH
23	45	Post	CME	CME	Sonnet	Hearing aid	1		AT+VT	FSH
24	68	Post	Unknown	Unknown	Nucleus 5	Nucleus 5	7	4	VT+AT	CRC
25	84	Post	Unknown		Unaided	Nucleus 6	16		AT+VT	CRC
26	59	Post	Genetic	Unknown	Unaided	Nucleus 6		6	VT+AT	CRC

HL: Hearing loss; Pre: prelingual; Post: postlingual; ANSD: Auditory neuropathy spectrum disorder; CME: Cronic middle ear diseases; Ménière's: Ménière's disease; AT: Auditory training; VT: Visual training; CRC: The HEARing CRC; FSH: Fiona Stanley Hospital; MQU: Macquarie University. Follow-up measures were assessed 1 month post-training at FSH and CRC, and 3 months post-training at MQU.

Table 2. Descriptive statistics for study participants for the first intervention period of the study

	Baseline (T1)		Baseline (T2)		Post-training (T3)		Follow-up (T4)	
	AT N=13	**VT N=13**	**AT N=13**	**VT N=13**	**AT N=13**	**VT N=13**	**AT N=13**	**VT N=13**
Time of follow-up								
3 months	6 (46.2%)	7 (53.8%)	6 (46.2%)	7 (53.8%)	6 (46.2%)	7 (53.8%)	6 (46.2%)	7 (53.8%)
1 month	7 (53.8%)	6 (46.2%)	7 (53.8%)	6 (46.2%)	7 (53.8%)	6 (46.2%)	7 (53.8%)	6 (46.2%)
Sentences in noise (condition easier)	38.0 [35.3;43.2]	41.3 [28.7;44.7]	40.3 [32.7;44.0]	43.7 [34.0;45.0]	36.0 [26.7;42.7]	45.3 [42.7;47.3]	37.0 [28.3;41.0]	43.3 [39.7;44.7]
10dB	4 (33.3%)	9 (69.2%)	3 (23.1%)	9 (69.2%)	3 (23.1%)	9 (69.2%)	3 (23.1%)	9 (69.2%)
20dB	8 (66.7%)	4 (30.8%)	10 (76.9%)	4 (30.8%)	10 (76.9%)	4 (30.8%)	10 (76.9%)	4 (30.8%)
Sentences in noise (condition harder)	18.7 [10.7;51.3]	19.3 [7.33;30.0]	38.3 (26.1)	26.2 (20.4)	20.7 [18.0;47.3]	27.3 [8.67;38.0]	30.0 [16.7;69.3]	26.0 [12.7;36.0]
0 dB	3 (23.1%)	9 (69.2%)	3 (23.1%)	9 (69.2%)	3 (23.1%)	9 (69.2%)	3 (23.1%)	9 (69.2%)
10dB	10 (76.9%)	4 (30.8%)	10 (76.9%)	4 (30.8%)	10 (76.9%)	4 (30.8%)	10 (76.9%)	4 (30.8%)
Word recognition (%)	24.0 [14.0;30.0]	58.0 [20.0;78.0]	33.2 (23.8)	55.5 (23.5)	30.0 [20.0;64.0]	60.0 [30.0;70.0]	32.0 [20.0;56.0]	60.0 [38.0;76.0]
Spectral resolution	1.53 [1.20;1.66]	1.50 [1.00;2.00]	1.76 [1.07;2.03]	1.76 [1.10;3.10]	1.96 [1.33;2.76]	1.53 [1.23;1.90]	1.46 [1.33;1.64]	1.80 [1.46;2.30]
Auditory attention (ms)	670 (59.0)	666 (73.4)	681 (64.8)	631 (73.2)	674 (57.7)	653 (69.2)	686 (43.8)	656 (72.5)
Visual Attention (ms)	513 (50.1)	488 (32.5)	520 (55.6)	477 (51.5)	514 (54.9)	494 (47.3)	506 (47.0)	481 (34.2)
Working memory (%)	42.9 (17.7)	49.4 (17.3)	51.4 (15.9)	54.2 (14.5)	57.1 (18.8)	58.7 (22.4)	24.0 [24.0;24.0]	24.0 [24.0;24.0]
Phonological representations (ms)	1553 (271)	1382 (512)	1424 (305)	1212 (335)	1354 (289)	1185 (317)	1424 (333)	1300 (405)
Phonological representations (%)	84.4 [71.9;90.6]	87.5 [71.9;93.8]	87.5 [75.0;91.4]	87.5 [71.9;90.6]	84.4 [78.1;93.8]	78.1 [53.1;90.6]	84.4 [81.2;90.6]	93.8 [87.5;96.9]
Inhibition control (ms)	1.18 [1.10;1.40]	1.31 [1.18;1.40]	1.18 [1.13;1.62]	1.15 [1.08;1.23]	1.26 [1.03;1.60]	1.21 [1.11;1.43]	1.36 (0.37)	1.33 (0.29)
Self-efficacy in communication	68.5 (38.0)	95.6 (38.7)	79.3 (33.9)	94.2 (39.1)	93.5 (41.1)	94.1 (35.5)	91.8 (34.9)	106 (44.4)
General Health	62.7 [25.0;79.9]	83.8 [66.7;95.0]	62.7 [25.0;77.1]	83.8 [67.5;97.0]	67.5 [60.0;86.7]	77.5 [61.7;82.0]	63.8 (26.7)	73.2 (24.6)

Mental Health	77.5 [50.0;95.0]	90.0 [85.0;95.0]	80.0 [53.8;91.2]	90.0 [90.0;95.0]	80.0 [65.0;90.0]	85.0 [80.0;90.0]	65.0 [60.0;80.0]	90.0 [90.0;90.0]
Emotional role	87.5 [66.7;100]	100 [100;100]	87.5 [72.9;100]	100 [83.3;100]	83.3 [75.0;100]	100 [91.7;100]	91.7 [58.3;100]	100 [100;100]
Social Functioning	93.8 [71.9;100]	100 [87.5;100]	87.5 [71.9;100]	100 [75.0;100]	87.5 [75.0;100]	87.5 [87.5;100]	75.0 [50.0;100]	100 [87.5;100]
Vitality	68.8 [29.7;70.3]	75.0 [56.2;75.0]	65.6 [29.7;70.3]	68.8 [56.2;75.0]	57.7 (22.1)	65.4 (19.4)	47.1 (19.5)	66.8 (13.1)
Perceived listening	3.62 (1.91)	4.43 (1.39)	3.50 (1.96)	4.50 (1.46)	3.74 (1.70)	4.37 (1.10)	3.75 (1.94)	4.65 (1.14)
Communication Apprehension	67.9 (16.7)	63.4 (18.7)	67.9 (15.4)	64.5 (19.5)	67.8 (14.4)	65.2 (18.4)	65.0 (16.4)	63.7 (20.5)
Quality of life	79.7 (13.7)	90.1 (9.41)	78.7 (14.0)	90.8 (10.5)	81.8 (10.3)	90.7 (11.0)	80.5 (11.4)	88.8 (10.6)

Table 3. Performance during auditory and visual training programs presented separately according to each period the training was received (6 weeks of training)

		Period 1 (AT+VT)				***Period 2 (VT+AT)***		
		Initial consonants	Final consonants	Sentences		Initial consonants	Final consonants	Sentences
	N	Estimate (SE)	Estimate (SE)	Estimate (SE)	N	Estimate (SE)	Estimate (SE)	Estimate (SE)
Auditory Training (AT)	11				13			
(Intercept)		13.88 (0.98)***	13.50 (0.89)***	3.87 (1.40)*		12.66 (0.43)***	12.23 (0.81)***	2.74 (0.52)***
Session		-0.12 (0.05)*	-0.08 (0.07)	-0.02 (0.02)		-0.17 (0.05)**	-0.14 (0.03)***	-0.04 (0.02)
Onset HL (Prelingual)		4.38 (1.68)*	3.59 (1.55)	4.35 (2.32)		3.54 (1.35)**	6.47 (2.20)*	6.75 (1.33)***
Session x Onset HL (Prelingual)		-0.16 (0.09)	-0.05 (0.12)*	-0.11 (0.04)**		0.18 (0.14)	-0.02 (0.08)	-0.07 (0.06)
Visual Training (VT)	13				11			
(Intercept)		42.77 (1.66)***	41.95 (2.83)***	37.64 (1.95)***		44.14 (2.52)***	45.80 (2.33)***	35.82 (1.41)***
Session		-0.20 (0.06)**	-0.11 (0.10)	-0.15 (0.04)***		-0.30 (0.08)**	-0.35 (0.09)**	-0.07 (0.06)
Onset HL (Prelingual)		0.31 (5.96)	-3.34 (10.19)	-3.57 (7.02)		0.92 (4.20)	-5.01 (3.88)	2.49 (2.36)
Session x Onset HL (Prelingual)		-0.30 (0.20)	0.09 (0.37)	-0.01 (0.14)		-0.03 (0.13)	0.23 (0.16)	-0.09 (0.10)

Table 4 . Performance during auditory and visual training programs presented separately according to each period the training was received (without first week of training)

		Period 1				*Period 2*		
		Initial consonants	Final consonants	Sentences		Initial consonants	Final consonants	Sentences
	N	Estimate (SE)	Estimate (SE)	Estimate (SE)	N	Estimate (SE)	Estimate (SE)	Estimate (SE)
Auditory Training (AT)	11				13			
(Intercept)		13.88 (0.98)***	13.50 (0.89)***	3.87 (1.40)*		12.66 (0.43)***	12.23 (0.81)***	2.74 (0.52)***
Session		-0.12 (0.05)*	-0.08 (0.07)	-0.02 (0.02)		-0.17 (0.05)**	-0.14 (0.03)***	-0.04 (0.02)
Onset HL (Prelingual)		4.38 (1.68)*	3.59 (1.55)	4.35 (2.32)		3.54 (1.35)**	6.47 (2.20)*	6.75 (1.33)***
Session x Onset HL (Prelingual)		-0.16 (0.09)	-0.05 (0.12)*	-0.11 (0.04)**		0.18 (0.14)	-0.02 (0.08)	-0.07 (0.06)
Visual Training (VT)	13				11			
(Intercept)		42.77 (1.66)***	41.95 (2.83)***	37.64 (1.95)***		44.14 (2.52)***	45.80 (2.33)***	35.82 (1.41)***
Session		-0.20 (0.06)**	-0.11 (0.10)	-0.15 (0.04)***		-0.30 (0.08)**	-0.35 (0.09)**	-0.07 (0.06)
Onset HL (Prelingual)		0.31 (5.96)	-3.34 (10.19)	-3.57 (7.02)		0.92 (4.20)	-5.01 (3.88)	2.49 (2.36)
Session x Onset HL (Prelingual)		-0.30 (0.20)	0.09 (0.37)	-0.01 (0.14)		-0.03 (0.13)	0.23 (0.16)	-0.09 (0.10)

Complete output of linear mixed models fitted for statistical analyses

On-task learning analysis

Formula: dependent variable ~ fixed factor 1* fixed factor 2+ fixed factor 3+ (random slope | random factor)

