LISTENING EFFORT IN CHILDREN WITH SEVERE-PROFOUND SENSORINEURAL UNILATERAL HEARING LOSS

by

ILZE OOSTHUIZEN

A thesis submitted in partial fulfilment of the requirements for the degree

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FACULTY OF HUMANITIES
UNIVERSITY OF PRETORIA

SUPERVISOR:
Professor De Wet Swanepoel

CO-SUPERVISORS:
Professor Lidia Pottas
Professor Erin M. Picou

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Ilze Oosthuizen
Department of Speech-Language Pathology and Audiology
University of Pretoria
Pretoria
South Africa

ilzeoosthuizen8@gmail.com

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"The LORD is my strength and my song." ~Psalm 118:14~

Soli Deo Gloria – To God be the glory.

Jesus, You are my redeemer, my provider, my hope, and my strength.

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"I carry your heart (I carry it in my heart)"

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UNIVERSITY OF PRETORIA
FACULTY OF HUMANITIES
DEPARTMENT OF SPEECH-LANGUAGE PATHOLOGY AND AUDIOLOGY

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Student Number: 24051285

Degree/Qualification: D. Phil (Communication Pathology: Audiology)

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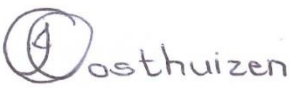

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ETHICS STATEMENT

The author, whose name appears on the title page of this thesis, has obtained, for the research described in this work, the applicable research ethics approval.

The author declares that she has observed the ethical standards required in terms of the University of Pretoria's Code of ethics for researchers and the Policy guidelines for responsible research.

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ABSTRACT

Title: Listening effort in children with severe-profound sensorineural unilateral hearing loss.
Name: Ilze Oosthuizen
Supervisor: Prof. De Wet Swanepoel
Co-supervisors: Prof. Lidia Pottas & Prof. Erin M. Picou
Department: Speech-language Pathology and Audiology
Degree: D. Phil Communication Pathology (Audiology)

Unilateral hearing loss, affecting up to 3% of school-aged children, is known to put this population at risk for speech-language, academic, and behavioral difficulties. These risks can even be more pronounced for children with severe-profound sensorineural unilateral hearing loss (described hereafter as limited useable hearing unilaterally, LUHU) relative to peers with normal hearing. Children in school spend the greater part of their school day listening, often in acoustical challenging situations. This can result in increased listening effort that can negatively affect academic performance and quality of life. Therefore, this research project focused on determining listening effort in school-aged children with limited useable hearing unilaterally, as well as evaluating the effect of non-surgical intervention options on the listening effort experienced by these children. Specific outcomes of digit triplet recognition and response times were focused on throughout the research project.

Study I aimed to develop novel, low-linguistic listening effort paradigms (single- and dual-task), with digit triplets as speech stimulus, that can be used in school-aged children form multilingual backgrounds (English as native language vs English as non-native language). A total of 60 school-aged children, aged 7 to 12 years, with normal hearing participated in the first study, 30 per language group. Significant effects of noise on response times were evident during both single-task (p < .001, η_p^2 = 0.58) and dual-task paradigms (p < .001, η_p^2 = 0.23), with an increase in noise resulting in longer response times, reflecting increased listening effort. The data also revealed a maturation effect for digit triplet recognition during both tasks with older children

presenting with improved performance of speech recognition in noise. A significant relationship between age and dual-task visual response times (r = -0.39, $p < .0001$) was evident, with response times decreasing with an increase in age. Language background had no significant effect on digit triplet recognition performance or response times ($p > .05$), demonstrating practical utility of these low-linguistic paradigms for measuring listening effort in school-aged children from multilingual backgrounds.

Consequently, Study II aimed to determine if school-aged children with LUHU experience more listening effort relative to peers with normal hearing by employing the low-linguistic single-task paradigm as well as subjective ratings. Specifically, two groups of school-aged children (aged 7-12 years) participated, 19 children with LUHU and 18 children with normal hearing bilaterally. Participants completed digit triplet recognition tasks in quiet and in noise (-12 dB signal-to-noise ratio) in three loudspeaker conditions: midline, direct, and indirect. Verbal response times during the recognition task were interpreted as behavioral listening effort. Subjective ratings of "task difficulty" and "hard to think" were interpreted as subjective listening effort. Participant age was included as a covariate in analysis of behavioral data. Results indicated that noise significantly decreased digit triplet recognition performance for both participant groups in the midline loudspeaker ($p < .001$, $\eta_p^2 = 0.77$). Participants with LUHU had significantly poorer recognition performance relative to peers with normal hearing in the direct condition with noise (p = <.001, M difference = 14.50 rau, 95% CI: 6.46 to 22.54 rau) and the indirect condition with noise ($p < .001$, M difference = 79.90 rau, 95% CI: 70.79 to 89.00 rau). Furthermore, participants with LUHU had significantly increased response times compared to peers with bilateral normal hearing in the indirect loudspeaker condition with noise ($p < .001$, M difference = 624 ms, 95% CI: 428 to 801 ms). Results from the subjective ratings indicated that participants with LUHU rated task difficulty as significantly higher ($p < .001$), their recognition performance as significantly lower ($p < .0001$), and the hard to think rating as significantly higher ($p = .004$) than participants with normal hearing for the indirect condition with noise. Differences between groups were evident even when age differences were controlled for statistically.

Given the increased listening effort that children with LUHU can experience in noisy situations, it was consequently important to evaluate the effects of two intervention options, namely a remote microphone system and a contralateral routing of signal (CROS) system, on listening effort in school-aged children with LUHU in Study III. Behavioral (verbal response time measures) and subjective indices of listening effort were employed. Results indicated that relative to the unaided condition, the remote microphone system significantly improved digit triplet recognition in the midline ($p < .001$, M difference = 61.50 rau, 95% CI = 39.09 to 83.91 rau), direct ($p = .035$, M difference = 13.58 rau, 95% CI = 0.79 to 26.38 rau), and indirect ($p < .001$, M difference = 103.45 rau, 95% CI = 92.06 to 114.84 rau) loudspeaker conditions and significantly reduced verbal response times in the midline ($p = .038$, M difference = -182 ms, 95% CI = -356 to -9 ms) and indirect ($p < .001$, M difference = -680 ms, 95% CI = -892 to -468 ms) conditions. Compared to the unaided condition, the CROS system significantly improved digit triplet recognition ($p < .001$, M difference = 41.95 rau, 95% CI = 29.51 to 54.39 rau) and reduced verbal response times ($p < .001$, M difference = -422 ms, 95% CI = -626 to -218 ms) only in the indirect condition. Consistent with the findings of digit triplet recognition and verbal response times, analyses of the subjective ratings indicated that the remote microphone system yielded more consistent benefits in terms of ease of listening and motivation to complete the listening task for most participants.

Findings of this research project indicate that due consideration should be given to the negative effects of increased listening effort that can be experienced in acoustic challenging situations even for young, normal hearing school-aged children. Increased listening effort can ultimately be detrimental to academic performance. Extending the evaluation of listening effort to the specific population of school-aged children with LUHU, the findings provide valuable baseline data for clinicians to consider the greater listening effort that can be experienced by school-aged children with LUHU and the effect that non-surgical intervention options of personal, ear-level remote microphone systems and CROS hearing aid systems, may have to reduce the listening effort experienced by this population. Reducing listening effort by means of appropriate intervention options may increase successful participation in academic and social situations for children with LUHU. Using self-report questionnaires can be valuable to support findings of behavioral listening effort measures as well as to determine perceived benefit of intervention options for reducing listening effort in school-aged children. Combining results of multiple indices of listening effort may contribute to management and educational plans for children with LUHU.

KEYWORDS

Behavioral measures

Contralateral routing of signal hearing aid

Digit triplet recognition

Dual-task paradigm

Limited useable hearing unilaterally

Listening effort

Midline

Monaural direct

Monaural indirect

Normal hearing

Remote microphone system

Response time

School-aged children

Signal-to-noise ratio

Single-task paradigm

Subjective measures

Verbal response time

ABBREVIATIONS

CROS	Contralateral Routing of Signal
dB	Decibel
dB HL	Decibel Hearing Level
ELU	Ease of Language Understanding
FUEL	Framework for Understanding Effortful Listening
Hz	Hertz
LUHU	Limited Useable Hearing Unilaterally
ms	Millisecond
NH	Normal hearing
RAU	Rationalized Arcsine Unit
RMS	Remote microphone system
RT	Response time
SNR	Signal-to-noise ratio
VRT	Verbal response time

CHAPTER 1

INTRODUCTION AND RATIONALE

1.1 INTRODUCTION

Listening effort and unilateral hearing loss (UHL) in children have been researched since the early 1980s to explore assessment methodologies and possible intervention procedures. However, before the 1980s, hearing professionals and educators did not recognize UHL as a risk for communicative and educational difficulties. In 1978 Northern and Downs stated that *"audiologists and otolaryngologists are not usually concerned over such deafness (unilateral), other than to identify its etiology and assure the parents that there will be no handicap"* (Northern & Downs, 1978:143). In contrast, numerous studies in the recent decades revealed that UHL indeed puts children at risk for academic, speech and language, and social and/or behavioral deficits (Bess & Tharpe, 1986a, 1986b; Bess et al., 1986; Lieu, 2013; Lieu, 2004). Despite increased understanding of the difficulties encountered by children with UHL, there remains a need for continued research as these children still present with difficulties in educational settings (Bagatto et al., 2019). A possible reason for continued academic risk for children with UHL might be that outcomes of previous work focused almost solely on the speech recognition performance of children with UHL with little consideration of the effects of possible increased listening effort experienced by children with UHL and its potential effects.

Listening is imperative in the educational setting. However, for school-aged children, listening and learning often occur in acoustically challenging environments, due to the presence of background noise and/or reverberation (Berg, 1993; Bistafa & Bradley, 2000; Crandell & Smaldino, 2000b). With average speech intensity measuring at 60 dB and classroom background noise levels varying from 34 to more than 70 dBA (e.g., Bradley & Sato, 2008; Knecht et al., 2002), the signal-to-noise ratios (SNRs) encountered in classrooms are often very unfavorable, ranging from -17 dB to +15 dB (Bradley & Sato, 2008; Crandell & Smaldino, 2000a; Larsen & Blair, 2008; Markides, 1986; Pearsons et al., 1977; Sato & Bradley, 2008). Background noise negatively affects speech recognition by reducing the audibility of acoustic cues that are important for understanding and distinguishing speech sounds (Nelson et al., 2008). This suggests that children in academic contexts often listen at SNRs poorer than the recommended minimum of +15 dB SNR for educational settings (American Speech-Language-Hearing Association, 2005). Furthermore, increased reverberation times are a major concern in typical classrooms (Crandell & Smaldino, 1994; Crukley et al., 2011). Increased reverberation times can smear and distort important speech sounds in the classroom, negatively affecting phonological processing (Klatte et al., 2010a) and speech recognition performance (Klatte et al., 2010b; Neuman et al., 2010; Valente et al., 2012).

The consequences of listening in such acoustically challenging environments include reduced speech perception, increased listening effort, and possibly fatigue, even for listeners with normal hearing (Picou et al., 2017; Picou et al., 2016; Prodi et al., 2010; Prodi et al., 2019; Sarampalis et al., 2009). Increased listening effort can have detrimental effects on school-aged children's learning abilities in the classroom, with cascading effects on their academic performance (Bess & Hornsby, 2014a, 2014b). Therefore, it is important to investigate factors that can affect listening effort for school-aged children (e.g., SNR, age) as well as to consider certain pediatric populations that might be at risk for increased listening effort (e.g., children with UHL).

1.2 RATIONALE

Listening effort and UHL have received increased interest in recent audiological research, especially in terms of enhanced understanding, assessment, and exploring effective intervention options. As a result, this research project is located in both of these areas with a specific focus on listening effort in school-aged children with limited useable hearing unilaterally (LUHU).

The choice of test method and stimuli is of utmost importance for valid measurement of listening effort in children. Test performance can be influenced by the child's vocabulary, language competency, and cognitive abilities (Mendel, 2008). Hence, special consideration should be taken for younger children and those from multilingual backgrounds. The use of digits as speech stimuli in a listening effort measure may pose several advantages compared to using open-set word or sentence recognition stimuli that makes it more applicable for use in a multilingual context, which is typical of school-aged children in South Africa. Therefore, it is valuable to investigate if the use of digit triplet recognition in quiet and in noise in a listening effort paradigm is a valid option to assess listening effort for young school-aged children as well as children listening to nonnative speech.

Based on the Framework For Understanding Effortful Listening (FUEL; Pichora-Fuller et al., 2016) and the Ease of Language Understanding model (ELU; Rönnberg et al., 2013; Rönnberg et al., 2008), it is expected that children with hearing loss are at risk to experience more listening effort, relative to their peers with normal hearing. Existing literature on listening effort in children report mostly on children with bilateral hearing loss (e.g., Hicks & Tharpe, 2002; Hughes & Galvin, 2013; McGarrigle et al., 2019; Stelmachowicz et al., 2007). Previous studies involving children with UHL did not find significant listening effort differences between children with normal hearing (NH) and those with UHL (Lewis et al., 2016; McFadden & Pittman, 2008). A possible explanation for the non-significant finding across participant groups is that children with only minimal to mild-moderate UHL were included and they might not have experienced more listening effort than children with normal hearing. Lewis et al. (2016) suggested that children with more severe degrees of UHL would demonstrate increased listening effort. It is important to consider listening effort in school-aged children with LUHU as these children are already at greater risk for poorer speech recognition (Bess et al., 1986; Lieu et al., 2013) and additional academic assistance (Culbertson & Gilbert, 1986; Lieu et al., 2013) relative to children with milder unilateral hearing loss. Yet, to date, there is a scarcity of studies focusing on listening effort in the LUHU cohort, and the effect of intervention options on listening effort exhibited by school-aged children with LUHU is not yet available. Determining if children with LUHU experience greater listening effort compared to peers with NH and subsequently exploring the effect that intervention options might have to reduce the expected increased listening effort in school-aged children with LUHU, can advance clinical knowledge of the UHL population and contribute to enhanced management for these children.

The following research questions were therefore posed as the focus of this research:

1) *What are the effects of noise and age on listening effort in school-aged children with normal hearing from multilingual backgrounds (native English; non-native English), employing single- and dual-task paradigms with low linguistic speech stimuli (digit triplets)?*
2) *Do school-aged children with LUHU experience more listening effort relative to peers with normal hearing?*
3) *What is the effect of a personal remote microphone system (RMS) and a contralateral routing of signal (CROS) system on listening effort experienced by school-aged children with LUHU?*

CHAPTER 2

BACKGROUND:

LISTENING EFFORT AND UNILATERAL HEARING LOSS IN CHILDREN

Both listening effort and unilateral hearing loss (UHL) constitute extensive research areas with various important aspects to be considered. Therefore, the aim of this chapter is to provide a framework for the areas of listening effort and UHL in the pediatric population. Specifically, the following aspects of listening effort will be discussed: models of listening effort, consequences of increased listening effort, factors affecting listening effort for school-aged children, and measures of listening effort. This will be followed by a discussion of UHL in the pediatric population, specifically referring to the prevalence, consequences of UHL, introducing the term of limited useable hearing unilaterally (LUHU), and a discussion of intervention options for the LUHU population.

2.1 LISTENING EFFORT

Listening effort is defined as *"the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a task that involves listening in order to understand speech"* (Pichora-Fuller et al., 2016 , 11S).

2.1.1 Models of listening effort

The model of Ease of Language Understanding (ELU; Rönnberg et al., 2013; Rönnberg et al., 2008) provides a conceptual framework for listening effort. This model proposes that language understanding involves both implicit and explicit processing. A listener will implicitly, automatically, and swiftly bind language segments, for example phonemes, and then compare these units to their long-term memory store. When an easy match between the language input and long-term memory occurs, speech recognition and understanding will be obtained with minimal effort. In contrast, in situations of a mismatch (for example when the speech signal is negatively affected by background noise), the listener has to use explicit processing and additional cognitive resources to understand speech. Consequently, it is expected that a listener will experience increased listening effort in acoustical challenging situations (Rönnberg, 2003; Rönnberg et al., 2013; Rönnberg et al., 2008). The Framework for Understanding Effortful Listening (FUEL; Pichora-Fuller et al., 2016) clearly describes that cognitive demand is a key factor to listening effort and listening effort refers to the cognitive resources used by a listener to meet cognitive demands. The FUEL model extends the ELU model by adding that several factors can increase the cognitive demand of a listening task. Therefore, listening effort depends on the hearing ability of the listener, the task demand (e.g., listening in a noisy or reverberant listening situation), as well as the listener's motivation or willingness to achieve the goal of completing a listening task and consequently attain rewards for completing the task on a personal and/or social level (Pichora-Fuller et al., 2016).

The listening effort exerted by a listener might change over the time course of an activity as a function of both demand (e.g., task difficulty) and motivation (e.g., evaluation of success importance; Pichora-Fuller et al., 2016; Peele, 2018). For example, in the scenario of a school-aged child listening to a conversation during break time on the playground/in the cafeteria, the following changes in effort due to changes in cognitive demands and motivation can be expected: when little background noise is present but the conversation topic becomes increasingly interesting, there will be little change in the listening effort (cognitive demands are low) with an increase in motivation; if the conversation continues to be highly interesting but the level of background noise increases (i.e., cognitive demand increases gradually) as more children arrive on the playground/in the cafeteria, an increase in effort can be expected, yet motivation is held more or less constantly high; when the speech understanding task becomes too difficult due to high levels of background noise and the highly interesting story that finishes, an abrupt decrease in listening effort can appear as motivation decreases rapidly while cognitive demands remain constantly high. This final part of the scenario is where the threshold for listening effort is reached (Pichora-Fuller et al., 2016).

2.1.2 Consequences of increased listening effort

The consequences of increased listening effort for adults may include communicative disengagement (Hétu et al., 1988), reduced vocational involvement (Kramer et al., 2006; Nachtegaal et al., 2009), mental fatigue (Hornsby, 2013), and decreased well-being and quality of life (Hua et al., 2013) .

For children who are still developing speech, language, and listening skills and even more so for children with hearing loss, increases in sustained listening effort and subsequent stress and fatigue may negatively affect their ability to learn in a noisy educational environment leading to possible academic difficulties (Bess & Hornsby, 2014a, 2014b). In the conceptual model linking hearing loss to fatigue and school performance, Bess and Hornsby (2014b) indicate that increased listening effort is repeatedly experienced by children with hearing loss throughout a school day. Due to the hearing loss and the presence of background noise, these children may experience a communicative breakdown. This communication interruption leads to more listening effort, with the effect that less cognitive resources are available for other processing (for example for memory recall of what has been taught in the classroom). Consequently, these children experience accumulating effort that leads to fatigue and degraded cognitive processing.

The effect of fatigue in children can be extensive and should not be underestimated as previous research in children with other chronic health conditions (for example cancer, sleep deprivation, cerebral palsy, rheumatic diseases, and chronic fatigue syndrome) indicated that fatigue in children is associated with increased absenteeism from school, reduced academic performance, an inability to participate in daily activities, sleep disturbances, changes in social relationships, and an overall negative impact on quality of life (e.g., Beebe, 2011; Berrin et al., 2006; Garralda & Rangel, 2002; McCabe, 2009; Ravid et al., 2009; Stoff et al., 1989). Ultimately, sustained increased listening effort can result in the child disengaging from participation in the classroom. Subsequently, the child's learning and behavioral skills can be compromised with a decline in the child's academic performance (Bess & Hornsby, 2014b).

2.1.3 Factors affecting listening effort for school-aged children

Due to the possible negative effects of sustained listening effort, understanding the factors that affect listening effort for school-aged children and measuring listening effort in this population is imperative. It is important to note that speech understanding and listening effort are related, yet distinct concepts as people with hearing loss often complain that listening is tiring and effortful even when speech is audible, and words are recognized correctly (Pichora-Fuller et al., 2016). Furthermore, some factors affect listening effort and not speech recognition (e.g., digital noise reduction; Sarampalis et al., 2009) or affect recognition but not listening effort (e.g., reverberation; Picou et al., 2019a). Therefore, examining listening effort in addition to speech understanding, can be of clinical importance, especially for school-aged children.

Hearing loss

Listening to and understanding speech in quiet, everyday environments occurs mainly without significant effort for people with normal hearing abilities. However, for adults and children with hearing loss listening to speech in general is more complicated. According to the FUEL (Pichora-Fuller et al., 2016) and the ELU (Rönnberg et al., 2013; Rönnberg et al., 2008), children with hearing loss are thought to be at risk to experience more listening effort, compared to their peers with normal hearing. Due to the hearing loss certain parts of a verbal message might not be clear enough for recognition and understanding. Thus, the hearing loss causes a mismatch between the incoming signal and long-term memory stores and consequently more effort has to be exerted to understand speech. As the focus of this research project is on the specific population of school-aged children with LUHU, section 2.2.2 further addresses listening effort in this cohort.

Noise

Recent evidence suggests that school-aged children spend 70% to 80% of their time in school listening and learning in the presence of background noise (Crukley et al., 2011; Ricketts et al., 2017). Listening in the presence of background noise can be especially challenging even for children with normal hearing as their speech in noise recognition abilities continue to develop into late childhood and adolescent years (Elliott, 1979; Koopmans et al., 2018). Therefore, to limit the impact of noise on listening and learning, signal-to-noise ratios (SNRs) of at least +15 dB have been recommended for children to achieve successful speech understanding in academic environments (American Speech-Language-Hearing Association, 2005). However, classroom SNRs seldom adhere to suggested minimum of +15 dB as previous studies suggest that it can vary from -17 dB to +15 dB (Bradley & Sato, 2008; Crandell & Smaldino, 2000a; Larsen & Blair, 2008; Markides, 1986; Pearsons et al., 1977; Sato & Bradley, 2008). In addition, previous research suggests that children with bilateral or unilateral hearing loss may require even more favorable SNRs than children with normal hearing to understand speech in noise and to achieve comparable speech recognition performance (Crandell, 1993; Leibold et al., 2013; Ruscetta et al., 2005). Numerous previous studies confirmed that increased background noise can result in increased listening effort in adults (Desjardins & Doherty, 2013; Picou et al., 2017; Picou & Ricketts, 2014; Picou et al., 2013; Sarampalis et al., 2009; Tun et al., 2009) and children (Gustafson et al., 2014; Howard et al., 2010; Lewis et al., 2016; McGarrigle et al., 2019; Picou et al., 2019a; Picou et al., 2017). It is thus clear that school-aged children can experience increased listening effort in modern classrooms.

Age

Younger children tend to have inferior speech recognition performance in noise compared to older children (Klatte et al., 2010b; Neuman et al., 2010), therefore they might also experience increased listening effort in noisy situations. Results of previous studies indicated that older adults (with normal or near normal pure tone detection thresholds) expend more listening effort to understand speech in noise than younger adults (Desjardins & Doherty, 2013; Gosselin & Gagné, 2011a, 2011b; Rakerd et al., 1996; Tun et al., 2009). A significant effect of age on listening effort in children with normal hearing has also been found by previous investigations with younger children showing increased listening effort (indicated by slower response times) relative to older children (Lewis et al., 2016).

An investigation of age effects and of SNR on listening effort in school-aged children with normal hearing as well children with LUHU can contribute to a better understanding of the negative effects of listening in noisy classrooms across a range of ages.

2.1.4 Measures of listening effort

As it is difficult to directly measure cognitive resources involved with listening effort, investigators have used several indirect measurements to assess listening effort. In general, the following different methods for measuring listening effort exist, namely physiological measures, behavioral paradigms of recall measures and reaction or response time measures, and subjective reports.

Physiological measures

Physiological measures rely on the natural changes that occur in the body with changes in effort, for example increased pupil dilatation (Borghini & Hazan, 2018; Koelewijn et al., 2014; McGarrigle et al., 2017; Zekveld et al., 2010; Zekveld & Kramer, 2014) and perspiration (Mackersie & Cones, 2011). Electroencephalography (EEG; e.g., Strauß et al., 2014; Strauss et al., 2010; Winneke et al., 2018), functional magnetic resonance imaging (fMRI; e.g., Evans & McGettigan, 2017; Peelle, 2014) as well as optical neuroimaging (Peelle, 2017) are other physiological methodologies that can be used to measure neural associations of listening effort.

Behavioral paradigms

Recall measures

Behavioral paradigms of recall or memory measures have been used by other investigators (e.g., McCoy et al., 2005; Rabbitt, 1991). These paradigms are derived from the limited cognitive capacity model (Kahneman, 1973) stating that as more cognitive resources are used to assist speech recognition, fewer cognitive resources are available for the processes involved with recall of heard information. Listening effort is therefore reflected in fewer items that can be recalled.

Response time measures

Another category of behavioral listening effort methodologies involves a timed response, either speed of speech repetition or timed secondary task (Gagne et al., 2017) . These behavioral paradigms also rely on the assumption of a fixed cognitive capacity, indicating that a listener shows limited cognitive capacity when he/she must allocate attention when attending to simultaneous competing tasks. When more cognitive resources are allocated to assist with a specific task (e.g. understanding speech in noise), fewer cognitive resources are available for responding quickly.

The dual-task paradigm is a classic and established method to quantify listening effort (Pals et al., 2013; Sarampalis et al., 2009) and requires the participant to perform two tasks simultaneously, a primary task of speech recognition and a secondary, competing task, such as monitoring of a visual stimulus or pattern tracing. The outcomes from a dual-task paradigm are speech recognition performance and secondary task response times. Any performance decrement on the secondary task when conducting a dual-task is interpreted as a behavioral index of listening effort (Gagne et al., 2017; Hsu et al., 2017; McGarrigle et al., 2019).

Picou and colleagues (2017) reported that dual-task paradigms are valid measures of listening effort in children. Dual-task paradigms also have high ecological validity for the pediatric population. In academic contexts, learners are often required to perform dual tasking, for example writing down notes while listening to the teacher's instructions (Howard et al., 2010; McGarrigle et al., 2019). In dual-task paradigms used with children, the primary task often consists of speech recognition in noise, using age-appropriate, standardized, pre-recorded word lists. A variety of secondary tasks have been used in previous studies with children, including responding to a simple visual probe (Hicks & Tharpe, 2002; Picou et al., 2017), responding to a complex visual stimulus (Picou et al., 2017), digit recall (Choi et al., 2008; Howard et al., 2010), and dot-to-dot tasks (McFadden & Pittman, 2008).

Results across studies using dual-task paradigms with children have been found to be inconsistent. For example, the results of some studies revealed decreasing SNRs cause increased listening effort as expected (e.g., Howard et al., 2010; Picou et al., 2019a; Picou et al., 2017), yet other investigations suggest somewhat unexpected non-significant effects of changes in SNR on behavioral listening effort (Hicks & Tharpe, 2002; McFadden & Pittman, 2008; McGarrigle et al., 2019). These discrepancies can be attributed to substantial differences in methodological approaches across studies. For example, the targeted performance level in the primary task may be a potential explanation of discrepancy in results among studies regarding the effect of SNR on listening effort as measured by dual-task paradigms (McGarrigle et al., 2019). As described earlier, a listening effort threshold exists, referring to the occurrence of a general increase in response times until a speech recognition task becomes too difficult, at which level listening effort will likely decrease as reflected by faster response times (Pichora-Fuller et al., 2016). Wu and colleagues (2016) describe this type of incidence as a point of cognitive overload. According to Wu et al. (2016), listening effort peaks around 30-50% speech recognition performance. For higher or lower performance levels, changes in speech recognition performance or SNR might result in smaller changes in effort because the task is too easy, or participants have disengaged due to possible cognitive overload. McGarrigle et al. (2019) stated that the more challenging SNRs that were used in their study (particularly for children with a hearing loss, resulting in < 50% word recognition) may have resulted in more frequent occurrences of cognitive overload, resulting in non-significant effects of SNR on listening effort with decreasing SNRs. In contrast, Howard et al. (2010) reported significant effects of SNR on listening effort in children with normal hearing with speech recognition scores of ~50% in noise and ~90% in quiet. However, in the study by Hicks and Tharpe (2002), the average word recognition performance of 85% resulted in nonsignificant effects of SNR in listening effort.

The use of secondary tasks that are not motivating or too distracting, for example the use of digit recall (Choi et al., 2008; Howard et al., 2010) and dot-to-dot games (McFadden & Pittman, 2008), may also cause a decline on the primary task performance and consequently lead to insignificant listening effort findings. In addition, factors such as cognitive resource allocation among multiple simultaneous tasks and attention allocation abilities are associated with the interpretation of dual-task results (Gagne et al., 2017; McGarrigle et al., 2019). These abilities might not yet be fully developed in school-aged children and could therefore contribute to the general variance in dual-task performance (Choi et al., 2008; McGarrigle et al., 2019).