Auditory training

initial_consonant_noise_level_finished = session final SNR in initial consonant module
final_consonant_noise_level_finished = session final SNR in final consonant module
sentences_noise_level_finished = session final SNR in final consonant module
session = session day
onset_cat = onset of hearing loss (Prelingual, Postlingual)
ID = participant
LogsAT = data frame containing six weeks of training
LogAT.red = data frame excluding first week of training
LogsAT_arm_1 = data frame with auditory training data for AT+VT participants
LogsAT_arm_2 = data frame with auditory training data for VT+AT participants

Initial consonants module (AT)

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: initial_consonant_noise_level_finished ~ session * onset_cat +
##     order + (session | ID)
##    Data: LogsAT
##
## REML criterion at convergence: 3479.4
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.6696 -0.6917 -0.0116  0.6187  2.7186
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept)  5.32196 2.307
##           session      0.01123 0.106    0.36
##  Residual             11.78262 3.433
## Number of obs: 639, groups:  ID, 24
##
## Fixed effects:
##                            Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                13.92029    0.94572 20.04551  14.719 3.29e-12
## session                    -0.15945    0.03094 18.45219  -5.153 6.19e-05
## onset_catPrelingual         4.01838    1.35838 22.72396   2.958   0.0071
## orderB                     -1.09441    1.14636 20.33402  -0.955   0.3509
## session:onset_catPrelingual -0.02141    0.06631 23.70082  -0.323   0.7496
##
```

```
## (Intercept)                 ***
## session                     ***
## onset_catPrelingual         **
## orderB
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.011
## onst_ctPrln -0.494  0.007
## orderB      -0.744  0.001  0.246
## sssn:nst_cP  0.010 -0.467 -0.104 -0.008
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: initial_consonant_noise_level_finished ~ session * onset_cat +
##     order + (session | ID)
##    Data: LogsAT.red
##
## REML criterion at convergence: 3317.3
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.65285 -0.69744 -0.01334  0.62156  2.69950
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept)  6.99825 2.6454
##           session      0.01208 0.1099   0.12
##  Residual             11.90384 3.4502
## Number of obs: 607, groups:  ID, 24
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                 13.73082    1.05314 18.54985  13.038 8.74e-11
## session                     -0.14888    0.03241 18.13159  -4.594 0.000222
## onset_catPrelingual          3.99840    1.56482 22.21671   2.555 0.017967
## orderB                      -1.15501    1.27029 19.31475  -0.909 0.374427
## session:onset_catPrelingual -0.01925    0.07221 25.97050  -0.267 0.791933
##
## (Intercept)                 ***
## session                     ***
## onset_catPrelingual         *
## orderB
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.118
## onst_ctPrln -0.460  0.082
## orderB      -0.734 -0.008  0.203
## sssn:nst_cP  0.036 -0.449 -0.290  0.027
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: initial_consonant_noise_level_finished ~ session * onset_cat +
##     (session | ID)
##    Data: LogsAT_arm_1
##
## REML criterion at convergence: 1533.1
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.69182 -0.67904 -0.02887  0.62039  2.75711
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept)  4.97378 2.2302
##           session      0.01238 0.1113   0.74
##  Residual             11.43070 3.3809
## Number of obs: 283, groups:  ID, 11
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                 13.88544    0.98696  7.98772  14.069 6.42e-07
## session                     -0.12177    0.05078  7.04222  -2.398   0.0474
## onset_catPrelingual          4.37674    1.68251  8.87599   2.601   0.0290
## session:onset_catPrelingual -0.16226    0.08917  8.64978  -1.820   0.1035
##
## (Intercept)                 ***
## session                     *
## onset_catPrelingual         *
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session      0.268
## onst_ctPrln -0.587 -0.157
## sssn:nst_cP -0.153 -0.570  0.178
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: initial_consonant_noise_level_finished ~ session * onset_cat +
##     (session | ID)
##    Data: LogsAT_arm_2
##
## REML criterion at convergence: 1963.9
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.65705 -0.64976 -0.05907  0.68514  2.33612
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept)  0.00000 0.0000
##           session      0.02597 0.1612    NaN
##  Residual             13.11759 3.6218
## Number of obs: 356, groups:  ID, 13
```

```
##
## Fixed effects:
##                              Estimate Std. Error        df t value
## (Intercept)                  12.66698    0.42811 341.06084  29.588
## session                      -0.17476    0.05452  14.50650  -3.205
## onset_catPrelingual           3.54456    1.35719 342.00167   2.612
## session:onset_catPrelingual   0.18399    0.14532  17.27082   1.266
##                             Pr(>|t|)
## (Intercept)                  < 2e-16 ***
## session                      0.00611 **
## onset_catPrelingual          0.00941 **
## session:onset_catPrelingual  0.22230
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.397
## onst_ctPrln -0.315  0.125
## sssn:nst_cP  0.149 -0.375 -0.473
## convergence code: 0
## unable to evaluate scaled gradient
## Model failed to converge: degenerate  Hessian with 1 negative eigenvalues
```

Final consonants module (AT)

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: final_consonant_noise_level_finished ~ session * onset_cat +
##     order + (session | ID)
##    Data: LogsAT
##
## REML criterion at convergence: 3646.9
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -3.04274 -0.61476  0.00534  0.66161  2.83646
##
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
##  ID       (Intercept)  4.506166 2.12277
##           session      0.009857 0.09928  0.10
##  Residual             14.571409 3.81725
## Number of obs: 647, groups:  ID, 24
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                 13.27998    0.89265 21.89428  14.877 6.29e-13
## session                     -0.11597    0.03073 18.03086  -3.773  0.00139
## onset_catPrelingual          4.53657    1.32411 25.10522   3.426  0.00212
## orderB                      -0.92834    1.06312 21.45467  -0.873  0.39221
## session:onset_catPrelingual -0.01245    0.06737 24.81814  -0.185  0.85486
##
## (Intercept)                 ***
## session                     **
## onset_catPrelingual         **
```

```
## orderB
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.181
## onst_ctPrln -0.483  0.121
## orderB      -0.731  0.002  0.232
## sssn:nst_cP  0.087 -0.456 -0.339 -0.007
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: final_consonant_noise_level_finished ~ session * onset_cat +
##     order + (session | ID)
##    Data: LogsAT.red
##
## REML criterion at convergence: 3476.1
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.77348 -0.62669  0.01395  0.66102  2.80763
##
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
##  ID       (Intercept)  6.921667 2.63091
##           session      0.006065 0.07788  -0.07
##  Residual             14.647094 3.82715
## Number of obs: 616, groups:  ID, 24
##
## Fixed effects:
##                               Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                   13.47025    1.03316 20.42547  13.038  2.3e-11
## session                       -0.11937    0.02800 20.79037  -4.263 0.000353
## onset_catPrelingual            3.66845    1.59166 21.98801   2.305 0.030998
## orderB                        -1.10987    1.20476 20.38194  -0.921 0.367702
## session:onset_catPrelingual    0.03257    0.06542 32.36685   0.498 0.621971
##
## (Intercept)                   ***
## session                       ***
## onset_catPrelingual           *
## orderB
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.269
## onst_ctPrln -0.460  0.176
## orderB      -0.711 -0.003  0.196
## sssn:nst_cP  0.104 -0.428 -0.472  0.016
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: final_consonant_noise_level_finished ~ session * onset_cat +
##     (session | ID)
```

```
##    Data: LogsAT_arm_1
##
## REML criterion at convergence: 1629.6
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.89249 -0.64069  0.06523  0.66242  2.76599
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept)  3.14991 1.7748
##           session      0.02676 0.1636   0.19
##  Residual             15.57951 3.9471
## Number of obs: 285, groups:  ID, 11
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                 13.50403    0.88771  8.29143  15.212 2.39e-07
## session                     -0.08049    0.06987  6.81731  -1.152   0.2882
## onset_catPrelingual          3.59443    1.55432 10.27912   2.313   0.0427
## session:onset_catPrelingual -0.05460    0.12183  8.17746  -0.448   0.6657
##
## (Intercept)                 ***
## session
## onset_catPrelingual         *
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.142
## onst_ctPrln -0.571  0.081
## sssn:nst_cP  0.082 -0.574 -0.217
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: final_consonant_noise_level_finished ~ session * onset_cat +
##     (session | ID)
##    Data: LogsAT_arm_2
##
## REML criterion at convergence: 2010.5
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.84671 -0.65090 -0.02262  0.66315  2.51529
##
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
##  ID       (Intercept)  5.219703 2.28467
##           session      0.002056 0.04534  -0.24
##  Residual             13.732520 3.70574
## Number of obs: 362, groups:  ID, 13
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                 12.23094    0.81091 10.92932  15.083 1.16e-08
```

```
## session                       -0.14060    0.02839 11.29783  -4.953   0.0004
## onset_catPrelingual            6.47210    2.20631 14.02303   2.933   0.0109
## session:onset_catPrelingual -0.01924    0.08419 19.07497  -0.229   0.8217
##
## (Intercept)                 ***
## session                     ***
## onset_catPrelingual         *
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.504
## onst_ctPrln -0.368  0.185
## sssn:nst_cP  0.170 -0.337 -0.572
```

Sentences module (AT)

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: sentences_noise_level_finished ~ session * onset_cat + order +
##     (session | ID)
##    Data: LogsAT
##
## REML criterion at convergence: 3400.5
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.7864 -0.7183  0.0285  0.7014  2.9010
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 6.565098 2.56224
##           session     0.001159 0.03404  0.80
##  Residual             6.943347 2.63502
## Number of obs: 693, groups:  ID, 24
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                  3.51122    0.95665 20.61476   3.670 0.001460
## session                     -0.03440    0.01570 19.83111  -2.191 0.040569
## onset_catPrelingual          5.31954    1.33783 20.92011   3.976 0.000692
## orderB                      -0.53676    1.15447 20.49020  -0.465 0.646876
## session:onset_catPrelingual -0.09580    0.03317 22.63638  -2.888 0.008387
##
## (Intercept)                 **
## session                     *
## onset_catPrelingual         ***
## orderB
## session:onset_catPrelingual **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
```

```
## session      0.083
## onst_ctPrln -0.503 -0.056
## orderB      -0.736 -0.011  0.238
## sssn:nst_cP -0.041 -0.473  0.080  0.008
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: sentences_noise_level_finished ~ session * onset_cat + order +
##     (session | ID)
##    Data: LogsAT.red
##
## REML criterion at convergence: 3223.7
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.7832 -0.7288  0.0207  0.6957  2.9029
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 6.828143 2.61307
##           session     0.001952 0.04418  0.48
##  Residual             6.812828 2.61014
## Number of obs: 658, groups:  ID, 24
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                  3.47039    0.98258 19.23471   3.532 0.002195
## session                     -0.03189    0.01755 20.37713  -1.818 0.083860
## onset_catPrelingual          5.37395    1.38466 20.20322   3.881 0.000915
## orderB                      -0.54345    1.19185 19.63003  -0.456 0.653413
## session:onset_catPrelingual -0.09820    0.03840 24.81222  -2.557 0.017052
##
## (Intercept)                 **
## session                     .
## onset_catPrelingual         ***
## orderB
## session:onset_catPrelingual *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session      0.008
## onst_ctPrln -0.486  0.000
## orderB      -0.736 -0.018  0.219
## sssn:nst_cP -0.026 -0.457 -0.062  0.039
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## sentences_noise_level_finished ~ session * onset_cat + (session |      ID)
##    Data: LogsAT_arm_1
##
## REML criterion at convergence: 1579.2
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
```