Verbal response time measures, as single-task paradigm, can also be employed as a behavioral measure of listening effort in the pediatric population (e.g., Gustafson et al., 2014; McGarrigle et al., 2019). Similar to a dual-task paradigm, the outcomes from a single-task paradigm also include both speech recognition performance and response times. In such a paradigm, participants repeat speech and the time between stimulus presentation and verbal response is recorded. Cowan and colleagues (2003) suggested that increases in verbal response times in nonword recognition tasks reflect an increase in the amount of time that children need to process a signal, with longer response times reflecting greater processing effort. Numerous previous studies in the pediatric population have successfully used verbal response time measures to indicate that increased listening effort is reflected by longer verbal response times (Gustafson et al., 2014; Houben et al., 2013; Lewis et al., 2016; McGarrigle et al., 2019; Pals et al., 2015; Prodi et al., 2019). These findings support the use of such a single-task paradigm as a listening effort measure for school-aged children.

There is no consensus yet on which behavioral method is the best to apply when measuring listening effort in adults and/or children (Gagne et al., 2017). Recently, McGarrigle and colleagues (2019) compared results with a single- and a dual-task paradigm with school-aged children (aged 6-13 years). Participants with normal hearing and hearing loss (unaided and aided) completed a single- and a dual-task paradigm in several SNRs. Results indicated that the verbal response times were significantly more sensitive to reveal the effects of SNR and hearing loss on listening effort relative to the secondary task response times (i.e., dual-task paradigm). The authors concluded that possible reasons for the nonsignificant findings could include the large variability in responses for the younger participants and that the speech recognition performance levels were too poor to be sensitive to changes in SNR. Therefore, it is imperative that measures of listening effort are valid and sensitive for the targeted population and context to be used in (Picou et al., 2017).

Subjective measures

In addition to objective, behavioral measures of effort, subjective measures can be used as an indirect measure of listening effort. Subjective indices of listening effort can include standardized questionnaires, for example The Speech, Spatial and Qualities of Hearing Scale (SSQ; Gatehouse & Noble, 2004) or rating scales of effort (e.g., Fraser et al., 2010; Picou et al., 2011). Reports of the use subjective indices of listening effort in the pediatric population is scarce. The few studies that have reported subjective effort with children have used study-specific questionnaires (Gustafson et al., 2014; Picou et al., 2019a). Although limited, this available data suggest that, as with adults, results of behavioral listening effort measures and subjective ratings can be discrepant, possibly reflecting that subjective measures target a different aspect of listening effort than behavioral measures (Gustafson et al., 2014; Hicks & Tharpe, 2002; Picou et al., 2019a). However, the use of self-report measures of listening effort can be useful as it has the advantages of low technological demands and high face validity. Furthermore, subjective ratings have the potential to determine the effect of listening effort in different listening situations for school-aged children with normal, peripheral hearing sensitivity and for school-aged children with hearing loss that is not directly assessed by traditional hearing assessments. Therefore, further investigation to determine if the results of subjective indices of listening effort correspond to the results of behavioral measures of listening effort in the school-aged population can be of clinical importance. Such measures can also include considerations of aspects that affects the motivation of the listener as it is known that motivation can also affect listening effort (Peelle, 2018; Pichora-Fuller et al., 2016).

Speech stimuli considerations

In addition to methodological considerations of paradigm choice, the choice of speech stimulus is also an important consideration for listening effort outcomes in modern classrooms with children from different language backgrounds. According to the ELU model and the FUEL, a factor that can also interfere with the input memory match and thus contribute to increased listening effort is a non-native listener's speech perception (e.g., listening to a speaker with an unfamiliar accent; Peelle, 2018; Pichora-Fuller et al., 2016; Rönnberg, 2003; Rönnberg et al., 2013; Van Engen & Peelle, 2014). Previous studies have demonstrated increased listening effort for non-native adult listeners compared to native listeners in adverse SNR and reverberating conditions by means of physiological (e.g., pupillometry; Borghini & Hazan, 2018) as well as dual-task and subjective measures (e.g., Peng & Wang, 2019).

Multilingualism in the educational context is a universal reality and classrooms often include learners from diverse native language backgrounds, leading them to communicate and learn in a non-native language. The typical speech materials used in listening effort measures are age-appropriate, standardized, pre-recorded word or sentence lists. In a multilingual context, the use of word lists, with a high linguistic demand, could pose a challenge for younger children and for children who may not be native speakers of the language of the word lists. Instead of words or sentences, digits offer a potential solution as speech stimuli as digits are universal, everyday concepts that children are exposed to from early childhood. Therefore, digits might be a suitable choice of speech stimulus for children from multilingual backgrounds, because they are highly familiar spoken words, stem from a closed set, and the linguistic demand is low (Kaandorp et al., 2016; Smits et al., 2013). In addition, Koopmans et al. (2018) reported that digit recognition in noise can be successfully and reliably used in children from as young as four years of age. It would be important to explore if digits as speech stimuli can be useful in behavioral measures of listening effort in young, school-aged children from multilingual backgrounds as it is not clear if the use of such low context, high familiarity speech stimuli will be immune to the potential effects of using non-native language during listening effort testing for children from multilingual backgrounds.

Considering the negative impact that listening effort and resultant fatigue can have on academic performance and general quality of life of school-aged children (Bess & Hornsby, 2014a, 2014b), it is important to investigate specific listening conditions and population characteristics that might increase listening effort. One population that might be at risk of experiencing increased listening effort, relative to children with normal hearing, is children with unilateral hearing loss (UHL).

2.2 UNILATERAL HEARING LOSS IN THE PEDIATRIC POPULATION

There is a renewed interest in the field of unilateral hearing loss (UHL) in children as these children still tend to struggle academically and behaviorally, despite the improved and earlier identification of UHL and intervention provided (Bagatto et al., 2019).

2.2.1 Definition and prevalence of UHL

Definition

UHL is defined as any degree of permanent hearing loss in one ear (pure-tone average [500, 1000, 2000 Hz] > 15 dB for children), regardless of etiology, with normal hearing in the opposite ear (Bagatto et al., 2019). Children with UHL, minimal (defined as pure-tone average greater than or equal to 15 dB HL and less than or equal to 25 dB HL; Porter et al., 2017) to mild bilateral hearing loss (bilateral sensorineural hearing loss with average air-conduction thresholds between 20 and 40 dB HL with air-bone gaps no greater than 10 dB at 1000, 2000 and 4000 Hz; Porter et al., 2017) as well as high frequency hearing loss (defined as air-conduction thresholds greater than 25 dB HL at two or more frequencies above 2000 Hz in one or both ears with air-bone gaps at 3000 and 4000 Hz no greater than 10 dB; Porter et al., 2017) have previously been grouped together under the umbrella term of 'minimal hearing loss' (Bess et al., 1998). Recently, it has been recommended that characteristics and outcomes of children with UHL should be reported separately from children with bilateral hearing losses as these populations have different listening needs and consequently intervention options and outcomes can differ (Bagatto et al., 2019). In addition, where the effects of UHL or management options can be expected to vary by the degree of severity of the UHL (e.g., Lieu et al., 2010), baseline characteristics and outcomes should be clearly defined in terms of categories of severity of UHL (Bagatto et al., 2019).

Prevalence

The prevalence of permanent sensorineural UHL is estimated at 1 per 1000 newborns (Prieve & Stevens, 2000). It is reported that approximately 2.5–3% of school-aged children present with unilateral hearing loss (UHL) with an increase in prevalence of up to 14% in adolescents (Bess et al., 1998; Shargorodsky et al., 2010). The increase in prevalence emphasizes the importance for continuous monitoring of children with UHL (Bagatto et al., 2019). The need for ongoing vigilance is furthermore accentuated by evidence that shows that UHL progresses to bilateral hearing loss in 7.5 to 17% of cases (Fitzpatrick et al., 2017; Haffey et al., 2013; Paul et al., 2017). The latter contributes to the finding that approximately 40% of children with UHL are at risk for deterioration of hearing either in the impaired ear and/or in the normal hearing ear (Fitzpatrick et al., 2017).

2.2.2 Consequences of UHL

General consequences associated with UHL

The fundamental difficulties associated with UHL is grounded in the fact that UHL can result in a loss of the advantages of binaural listening skills due to the loss of interaural time difference (ITD) and interaural level difference (ILD) cues. ITDs and ILDs are the primary cues used in binaural hearing and assist the auditory system to separate relevant from irrelevant acoustic cues (Arndt et al., 2014). This is imperative for speech understanding in noisy environments, such as typical classrooms. ILD cues are relevant to low frequency sounds and ITDs to high frequency sounds, resulting in the head-shadow effect, summation effect and the squelch effect (i.e., binaural release of masking; Colburn & Latimer, 1978). Combined, these effects support speech recognition in noise (spatially separated speech and noise conditions), and even with midline signals (Van Deun et al., 2010).

For children with UHL the loss of ITD and ILD cues causes the loss of binaural hearing with a direct negative impact on localization (Johnstone et al., 2010) as well as speech perception (Bess et al., 1986), especially in noise (Bess & Tharpe, 1986b; Bess et al., 1986; Ruscetta et al., 2005). As a result, there is cumulative evidence that children with UHL have a greater risk of poorer speech, language, and cognitive outcomes compared to normal hearing peers (Ead et al., 2013; Lieu, 2013). This could lead to behavioral problems (Lieu, 2004) and academic difficulties such as increased need for additional academic assistance (Bess et al., 1986; Lieu, 2004; Oyler et al., 1988).

Consequences associated with limited useable hearing unilaterally (LUHU)

The afore-mentioned risks can even be more pronounced for children with unaidable unilateral hearing loss (Bess et al., 1986; Culbertson & Gilbert, 1986; Lieu et al., 2013), defined as greater than severe unilateral sensorineural hearing loss and/or poor word recognition. Unaidable unilateral hearing loss has been referred to as "single sided deafness" (SSD) or "limited useable hearing unilaterally" (LUHU; Picou et al., 2020a; Picou et al., 2020b; Picou et al., 2019b). The term LUHU will be used hereafter because it is a more specific description of a person's expected auditory abilities.

Compared to children with milder degrees of unilateral hearing loss, children with LUHU have a greater risk of poorer speech recognition (Bess et al., 1986; Lieu et al., 2013) and an increased need for academic assistance (Culbertson & Gilbert, 1986; Lieu et al., 2013). In addition to difficulties with speech understanding in noise, children with LUHU are expected to have significant difficulty understanding indirect speech (Corbin et al., 2017; Kenworthy et al., 1990). Speech understanding deficits for children with LUHU relative to peers with normal hearing have also been reported for conditions where speech is presented from the midline (Ruscetta et al., 2005), and even in a more favorable, direct listening situations (Bess et al., 1986).

The listening difficulties that children with LUHU experience reflect back to the loss of binaural listening advantages of binaural summation, head shadow effect, and binaural squelch (i.e., binaural release from masking) due to a loss of ITD and ILD cues. In situations where speech and noise are spatially separated, the head shadow effect will lead to differences in SNR at the two ears. Listeners with bilateral normal hearing can selectively attend to the ear with the more favorable SNR and consequently achieve superior levels of speech perception, when compared to listeners with only monaural hearing (Van Deun et al., 2010). Conversely, children with LUHU will not be able to make use of ITD and ILD cues for spatially separated speech and noise signals in order to effectively suppress the noise signal and enhance the speech signal. The head shadow effect is greatest in the high frequencies. Therefore, a reduction in high frequency speech sounds when the speech signal is from the LUHU side (i.e., indirect speech) can be expected. This could lead to significant speech recognition difficulties since high frequency consonant sounds are known to provide 60% of speech intelligibility (Bess & Tharpe, 1986b).

Children with LUHU will also not be able to take advantage of binaural summation, the advantage from listening to sound that is presented to both ears simultaneously. This may contribute to improved speech understanding in difficult listening situations where the competing sound source (noise) and the speech source are spatially separated (Colburn & Latimer, 1978; Van Deun et al., 2010). Children with NH may also benefit from binaural summation in a listening condition where there are few interaural time or level differences (i.e., spatially coincident speech and noise) to improve speech recognition performance in noise (Bronkhorst & Plomp, 1988; Davis et al., 1990; Gallun et al., 2005). Conversely, children with LUHU will not be able to benefit from binaural summation in such a situation.

Taken together, findings of the extant literature emphasize that children with LUHU might be at a disadvantage for speech understanding in all noisy listening conditions. However, it is less clear if children with LUHU are at risk to experience more listening effort in noisy listening scenarios compared to peers with NH.

Listening effort in children with LUHU

From the FUEL and the ELU model, if the loss of unilateral audibility and loss of binaural cues impede a match between the incoming signal and long-term memory stores, children with LUHU would also be expected to exhibit more listening effort than peers with normal hearing, especially in noisy listening situations. However, conclusions regarding the effect of UHL on listening effort have been indefinite.

Previous studies of listening effort in children with UHL included children with various degrees of UHL, mostly mild to moderate as well as children with mild bilateral hearing loss and children with NH (Lewis et al., 2016; McFadden & Pittman, 2008). The results of studies by Lewis et al. (2016), and McFadden and Pittman (2008), using a single-task paradigm (verbal response time) and a dual-task paradigm respectively, resulted in similar response times for children with NH, children with UHL and those with mild bilateral hearing loss. The authors stated that a possible reason for the absence of significant hearing status differences in these studies is the inclusion of heterogeneous degrees of unilateral and/or bilateral hearing loss. Children with mild degrees of bilateral hearing loss and children with minimal to mild-moderate degrees unilateral hearing loss were included and possibly did not experience increased listening effort compared to their peers with normal hearing. Lewis et al. (2016) suggested that children with more severe degrees of UHL could possibly exhibit more pronounced listening effort effects that are not seen in participants with milder degrees of UHL. This can be inferred by the fact that children with more severe UHL are at greater risk than children with milder degrees of UHL for speech recognition (Bess et al., 1986; Lieu et al., 2013) and academic difficulties (Culbertson & Gilbert, 1986; Lieu et al., 2013). To date, no previous studies focused on the sub-group of school-aged children with LUHU in terms of possible greater listening effort compared to peers with bilateral normal hearing.