```
## -3.12649 -0.72731  0.01954  0.70090  2.93499
##
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
##  ID       (Intercept) 1.273e+01 3.56725
##           session     2.928e-04 0.01711  1.00
##  Residual             7.269e+00 2.69608
## Number of obs: 318, groups:  ID, 11
##
## Fixed effects:
##                              Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                   3.87323    1.40125  8.95797   2.764   0.0221
## session                      -0.02193    0.02245 39.59322  -0.977   0.3345
## onset_catPrelingual           4.35050    2.32774  9.02132   1.869   0.0944
## session:onset_catPrelingual -0.11497    0.04029 49.33411  -2.854   0.0063
##
## (Intercept)                 *
## session
## onset_catPrelingual         .
## session:onset_catPrelingual **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session      0.050
## onst_ctPrln -0.602 -0.030
## sssn:nst_cP -0.028 -0.557  0.024
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## sentences_noise_level_finished ~ session * onset_cat + (session |      ID)
##    Data: LogsAT_arm_2
##
## REML criterion at convergence: 1816.8
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.8041 -0.6664  0.0586  0.6810  2.5232
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 2.02742  1.42387
##           session     0.00396  0.06293  0.53
##  Residual             6.57910  2.56498
## Number of obs: 375, groups:  ID, 13
##
## Fixed effects:
##                              Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                   2.74361    0.52064 10.70603   5.270 0.000289
## session                      -0.04226    0.02560 10.55794  -1.651 0.128197
## onset_catPrelingual           6.75067    1.33379 10.90988   5.061 0.000375
## session:onset_catPrelingual -0.07212    0.06666 11.38856  -1.082 0.301686
##
## (Intercept)                 ***
```

```
## session
## onset_catPrelingual         ***
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.006
## onst_ctPrln -0.390  0.002
## sssn:nst_cP  0.002 -0.384 -0.026
```

Visual training

initial_consonant_noise_level_finished = session final TRT in initial consonant module

final_consonant_noise_level_finished = session final TRT in final consonant module

sentences_noise_level_finished = session final TRT in final consonant module

session = session day

onset_cat = onset of hearing loss (Prelingual, Postlingual)

ID = participant

LogsVT = data frame containing six weeks of training

LogVT.red = data frame excluding first week of training

LogsVT_arm_1 = data frame with auditory training data for VT+AT participants

LogsVT_arm_2 = data frame with auditory training data for AT+VT participants

Initial consonants module (VT)

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: initial_consonant_noise_level_finished ~ session * onset_cat +
##     order + (session | ID)
##    Data: LogsVT
##
## REML criterion at convergence: 4933.7
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.3481 -0.7166 -0.1183  0.6519  6.1254
##
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
##  ID       (Intercept) 26.086629 5.10751
##           session      0.004387 0.06624  -1.00
##  Residual             69.951162 8.36368
```

```
## Number of obs: 690, groups:  ID, 24
##
## Fixed effects:
##                              Estimate Std. Error        df t value
## (Intercept)                  43.25776    1.53600  26.46296  28.163
## session                      -0.23657    0.04498  86.02214  -5.259
## onset_catPrelingual           1.49357    3.13841  24.15170   0.476
## orderB                        0.04572    1.82570  21.64357   0.025
## session:onset_catPrelingual  -0.14681    0.10277 102.85404  -1.428
##                             Pr(>|t|)
## (Intercept)                  < 2e-16 ***
## session                     1.04e-06 ***
## onset_catPrelingual            0.638
## orderB                         0.980
## session:onset_catPrelingual    0.156
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.649
## onst_ctPrln -0.282  0.316
## orderB      -0.439  0.004 -0.257
## sssn:nst_cP  0.275 -0.438 -0.693  0.019
## convergence code: 0
## Model failed to converge with max|grad| = 0.00362795 (tol = 0.002, compone
nt 1)
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: initial_consonant_noise_level_finished ~ session * onset_cat +
##     order + (session | ID)
##    Data: LogsVT.red
##
## REML criterion at convergence: 4570.4
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.2283 -0.7672 -0.1362  0.6307  6.1569
##
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
##  ID       (Intercept) 26.646828 5.16206
##           session      0.005233 0.07234  -1.00
##  Residual             69.275770 8.32321
## Number of obs: 640, groups:  ID, 24
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                 42.63543    1.59293 28.74721  26.765  < 2e-16
## session                     -0.20491    0.04959 83.13247  -4.132 8.53e-05
## onset_catPrelingual          0.81438    3.29245 25.01032   0.247    0.807
## orderB                       0.04488    1.79346 21.59632   0.025    0.980
## session:onset_catPrelingual -0.11004    0.11321 97.92115  -0.972    0.333
##
## (Intercept)                 ***
```

```
## session                        ***
## onset_catPrelingual
## orderB
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.693
## onst_ctPrln -0.300  0.336
## orderB      -0.412 -0.002 -0.247
## sssn:nst_cP  0.293 -0.438 -0.738  0.027

## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: initial_consonant_noise_level_finished ~ session * onset_cat +
##     (session | ID)
##    Data: LogsVT_arm_1
##
## REML criterion at convergence: 2719.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.1695 -0.7103 -0.1407  0.5751  6.0375
##
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
##  ID       (Intercept) 22.578240 4.75166
##           session      0.004144 0.06438  -1.00
##  Residual             72.578432 8.51930
## Number of obs: 379, groups:  ID, 13
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                 42.76817    1.65919 11.71822  25.777  1.1e-11
## session                     -0.19803    0.05718 47.85752  -3.463  0.00114
## onset_catPrelingual          0.30769    5.95893 11.53271   0.052  0.95970
## session:onset_catPrelingual -0.29718    0.19927 41.80998  -1.491  0.14337
##
## (Intercept)                 ***
## session                     **
## onset_catPrelingual
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.733
## onst_ctPrln -0.278  0.204
## sssn:nst_cP  0.210 -0.287 -0.738

## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: initial_consonant_noise_level_finished ~ session * onset_cat +
##     (session | ID)
```

```
##    Data: LogsVT_arm_2
##
## REML criterion at convergence: 2209.2
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.37773 -0.70464 -0.08621  0.70281  3.08820
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 35.10128 5.92463
##           session      0.00789 0.08882  -1.00
##  Residual             66.49758 8.15460
## Number of obs: 311, groups:  ID, 11
##
## Fixed effects:
##                               Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                   44.14656    2.52790  9.23765  17.464 2.18e-08
## session                       -0.30311    0.07618 23.08027  -3.979  0.00059
## onset_catPrelingual            0.92410    4.20488  9.35457   0.220  0.83077
## session:onset_catPrelingual   -0.03676    0.13211 27.79335  -0.278  0.78288
##
## (Intercept)                   ***
## session                       ***
## onset_catPrelingual
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.754
## onst_ctPrln -0.601  0.453
## sssn:nst_cP  0.435 -0.577 -0.742
```

Final consonants module (VT)

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: final_consonant_noise_level_finished ~ session * onset_cat +
##     order + (session | ID)
##    Data: LogsVT.red
##
## REML criterion at convergence: 4651.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.7768 -0.7178 -0.1034  0.6399  6.1823
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 74.23488 8.6160
##           session      0.09699 0.3114   -0.84
##  Residual             75.15103 8.6690
## Number of obs: 640, groups:  ID, 24
##
```

```
## Fixed effects:
##                              Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)                   42.6580     2.3248 24.0697  18.349 1.18e-15
## session                       -0.1501     0.0873 20.9539  -1.719    0.100
## onset_catPrelingual           -4.4208     4.8726 21.3287  -0.907    0.374
## orderB                        -0.8518     2.2291 21.0479  -0.382    0.706
## session:onset_catPrelingual    0.1970     0.1951 22.4399   1.010    0.323
##
## (Intercept)                  ***
## session
## onset_catPrelingual
## orderB
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.790
## onst_ctPrln -0.345  0.375
## orderB      -0.356  0.004 -0.202
## sssn:nst_cP  0.349 -0.447 -0.824  0.010
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: final_consonant_noise_level_finished ~ session * onset_cat +
##     order + (session | ID)
##    Data: LogsVT.red
##
## REML criterion at convergence: 4651.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.7768 -0.7178 -0.1034  0.6399  6.1823
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 74.23488 8.6160
##           session      0.09699 0.3114   -0.84
##  Residual             75.15103 8.6690
## Number of obs: 640, groups:  ID, 24
##
## Fixed effects:
##                              Estimate Std. Error      df t value Pr(>|t|)
## (Intercept)                   42.6580     2.3248 24.0697  18.349 1.18e-15
## session                       -0.1501     0.0873 20.9539  -1.719    0.100
## onset_catPrelingual           -4.4208     4.8726 21.3287  -0.907    0.374
## orderB                        -0.8518     2.2291 21.0479  -0.382    0.706
## session:onset_catPrelingual    0.1970     0.1951 22.4399   1.010    0.323
##
## (Intercept)                  ***
## session
## onset_catPrelingual
## orderB
## session:onset_catPrelingual
## ---
```

```
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.790
## onst_ctPrln -0.345  0.375
## orderB      -0.356  0.004 -0.202
## sssn:nst_cP  0.349 -0.447 -0.824  0.010
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: final_consonant_noise_level_finished ~ session * onset_cat +
##     (session | ID)
##    Data: LogsVT_arm_1
##
## REML criterion at convergence: 2776.9
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.7246 -0.7233 -0.0564  0.6287  5.3744
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 84.6556  9.2008
##           session      0.0903  0.3005   -0.80
##  Residual             80.2736  8.9596
## Number of obs: 379, groups:  ID, 13
##
## Fixed effects:
##                            Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                41.94719    2.83247 11.01909  14.809 1.28e-08
## session                    -0.11038    0.10395 10.93296  -1.062    0.311
## onset_catPrelingual        -3.34029   10.19486 10.94336  -0.328    0.749
## session:onset_catPrelingual  0.09703    0.36989 10.41035   0.262    0.798
##
## (Intercept)                ***
## session
## onset_catPrelingual
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.797
## onst_ctPrln -0.278  0.221
## sssn:nst_cP  0.224 -0.281 -0.799
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: final_consonant_noise_level_finished ~ session * onset_cat +
##     (session | ID)
##    Data: LogsVT_arm_2
##
## REML criterion at convergence: 2269.6
##
## Scaled residuals:
```

```
##     Min      1Q  Median      3Q     Max
## -1.9655 -0.7427 -0.1011  0.6112  5.9955
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 26.18146 5.117
##           session      0.02371 0.154    -0.66
##  Residual             81.06478 9.004
## Number of obs: 311, groups:  ID, 11
##
## Fixed effects:
##                              Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                  45.80508    2.32888  8.68728  19.668 1.66e-08
## session                      -0.35185    0.09568  8.86912  -3.677  0.00523
## onset_catPrelingual          -5.01595    3.88128  8.86047  -1.292  0.22892
## session:onset_catPrelingual  0.23694    0.16503 10.09235   1.436  0.18134
##
## (Intercept)                  ***
## session                      **
## onset_catPrelingual
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.721
## onst_ctPrln -0.600  0.433
## sssn:nst_cP  0.418 -0.580 -0.718
```

Sentences module (VT)

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: sentences_noise_level_finished ~ session * onset_cat + order +
##     (session | ID)
##    Data: LogsVT
##
## REML criterion at convergence: 4525.7
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.9096 -0.6649 -0.1451  0.6085  3.3103
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 25.49823 5.04958
##           session      0.00142 0.03769  -1.00
##  Residual             37.73826 6.14315
## Number of obs: 690, groups:  ID, 24
##
## Fixed effects:
##                               Estimate Std. Error        df t value
## (Intercept)                   36.68741    1.46614  24.40627  25.023
## session                       -0.12420    0.03230 122.64925  -3.845
## onset_catPrelingual            0.21029    2.92950  22.62066   0.072
```

```
## orderB                        0.78133    1.95576  21.09199   0.400
## session:onset_catPrelingual  -0.04447    0.07405 146.91564  -0.600
##                             Pr(>|t|)
## (Intercept)                  < 2e-16 ***
## session                     0.000192 ***
## onset_catPrelingual         0.943405
## orderB                      0.693541
## session:onset_catPrelingual 0.549117
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.520
## onst_ctPrln -0.236  0.258
## orderB      -0.492  0.003 -0.292
## sssn:nst_cP  0.219 -0.436 -0.567  0.015
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: sentences_noise_level_finished ~ session * onset_cat + order +
##     (session | ID)
##    Data: LogsVT.red
##
## REML criterion at convergence: 4198.2
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.8401 -0.6639 -0.1600  0.5951  3.3017
##
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
##  ID       (Intercept) 22.704540 4.7649
##           session      0.001841 0.0429   -0.66
##  Residual             37.633970 6.1347
## Number of obs: 640, groups:  ID, 24
##
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                 36.57798    1.44659 22.15816  25.286  < 2e-16
## session                     -0.11498    0.03585 15.35064  -3.207  0.00574
## onset_catPrelingual          0.78809    2.88744 19.06535   0.273  0.78784
## orderB                       0.57122    1.94812 20.99631   0.293  0.77224
## session:onset_catPrelingual -0.06862    0.08225 17.31949  -0.834  0.41545
##
## (Intercept)                 ***
## session                     **
## onset_catPrelingual
## orderB
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P orderB
## session     -0.506
```

```
## onst_ctPrln -0.231  0.253
## orderB      -0.496  0.002 -0.295
## sssn:nst_cP  0.214 -0.436 -0.557  0.013

## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: 
## sentences_noise_level_finished ~ session * onset_cat + (session |      ID)
##    Data: LogsVT_arm_1
## 
## REML criterion at convergence: 2473.1
## 
## Scaled residuals: 
##     Min      1Q  Median      3Q     Max 
## -3.0743 -0.6062 -0.1603  0.5961  2.9521 
## 
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr 
##  ID       (Intercept) 40.463335 6.36108       
##           session      0.002681 0.05178  -1.00
##  Residual             36.202975 6.01689       
## Number of obs: 379, groups:  ID, 13
## 
## Fixed effects:
##                             Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                 37.63958    1.95111 11.10391  19.291 6.85e-10
## session                     -0.15408    0.04104 40.85530  -3.754 0.000542
## onset_catPrelingual         -3.57062    7.02473 11.03988  -0.508 0.621251
## session:onset_catPrelingual -0.01811    0.14309 35.88346  -0.127 0.900009
##                                
## (Intercept)                 ***
## session                     ***
## onset_catPrelingual            
## session:onset_catPrelingual    
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
## 
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.617              
## onst_ctPrln -0.278  0.171       
## sssn:nst_cP  0.177 -0.287 -0.625

## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: 
## sentences_noise_level_finished ~ session * onset_cat + (session |      ID)
##    Data: LogsVT_arm_2
## 
## REML criterion at convergence: 2045.7
## 
## Scaled residuals: 
##     Min      1Q  Median      3Q     Max 
## -1.8003 -0.7396 -0.0857  0.6113  3.2574 
## 
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
```

```
##  ID       (Intercept)  8.253327 2.87286
##           session      0.002848 0.05337  -0.46
##  Residual             39.550983 6.28896
## Number of obs: 311, groups:  ID, 11
##
## Fixed effects:
##                               Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)                   35.82044    1.41381  8.46120  25.336 2.82e-09
## session                       -0.07119    0.05661  7.78319  -1.258    0.245
## onset_catPrelingual            2.48897    2.35917  8.66918   1.055    0.320
## session:onset_catPrelingual -0.08882    0.09879  9.11612  -0.899    0.392
##
## (Intercept)                   ***
## session
## onset_catPrelingual
## session:onset_catPrelingual
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Correlation of Fixed Effects:
##             (Intr) sessin onst_P
## session     -0.647
## onst_ctPrln -0.599  0.388
## sssn:nst_cP  0.371 -0.573 -0.648
```

Outcome measures

`Formula: dependent variable ~ fixed factor (…) + fixed factor * fixed factor + (random slope| random factor)`

`onset_cat = onset of hearing loss (Prelingual, postlingual)`

`Training_order = Training allocation order (AT+VT, VT+AT)`

`session_amount = amount of training sessions completed`

`Time = timepoint (T1, T2, T3, T4)`

`WM_perc = percentage score in reading span test (i.e. working memory)`

`dur_deaf_less_dep_ear = duration of deafness`

`exp_latest_CI = cochlear implant experience`

`Training = Auditory training or Visual training`

`ID = Participant`

BKB easier condition

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## BKB_Easier_avg_perc ~ Age + onset_cat + Training_order + session_amount *
##     Time + WM_perc * Time + dur_deaf_less_dep_ear + exp_latest_CI +
```

```
##     Training * Time + (Time | ID)
##    Data: dados.longo.merge
## 
## REML criterion at convergence: 1396.3
## 
## Scaled residuals: 
##     Min      1Q  Median      3Q     Max 
## -3.0975 -0.2949  0.1421  0.5251  2.7083 
## 
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr             
##  ID       (Intercept) 295.753  17.197                    
##           Time1        21.564   4.644   -0.33            
##           Time3         7.707   2.776   -0.58 -0.58      
##           Time4        27.329   5.228   -0.87  0.74  0.11
##  Residual             127.546  11.294                    
## Number of obs: 179, groups:  ID, 25
## 
## Fixed effects:
##                          Estimate Std. Error        df t value Pr(>|t|)   
## (Intercept)              69.89692   25.82183  64.73842   2.707  0.00868 **
## Age                      -0.23277    0.30246  22.28774  -0.770  0.44962   
## onset_catPrelingual      -5.54521   10.39001  19.98711  -0.534  0.59943   
## Training_orderVT + AT     8.22987    6.75095  19.86754   1.219  0.23710   
## session_amount            0.23416    0.40821 111.32150   0.574  0.56737   
## Time1                    13.80319   19.88390  77.39315   0.694  0.48964   
## Time3                    15.74298   19.61497 106.64994   0.803  0.42399   
## Time4                     4.30001   20.26954 103.72397   0.212  0.83241   
## WM_perc                   0.11449    0.15284  83.03256   0.749  0.45594   
## dur_deaf_less_dep_ear    -0.24711    0.17106  20.85360  -1.445  0.16342   
## exp_latest_CI             1.43576    0.68104  22.42974   2.108  0.04641 * 
## TrainingVT               -2.19808    3.50079 120.42544  -0.628  0.53127   
## session_amount:Time1     -0.53301    0.50259  80.85926  -1.061  0.29206   
## session_amount:Time3     -0.49250    0.49252 105.21783  -1.000  0.31962   
## session_amount:Time4     -0.18077    0.50099 105.13051  -0.361  0.71895   
## Time1:WM_perc             0.02523    0.16062  56.46778   0.157  0.87575   
## Time3:WM_perc            -0.01349    0.14986  97.99439  -0.090  0.92848   
## Time4:WM_perc             0.04453    0.16260  80.69529   0.274  0.78489   
## Time1:TrainingVT         -0.99429    4.87955 123.70718  -0.204  0.83887   
## Time3:TrainingVT          2.56946    4.84470 120.34289   0.530  0.59684   
## Time4:TrainingVT          1.46288    4.87295 121.45669   0.300  0.76453   
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

## [1] 1460.339
```

BKB easier condition

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: 
## BKB_harder_avg_perc ~ Age + onset_cat + Training_order + session_amount *  
##     Time + WM_perc * Time + dur_deaf_less_dep_ear + exp_latest_CI +  
```

```
##     Training * Time + (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1439
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.1722 -0.4860 -0.0526  0.4673  3.6028
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 464.68   21.556
##           Time1        60.17    7.757   -0.30
##           Time3        11.33    3.367   -0.37 -0.78
##           Time4        25.51    5.050   -0.26  1.00 -0.80
##  Residual             145.29   12.054
## Number of obs: 180, groups:  ID, 25
##
## Fixed effects:
##                          Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)             42.931489  32.232162  45.095160   1.332   0.1896
## Age                      0.004228   0.415597  20.872438   0.010   0.9920
## onset_catPrelingual     -0.595963  14.416212  19.115918  -0.041   0.9675
## Training_orderVT + AT   -3.113349   9.362830  18.958350  -0.333   0.7431
## session_amount          -0.320947   0.434625 113.976085  -0.738   0.4618
## Time1                  -33.628296  22.073121  84.258094  -1.523   0.1314
## Time3                   -4.829382  20.958500 111.283555  -0.230   0.8182
## Time4                   12.889232  21.692375  97.998289   0.594   0.5538
## WM_perc                 -0.026632   0.162827  93.119699  -0.164   0.8704
## dur_deaf_less_dep_ear   -0.179650   0.235105  19.448783  -0.764   0.4540
## exp_latest_CI            1.860288   0.926747  20.357481   2.007   0.0582 .
## TrainingVT              -6.915148   3.734839 118.836344  -1.852   0.0666 .
## session_amount:Time1     0.316810   0.557889  90.241128   0.568   0.5715
## session_amount:Time3     0.093295   0.527024 110.131477   0.177   0.8598
## session_amount:Time4    -0.390664   0.537563  97.502804  -0.727   0.4691
## Time1:WM_perc            0.292994   0.179531  58.548489   1.632   0.1080
## Time3:WM_perc           -0.008771   0.159491 106.165169  -0.055   0.9562
## Time4:WM_perc            0.104796   0.173218  77.767638   0.605   0.5469
## Time1:TrainingVT         9.145645   5.206456 123.305705   1.757   0.0815 .
## Time3:TrainingVT         6.716583   5.173736 118.572646   1.298   0.1967
## Time4:TrainingVT        -3.903166   5.203086 119.624792  -0.750   0.4546
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

##
```