2.2.3 Intervention options for LUHU

There is little evidence of effective intervention options that can alleviate the pronounced speech-in-noise recognition, behavioral, and academic difficulties experienced by children with LUHU (Bagatto et al., 2019). Considering the various negative consequences that increased listening effort may have, it would be important to determine the effect of intervention options on listening effort in children with LUHU. This can support clinicians' recommendation of the type of intervention options for school-aged children with LUHU.

The audiological management of children with UHL should be patient- and family-centered and decisions regarding the choice of intervention should be done on an individual basis based on unique family-identified concerns, priorities, goals, and desires (Bagatto et al., 2019; Moeller et al., 2013; Porter et al., 2017).

Surgical intervention options

Surgical or implantable intervention options for children with LUHU include bone-conduction devices and cochlear implantation (Bagatto et al., 2019). Yet, limited data are available on the use and benefit of implantable bone-conduction technology in children with LUHU (American Academy of Audiology, 2013; Christensen et al., 2010; Porter et al., 2017). The use of cochlear implantation as treatment option for children and adults with LUHU is emerging. Although limited, preliminary studies of cochlear implantation in children with LUHU reveal encouraging results such as improved word and sentence recognition on the implanted, LUHU side (Friedmann et al., 2016; Sladen et al., 2017a; Sladen et al., 2017b), and modest improvements in overall speech recognition in noise (Friedmann et al., 2016; Rahne & Plontke, 2016; Sladen et al., 2017b). However, it should be noted that there are also reports of children with congenital UHL and longer periods of auditory deprivation that present with limited use of their cochlear implant device or who became non-users after implantation (Sladen et al., 2017a; Távora-Vieira & Rajan, 2015; Thomas et al., 2017). Therefore, continued research is needed to provide evidence based findings of the viability of cochlear implantation in children with LUHU (Krishnan & Van Hyfte, 2016; Porter et al., 2017).

Non-surgical intervention options

Current non-surgical intervention options for children with LUHU include preferential seating alone or in combination with either a remote microphone system (RMS) or a contralateral routing of signal (CROS) system.

Remote microphone system (RMS)

An RMS is recommended as first-line treatment for certain listening situations if the UHL is profound in degree, thus for an unaidable ear. An RMS is a wireless microphone system that converts audio signals into radio or digital signals and transmits sounds via frequency modulation (FM) or digital modulation (DM) to a receiver at the listener's ear or a receiver near the listener (Bagatto et al., 2019). Remote receiver options include a personal ear level RMS, a classroom audio distribution system, or a personal desktop speaker. RMSs improve the signal-to-noise ratio for the listener by overcoming noise, distance, and reverberation by placing a microphone (transmitter) close to the mouth of a talker (Thibodeau, 2014; Wolfe et al., 2016). Current guidelines state that RMSs are the preferred choice of intervention recommended for school-aged with LUHU in classrooms as they offer the most consistent speech recognition benefits by increasing the SNR (e.g., American Academy of Audiology, 2013). The provision of a conventional hearing aid as a first-line treatment is not recommended for children with LUHU but rather only for children with UHL that is moderate to severe in degree (Bagatto et al., 2019).

Contralateral routing of signal (CROS) system

In a CROS system, which includes two ear-level devices, sound is transmitted from the ear with limited useable hearing to the ear with better hearing. Currently, CROS systems are typically used when no benefit is expected from fitting conventional amplification to the ear with hearing loss (Bagatto et al., 2019). The purpose of CROS fittings is to re-route speech that is directed to the ear with limited useable hearing (i.e., indirect speech) to the ear with better hearing. It is important to counsel children with LUHU and their families on the following considerations when considering the fitting of a CROS system (Bagatto et al., 2019):

1) When fitting a conventional CROS system, occlusion of the normal hearing ear by an earmold should be avoided to prevent reduced benefit from natural hearing.
2) The use of a CROS system is unlikely to improve localization as it does not enable the use of binaural hearing abilities, which is necessary for sound localization.
3) As stated, CROS fittings can improve detection of speech on the side of the limited useable hearing under quiet listening situations by re-routing the speech to the better ear. However, the use of a CROS can be detrimental with direct speech and indirect noise. In such a situation the CROS would enable the presentation of interfering noise to the ear with normal hearing when the noise would previously have been reduced due to head shadow effects in the unaided

condition. Therefore, the CROS system might impair speech recognition in complex listening situations, especially if children are unable to control their device or orient themselves in the listening environment (e.g., American Academy of Audiology, 2013; Lieu, 2015; McKay et al., 2008). As a result, CROS hearing aid systems have not previously been recommended for young children (McKay et al., 2008).

These recommendations of RMS and CROS as non-surgical intervention options for children with LUHU are based in part on two studies conducted in the 1990s focusing on speech recognition in noise performance (Kenworthy et al., 1990; Updike, 1994). Kenworthy and colleagues (1990), evaluated speech recognition in noise for 6 children (8- to 12-year-old children) with moderate to profound UHL. Three interventions (none, CROS, RMS) were evaluated in three listening configurations: monaural direct (speech presented at 45˚ relative to ear with normal hearing; noise presented at 45˚ relative to ear with unilateral hearing loss), monaural indirect (speech presented at 45˚ relative to ear with unilateral hearing loss; noise presented at 45˚ relative to ear with normal hearing), and midline signal (speech presented at 0˚; noise presented at 135˚, 180˚, 225˚ relative to midline). The remote microphone was always placed near the speaker from where the speech signal was presented. Results revealed RMS benefits for improved speech recognition in noise in the midline and indirect speaker conditions, and CROS benefits limited to only the indirect condition. CROS detriments were evident in the midline and direct speaker conditions. Updike (1994) confirmed consistent benefits of RMS for children with UHL to achieve improved speech recognition in noise in a midline listening situation.

The current applicability of the afore-mentioned studies by Kenworthy and colleagues (1990) and Updike (1994) is limited by the small number of subjects as well as more recent advances in all classes of amplification technologies (Bagatto et al., 2019). Furthermore, modern classrooms environments are dynamic in nature and everyone in the classroom can be a potential speaker of interest. Thus, CROS systems might have more potential to improve classroom communication than was suggested by previous laboratory studies (Picou et al., 2020b). Indeed, results from a recent study by Picou and colleagues (2020a) revealed a significant benefit of a CROS system over an RMS when the remote microphone had a single location (i.e., the remote microphone stayed in front of the child). The CROS significantly improved sentence recognition and story comprehension in an indirect listening situation for children with LUHU.

It is clear that the majority of previous studies that reported on the effect of various intervention options for children with LUHU focused on speech recognition performance. With reference to the FUEL framework, research exploring within-subject comparisons on how listening effort is affected by intervention options is warranted (Pichora-Fuller et al., 2016). Determining the effect of intervention options on listening effort for children with LUHU is important given the increased academic difficulties that these children might experience together with the detrimental effects that listening effort and the resultant fatigue can have on academic performance and quality of life (Bess & Hornsby, 2014a, 2014b). However, no previous research studies examined the effect of non-surgical intervention options of RMS and a CROS system on listening effort for children with LUHU.

2.2.4 Conclusion

From the discussion of listening effort, the effects thereof and the consequences of UHL that are more pronounced for children with LUHU, research focusing on listening effort in the specific population of school-aged children with LUHU is warranted. Focusing specifically on the sub-group of LUHU is in accordance with the guidelines in the recent consensus practice parameter for children with UHL, stating that where the effects of UHL or intervention options can be expected to vary by the degree of severity of the UHL, outcomes should be reported according to categories of severity (Bagatto et al., 2019).

Determining if school-aged children with LUHU experience more listening effort compared to children with bilateral normal hearing has the potential to advance the discipline of pediatric audiology. Furthermore, it would be important to examine the efficacy that non-surgical intervention options of RMS and CROS for children with

LUHU might have on reducing increased listening effort experienced in noisy situations. The goal of reducing listening effort by means of these intervention options would be to enable these children to accomplish successful participation in academic and social situations (Pichora-Fuller et al., 2016). Findings of such research studies have the potential to advance clinicians' understanding of the speech-in-noise recognition difficulties that children with LUHU present with by extending it to a more comprehensive picture of the cognitive impact (i.e., listening effort) of listening in noise as well as to support recommendations in terms of the type of intervention option recommended for these children.

CHAPTER 3

METHOD

3.1 RESEARCH OBJECTIVES AND STUDY DESIGN

The main aim of this study was to investigate listening effort in school-aged children with LUHU. In order to achieve this main aim, the research project was divided into three research objectives, each constituting a research study that was submitted as an article to an accredited, peer reviewed journal upon completion. These three studies are summarized below according to titles, objectives, and research design.

3.1.1 STUDY I: Listening effort in native and non-native English-speaking children using low linguistic single- and dual-task paradigms

Research objectives

To develop single- and dual-task listening effort paradigms with low-linguistic speech stimuli (digit triplets) in order to explore the effects of SNR on listening effort in multilingual school-aged children (native English; non-native English), and to determine age effects on digit triplet recognition and response times.

Study design

A descriptive and comparative cross-sectional research designs were applied to explore the effects of SNR, language background, and age on the outcomes of digit triplet recognition and response times (Leedy & Ormrod, 2014).

3.1.2 STUDY II: Listening effort in school-aged children with normal hearing compared to children with limited useable hearing unilaterally

Research objectives

To determine if school-aged children with limited useable hearing unilaterally (LUHU) experience more listening effort relative to peers with bilateral normal hearing (NH), by employing behavioral and subjective indices of listening effort, namely a single-task paradigm as well as subjective ratings.

Study design

This study followed descriptive and comparative cross-sectional research designs to compare listening effort exhibited by school-aged children with LUHU relative to listening effort exhibited by school-aged children with normal hearing (Leedy & Ormrod, 2014; Strydom, 2011). Age was included as a covariate in the statistical analyses.

3.1.3 STUDY III: Listening effort in school-aged children with limited useable hearing unilaterally: Examining the effects of a personal, digital remote microphone system and a contralateral routing of signal system

Research objectives

To evaluate the effects of a personal, digital RMS and CROS hearing aid system on listening effort experienced by school-aged children with limited useable hearing unilaterally by means of a single-task, listening effort paradigm and subjective ratings.

Study design

A quantitative within-subject design was followed to determine the effects of two intervention options on listening effort experienced by school-aged children with LUHU (Leedy & Ormrod, 2014).

3.2 RESEARCH PARTICIPANTS

The research study included a total of 97 school-aged children, aged 7 to 12 years. The research was conducted at the Eduplex Audiology Department at the Eduplex Primary School in Pretoria, Gauteng Province. Data collection also took place at a private audiology practice in the Western Cape Province.

Table 3.1 provides a detailed summary of the participant selection criteria, participant sampling method, and sample size.

TABLE 3.1 Participant selection criteria, sampling method, and sample size

Study	I	II	III
Title	Listening effort in native and non-native English-speaking children using low linguistic single- and dual-task paradigms	Listening effort in school-aged children with normal hearing compared to children with limited useable hearing unilaterally	Listening effort in school-aged children with limited useable hearing unilaterally: Examining the effects of a personal, digital remote microphone system and a contralateral routing of signal system
Participant selection criteria	School-aged children: 7-12 years of age. Participants were grouped into three age groups, namely 7-8 years of age, 9-10 years of age, and 11-12 years of age. The different age groups were used to explore age effect on digit triplet recognition and response times. Language: English native or English non-native speakers. Normal otoscopic examination findings and normal middle ear function as determined by tympanometry. If abnormal middle-ear functioning was present, the participant was referred to an Ear, Nose, and Throat (ENT) specialist for treatment. Tympanometry was repeated after treatment to ensure normal middle ear function before data collection commenced. Normal peripheral hearing sensitivity in both ears (≤ 15 dB HL for octave frequencies from 250 to 8000 Hz; and correlating speech audiometry results including speech reception threshold testing by means of spondee words and phonetically-balanced monosyllabic word recognition testing as described in section 3.4.1). No otologic, cognitive, or neurological disorders, as evident from parental and/or	**Group1:** School-aged children with bilateral normal hearing (NH) Target age group: 7-12 years of age. Participants with normal hearing had a peer with LUHU of similar age and language background. Language: native English or non-native English. Normal otoscopic examination findings and normal middle ear function as determined by tympanometry. If abnormal middle-ear functioning was present, the participant was referred to an Ear, Nose, and Throat (ENT) specialist for treatment. Tympanometry was repeated after treatment to ensure normal middle ear function before data collection commenced. Normal peripheral hearing sensitivity in both ears (≤ 15 dB HL for octave frequencies from 250 to 8000 Hz; and correlating speech audiometry results including speech reception threshold testing by means of spondee words and phonetically-balanced monosyllabic word recognition testing as described in section 3.4.2). No otologic, cognitive, or neurological disorders, as evident from parental and/or	Target age group: 7-12 years of age. Language: native English or non-native English. Normal otoscopic examination findings and normal middle ear function as determined by tympanometry. If abnormal middle-ear functioning was present, the participant was referred to an Ear, Nose, and Throat (ENT) specialist for treatment. Tympanometry was repeated after treatment to ensure normal middle ear function before data collection commenced. Normal peripheral hearing sensitivity in one ear (≤ 15 dB HL for octave frequencies from 250 to 8000 Hz; and correlating speech audiometry results including speech reception threshold testing by means of spondee words and phonetically-balanced monosyllabic word recognition testing as described in section 3.4.3). Limited useable hearing in the opposite ear characterized by air conduction thresholds > 70 dB HL from 250 Hz to 8000 Hz, an average air-bone gap no greater than 10 dB at 1000 Hz, 2000 Hz, and 4000 Hz, as well as poor phonetically-balanced monosyllabic word recognition (<70%; Madell et al., 2011).

teacher report. Participants had normal speech, language, and motor development as confirmed by parental report.
Participants had normal visual acuity as determined by a visual acuity screening test (smartphone application for Tumbling-E visual acuity testing;Rono et al., 2018). If the visual screening was failed, a diagnostic visual examination was recommended before data collection commenced.

teacher report. Participants had normal speech, language, and motor development as confirmed by parental report.

Group 2: School-aged children with LUHU

Target age group: 7-12 years of age.
Language: native English or non-native English
Normal otoscopic examination findings and normal middle ear function as determined by tympanometry. If abnormal middle-ear functioning was present, the participant was referred to an Ear, Nose, and Throat (ENT) specialist for treatment. Tympanometry was repeated after treatment to ensure normal middle ear function before data collection commenced.
Normal peripheral hearing sensitivity in one ear (≤ 15 dB HL for octave frequencies from 250 to 8000 Hz; and correlating speech audiometry results including speech reception threshold testing by means of spondee words and phonetically-balanced monosyllabic word recognition testing as described in section 3.4.2).
Limited useable hearing in the opposite ear characterized by air conduction thresholds > 70 dB HL from 250 Hz to 8000 Hz, an average air-bone gap no greater than 10 dB at 1000 Hz, 2000 Hz, and 4000 Hz, as well as poor phonetically-balanced monosyllabic word recognition (<70%; Madell et al., 2011).
No cognitive or neurological disorders, as evident from parental and/or teacher report. Participants had typical speech, language, and motor development as confirmed by parental report.