BKB analysis by SNR

`BKB_score_10 = BKB sentences tested at 10dB SNR`

`BKB_score_20 = BKB sentences tested at 20dB SNR`

`BKB_score_0 = BKB sentences tested at 0dB SNR`

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## BKB_score_10 ~ Age + onset_cat + Training_order + session_amount *
##     Time + WM_perc * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     Training * Time + (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1441.5
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -3.15818 -0.47257  0.00873  0.51983  2.74107
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 459.98   21.447
##           Time1        74.97    8.658   -0.25
##           Time3        20.81    4.562   -0.22 -0.89
##           Time4        34.92    5.909   -0.70  0.87 -0.55
##  Residual             145.25   12.052
## Number of obs: 180, groups:  ID, 25
##
## Fixed effects:
##                         Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)             41.77585   30.85590  47.83963   1.354   0.1821
## Age                      0.25065    0.38994  20.37841   0.643   0.5275
## onset_catPrelingual    -20.54319   13.52552  18.61898  -1.519   0.1456
## Training_orderVT + AT   12.92474    8.79279  18.52431   1.470   0.1584
## session_amount          -0.25720    0.43608 111.80607  -0.590   0.5565
## Time1                  -25.48678   22.32191  82.40685  -1.142   0.2569
## Time3                   -2.96527   21.20584 105.39252  -0.140   0.8891
## Time4                   -3.20146   21.72494 104.31383  -0.147   0.8831
## WM_perc                  0.05017    0.16488  90.01591   0.304   0.7616
## dur_deaf_less_dep_ear   -0.21000    0.22159  19.21290  -0.948   0.3550
## exp_latest_CI            2.00858    0.87547  20.27761   2.294   0.0326 *
## TrainingVT              -3.10317    3.73660 118.42704  -0.830   0.4079
## session_amount:Time1     0.20617    0.56356  88.66236   0.366   0.7154
## session_amount:Time3     0.10368    0.53294 105.28992   0.195   0.8461
## session_amount:Time4    -0.05911    0.53734 105.29600  -0.110   0.9126
## Time1:WM_perc            0.25803    0.18270  57.05479   1.412   0.1633
## Time3:WM_perc           -0.04051    0.16179  95.27278  -0.250   0.8028
## Time4:WM_perc            0.17186    0.17468  83.36696   0.984   0.3280
## Time1:TrainingVT         5.07929    5.21287 122.11563   0.974   0.3318
## Time3:TrainingVT         6.54243    5.18195 119.09449   1.263   0.2092
## Time4:TrainingVT        -3.26613    5.20349 119.04594  -0.628   0.5314
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## BKB_score_20 ~ Age + onset_cat + Training_order + session_amount *
##     Time + WM_perc * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     Training * Time + (Time | ID)
##    Data: dados.longo.merge
```

```
##
## REML criterion at convergence: 685.2
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.50230 -0.41554  0.09016  0.48753  2.37857
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 205.870  14.348
##           Time1         5.891   2.427   -0.81
##           Time3        17.028   4.126   -0.28  0.79
##           Time4         6.943   2.635   -0.68  0.98  0.89
##  Residual              66.140   8.133
## Number of obs: 99, groups:  ID, 15
##
## Fixed effects:
##                       Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)           30.74364   28.80889 30.28712   1.067    0.294
## Age                   -0.12344    0.35584  9.80392  -0.347    0.736
## onset_catPrelingual    2.87306   10.43333  9.28896   0.275    0.789
## Training_orderVT + AT  4.15496    8.66948  9.33868   0.479    0.643
## session_amount         0.33715    0.51907 58.34225   0.650    0.519
## Time1                 15.83589   22.39465 51.93152   0.707    0.483
## Time3                  6.23187   23.74774 27.35996   0.262    0.795
## Time4                  9.46244   23.96629 60.00921   0.395    0.694
## WM_perc                0.01003    0.17163 37.66721   0.058    0.954
## dur_deaf_less_dep_ear -0.31617    0.19510  9.75634  -1.621    0.137
## exp_latest_CI          1.01064    0.69776 10.04408   1.448    0.178
## TrainingVT            -5.31857    3.61636 65.24845  -1.471    0.146
## session_amount:Time1  -0.60340    0.55088 48.41080  -1.095    0.279
## session_amount:Time3  -0.48540    0.58662 23.79244  -0.827    0.416
## session_amount:Time4  -0.40812    0.57218 53.99380  -0.713    0.479
## Time1:WM_perc          0.04295    0.20562 50.88568   0.209    0.835
## Time3:WM_perc          0.11363    0.19801 23.53482   0.574    0.572
## Time4:WM_perc          0.03829    0.20542 53.12003   0.186    0.853
## Time1:TrainingVT      -1.08919    4.94441 61.95824  -0.220    0.826
## Time3:TrainingVT       6.72468    4.86722 68.62753   1.382    0.172
## Time4:TrainingVT       6.43679    4.86576 62.98574   1.323    0.191
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: BKB_score_0 ~ Age + Training_order + session_amount * Time +
##     WM_perc * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     Training * Time + (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 525.3
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.9883 -0.4715  0.1093  0.5243  1.5581
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 136.760  11.694
```

```
##           Time1        54.177   7.360   -0.84
##           Time3         5.956   2.440   -0.48  0.05
##           Time4        40.136   6.335   -0.84  0.77  0.01
##  Residual             50.485   7.105
## Number of obs: 79, groups:  ID, 11
##
## Fixed effects:
##                        Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)           140.85984   51.96105   9.98036   2.711   0.0219 *
## Age                    -1.51079    0.60572   7.87795  -2.494   0.0377 *
## Training_orderVT + AT  11.55901    5.15558   5.91173   2.242   0.0668 .
## session_amount         -0.18136    0.33657  34.56130  -0.539   0.5935
## Time1                 -23.84068   19.60914  30.24985  -1.216   0.2335
## Time3                  -1.01727   17.71818  32.59722  -0.057   0.9546
## Time4                   0.54809   19.50128  31.26739   0.028   0.9778
## WM_perc                -0.11924    0.18264  36.64933  -0.653   0.5179
## dur_deaf_less_dep_ear   0.08903    0.16192   6.65618   0.550   0.6004
## exp_latest_CI          -3.72491    2.32588   5.68086  -1.602   0.1631
## TrainingVT             -2.36486    3.27165  34.13745  -0.723   0.4747
## session_amount:Time1    0.19939    0.44048  36.17005   0.453   0.6535
## session_amount:Time3   -0.14147    0.41312  34.47495  -0.342   0.7341
## session_amount:Time4   -0.15224    0.43214  37.50472  -0.352   0.7266
## Time1:WM_perc           0.26816    0.17495  18.04674   1.533   0.1427
## Time3:WM_perc           0.13921    0.14483  25.18920   0.961   0.3456
## Time4:WM_perc           0.13625    0.17338  17.10148   0.786   0.4427
## Time1:TrainingVT       -0.68073    4.66564  36.39117  -0.146   0.8848
## Time3:TrainingVT       -2.93315    4.55484  34.14636  -0.644   0.5239
## Time4:TrainingVT       -3.88477    4.70209  37.02019  -0.826   0.4140
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

CNC words

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: CNC_perc_words ~ Age + onset_cat + Training_order + Training *
##     Time + WM_perc * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     Time * Training + (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1374.6
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.0930 -0.4471  0.0531  0.4955  3.4703
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 307.813  17.545
##           Time1        40.743   6.383   0.38
##           Time3         9.845   3.138   0.67 0.94
##           Time4        23.972   4.896   0.31 1.00 0.91
##  Residual             96.197   9.808
## Number of obs: 180, groups:  ID, 25
```

```
##
## Fixed effects:
##                         Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)             6.217343  25.761360  26.351638   0.241   0.8112
## Age                     0.309035   0.375866  19.770150   0.822   0.4208
## onset_catPrelingual   -22.943229  13.054586  18.135542  -1.757   0.0957 .
## Training_orderVT + AT  10.140682   8.515697  18.284394   1.191   0.2490
## TrainingVT              4.693865   2.977756 127.942387   1.576   0.1174
## Time1                  -6.196312   8.068644  41.296979  -0.768   0.4469
## Time3                  -1.091644   7.436715  91.986874  -0.147   0.8836
## Time4                   2.215273   8.069750  57.059653   0.275   0.7847
## WM_perc                 0.169366   0.128349  60.623565   1.320   0.1919
## dur_deaf_less_dep_ear  -0.119840   0.212144  18.242050  -0.565   0.5790
## exp_latest_CI           1.694120   0.843555  19.627912   2.008   0.0586 .
## TrainingVT:Time1       -3.824913   4.174204 131.769387  -0.916   0.3612
## TrainingVT:Time3       -7.790917   4.158210 122.983096  -1.874   0.0634 .
## TrainingVT:Time4       -4.194681   4.190429 127.438183  -1.001   0.3187
## Time1:WM_perc           0.077438   0.141087  39.290699   0.549   0.5862
## Time3:WM_perc           0.132518   0.125909  86.634246   1.052   0.2955
## Time4:WM_perc          -0.006518   0.137450  54.297505  -0.047   0.9623
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Spectral resolution

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: ripplesperoctave ~ Age + onset_cat + Training_order + Training *
##     Time * time_t4 + dur_deaf_less_dep_ear + exp_latest_CI +
##     (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 479.6
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.5762 -0.5975 -0.1122  0.4839  2.9909
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 1.34154  1.1582
##           Time1       0.03089  0.1758   -0.83
##           Time3       0.09034  0.3006   -0.46  0.88
##           Time4       0.03454  0.1859    0.42  0.17  0.61
##  Residual             0.47344  0.6881
## Number of obs: 186, groups:  ID, 26
##
## Fixed effects:
##                                   Estimate Std. Error         df t value
## (Intercept)                       2.931378   1.450124  21.212824   2.021
## Age                               0.002788   0.021080  19.950986   0.132
## onset_catPrelingual               0.413767   0.759123  20.253562   0.545
## Training_orderVT + AT             0.102899   0.482594  20.050427   0.213
## TrainingVT                       -0.461097   0.284454 128.544212  -1.621
```

```
## Time1                               -0.373127   0.285281 119.105392  -1.308
## Time3                                0.125238   0.293832  67.084875   0.426
## Time4                               -0.272513   0.293312 109.955705  -0.929
## time_t41 month                      -0.951380   0.569037  27.865287  -1.672
## dur_deaf_less_dep_ear               -0.017352   0.012570  20.517393  -1.380
## exp_latest_CI                       -0.059111   0.049926  21.445048  -1.184
## TrainingVT:Time1                     0.221738   0.402841 125.533124   0.550
## TrainingVT:Time3                    -0.234746   0.398622 133.142729  -0.589
## TrainingVT:Time4                     0.454661   0.403138 126.822808   1.128
## TrainingVT:time_t41 month            0.561205   0.408335 129.915083   1.374
## Time1:time_t41 month                 0.441456   0.403481 118.954283   1.094
## Time3:time_t41 month                 0.085525   0.415561  67.071565   0.206
## Time4:time_t41 month                 0.292914   0.409598 108.784050   0.715
## TrainingVT:Time1:time_t41 month     -0.620336   0.572403 125.886791  -1.084
## TrainingVT:Time3:time_t41 month      0.021983   0.570621 135.473644   0.039
## TrainingVT:Time4:time_t41 month     -0.503405   0.572786 127.495927  -0.879
##                                    Pr(>|t|)
## (Intercept)                           0.056 .
## Age                                   0.896
## onset_catPrelingual                   0.592
## Training_orderVT + AT                 0.833
## TrainingVT                            0.107
## Time1                                 0.193
## Time3                                 0.671
## Time4                                 0.355
## time_t41 month                        0.106
## dur_deaf_less_dep_ear                 0.182
## exp_latest_CI                         0.249
## TrainingVT:Time1                      0.583
## TrainingVT:Time3                      0.557
## TrainingVT:Time4                      0.262
## TrainingVT:time_t41 month             0.172
## Time1:time_t41 month                  0.276
## Time3:time_t41 month                  0.838
## Time4:time_t41 month                  0.476
## TrainingVT:Time1:time_t41 month       0.281
## TrainingVT:Time3:time_t41 month       0.969
## TrainingVT:Time4:time_t41 month       0.381
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Cognitive abilities

Visual attention

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: VT_Avg_RT ~ Age + onset_cat + Training_order + Training * Time +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1667.6
##
```

```
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.20988 -0.67923 -0.05555  0.59042  2.57828
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 2412.3   49.12
##           Time1        171.8   13.11    -0.97
##           Time3        114.6   10.71    -0.55  0.34
##           Time4        170.8   13.07    -0.96  1.00  0.30
##  Residual              514.9   22.69
## Number of obs: 183, groups:  ID, 26
##
## Fixed effects:
##                         Estimate Std. Error       df t value Pr(>|t|)
## (Intercept)             507.4651    51.9919  39.6908   9.760  4.2e-12 ***
## Age                       0.5160     0.7002  21.7595   0.737   0.4690
## onset_catPrelingual     -21.4292    25.1762  21.9176  -0.851   0.4039
## Training_orderVT + AT  -17.1134    16.1583  22.1553  -1.059   0.3010
## TrainingVT              -15.2950     6.9827 125.1880  -2.190   0.0303 *
## Time1                   -45.5833    31.0405 118.7217  -1.469   0.1446
## Time3                   -30.4693    31.4030  90.3869  -0.970   0.3345
## Time4                   -53.1776    31.1285 118.3462  -1.708   0.0902 .
## session_amount           -1.0876     0.8187 120.7904  -1.328   0.1865
## dur_deaf_less_dep_ear    0.1457     0.4157  23.1673   0.351   0.7291
## exp_latest_CI            0.9879     1.6535  24.3001   0.597   0.5557
## TrainingVT:Time1         11.3971     9.7164 125.6941   1.173   0.2430
## TrainingVT:Time3          9.4599     9.5950 129.5386   0.986   0.3260
## TrainingVT:Time4         16.8826     9.6943 125.0865   1.741   0.0841 .
## Time1:session_amount      1.5196     0.9672 119.2457   1.571   0.1188
## Time3:session_amount      1.0249     0.9820  89.6646   1.044   0.2994
## Time4:session_amount      1.6714     0.9714 118.8970   1.721   0.0879 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Auditory attention

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: AT_Avg_RT ~ Age + onset_cat + Training_order + Training * Time +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1835.8
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.5652 -0.4982 -0.0351  0.5857  2.6121
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 2528.0   50.28
##           Time1        220.2   14.84    -0.39
```

```
##           Time3        101.8   10.09    -0.30  0.99
##           Time4        305.7   17.49    -0.43  1.00  0.99
##  Residual             1609.3   40.12
## Number of obs: 183, groups:  ID, 26
##
## Fixed effects:
##                         Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)            677.49301   73.56430  40.70300   9.210 1.66e-11 ***
## Age                      0.05616    0.95279  19.85419   0.059   0.9536
## onset_catPrelingual     -4.20669   34.20434  19.91178  -0.123   0.9034
## Training_orderVT + AT  -15.40433   21.88591  20.00811  -0.704   0.4896
## TrainingVT             -24.49236   12.29546 134.88746  -1.992   0.0484 *
## Time1                   69.47928   55.03802  86.96739   1.262   0.2102
## Time3                  -60.81851   53.95311  97.45075  -1.127   0.2624
## Time4                  -64.09836   55.82576  67.02436  -1.148   0.2550
## session_amount          -0.82895    1.40909 108.66320  -0.588   0.5576
## dur_deaf_less_dep_ear    1.37861    0.55863  20.79029   2.468   0.0224 *
## exp_latest_CI            0.02712    2.19971  21.58365   0.012   0.9903
## TrainingVT:Time1        34.53797   17.17452 132.54138   2.011   0.0464 *
## TrainingVT:Time3        34.94028   16.90043 126.72059   2.067   0.0407 *
## TrainingVT:Time4        39.65855   17.18220 138.08811   2.308   0.0225 *
## Time1:session_amount    -2.42314    1.71991  85.57608  -1.409   0.1625
## Time3:session_amount     1.36461    1.68754  96.48250   0.809   0.4207
## Time4:session_amount     1.56897    1.74700  66.03082   0.898   0.3724
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Stroop sustained attention/inhibition control

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: StroopCperW_time ~ Age + onset_cat + Training_order + Training *
##     Time + session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 114.1
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -1.8433 -0.5445 -0.0643  0.5688  3.2125
##
## Random effects:
##  Groups   Name        Variance  Std.Dev. Corr
##  ID       (Intercept) 0.1188617 0.34476
##           Time1       0.0093350 0.09662  -0.79
##           Time3       0.0004102 0.02025   0.28 -0.81
##           Time4       0.0088193 0.09391  -0.75  1.00 -0.85
##  Residual             0.0485241 0.22028
## Number of obs: 180, groups:  ID, 25
##
## Fixed effects:
##                          Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)            5.604e-01  4.402e-01  3.561e+01   1.273    0.211
```