No cognitive or neurological disorders, as evident from parental and/or teacher report. Participants had typical speech, language, and motor development as confirmed by parental report.

Participant sampling method	Non-probability purposive sampling (Leedy & Ormrod, 2014)		
Sample size	60 school-aged children (aged 7-12 years) with bilateral normal hearing: 30 with English as native language and 30 with English as non-native language.	37 school-aged children (aged 7-12 years): 18 with bilateral normal hearing; 19 with LUHU.	19 school-aged children (aged 7-12 years) with LUHU.

3.3 RESEARCH EQUIPMENT AND MATERIAL

The following equipment and material were used during data collection procedures of the proposed studies.

3.3.1 Otoscopy and tympanometry

A Heine Mini 3000™ (Heine, Germany) otoscope with reusable specula was used to visualize and identify any obvious abnormalities of the outer ear canal and tympanic membrane of all participants. A Grason-Stadler GSI Tympstar V2™ diagnostic tympanometer (Grayson Stadler, Eden Prairie, USA) with a probe tone of 226 Hz was used to determine middle ear functioning. Normal middle ear functioning was indicated by a type A tympanogram in terms of ear canal volume of 0.42 to 0.97 cm^3, middle ear pressure of -151 to 59 daPa, and compliance of 0.22 to 0.9 ml (Martin & Clark, 2003; Palmu & Rahko, 2003). The Tympstar V2™ was calibrated according to the SANS 10154-1/2 10182 standards.

3.3.2 Diagnostic audiometry

Diagnostic audiometric procedures of pure tone audiometry and speech audiometry was conducted on all participants using a diagnostic Grason-Stadler GSI Audiostar Pro™ audiometer (Grayson Stadler, Eden Prairie, USA). The audiometer was calibrated according to the SANS 10154-1/2 10182 standards utilizing the Telephonics TDH-50P audiometric earphones. All procedures for diagnostic audiometric as well as for listening effort testing were conducted in a double-walled, sound-attenuating audiometric test booth (2.13m x 2.03m x 2.43m). For the listening effort test procedures, three (3) Grason-Stadler GSI 90 dB loudspeakers (Grayson Stadler, Eden Prairie, USA) were located at 0°, 90° and 270° in the booth in order to create three listening configurations of midline, monaural direct, and monaural indirect (see detailed descriptions at 3.4.2 and 3.4.3). The loudspeakers were situated at a distance of 1 meter from the participant.

3.3.3 Visual acuity assessment

A validated smartphone vision screening application called Peek Acuity™ (smartphone application for Tumbling-E visual acuity testing; Rono et al., 2018) was used on a

Huawei P-Smart device to conduct a visual screening test on each participant of Study I. This was done to ensure normal visual acuity as participants were required to respond to visual stimuli on a touchscreen computer during dual-task testing of the listening effort test procedures (see description at 3.3.4).

3.3.4 Single- and dual-task paradigms: equipment development and recordings

Low-linguistic listening effort tests (single-task and dual-task paradigms) were developed in English in collaboration with supervisors and Prof Herman Myburgh, co-author on the research papers.

Dual-task paradigm

Primary Task

The primary task consisted of digit triplet recognition. The digit triplets used were from the digit triplets available from the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018). South African English mono- and bi-syllabic digits (0–9), spoken by a female speaker were selected and recorded to create digit triplet sets. A detailed description of the development of this digit-in-noise test can be found in Potgieter et al. (2018, 2016). Twenty-five lists consisting of 20 digit triplets each were created in order to ensure no repetition of a digit triplet list in various test conditions. Digit noise files from the digit-in-noise test were also stored on the audiometer and selected from the internal files for test conditions with noise. Digit triplets were presented through custom programming of MATLAB software (MATLAB R2015a) on a Dell OPTIPLEX 7460 AIO 23.8" touchscreen computer, routed to the audiometer, and then to a loudspeaker. During noise conditions, digit noise was routed from the audiometer to a loudspeaker(s). Output levels for digit triplets and digit noise were measured by means of a sound level meter to ensure the correct output level in the sound field. The microphone of the sound level meter was at a position equivalent to center of the participant's head. The digit noise was used during the measurement of output levels because it matches the long-term average speech spectrum of the digits (Potgieter et al., 2016). Participants' verbal responses were recorded by a head-worn microphone of an OVLENG X6 headphone set (OVLENG, Shenzhen, China) and saved by a custom software program (MATLAB R2015a) in participant specific files.

Percent correct digit triplet recognition scores were calculated by scoring the participants' verbal responses to the digit triplets that were presented in a specific list.

Secondary Task

The secondary task was a measure of response time (RT) to a visual stimulus presented through a custom programming of MATLAB software (MATLAB R2015a) on a touchscreen computer (Dell OPTIPLEX 7460 AIO 23.8" touchscreen computer) placed directly in front of a participant. A colored shape (basic shapes, namely circle, triangle, or square presented in basic colors of red, blue, yellow, or green) of 10 cm in diameter appeared against a black background on the touchscreen and disappeared as soon as the participant touched on the shape on the touchscreen or after 3000 ms. The color and the shape of the visual stimuli were varied randomly to help keep participants' interest to the listening task. RTs to each visual stimulus as well as the mean RT per list were automatically recorded using customized software on MATLAB and stored in participant specific files.

Dual-Task Conditions

In dual-task conditions, both the primary and secondary tasks had to be completed simultaneously. Visual stimuli appeared 500 ms after digit triplet onset. The visual stimuli were programmed to appear randomly with a 50% probability rate. The measure of listening effort was the RT to the visual stimuli. Participants' RTs to visual stimuli were automatically recorded using customized software on MATLAB and stored in participant specific files.

Single-task paradigm

The speech stimuli in the single-task paradigm were the same as those in the dual-task paradigm. Participants' verbal responses were recorded by a head-worn microphone (as described earlier). The verbal response time (VRT) for each verbal response of the participants as well as the mean VRT for each digit triplet list were automatically analyzed by the programming software on the custom MATLAB program (MATLAB R2015a) and saved in specific files for each participant. VRTs were automatically calculated by the MATLAB program by measuring the time elapsed from the end of the digit triplet to the onset of the participant's response.

3.3.5 Intervention technology options: fitting and verification (Study III)

Remote microphone system (RMS)

A digital ear-level, personal RMS receiver, Phonak Roger™ Focus, was fitted on the normal hearing ear of each participant. The ear-level RMS receiver was paired to a Phonak Roger™ Touchscreen remote microphone. The remote microphone was always placed at the loudspeaker of interest, as displayed by a rectangle labelled 'remote mic' in Figure 6.1.

Contralateral routing of signal (CROS) system

A CROS hearing aid, Phonak CROS B-312, was fitted to the ear with the severe-profound sensorineural hearing loss with a helix hook for stability and retention. A receiver hearing aid, Phonak Sky B70-M, (open fitting) was fitted to the normal hearing ear of each participant.

Audioscan Verifit Real Ear System

Prior to the data collection of Study III, fitting and verification procedures for the RMS and CROS system were conducted on each participant using the Audioscan Verifit Real Ear System (Audioscan, Dorchester, Ontario). These procedures are discussed in detail at section 3.4.3.

3.3.6 Data collection material

Each research site, school, and participating private audiology practices were provided with an information letter explaining the purpose of the research project and requesting permission to use the site to access participants and/or assist in recruitment of participants (Appendices B and C). Parents/guardians of participants were provided with an information letter and consent form that explained all the test procedures in detail before testing commenced (Appendix D). The parent/guardian signed the informed consent form after he/she read through the procedure letter and understood the procedures to be conducted for the research project. Participants were provided with an assent form (available in Afrikaans and English) that they read and signed or gave verbal assent after the procedures to be conducted were explained (Appendix E). An audiogram was used to record pure tone and speech audiometric data as well as to indicate reliability of participants' behavioral audiometric testing and behavioral responses during listening effort measures (Appendix F). For speech audiometry (Appendix G), 20 easily pictured spondees (from the CID W-1 and W-2 tests) (Frank, 1980), the *Afrikaanse Spondee Woordelyste* (spondee word lists) (Laubscher & Tesner, 1966b), the *Afrikaanse Foneties Gebalanseerde Woordelys* (phonetically balanced word lists, containing 25 words per list) (Laubscher & Tesner, 1966a), and the *University of Pretoria, English Phonetically Balanced Word Lists* (lists of 25 words) were used. All the audiometric data was recorded on an audiogram. A questionnaire with subjective ratings of listening effort was completed by each participant of Studies II and III (Appendix H). An Excel data sheet was used to record all the data.

3.4 DATA COLLECTION PROCEDURES

The various research sites (Eduplex Audiology Department at Eduplex Primary School, A van der Merwe Inc. private audiology practices in Gauteng and the Western Cape, and Carel du Toit Centre) were contacted and informed of the research project after ethical clearance was obtained from the Faculty of Humanities at the University of Pretoria (Appendix A). Data collection was conducted by the researcher (Ilze Oosthuizen, M. Communication Pathology, STA 0029076). Each site provided written informed consent that the site might be used to access participants for the research study (Appendices B and C). Permission was obtained from these sites as well as other private audiology practices in Gauteng and the Carel du Toit Centre, Western Cape, to participate in terms of recruiting of possible participants for the research project (Appendices B and C).

3.4.1 STUDY I: Data collection procedures

- Before data collection commenced, informed consent was obtained from each participant's parent/guardian (Appendix D) and assent was obtained from the participants (Appendix E).
- An otoscopic examination was conducted to observe the external ear canal for inflammation, foreign objects, growths, and cerumen that may have caused obstruction. Tympanic membrane structures that were observed include the pars flaccida, pars tensa, the manubrium of the malleus, the umbo, and the cone of light (Martin & Clark, 2003).
- Tympanometry was conducted to evaluate middle ear functioning in terms of the external ear canal volume, middle ear pressure, and tympanic membrane compliance (Martin & Clark, 2003).
- Standard pure tone and speech audiometric measures followed. A calibrated, diagnostic audiometer was operated to determine hearing sensitivity at 250-8000 Hz. Speech audiometry included speech reception threshold (SRT) and word recognition testing. Speech testing was presented with live voice in Afrikaans or English (open-set, auditory alone). As recommended by ASHA (1988), a list of 20 easily pictured spondees (from the CID W-1 and W-2 tests) for use with children were used to measure SRT (Frank, 1980). The *Afrikaanse Spondee Woordelyste* (spondee word lists) (Laubscher & Tesner, 1966b) were used to measure SRT for Afrikaans speaking participants. Word recognition was determined by administering the *Afrikaanse Foneties Gebalanseerde Woordelys* (phonetically balanced word lists containing 25 words per list) to Afrikaans speaking participants (Laubscher & Tesner, 1966a). The *University of Pretoria, English Phonetically Balanced Word Lists* (25 words per list) were used for native English-speaking participants. See Appendix G for speech audiometry word lists. All the audiometric data was recorded on an audiogram (Appendix F). Codes were assigned to all subjects.
- Prior to listening effort measures, a visual screening test was conducted on each participant. The researcher used the Peek Acuity vision screening application on a smartphone at a distance of 2 meters. Each eye of the participant was tested separately, with the non-test eye being covered with the participant's hand. The

application randomly presented a series of up to five Tumbling-E optotypes equivalent in size to Snellen 6/12. The participant had to point in the direction he/she perceived the arms of the letter E to be pointing. The researcher used the smartphone's touch screen to swipe in the same direction to enter the participant's response, without looking at the phone's screen. The test automatically determined if the participant has passed or failed the screening test (Rono et al., 2018).

- Training rounds of the listening effort tests were conducted prior to data collection to ensure that the participant understood the listening effort measures. Training rounds consisted of the following: primary task in quiet and in noise, secondary task in quiet and in noise, and dual-task in quiet and in noise. Participants then performed only the secondary task again. Training lists (containing10 digit triplets) were not repeated during the experimental testing.
- Conductance of the low-linguistic listening effort paradigms followed. Participants were tested in a total of six conditions, which varied by listening effort task (single-task paradigm, dual-task paradigm) and by signal-to-noise ratio (SNR: quiet, −10 dB, −15 dB). Digit triplets were presented through custom programming of MATLAB software (MATLAB R2015a) on a Dell OPTIPLEX 7460 AIO 23.8" touchscreen computer, routed to an audiometer (GSI AudioStar Pro), to a loudspeaker (GSI 90 dB) located at 0° azimuth at a distance of 1 m from the participant. The audiometer was used to adjust the output intensity level of the digit triplets to 60 dB(A). Noise files, containing steady state noise with the same long-term average spectrum as the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018), were stored on the audiometer and selected from the internal files for the noise conditions. During noise conditions, identical noise was routed synchronously from the audiometer to two loudspeakers (GSI 90 dB loudspeakers) placed at 90° and 270° azimuths, situated at 1 m from the participant. For the noise conditions, fixed SNR levels of −10 dB and −15 dB were used. Noise output levels were therefore measured at 70 dB(A) and 75 dB(A), respectively. Output levels for digit triplets and digit noise were measured by means of a sound level meter to ensure the correct output level in the sound field. The microphone of the sound level meter was at a position equivalent to center of the participant's head. The digit noise was used during the measurement of output

levels because it matches the long-term average speech spectrum of the digits (Potgieter et al., 2016).

- During single- and dual-tasks, participants' verbal responses of digit triplets were recorded by a head-worn microphone and saved by a custom software program (MATLAB R2015a) in participant specific files. Percent correct digit triplet recognition scores were calculated by scoring the participants' verbal responses to the digit triplets that were presented in a specific list.
- During the single-tasks, participants' VRTs were automatically calculated by the MATLAB program by measuring the time elapsed from the end of the digit triplet to the onset of the participant's response. The VRT for each verbal response of the participants as well as the mean VRT for each digit triplet list were automatically analyzed by the programming software on the custom MATLAB program (MATLAB R2015a) and saved in specific files for each participant.
- During dual-tasks, the secondary task consisted of a measure of RT to a visual stimulus presented through a custom programming of MATLAB software on the touchscreen computer. Participants' RTs to each visual stimulus as well as the mean RT per dual-task round were automatically recorded using customized software on MATLAB and stored in participant specific files.