```
## Age                    7.134e-03  5.847e-03  1.812e+01   1.220    0.238
## onset_catPrelingual    1.353e-01  2.089e-01  1.829e+01   0.648    0.525
## Training_orderVT + AT -2.142e-02  1.359e-01  1.824e+01  -0.158    0.877
## TrainingVT            -1.274e-02  6.810e-02  1.224e+02  -0.187    0.852
## Time1                 -4.291e-02  3.018e-01  1.038e+02  -0.142    0.887
## Time3                 -2.448e-01  2.928e-01  1.182e+02  -0.836    0.405
## Time4                 -3.186e-02  3.018e-01  9.372e+01  -0.106    0.916
## session_amount         1.045e-02  7.717e-03  1.147e+02   1.354    0.178
## dur_deaf_less_dep_ear -2.373e-03  3.441e-03  1.931e+01  -0.690    0.499
## exp_latest_CI         -1.618e-03  1.356e-02  2.032e+01  -0.119    0.906
## TrainingVT:Time1      -4.594e-03  9.440e-02  1.257e+02  -0.049    0.961
## TrainingVT:Time3      -4.644e-03  9.403e-02  1.199e+02  -0.049    0.961
## TrainingVT:Time4      -3.698e-03  9.440e-02  1.263e+02  -0.039    0.969
## Time1:session_amount   3.403e-03  9.407e-03  1.035e+02   0.362    0.718
## Time3:session_amount   9.182e-03  9.131e-03  1.181e+02   1.006    0.317
## Time4:session_amount   9.658e-04  9.409e-03  9.311e+01   0.103    0.918
```

Phonological representations (% correct)

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## Rhyming_perc_correct ~ Age + onset_cat + Training_order + Training *
##     Time + session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1405
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.2605 -0.2745  0.1139  0.5488  1.6296
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept)  37.35    6.111
##           Time1        54.99    7.415   -0.13
##           Time3        18.45    4.295   -0.99  0.29
##           Time4        26.50    5.147   -0.24  0.99  0.39
##  Residual             123.94   11.133
## Number of obs: 185, groups:  ID, 26
##
## Fixed effects:
##                         Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)           102.591611  13.775665  71.473928   7.447  1.7e-10
## Age                    -0.087500   0.124328  22.888525  -0.704  0.48866
## onset_catPrelingual    -4.730526   4.486150  23.343590  -1.054  0.30246
## Training_orderVT + AT   3.406045   2.874651  23.527637   1.185  0.24791
## TrainingVT             -2.484373   3.386316 140.126587  -0.734  0.46439
## Time1                 -10.666955  16.222680  77.969820  -0.658  0.51277
## Time3                  23.581610  15.282435  99.120789   1.543  0.12600
## Time4                   2.592164  15.434925 101.306160   0.168  0.86696
## session_amount         -0.676892   0.371713  86.099789  -1.821  0.07208
## dur_deaf_less_dep_ear   0.218225   0.075805  26.029254   2.879  0.00788
```

```
## exp_latest_CI          0.475567   0.309812  30.564762   1.535  0.13507
## TrainingVT:Time1      -1.651499   4.749536 140.109943  -0.348  0.72857
## TrainingVT:Time3      -2.943589   4.714788 132.057125  -0.624  0.53349
## TrainingVT:Time4       4.905029   4.705387 135.015663   1.042  0.29908
## Time1:session_amount   0.424495   0.508007  77.941568   0.836  0.40593
## Time3:session_amount  -0.665160   0.478939  98.386044  -1.389  0.16802
## Time4:session_amount   0.007032   0.483567 100.486791   0.015  0.98843
##
## (Intercept)           ***
## Age
## onset_catPrelingual
## Training_orderVT + AT
## TrainingVT
## Time1
## Time3
## Time4
## session_amount        .
## dur_deaf_less_dep_ear **
## exp_latest_CI
## TrainingVT:Time1
## TrainingVT:Time3
## TrainingVT:Time4
## Time1:session_amount
## Time3:session_amount
## Time4:session_amount
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Phonological representations (reaction time)

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula:
## Rhyming_avg_dur_all ~ Age + onset_cat + Training_order + Training *
##     Time + session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 2371.4
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.04631 -0.56630 -0.01936  0.46621  2.84507
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 72630    269.50
##           Time1       26061    161.43    0.33
##           Time3        8215     90.64   -0.23  0.44
##           Time4        9668     98.32    0.15  0.92  0.70
##  Residual             24028    155.01
## Number of obs: 187, groups:  ID, 26
##
## Fixed effects:
##                        Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)            815.1595   364.5305   29.6268   2.236   0.0330 *
```

```
## Age                        2.9227     5.1826   19.7005   0.564   0.5792
## onset_catPrelingual      -65.5347   185.9852   19.7389  -0.352   0.7283
## Training_orderVT + AT -181.6686   118.9237   19.7854  -1.528   0.1424
## TrainingVT                12.1840    47.7663   80.2991   0.255   0.7993
## Time1                    517.7418   240.6354   76.9856   2.152   0.0346 *
## Time3                    134.8578   221.9890   60.9581   0.607   0.5458
## Time4                    -13.2065   221.1404   65.7407  -0.060   0.9526
## session_amount            11.2299     5.6458   88.8904   1.989   0.0498 *
## dur_deaf_less_dep_ear      1.6904     3.0433   20.7468   0.555   0.5845
## exp_latest_CI              3.0819    12.0201   21.7375   0.256   0.8001
## TrainingVT:Time1           0.6639    66.5966   82.8259   0.010   0.9921
## TrainingVT:Time3         -17.5364    65.8282   83.0785  -0.266   0.7906
## TrainingVT:Time4          87.1426    65.7921   81.5546   1.325   0.1890
## Time1:session_amount     -13.0242     7.5246   76.9958  -1.731   0.0875 .
## Time3:session_amount      -5.1488     6.9600   60.4380  -0.740   0.4623
## Time4:session_amount       0.1501     6.9270   65.1326   0.022   0.9828
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Visual working memory scores

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: WM_perc ~ Age + onset_cat + Training_order + Training * Time +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (Time | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1356.3
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -5.2688 -0.4543  0.0884  0.4983  1.8367
##
## Random effects:
##  Groups   Name        Variance Std.Dev. Corr
##  ID       (Intercept) 136.8297 11.6974
##           Time1         2.5564  1.5989   0.68
##           Time3         0.8422  0.9177   0.92  0.34
##           Time4        33.3242  5.7727  -0.16  0.62 -0.53
##  Residual             100.5217 10.0261
## Number of obs: 180, groups:  ID, 25
##
## Fixed effects:
##                         Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)            112.97705   18.29286  34.99817   6.176 4.53e-07 ***
## Age                     -0.88779    0.24297  18.63116  -3.654  0.00173 **
## onset_catPrelingual     -8.27587    8.67227  18.72872  -0.954  0.35209
## Training_orderVT + AT   4.28421    5.64260  18.68626   0.759  0.45717
## TrainingVT              -1.34894    3.08742 124.56624  -0.437  0.66293
## Time1                  -11.94701   13.35539 117.69812  -0.895  0.37286
## Time3                    4.99109   13.31292 120.64030   0.375  0.70839
## Time4                    0.05386   14.34169  73.98098   0.004  0.99701
## session_amount          -0.32268    0.34112 114.41537  -0.946  0.34618
## dur_deaf_less_dep_ear    0.08163    0.14238  19.53903   0.573  0.57297
## exp_latest_CI            0.99602    0.55924  20.33815   1.781  0.08985 .
```

```
## TrainingVT:Time1        2.20027    4.28119 122.59515   0.514  0.60822
## TrainingVT:Time3        3.47420    4.27949 122.36511   0.812  0.41847
## TrainingVT:Time4        5.43339    4.32120 131.90519   1.257  0.21084
## Time1:session_amount    0.30293    0.41650 117.63346   0.727  0.46848
## Time3:session_amount   -0.08919    0.41519 120.66180  -0.215  0.83026
## Time4:session_amount    0.06826    0.44766  73.38378   0.152  0.87922
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Self-perceived auditory abilities

Self-perceived listening

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: SSQ_AVG ~ Age + onset_cat + Training_order + Training * Time +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (1 | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 461.4
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.63705 -0.53931 -0.03588  0.52158  2.41625
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept) 1.8867   1.3736
##  Residual             0.3651   0.6042
## Number of obs: 182, groups:  ID, 26
##
## Fixed effects:
##                         Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)            3.633e+00  1.798e+00  2.571e+01   2.020   0.0539 .
## Age                   -1.209e-02  2.679e-02  1.993e+01  -0.451   0.6567
## onset_catPrelingual   -5.373e-01  9.619e-01  1.997e+01  -0.559   0.5827
## Training_orderVT + AT  1.316e+00  6.146e-01  1.995e+01   2.142   0.0448 *
## TrainingVT            -1.612e-01  1.824e-01  1.454e+02  -0.883   0.3785
## Time1                 -1.245e-02  7.978e-01  1.450e+02  -0.016   0.9876
## Time3                  1.736e-01  8.004e-01  1.450e+02   0.217   0.8286
## Time4                  4.359e-01  8.127e-01  1.450e+02   0.536   0.5925
## session_amount        -1.201e-02  2.102e-02  1.492e+02  -0.572   0.5685
## dur_deaf_less_dep_ear  3.539e-02  1.558e-02  2.025e+01   2.271   0.0342 *
## exp_latest_CI          9.495e-02  6.096e-02  2.047e+01   1.557   0.1347
## TrainingVT:Time1      -8.237e-02  2.525e-01  1.450e+02  -0.326   0.7448
## TrainingVT:Time3       2.330e-01  2.539e-01  1.450e+02   0.918   0.3601
## TrainingVT:Time4       3.161e-01  2.613e-01  1.450e+02   1.210   0.2283
## Time1:session_amount   5.101e-04  2.494e-02  1.450e+02   0.020   0.9837
## Time3:session_amount  -8.456e-03  2.503e-02  1.450e+02  -0.338   0.7360
## Time4:session_amount  -1.649e-02  2.535e-02  1.450e+02  -0.650   0.5164
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Communication aprehension

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: PRCA_overall ~ Age + onset_cat + Training_order + Training *
##     Time + session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (1 | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1244.9
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.70940 -0.54092 -0.02811  0.52504  3.04145
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept) 325.48   18.041
##  Residual              43.93    6.628
## Number of obs: 180, groups:  ID, 26
##
## Fixed effects:
##                           Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)               71.26930   23.11545  24.23210   3.083  0.00505 **
## Age                       -0.16260    0.35044  20.07598  -0.464  0.64764
## onset_catPrelingual       -0.70027   12.59215  20.18783  -0.056  0.95620
## Training_orderVT + AT     -3.11609    8.03537  20.07637  -0.388  0.70225
## TrainingVT                 1.19548    2.01575 143.41618   0.593  0.55407
## Time1                      2.03016    8.90170 143.09245   0.228  0.81992
## Time3                      2.86405    8.89840 143.15453   0.322  0.74803
## Time4                     -0.84893    9.03123 143.17618  -0.094  0.92524
## session_amount             0.11077    0.23850 146.11673   0.464  0.64302
## dur_deaf_less_dep_ear      0.02217    0.20355  20.28795   0.109  0.91432
## exp_latest_CI              0.28937    0.79600  20.48409   0.364  0.71994
## TrainingVT:Time1          -1.60907    2.78670 143.09245  -0.577  0.56457
## TrainingVT:Time3          -1.61285    2.80133 143.13732  -0.576  0.56569
## TrainingVT:Time4           2.86950    2.88227 143.16842   0.996  0.32114
## Time1:session_amount      -0.03478    0.28133 143.09245  -0.124  0.90178
## Time3:session_amount      -0.05521    0.28038 143.17881  -0.197  0.84419
## Time4:session_amount      -0.03956    0.28385 143.19728  -0.139  0.88934
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Self-efficacy

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: SESMQ_Total_M ~ Age + onset_cat + Training_order + Training *
##     Time + session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (1 | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1599.7
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
```

```
## -2.9904 -0.4984 -0.0176  0.4771  2.2829
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept) 1085.9   32.95
##  Residual              388.6   19.71
## Number of obs: 182, groups:  ID, 26
##
## Fixed effects:
##                          Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)             124.92224   45.82233  30.89720   2.726   0.0105 *
## Age                      -1.02796    0.65084  20.02001  -1.579   0.1299
## onset_catPrelingual     -32.68491   23.38392  20.12784  -1.398   0.1774
## Training_orderVT + AT    17.05543   14.92834  20.05053   1.142   0.2667
## TrainingVT                2.56829    5.98532 145.82482   0.429   0.6685
## Time1                    17.68016   26.29201 145.09013   0.672   0.5024
## Time3                    -6.56375   26.29201 145.09013  -0.250   0.8032
## Time4                     5.71359   26.80906 145.18305   0.213   0.8315
## session_amount            0.10500    0.70100 151.98059   0.150   0.8811
## dur_deaf_less_dep_ear     0.43424    0.37947  20.53072   1.144   0.2656
## exp_latest_CI             2.69439    1.48766  20.94380   1.811   0.0845 .
## TrainingVT:Time1          2.48190    8.26770 145.06951   0.300   0.7645
## TrainingVT:Time3         -9.62082    8.26770 145.06951  -1.164   0.2465
## TrainingVT:Time4          2.51773    8.55999 145.19103   0.294   0.7691
## Time1:session_amount     -0.65158    0.82737 145.11011  -0.788   0.4323
## Time3:session_amount      0.50844    0.82737 145.11011   0.615   0.5398
## Time4:session_amount      0.04114    0.84195 145.20091   0.049   0.9611
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Quality of life

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: QOL_total ~ Age + onset_cat + Training_order + Training * Time +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (1 | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1156.3
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -4.4413 -0.5236 -0.0042  0.5913  2.2958
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept) 112.39   10.601
##  Residual              25.04    5.004
## Number of obs: 182, groups:  ID, 26
##
## Fixed effects:
##                          Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)              75.51176   14.03183  26.53546   5.381 1.16e-05 ***
```

```
## Age                     -0.03848    0.20724  19.88478  -0.186   0.8546  
## onset_catPrelingual     -6.26001    7.44080  19.93427  -0.841   0.4102  
## Training_orderVT + AT    8.98130    4.75381  19.91703   1.889   0.0735 .
## TrainingVT               2.25303    1.51059 145.46304   1.491   0.1380  
## Time1                   -2.33574    6.60689 144.92204  -0.354   0.7242  
## Time3                    9.64862    6.62891 144.93136   1.456   0.1477  
## Time4                    0.03032    6.72597 144.96839   0.005   0.9964  
## session_amount           0.05138    0.17397 149.76992   0.295   0.7681  
## dur_deaf_less_dep_ear    0.01349    0.12061  20.25223   0.112   0.9120  
## exp_latest_CI            0.78910    0.47197  20.50090   1.672   0.1097  
## TrainingVT:Time1        -0.51266    2.09118 144.92204  -0.245   0.8067  
## TrainingVT:Time3        -2.30635    2.10240 144.93699  -1.097   0.2745  
## TrainingVT:Time4        -0.18471    2.16599 145.01449  -0.085   0.9322  
## Time1:session_amount     0.06683    0.20658 144.92204   0.324   0.7468  
## Time3:session_amount    -0.16231    0.20730 144.93182  -0.783   0.4349  
## Time4:session_amount     0.04755    0.20982 144.96725   0.227   0.8210  
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

SF-36 General Health

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: SF36_GH ~ Age + onset_cat + Training_order + Training * Time +  
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +  
##     (1 | ID)
##    Data: dados.longo.merge
## 
## REML criterion at convergence: 1431
## 
## Scaled residuals: 
##      Min       1Q   Median       3Q      Max 
## -2.56568 -0.38989  0.03491  0.46358  2.85210 
## 
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept) 565.0    23.77   
##  Residual             148.9    12.20   
## Number of obs: 180, groups:  ID, 26
## 
## Fixed effects:
##                         Estimate Std. Error        df t value Pr(>|t|)  
## (Intercept)             44.29081   31.99689  27.95230   1.384  0.17724  
## Age                      0.05591    0.46630  19.92014   0.120  0.90576  
## onset_catPrelingual      5.03076   16.77673  20.13196   0.300  0.76735  
## Training_orderVT + AT   17.78268   10.69223  19.92271   1.663  0.11194  
## TrainingVT               5.68173    3.70964 143.56034   1.532  0.12782  
## Time1                    1.50716   16.39043 142.95548   0.092  0.92686  
## Time3                   29.92309   16.38272 143.07338   1.827  0.06986 .
## Time4                   13.77232   16.62670 143.11493   0.828  0.40887  
## session_amount           0.31260    0.43699 148.48112   0.715  0.47551  
## dur_deaf_less_dep_ear    0.18168    0.27149  20.31613   0.669  0.51089  
## exp_latest_CI           -0.68243    1.06401  20.69546  -0.641  0.52832  
## TrainingVT:Time1         0.18034    5.13107 142.95548   0.035  0.97201  
```

```
## TrainingVT:Time3      -14.56266    5.15764 143.04061  -2.824  0.00543 **
## TrainingVT:Time4      -11.46304    5.30639 143.09977  -2.160  0.03242 *
## Time1:session_amount   -0.09284    0.51800 142.95548  -0.179  0.85802
## Time3:session_amount   -0.79240    0.51619 143.11951  -1.535  0.12696
## Time4:session_amount   -0.29094    0.52256 143.15476  -0.557  0.57856
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: SF36_GH ~ onset_cat + Training_order + Training * Time * Age +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (1 | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1419.9
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.44596 -0.44941 -0.01213  0.53261  2.50113
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept) 571.8    23.91
##  Residual             139.7    11.82
## Number of obs: 180, groups:  ID, 26
##
## Fixed effects:
##                         Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)             64.23798   33.93891  34.42949   1.893   0.0668 .
## onset_catPrelingual      5.74866   16.85162  20.12309   0.341   0.7365
## Training_orderVT + AT   17.44236   10.74180  19.92730   1.624   0.1201
## TrainingVT             -49.36284   21.44906 136.34643  -2.301   0.0229 *
## Time1                   -1.29863   23.72544 135.95707  -0.055   0.9564
## Time3                   21.25443   23.72302 135.95822   0.896   0.3719
## Time4                  -23.47049   24.26073 136.03713  -0.967   0.3350
## Age                     -0.28255    0.51494  28.90349  -0.549   0.5874
## session_amount           0.36933    0.43255 140.91135   0.854   0.3946
## dur_deaf_less_dep_ear    0.16530    0.27280  20.33724   0.606   0.5513
## exp_latest_CI           -0.64237    1.06917  20.71885  -0.601   0.5545
## TrainingVT:Time1         5.36175   29.87855 135.95707   0.179   0.8579
## TrainingVT:Time3        41.62330   30.12014 136.09555   1.382   0.1693
## TrainingVT:Time4        66.11031   31.55583 136.16400   2.095   0.0380 *
## TrainingVT:Age           0.87579    0.33621 136.34050   2.605   0.0102 *
## Time1:Age                0.04819    0.32430 135.95707   0.149   0.8821
## Time3:Age                0.10430    0.32110 136.04462   0.325   0.7458
## Time4:Age                0.62128    0.32692 136.11702   1.900   0.0595 .
## Time1:session_amount    -0.10117    0.51568 135.95707  -0.196   0.8448
## Time3:session_amount    -0.73420    0.51127 136.12810  -1.436   0.1533
## Time4:session_amount    -0.35921    0.51670 136.15481  -0.695   0.4881
## TrainingVT:Time1:Age    -0.08219    0.46764 135.95707  -0.176   0.8607
## TrainingVT:Time3:Age    -0.88759    0.47056 136.06654  -1.886   0.0614 .
## TrainingVT:Time4:Age    -1.22897    0.49035 136.13222  -2.506   0.0134 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

SF-36 Vitality

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: SF36_VT ~ Age + onset_cat + Training_order + Training * Time +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (1 | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1325.7
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.4769 -0.4510  0.0400  0.4717  2.2530
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept) 276.67   16.633
##  Residual              78.81    8.878
## Number of obs: 180, groups:  ID, 26
##
## Fixed effects:
##                         Estimate Std. Error         df t value Pr(>|t|)
## (Intercept)            35.549391  22.562536  28.368192   1.576   0.1262
## Age                    -0.007581   0.326830  19.755412  -0.023   0.9817
## onset_catPrelingual    -8.317320  11.761138  19.981774  -0.707   0.4876
## Training_orderVT + AT  16.336420   7.494158  19.758449   2.180   0.0415 *
## TrainingVT             -1.321021   2.698350 143.444959  -0.490   0.6252
## Time1                  -0.959389  11.923202 142.792000  -0.080   0.9360
## Time3                  -4.639181  11.917406 142.919601  -0.389   0.6977
## Time4                   3.154455  12.094816 142.964649   0.261   0.7946
## session_amount          0.358025   0.317642 148.736364   1.127   0.2615
## dur_deaf_less_dep_ear   0.101066   0.190356  20.177711   0.531   0.6013
## exp_latest_CI           1.287115   0.746305  20.584513   1.725   0.0996 .
## TrainingVT:Time1       -2.417565   3.732591 142.792000  -0.648   0.5182
## TrainingVT:Time3       -2.327965   3.751878 142.884123  -0.620   0.5359
## TrainingVT:Time4        7.424936   3.860054 142.948173   1.924   0.0564 .
## Time1:session_amount    0.022276   0.376820 142.792000   0.059   0.9529
## Time3:session_amount    0.170863   0.375491 142.969531   0.455   0.6498
## Time4:session_amount   -0.282650   0.380125 143.007713  -0.744   0.4584
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

SF-36 Social functioning

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: SF36_SF ~ Age + onset_cat + Training_order + Training * Time +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (1 | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1459.1
##
```

```
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -2.8993 -0.4161  0.1012  0.5662  2.6286
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept) 364.0    19.08
##  Residual             191.7    13.85
## Number of obs: 180, groups:  ID, 26
##
## Fixed effects:
##                         Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)             80.35096   28.00507  34.37098   2.869  0.00699 **
## Age                      0.01130    0.38166  19.13858   0.030  0.97669
## onset_catPrelingual      1.63773   13.76463  19.52726   0.119  0.90651
## Training_orderVT + AT   13.94817    8.75185  19.14863   1.594  0.12737
## TrainingVT              -7.82229    4.20469 143.32132  -1.860  0.06488 .
## Time1                   -0.39413   18.59542 142.18764  -0.021  0.98312
## Time3                  -22.57574   18.58320 142.41535  -1.215  0.22643
## Time4                    2.62434   18.85869 142.49730   0.139  0.88952
## session_amount          -0.03548    0.49131 152.09051  -0.072  0.94253
## dur_deaf_less_dep_ear   -0.27300    0.22319  19.84861  -1.223  0.23558
## exp_latest_CI            0.52031    0.87840  20.57490   0.592  0.56008
## TrainingVT:Time1        -1.02646    5.82135 142.18764  -0.176  0.86029
## TrainingVT:Time3         6.19922    5.85071 142.35180   1.060  0.29114
## TrainingVT:Time4        11.69847    6.01888 142.46666   1.944  0.05391 .
## Time1:session_amount     0.04798    0.58769 142.18764   0.082  0.93505
## Time3:session_amount     0.58386    0.58548 142.50449   0.997  0.32034
## Time4:session_amount    -0.30691    0.59267 142.57332  -0.518  0.60537
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

SF-36 Emotional role limitation

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: SF36_RE ~ Age + onset_cat + Training_order + Training * Time +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (1 | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1419
##
## Scaled residuals:
##     Min      1Q  Median      3Q     Max
## -3.4707 -0.3415  0.0883  0.4661  2.3677
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept)  78.44    8.856
##  Residual             174.02   13.191
## Number of obs: 180, groups:  ID, 26
##
## Fixed effects:
##                         Estimate Std. Error        df t value Pr(>|t|)
## (Intercept)             56.92711   18.23781  64.41229   3.121  0.00269 **
```

```
## Age                      0.24099    0.19739  17.74845   1.221  0.23809  
## onset_catPrelingual    -13.85080    7.19895  18.86153  -1.924  0.06958 .
## Training_orderVT + AT  10.09417    4.52859  17.81203   2.229  0.03894 *
## TrainingVT             -1.70913    3.98983 144.05285  -0.428  0.66902  
## Time1                   5.36135   17.71697 140.93737   0.303  0.76263  
## Time3                  -5.95224   17.69011 141.64798  -0.336  0.73701  
## Time4                  12.03170   17.94646 141.93461   0.670  0.50368  
## session_amount          0.54215    0.45036 161.91071   1.204  0.23042  
## dur_deaf_less_dep_ear  -0.19498    0.11768  19.64618  -1.657  0.11341  
## exp_latest_CI           0.27048    0.47277  22.27356   0.572  0.57298  
## TrainingVT:Time1        2.27314    5.54635 140.93737   0.410  0.68254  
## TrainingVT:Time3       -3.76761    5.57088 141.44668  -0.676  0.49995  
## TrainingVT:Time4        1.82103    5.72845 141.82741   0.318  0.75103  
## Time1:session_amount   -0.20889    0.55993 140.93737  -0.373  0.70966  
## Time3:session_amount    0.09349    0.55715 141.92668   0.168  0.86698  
## Time4:session_amount   -0.52957    0.56384 142.15855  -0.939  0.34922  
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

SF-36 Mental Health