3.4.2 STUDY II: Data collection procedures

- Informed consent was obtained from each participant's parent/guardian (Appendix D) and assent was obtained from the participants (Appendix E) before data collection commenced.
- An otoscopic examination was conducted to observe the external ear canal for inflammation, foreign objects, growths, and cerumen that may have caused obstruction. Tympanic membrane structures that were observed include the pars flaccida, pars tensa, the manubrium of the malleus, the umbo, and the cone of light (Martin & Clark, 2003).
- Tympanometry was conducted to evaluate middle ear functioning in terms of external ear canal volume, middle ear pressure, and tympanic membrane compliance (Martin & Clark, 2003).

- Standard pure tone and speech audiometric measures followed to confirm normal bilateral hearing sensitivity for participants with NH as well as to confirm normal hearing in one ear and a severe-profound sensorineural hearing loss in the opposite ear for participants with LUHU. The degree of severity of the unilateral hearing loss was categorized according to the classification in Clark (1981): severe hearing loss (hearing thresholds ranged from 71 to 90 dB HL); profound hearing loss (hearing thresholds of ≥ 91 dB HL). The unilateral hearing loss was categorized as severe-profound if the hearing thresholds ranged between 71 to ≥91 dB HL. A calibrated, diagnostic audiometer was operated to determine hearing sensitivity at 250-8000 Hz. The plateau masking method was applied during pure tone audiometry to ensure that thresholds from the impaired ear were true and reliable and that the non-test ear did not respond (Yacullo, 2015). Speech audiometry included speech reception threshold (SRT) and word recognition testing. Speech testing was presented with live voice in Afrikaans or English (open-set, auditory alone). As recommended by ASHA (1988), a list of 20 easily pictured spondees (from the CID W-1 and W-2 tests) for use with children were used to measure SRT (Frank, 1980). The *Afrikaanse Spondee Woordelyste* (spondee word lists) (Laubscher & Tesner, 1966b) were used to measure SRT for Afrikaans speaking participants. Word recognition was determined by administering the *Afrikaanse Foneties Gebalanseerde Woordelys* (phonetically balanced word lists consisting of 25 words per list) to Afrikaans speaking participants (Laubscher & Tesner, 1966a). The *University of Pretoria, English Phonetically Balanced Word Lists* (25 words per list) were used for native English-speaking participants. See Appendix G for speech audiometry word lists. Speech masking was applied when the presentation level - IA (intra-aural attenuation) > lowest bone conduction threshold of the non-test ear at 500, 1000 Hz, 2000, 4000 Hz. The amount of masking applied was calculated as follow: presentation level - IA + largest air bone gap at 500 Hz, 1000 Hz, or 2000 Hz (Guthrie & Mackersie, 2009). All the audiometric data was recorded on an audiogram (Appendix F). Codes were assigned to all subjects.
- Training rounds were conducted to ensure that the participants understood the listening effort tasks. Training rounds consisted of digit triplet recognition tasks (VRT measure) in quiet and in noise. Training lists (consisting of 10 digit triplets)

were not repeated during the experimental testing. After the training rounds, participants were prepared to start with data collection testing.

- Behavioral measure of listening effort of VRT followed. Participants were tested in a total of 6 conditions, which varied by SNR (quiet, -12 dB) and three loudspeaker conditions:

  Midline condition

  Digit triplets were presented through the loudspeaker directly in front of the participant (0°). During noise conditions, identical noise was routed synchronously from the audiometer to two loudspeakers (GSI 90 dB loudspeakers) placed at 90° and 270° azimuths.

  Monaural direct condition

  Digit triplets were presented through the loudspeaker directed towards the ear with normal hearing and noise was presented through a loudspeaker directed towards the ear with limited hearing unilaterally. That is, for a participant with LUHU in the left ear, digit triplets were presented from 90° and noise from 270°.

  Monaural indirect condition

  Digit triplets were presented through the loudspeaker directed towards the ear with limited hearing unilaterally and noise was presented through a loudspeaker directed towards the ear with normal hearing. For example, for a participant with LUHU in the left ear, digit triplets were presented from 270° and noise from 90°.

  To facilitate comparisons between groups for the direct and indirect conditions, the 90° loudspeaker was always designated as the “direct” loudspeaker (i.e., digit triplets presented from 90° and noise presented from 270°), whereas the 270° loudspeaker was always designated as the “indirect” loudspeaker (i.e., digit triplet presented from 270° and noise presented from 90°) for participants with NH.

- A single list with 20 digit triplets was used in each condition. Twenty-five (25) lists consisting of 20 digit triplets each were created in order to ensure no repetition of a digit triplet list in the various test conditions. The order of the loudspeaker conditions (midline, monaural direct, monaural indirect) and SNR condition (quiet, -12 dB) and digit triplet list were randomized across participants.

- Digit triplets were presented through custom programming of MATLAB software (MATLAB R2015a) on a Dell OPTIPLEX 7460 AIO 23.8" touchscreen computer, routed to an audiometer (GSI AudioStar Pro), to a loudspeaker (GSI 90 dB) located at a distance of 1 m from the participant. The audiometer was used to adjust the output intensity level of the digit triplets to 60 dB(A). Noise files, containing steady state noise with the same long-term average spectrum as the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018), were stored on the audiometer and selected from the internal files for the noise conditions. For the noise conditions, a fixed SNR level of −12 dB was used. Noise output levels were therefore measured at 72 dB(A). Output levels for digit triplets and digit noise were measured by means of a sound level meter to ensure the correct output level in the sound field. The microphone of the sound level meter was at a position equivalent to center of the participant's head. The digit noise was used during the measurement of output levels because it matches the long-term average speech spectrum of the digits (Potgieter et al., 2016).
- Participants' verbal responses were recorded by a head-worn microphone. Participants' VRTs were automatically calculated by the MATLAB program by measuring the time elapsed from the end of the digit triplet to the onset of the participant's response. The VRTs of each digit triplet as well as the mean VRT for a given digit triplet list were automatically analyzed by the programming software on the custom MATLAB program (MATLAB R2015a) and saved in specific files for each participant.
- Directly after each digit triplet list was presented, participants provided subjective ratings by answering three questions on a non-standardized, self-reported rating questionnaire (Appendix H). Questions asked were as follows: 1) *"How did you find the listening task?"* (task difficulty); 2) *"How many numbers do you think you got right?"* (recognition performance); 3*) "Was it hard to think when you were listening?"* (hard to think). A simple scoring method was used in the form of a 5-point emoji rating scale that varied between 1 "very easy/everything/very easy" (big smile) and 5 meaning "very hard/nothing/very hard" (big frown).

3.4.3 STUDY III: Data collection procedures

- Before data collection commenced, informed consent was obtained from each participant's parent/guardian (Appendix D) and assent was obtained from the participants (Appendix E).
- An otoscopic examination was conducted to observe the external ear canal for inflammation, foreign objects, growths, and cerumen that may have caused obstruction. Tympanic membrane structures that were observed include the pars flaccida, pars tensa, the manubrium of the malleus, the umbo, and the cone of light (Martin & Clark, 2003).
- Tympanometry was conducted to evaluate middle ear functioning in terms of the external ear canal volume, middle ear pressure, and tympanic membrane compliance (Martin & Clark, 2003).
- Standard pure tone and speech audiometric measures followed to confirm normal hearing in one ear and a severe-profound sensorineural hearing loss in the opposite ear for participants with LUHU. The degree of severity of the unilateral hearing loss was categorized according to the classification in Clark (1981): severe hearing loss (hearing thresholds ranged from 71 to 90 dB HL); profound hearing loss (hearing thresholds of ≥ 91 dB HL). The unilateral hearing loss was categorized as severe-profound if the hearing thresholds ranged between 71 to ≥91 dB HL. A calibrated, diagnostic audiometer was operated to determine hearing sensitivity at 250-8000 Hz. The plateau masking method was applied during pure tone audiometry to ensure that thresholds from the impaired ear were true and reliable and that the non-test ear did not respond (Yacullo, 2015). Speech audiometry included speech reception threshold (SRT) and word recognition testing. Speech testing was presented with live voice in Afrikaans or English (open-set, auditory alone). As recommended by ASHA (1988), a list of 20 easily pictured spondees (from the CID W-1 and W-2 tests) for use with children were used to measure SRT (Frank, 1980). The *Afrikaanse Spondee Woordelyste* (spondee word lists) (Laubscher & Tesner, 1966b) were used to measure SRT for Afrikaans speaking participants. Word recognition was determined by administering the *Afrikaanse Foneties Gebalanseerde Woordelys* (phonetically balanced word lists with 25 words per list) to Afrikaans speaking participants (Laubscher & Tesner, 1966a).

The *University of Pretoria, English Phonetically Balanced Word Lists* (consisting of 25 words per list) were used for native English-speaking participants. See Appendix G for speech audiometry word lists. Speech masking was applied when the presentation level - IA (intra-aural attenuation) > lowest bone conduction threshold of the non-test ear at 500, 1000 Hz, 2000, 4000 Hz. The amount of masking applied was calculated as follow: presentation level - IA + largest air bone gap at 500 Hz, 1000 Hz or 2000 Hz (Guthrie & Mackersie, 2009). All the audiometric data was recorded on an audiogram (Appendix F). Codes were assigned to all subjects.

- Fitting and verification procedures of the RMS and CROS followed and were conducted on each participant. A digital ear-level, personal RMS receiver (Phonak Roger™ Focus) was fitted on the normal hearing ear of each participant. Acoustic coupling was a standard slim tube and a small, non-occluding, non-custom eartip. Slim tube length was measured and changed accordingly for each participant. The ear-level RMS receiver was paired to a remote microphone (Phonak Roger™ Touchscreen). Real-ear measurements were conducted on the Audioscan Verifit Real Ear System (Audioscan, Dorchester, Ontario) as recommended by the American Academy of Audiology (2011) and Schafer et al. (2014) to verify that estimated uncomfortable loudness levels (UCLs) were not exceeded and prescriptive targets were met. During these measurements, the remote microphone was placed in the test box and the real-ear microphone was placed in the participant's ear. Specifically, the maximum power output (MPO) stimulus was selected on the Verifit. The examiner visually compared the MPO (based on the default volume setting) with the estimated UCL from the Desired Sensation Level (DSL) v5.0 software (Scollie et al., 2005) to ensure that the MPO did not exceed predicted UCL levels. Next, the output from the RMS receiver was compared to DSL v5.0 targets (Scollie et al., 2005) using the Verifit's "standard speech signal" presented in the test box at an intensity appropriate for a chest-level transmitter microphone (i.e., 84 dB SPL) to ensure that the output from the child's ear met the DSL v5.0 prescriptive targets at 1000, 2000, and 4000 Hz. If volume-adjustments were done, the MPO measurement was repeated at the volume adjusted level.

Subsequently, a CROS hearing aid (Phonak CROS B-312) was fitted to the ear with the severe-profound sensorineural hearing loss with a helix hook for stability and retention. A receiver hearing aid (Phonak Sky B70-M, open fitting) was fitted to the normal hearing ear of each participant. Acoustic coupling was a standard slim tube and a small, non-occluding, non-custom eartip. Slim tube length was measured and changed accordingly for each participant. The automatic features in the receiver hearing aid were deactivated, including automatic program selection, digital noise reduction, and wind noise reduction. The microphone was set to mild, fixed-directional. The CROS microphone was set to be a "real-ear" microphone. Real-ear measurements were conducted on the Audioscan Verifit Real Ear System (Audioscan, Dorchester, Ontario) prior to data collection to ensure that the receiver hearing aid of the CROS system was acoustically appropriate for each participant's individual hearing thresholds. The CROS receiver hearing aid output in the participant's ear, at octave frequencies, was compared to Desired Sensation Level (DSL) (Scollie et al., 2005) v5.0 targets using the Verifit's "standard speech signal" (the carrot passage) presented at 65 dB SPL. Furthermore, real ear unaided responses (REUR) were measured and compared to real ear occluded responses (REOR) with the ear-level RMS receiver and the CROS receiver hearing aid turned off to ensure that there was minimal insertion loss.

- Training rounds followed to ensure that the participants understood the listening task. Training rounds consisted of digit triplet recognition tasks (VRT measure) in quiet and in noise. Training lists (containing 10 digit triplets) were not repeated during the experimental testing. After the training rounds, participants were prepared to start with data collection testing.
- The behavioral measure of listening effort of VRT followed. Participants were tested in a total of 9 conditions, which varied by intervention condition (unaided, RMS, CROS) and loudspeaker conditions (midline signal, monaural direct, monaural indirect). The setup of the loudspeaker conditions was similar to the loudspeaker configurations used in Study II. The order of the loudspeaker conditions, intervention conditions, and digit triplet lists were randomized across participants.

- A single digit triplet list (with 20 digit triplets) was used in each condition. Twenty-five (25) lists consisting of 20 digit triplets each were created in order to ensure no repetition of a digit triplet list in the various test conditions.
- Digit triplets were presented through custom programming of MATLAB software (MATLAB R2015a) on a Dell OPTIPLEX 7460 AIO 23.8" touchscreen computer, routed to an audiometer (GSI AudioStar Pro), to a loudspeaker (GSI 90 dB) located at a distance of 1 m from the participant. The audiometer was used to adjust the output intensity level of the digit triplets to 60 dB(A). Noise files, containing steady state noise with the same long-term average spectrum as the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018), were stored on the audiometer and selected from the internal files. A fixed SNR level of −12 dB was used. Noise output levels were therefore measured at 72 dB(A). Output levels for digit triplets and digit noise were measured by means of a sound level meter to ensure the correct output level in the sound field. The microphone of the sound level meter was at a position equivalent to center of the participant's head. The digit noise was used during the measurement of output levels because it matches the long-term average speech spectrum of the digits (Potgieter et al., 2016).
- For the aided conditions in the midline loudspeaker condition digit triplets were presented from the loudspeaker at 0° azimuth with the remote microphone/transmitter also situated at the loudspeaker at 0° azimuth. Noise was routed synchronously from the audiometer to two loudspeakers (GSI 90 dB loudspeakers) placed at 90° and 270° azimuths. For the CROS conditions, the remote microphone was removed from the loudspeaker at 0° azimuth.
- Monaural direct aided conditions: For the RMS condition, digit triplets were presented from the loudspeaker directed towards the ear with normal hearing with the remote microphone also placed at the loudspeaker of interest, (see rectangle labelled 'remote mic' in Figure 6.1) and noise was presented from the loudspeaker directed towards the ear with LUHU. For the CROS condition, the remote microphone was removed. Digit triplets were presented from the loudspeaker directed towards the ear with normal hearing with the receiver hearing aid on and noise was directed towards ear with the hearing loss with the CROS aid on.

- Monaural indirect aided conditions: For the RMS condition, digit triplets were presented from the loudspeaker directed towards the ear with hearing loss with the remote microphone placed at this loudspeaker and noise was presented from the loudspeaker directed towards the ear with normal hearing. For the CROS condition, the remote microphone was removed, digit triplets were presented from the loudspeaker directed towards ear with hearing loss with the CROS aid on and noise was directed towards the ear with normal hearing with the receiver hearing aid on.
- Directly after each digit triplet list was presented when listening in either the RMS or the CROS condition, participants completed non-standardized, self-reported rating questionnaire (Appendix H). Questions asked were: 1) *"Did the remote microphone system (FM system)/hearing aids make it easier for you to listen when it was noisy?"* (ease of listening); 2) *"Did the remote microphone system (FM system)/hearing aids help you to keep trying?"* (motivation to complete listening task). A simple scoring method was used in the form of a binary (yes/no) emoji scale [1) yes = big smile, thumb up; 2) no = big frown, thumb down]. The questions were typed on a piece of paper with the emoji options scale below each one. No questions were asked after unaided conditions.

3.5 DATA PROCESSING AND ANALYSIS

The proposed research project was divided into three different studies; therefore, the data processing and analyses procedures will be discussed for each study separately. The results of digit triplet recognition and response time measures were extracted from the participant specific files created by the custom MATLAB program. The data of each study was recorded in specific Excel data sheets, and according to a code assigned to each participant. Data analyses for Studies I and III were completed in SPSS (IBM Corporation, v 26). Data analyses for Study II were conducted in R (v 3.6.1; R Core Team, 2019).

3.5.1 STUDY 1: Data processing and analysis

- Descriptive statistics were applied to describe and analyze the mean and standard deviations (SD) for the digit triplet recognition and RT data from each participant.

- Prior to analysis, digit triplet recognition scores were converted to rationalized arcsine units (rau) to normalize the variance near the extremes, according to the equations in Studebaker (1985).
- RTs within ± 2.5 standard deviations of the mean RT for a participant in a given digit triplet list were included in the analysis.
- A repeated measure of analysis of variance (ANOVA) was used to determine the effect of SNR and language background on triplet recognition and RTs for each listening effort task separately, with $p < .05$ used to indicate a significant effect.
- Pearson correlation analyses were conducted to explore the effects of age on digit triplet recognition and RTs collapsed across single- and dual-tasks, SNR, and Language Group.

3.5.2 STUDY II: Data processing and analysis

- Descriptive statistics were applied to describe and analyze the mean and standard deviations (SD) for the digit triplet recognition and VRT data from each participant.
- Prior to analysis, digit triplet recognition scores were converted to rationalized arcsine units (rau) to normalize the variance near the extremes, according to the equations in Studebaker (1985).
- Subjective checks of all VRT recordings were done to identify occurrences of speech fillers such as “umm” and “uh”, stutters, and nonspeech sounds (e.g., breathing, yawns) that occurred before a digit triplet was spoken as well for trials with self-corrections. In these cases, fillers and false starts were replaced with silence in the Audacity software and the beginning of the participant's actual response was determined by inspection. The verbal response onset-time was marked as the onset of the self-corrected, second utterance.
- To ensure the VRTs were calculated correctly by the MATLAB program, the responses of each participant to a single digit triplet were analyzed. Each recording contained a version of the presented digit triplet, followed by the participant's response. The following steps were followed the determine the VRT for each recording:
  1) The last sample of the presented digit triplet (which was also recorded) was found by reconstructing the relevant digit triplet from the source digit triplet

sound files and correlating the reconstructed digit triplets with the first two seconds of the recording. The point of maximum correlation was used to determine the last sample of the triplet. The next sample was taken as the first sample of the silence after the digit triplet.

2) The beginning of the participant's response was determined by calculating the running average energy over 20 samples and stopping when the average energy went above 0.0035. This threshold was determined experimentally to account for recordings that included noise.
3) The sample related to the beginning of the silence was subtracted from the sample related to the beginning of the child's response, and the result was divided by the sampling rate (44100).
4) The resultant VRT was compared to that produced by the MATLAB program.

- VRTs for verbal responses not containing digits (e.g., “I don’t know/I didn’t hear”) were excluded from analysis. In addition, VRTs were included in the analysis only if they were within +/- 2.5 standard deviations of the mean VRT for the participant in a given digit triplet list.
- An analysis of co-variance (ANCOVA) was conducted to determine if group differences between children with NH and children with LHUH exist for digit triplet recognition and verbal response times in each of the Loudspeaker (midline, indirect, direct) and Condition (quiet and noise) test conditions. The *p*-values were corrected for numerous comparisons. Age (in years, centered at 0 via linear transformation) was included as a covariate. Significant effects of the covariate were explored using Pearson correlation analysis.
- Subjective ratings were analyzed using non-parametric, Mann-Whitney U analyses to determine differences for perceived listening effort between participants with NH and those with LUHU.
- Exploratory Spearman’s rank-order correlation analyses between age, behavioral, and subjective measures were conducted for the indirect condition with noise. Correlations were conducted separately for participants with NH and with LUHU.

3.5.3 STUDY III: Data processing and analysis

- Descriptive statistics were applied to describe and analyze the mean and standard deviations (SD) for the triplet recognition and VRT data from each participant.
- Prior to analysis, digit triplet recognition scores were converted to rationalized arcsine units (rau) to normalize the variance near the extremes, according to the equations in Studebaker (1985).
- Subjective checks of all VRT recordings were done to identify occurrences of speech fillers such as “umm” and “uh”, stutters, and nonspeech sounds (e.g., breathing, yawns) that occurred before a digit triplet was spoken as well for trials with self-corrections. In these cases, fillers and false starts were removed and replaced with silence in the Audacity software and the beginning of the participant's actual response was determined by inspection. The verbal response onset-time was marked as the onset of the self-corrected, second utterance.
- To ensure the VRTs were calculated correctly by the MATLAB program, the responses of each participant to a single digit triplet were analyzed. Each recording contained a version of the presented digit triplet, followed by the participant's response. The following steps were followed the determine the VRT for each recording:
    1) The last sample of the presented digit triplet (which was also recorded) was found by reconstructing the relevant digit triplet from the source digit triplet sound files and correlating the reconstructed digit triplets with the first two seconds of the recording. The point of maximum correlation was used to determine the last sample of the triplet. The next sample was taken as the first sample of the silence after the digit triplet.
    2) The beginning of the participant's response was determined by calculating the running average energy over 20 samples and stopping when the average energy went above 0.0035. This threshold was determined experimentally to account for recordings that included noise.
    3) The sample related to the beginning of the silence was subtracted from the sample related to the beginning of the child's response, and the result was divided by the sampling rate (44100).
    4) The resultant VRT was compared to that produced by the MATLAB program.

- VRTs for verbal responses not containing digits (e.g., "I don't know/I didn't hear") were excluded from analysis. In addition, VRTs were included in the analysis only if they were within +/- 2.5 standard deviations of the mean VRT for the participant in a given digit triplet list.
- A repeated measure of analysis of variance (ANOVA) was used to determine the effect of intervention condition (unaided, RMS, CROS) on digit triplet recognition performance and VRTs in each of the three loudspeaker conditions (i.e., midline, monaural direct and monaural indirect) with $p < .05$ used to indicate a significant effect.
- Subjective ratings were analyzed using non-parametric, exact McNemar's tests to describe to perceived effect of the RMS and CROS intervention options on ease of listening and motivation to complete a listening task.

3.6 ETHICAL CONSIDERATIONS

Medical and health care research are subject to ethical standards that promote respect for all human beings and protect their health and rights (South African National Health Act, 2013). Research ethics provide researchers with a code of moral guidelines on how to conduct research in a suitable way (Struwig & Stead, 2001). The current research was conducted within the framework of the ethical guidelines set out in the South African National Health Act (2013).

3.6.1 Ethical approval of the research study

The research study was conducted in compliance with the protocol that has received prior institutional review board and independent ethics committee approval. The research project was approved by the Research Ethics Committee of the Faculty of Humanities, University of Pretoria (protocol number: HUM005/0219) (Appendix A).

3.6.2 Ethical obligation of the researcher to be experienced, truthful and capable to conduct the various testing procedures

The researcher was competent due to her qualification as an Audiologist and registration with the Health Professions Council of South Africa (STA 0029076).

3.6.3 Protection from harm

According to Strydom (2011) the researcher should not expose the participants to any form of anxiety, discomfort, physical, or psychological discomfort that might arise from the research study, within all probable realistic limits. The welfare of all the participants was held paramount in this study. The research involved non-invasive audiometric testing; thus, no harm was inflicted. This was clearly explained in the participant assent form and the informed consent letter provided to the parents/caregivers of participants. Participants were also provided with a clear explanation of what was expected of him/her.

3.6.4 Informed consent

According to Leedy and Ormrod (2014), research participation should be voluntary and informed consent should be provided by the participants. Furthermore, the research participants should be informed on the aims, methodology, potential risks, and benefits of the research study.

A letter explaining the purpose of Study I was provided to the Eduplex Primary School. The principal provided written informed consent for the researcher to use the school as research site to access participants (Appendix B). An information letter explaining the purpose of Studies II and III was provided to the principal of Carel du Toit School. The principal provided written informed consent for the researcher to use the school as research site to access participants (Appendix B). A letter explaining the purpose of Studies II and III was also provided to various private audiology practices (Appendix C). The audiologists provided written informed consent to indicate that they made the contact details of the parents of possible participants for Studies II and III available to the researcher. The audiologist/director from private audiology practices in Gauteng and the Western Cape also provided informed consent that the practice facilities could be used as research site (Appendix C).

Parents/caregivers of each participant (Studies I, II and III) received a letter explaining the research and requesting permission for their child to partake in the research as well as permission to have access to their child's developmental and medical history as documented in the child's educational and/or audiological file (Appendix D). The parents/caregivers provided written informed consent that the researcher may access the child's developmental and medical history as well as for their child to partake in the research. Each participant received a written assent form (available in English and Afrikaans as these languages are the languages of learning and teaching of the participants) before the testing commenced (Appendix E). The letter described the nature of the components of the study, and the terms and conditions for participation. The letter also stated that participation is voluntary, and that subjects could withdraw from the study at any time. Contact details of the researcher and study supervisors were provided whenever the subjects had any questions. Participants signed the written assent before testing commenced.

Data collection only took place once informed consent from parents/caregivers and assent from participants were obtained. All participants were made aware that participation is voluntary and that they may withdraw from the study at any time.

3.6.5 Confidentiality

Confidentiality of participant information was maintained at all times (Leedy & Ormrod, 2014; Strydom, 2011). No names were used when describing the participants. The researcher assigned codes to all participants to organize the data in electronic format for analysis. Only the researcher and supervisors had access to the information.

3.6.6 Release of research findings

Accurate results of the three separate research studies were reported when manuscripts were submitted to accredited, peer reviewed journals for publication (Leedy & Ormrod, 2014; Struwig & Stead, 2001). A scientific article of each study was made available to the scientific community and research participants upon completion (Leedy & Ormrod, 2014; Struwig & Stead, 2001). The manuscripts contained all the information necessary for the readers to understand what had been investigated and the outcomes of each investigation (Strydom, 2011). In the consent letter to the parents/caregivers, it was stated that the results obtained from the research study will be reported in the form of a scientific article which will be available to professionals in the field of audiology; that the results from the research study may be used by future researchers; and if data is to be used for further research, participants' permission will be obtained through an informed consent form. Results of the study were also be made available to the parents/guardians of the participants after conclusion of the study.

3.6.7 Storage of data

As determined by the University of Pretoria, data must be securely stored for a minimum of 15 years. Data will be stored in hard copy and electronically and will be archived at the University of Pretoria, at the Department of Speech-Language Pathology and Audiology (Appendix I).

CHAPTER 4

LISTENING EFFORT IN NATIVE AND NON-NATIVE ENGLISH-SPEAKING CHILDREN USING LOW LINGUISTIC SINGLE- AND DUAL-TASK PARADIGMS

Authors: Ilze Oosthuizen, Erin M. Picou, Lidia Pottas, Hermanus C. Myburgh, and De Wet Swanepoel

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4.1 ABSTRACT

Purpose: It is not clear if behavioral indices of listening effort are sensitive to changes in signal-to-noise ratio (SNR) for young children (7–12 years old) from multilingual backgrounds. The purpose of this study was to explore the effects of SNR on listening effort in multilingual school-aged children (native English, nonnative English) as measured with a single- and a dual-task paradigm with low-linguistic speech stimuli (digits). The study also aimed to explore age effects on digit triplet recognition and response times (RTs).

Method: Sixty children with normal hearing participated, 30 per language group. Participants completed single and dual tasks in three SNRs (quiet, −10 dB, and −15 dB). Speech stimuli for both tasks were digit triplets. Verbal RTs were the listening effort measure during the single-task paradigm. A visual monitoring task was the secondary task during the dual-task paradigm.

Results: Significant effects of SNR on RTs were evident during both single- and dual-task paradigms. As expected, language background did not affect the pattern of RTs. The data also demonstrate a maturation effect for triplet recognition during both tasks and for RTs during the dual-task only.

Conclusions: Both single- and dual-task paradigms were sensitive to changes in SNR for school-aged children between 7 and 12 years of age. Language background (English as native language vs. English as nonnative language) had no significant effect on triplet recognition or RTs, demonstrating practical utility of low-linguistic stimuli for testing children from multilingual backgrounds.