```
## Linear mixed model fit by REML. t-tests use Satterthwaite's method [
## lmerModLmerTest]
## Formula: SF36_MH ~ Age + onset_cat + Training_order + Training * Time +
##     session_amount * Time + dur_deaf_less_dep_ear + exp_latest_CI +
##     (1 | ID)
##    Data: dados.longo.merge
##
## REML criterion at convergence: 1323.6
##
## Scaled residuals:
##      Min       1Q   Median       3Q      Max
## -2.98942 -0.45146  0.01826  0.61579  1.81325
##
## Random effects:
##  Groups   Name        Variance Std.Dev.
##  ID       (Intercept) 133.22   11.542
##  Residual              85.35    9.238
## Number of obs: 180, groups:  ID, 26
##
## Fixed effects:
##                        Estimate Std. Error        df t value Pr(>|t|)  
## (Intercept)            28.59691   17.50777  37.75913   1.633   0.1107  
## Age                     0.26151    0.23279  19.32909   1.123   0.2750  
## onset_catPrelingual    -5.32776    8.40363  19.79554  -0.634   0.5334  
## Training_orderVT + AT  14.36576    5.33815  19.34334   2.691   0.0143 *
## TrainingVT              4.29392    2.80453 143.72534   1.531   0.1280  
## Time1                   7.59357   12.40778 142.41170   0.612   0.5415  
## Time3                   2.64548   12.39869 142.67873   0.213   0.8313  
## Time4                  19.50462   12.58216 142.77569   1.550   0.1233  
## session_amount          0.70372    0.32666 153.64917   2.154   0.0328 *
## dur_deaf_less_dep_ear  -0.06617    0.13637  20.17401  -0.485   0.6327  
## exp_latest_CI           1.40383    0.53762  21.06117   2.611   0.0163 *
## TrainingVT:Time1       -1.85854    3.88429 142.41170  -0.478   0.6330  
```

```
## TrainingVT:Time3       -6.08183    3.90367 142.60409  -1.558   0.1215
## TrainingVT:Time4       -2.85675    4.01572 142.73919  -0.711   0.4780
## Time1:session_amount   -0.26712    0.39213 142.41170  -0.681   0.4969
## Time3:session_amount   -0.08386    0.39062 142.78328  -0.215   0.8303
## Time4:session_amount   -0.72076    0.39541 142.86439  -1.823   0.0704 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Appendix D. Supporting Information for Chapter 4

Example of terms used to search records in Pubmed

(((((((((((((hearing loss[MeSH Terms]) OR persons with hearing impairment[MeSH Terms]) OR aid[MeSH Terms]) OR hearing aid*[Title/Abstract]) OR hearing device*[Title/Abstract]) OR hearing instrument*[Title/Abstract]) OR cochlear implant*[Title/Abstract]) OR auditory prosthes*[Title/Abstract]) OR cochlear prosthes*[Title/Abstract]) AND auditory training[Title/Abstract]) OR perceptual training[Title/Abstract]) OR auditory learning[Title/Abstract]) OR perceptual learning[Title/Abstract]) OR listening training[Title/Abstract]) AND ("2012/12/01"[Date - Publication] : "3000"[Date - Publication])