4.2 INTRODUCTION

Listening is imperative in the educational setting as 45%–75% of a school day is dedicated to listening activity (Crandell & Smaldino, 2000a; Dahlquist, 1998). However, listening and learning occur in a variety of environments, many of which are acoustically disadvantaged as a result of background noise and/or reverberation (Berg, 1993; Bistafa & Bradley, 2000; Crandell & Smaldino, 2000b). For example, the signal-to-noise ratios (SNRs) encountered in classrooms are often very unfavorable, ranging from −17 to +15 dB (Bradley & Sato, 2008; Crandell & Smaldino, 2000a; Larsen & Blair, 2008; Markides, 1986; Pearsons et al., 1977; Sato & Bradley, 2008). Background noise negatively affects speech recognition by reducing the audibility of acoustic cues that are important for understanding and distinguishing speech sounds (Nelson et al., 2008). This suggests that children in academic contexts often listen at SNRs poorer than the recommended minimum of +15 dB SNR for educational settings (American Speech-Language-Hearing Association, 2005). The consequence of listening in such acoustically challenging environments includes reduced speech perception for children in addition to increased listening effort (Prodi et al., 2010). Listening effort refers to the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a task that involves listening in order to understand speech (Pichora-Fuller et al., 2016). The ease of language understanding (ELU) model (Rönnberg, 2003; Rönnberg et al., 2008) provides a conceptual framework for listening effort. This model proposes that language understanding involves both implicit and explicit processing. Listeners will implicitly compare language segments to their long-term memory store. When an easy match between the language input and long-term memory occurs, speech understanding is obtained with minimal effort. In contrast, in situations of an input–memory mismatch (e.g., when the speech signal is masked by background noise), the listener must use explicit processing and additional cognitive resources to understand speech. Consequently, it is expected that a listener will experience increased listening effort in acoustical challenging situations (Rönnberg, 2003; Rönnberg et al., 2013; Rönnberg et al., 2008). The FUEL model (Framework for Understanding Effortful Listening) extends the ELU model by adding that listening effort depends on the hearing ability of a listener, the task demands (e.g., a noisy or reverberant listening situation), as well as the listener's motivation to achieve the goal of completing a listening task (Pichora-Fuller et al., 2016).

According to the ELU model and the FUEL, another factor that can interfere with the input–memory match and thus contribute to increased listening effort is a nonnative listener's speech perception (Peelle, 2018; Pichora-Fuller et al., 2016; Rönnberg, 2003; Rönnberg et al., 2013; Rönnberg et al., 2008). Multilingualism is a universal reality, and classrooms often include learners with diverse native languages leading them to communicate and learn in a nonnative language. Nonnative listeners who already perform more poorly on speech understanding tasks due to lower English-language proficiency may experience an escalation in listening effort in comparison to native listeners to understand English in adverse listening conditions (Bent et al., 2010; Bradlow & Alexander, 2007; Bradlow & Bent, 2002; Rogers et al., 2006). Between-group comparisons of listening effort in native versus nonnative speakers may be of interest as listener factors such as language abilities can contribute to increasing listening effort (Pichora-Fuller et al., 2016). However, studies reporting on the effects of these factors on listening effort are limited (Borghini & Hazan, 2018; Peng & Wang, 2019; Van Engen & Peelle, 2014). Based on findings of dual-task and subjective rating scale measures with nonnative adult listeners, which demonstrate a trend of greater listening effort for nonnative listeners compared to native listeners in adverse SNR and reverberating conditions (Peng & Wang, 2019), it would be expected children would also exhibit increased listening effort when listening to nonnative speech.

The choice of speech stimulus is a methodological consideration important for considering outcomes in modern classrooms with children from different language backgrounds. The speech materials used for listening effort testing are usually age-appropriate, standardized, prerecorded word lists. In a multilingual context, the use of word lists, with a high-linguistic demand, could pose a challenge for younger children and for children who may not be native speakers of the language of the word lists. Instead of words or sentences, digits offer a potential solution because they are highly familiar spoken words, a closed set, and the linguistic demand is low (Kaandorp et al., 2016; Smits et al., 2013). Digit recognition in noise can be successfully and reliably used in children from as young as 4 years of age (Koopmans et al., 2018). Thus, using digit recognition in quiet and in noise in a listening effort paradigm might be a valid option for young school-aged children as well as nonnative children to assess listening effort. However, it is not clear if the use of low context, high-familiarity speech stimuli will be immune to the potential effects of using nonnative language during listening effort testing for children.

One category of behavioral listening effort methodologies involves a timed response, either speed of speech repetition or timed secondary task (Gagne et al., 2017). Such behavioral paradigms are derived from the limited cognitive capacity model of general attention (Kahneman, 1973) stating that a listener shows limited cognitive capacity when he/she must allocate attention when attending to simultaneous competing tasks. Thus, when more cognitive resources are allocated to assist with a specific task (e.g., understanding speech in noise), fewer resources are available for responding quickly. The classic dual-task paradigm requires the participant to perform two tasks simultaneously, a speech recognition task and a secondary, competing task, such as monitoring of a visual stimulus or vibrotactile pattern recognition. Thus, the outcomes from a dual-task paradigm are speech recognition performance and secondary task response times (RTs). Any performance decrement on the secondary task (reduced accuracy or increased RT) when dual tasking is interpreted as a behavioral index of listening effort (Gagne et al., 2017; Hsu et al., 2017; McGarrigle et al., 2019). Dual-task paradigms also have high ecological validity. For example, in academic contexts, learners are often required to perform dual tasking for example writing down notes, while listening to the teacher’s instructions (Howard et al., 2010; McGarrigle et al., 2019).

However, some investigators have reported difficulty using dual-task paradigms with children. For example, although the results of some investigations revealed decreasing SNRs increase listening effort as expected (Gustafson et al., 2014; Picou et al., 2019a; Picou et al., 2017; Prodi et al., 2010), other investigations suggest somewhat unexpected nonsignificant effects of changes in SNR on behavioral listening effort (Hicks & Tharpe, 2002; McGarrigle et al., 2017; McGarrigle et al., 2019). The discrepancy in the literature has been attributed, in part, to secondary tasks that are not motivating or too distracting (Choi et al., 2008; McFadden & Pittman, 2008). Another possible reason for inconsistent results with dual-task paradigms in the pediatric population is because the interpretation of dual-task results relies on the assumption that specific tasks can be prioritized and/or cognitive resources be distributed among multiple simultaneous tasks (Gagné et al., 2017). This ability might not yet be fully developed in school-aged children (Choi et al., 2008).

As an alternative to a dual-task paradigm, a single-task paradigm could also be used to evaluate listening effort behaviorally. Outcomes from a single-task paradigm also include both speech recognition performance and RTs. In such a paradigm, participants repeat speech and the time between stimulus presentation and verbal response is recorded, hereafter referred to as “verbal response time.” As with RTs during a secondary task, verbal RTs can also indicate listening effort and have been used in the pediatric population, with slower responses indicating more listening effort (Gustafson et al., 2014; Houben et al., 2013; McGarrigle et al., 2019; Pals et al., 2015).

Recently, McGarrigle et al. (2019) compared results with a single- and a dual-task paradigm with children (6- to 13-year-old children). Participants with normal hearing and hearing loss (unaided and aided) completed a single- and a dual-task paradigm in several SNRs. Participants were asked to respond as quickly as possible to a brief shape that appeared randomly during the consonant–vowel– consonant recognition task. The results suggested that the verbal RTs were more sensitive to the effects of SNR and hearing loss than the secondary task RTs. However, the nonsignificant findings could be the result of large variability in responses for the younger participants. Although the authors did not report the differences in RTs across the age range, previous results suggest secondary task RTs are less stable in younger children (< 12 year old) than in older children (Picou et al., 2017). In addition, it is possible that the speech recognition performance levels during the experimental tasks were too poor to be sensitive to changes in SNR; it was less than 50% for children with hearing loss. The work of Wu et al. demonstrates that RTs during listening effort tasks can reveal an inverse U-shaped function (Wu et al., 2016), where RTs progressively increase until a point of cognitive overload where participants exert less effort because cognitive demands exceed cognitive resources (e.g., Granholm et al., 1996; Zekveld et al., 2014). In adults, RTs peak around 30%–50% correct performance levels (Wu et al., 2016). Thus, it is possible that a dual-task paradigm could be as sensitive to changes in SNR as a single-task measure if word recognition performance is higher or for older children.

Therefore, the purpose of this study was to explore the effect of SNR on listening effort in school-aged children with normal hearing as measured with novel, low linguistic single- and dual-task paradigms. It was expected that, when factors such as age and speech recognition accuracy are accounted for, the single-task paradigm would be more sensitive than the dual-task paradigm to the effects of changing the SNR, based on the findings of McGarrigle et al. (2019). The study also aimed to explore age effects on triplet recognition and RTs during single- and dual-task performances. It was expected that speech recognition would improve with age and that older children would exhibit faster RTs. The results of this study were expected to elucidate the relative task sensitivity of single- and dual-task paradigms for measuring listening effort in school-aged children from multilingual backgrounds. It was expected that these single- and dual-task paradigms would not be sensitive to language differences (native English vs. nonnative English) due to the use of low linguistic speech stimuli (digit triplets).

4.3 MATERIALS AND METHODS

4.3.1 Participants

Two groups of school-aged children participated in the study: 30 children with English as a nonnative language (M = 9.4 years, SD = 1.7, range: 7–12) and 30 children with English as a native language (M = 9.6 years, SD = 1.7, range: 7–12). All participants had normal middle ear function as verified by tympanometry measures and normal otoscopic examination findings on the day of testing. All participants had normal-hearing sensitivity in both ears (≤ 15 dB HL for octave frequencies from 250 to 8000 Hz). No participant had otologic, cognitive, or neurological disorders, as evident from parental and/or teacher report. All participants had normal speech, language, and motor development as confirmed by parental report. Furthermore, participants had normal visual acuity as confirmed for each participant by performing a visual acuity screening test (smartphone application for Tumbling-E visual acuity testing; Rono et al., 2018). Institutional review board approval was granted for this study by the Research Ethics Committee of the Faculty of Humanities, University of Pretoria.

4.3.2 Dual-Task Paradigm

Primary Task

The primary task consisted of digit triplet recognition. The digit triplets used were from the digit triplets available from the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018). South African English mono- and bi-syllabic digits (0–9), spoken by a female speaker were selected and recorded to create digit triplet sets. A detailed description of the development of this digit-in-noise test can be found in Potgieter et al. (2016; 2018). Mono- and bi-syllabic digits were used in the triplets because the recognition probabilities of all the digits are equalized so that a potential difference in recognition probabilities is eliminated (Smits, 2016). The use of a digits-in-noise test was found a reliable test to assess speech recognition abilities of normal-hearing children from the age of 4 years and older, making it applicable to a wide clinical population (Koopmans et al., 2018). Most children aged 6 years and older have the necessary auditory memory abilities for a digit span of three digits, which is required to perform the digits-in-noise test (Koopmans et al., 2018; Wechsler, 2003). Participants were required to listen to, and repeat digit triplets presented in quiet and in noise. Participants were encouraged to guess if they were unsure of the digit triplet that was presented. Participants' verbal responses were recorded by a head-worn microphone and saved by a custom software program (MATLAB R2015a) in participant specific files. Percent correct scores were calculated by scoring the verbal responses to the digits.

Secondary Task

The secondary task was a measure of RT to a visual stimulus presented through a custom programming of MATLAB software (MATLAB R2015a) on a touchscreen computer (Dell OPTIPLEX 7460 AIO 23.8" touchscreen computer) placed directly in front of a participant. A colored shape (basic shapes, namely circle, triangle, or square presented in basic colors of red, blue, yellow, or green) of 10 cm in diameter appeared against a black background on the touchscreen and disappeared as soon as the participant touched on the shape on the touchscreen or after 3,000 ms. RTs to visual stimuli were automatically recorded using customized software on MATLAB and stored in participant specific files. The color and the shape of the visual stimuli in this study were varied randomly to help keep participants' interest to the listening task, but participants were not instructed to respond differently based on the color or shape.

Dual-Task Conditions

In dual-task conditions, participants completed both tasks simultaneously. Visual stimuli appeared 500 ms after digit triplet onset. The visual stimuli were programmed to appear randomly with a 50% probability rate. The measure of listening effort was the RT to the visual stimuli, hence referred to as dual-task visual RT. Participants were not asked to prioritize one task over the other, given that this strategy has been shown to be ineffective for this particular age group (Choi et al., 2008).

4.3.3 Single-task Paradigm

The speech stimuli in the single-task paradigm were the same as those in the dual-task paradigm. Thus, participants were instructed to listen to, and repeat digit triplets presented in quiet and in noise (SNRs of −10 dB and −15 dB). Participants' verbal responses were recorded by a head-worn microphone. The verbal RTs were then automatically analyzed by the programming software on the custom MATLAB program and saved in specific files for each participant. RTs were automatically calculated by the MATLAB program by measuring the time elapsed from the offset of the digit triplet to the onset of the participant's response.

4.3.4 Test Environment

Listening effort measures were conducted in a sound-attenuating booth (2.13 × 2.03 × 2.43 m). Three loudspeakers were located at 0°, 90°, and 270° at 1 m from the participant. Participants were seated in the sound-attenuating booth, 1 m from the loudspeakers, at a school desk with a touchscreen desktop computer (Dell OPTIPLEX 7460 AIO 23.8" touchscreen computer) located directly in front of the participant. Handprints were placed on the desk's surface showing participants where to place their hands during testing. Participants were instructed to keep their hands on the handprints during all tasks except when they needed to touch the screen during the dual-task conditions. Furthermore, participants were instructed to keep their head still and face forward for the duration of the testing.

4.3.5 Test Conditions

Participants were tested in a total of six conditions, which varied by listening effort task (single-task paradigm, dual-task paradigm) and by SNR (quiet, −10 dB, −15 dB). Digit triplets were presented through custom programming of MATLAB software (MATLAB R2015a), routed to an audiometer (GSI AudioStar Pro), to a loudspeaker (GSI 90 dB) located at 0° azimuth at a distance of 1 m from the participant. The audiometer was used to adjust the output intensity level of the digit triplets to 60 dB(A). Thus, the SNR was varied by adjusting the noise level and keeping the speech level at a constant intensity of 60 dB in order to resemble an average conversational intensity. Keeping the speech intensity constant and varying the noise intensity level also prevented that speech stimuli would be presented at intensities softer than average conversational loudness. The background noise was the steady state noise with the same long-term average spectrum as the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018). Noise files were stored on the audiometer and selected from the internal files for the noise conditions. During noise conditions, identical noise was routed synchronously from the audiometer to two loudspeakers (GSI 90 dB loudspeakers) placed at 90° and 270° azimuths, situated at 1 m from the child. For the noise conditions, fixed SNR levels of −10 dB and −15 dB were used; thus, noise output levels were measured at 70 dB(A) and 75 dB(A), respectively. Output levels for digit triplets and digit noise were measured by means of a sound level meter to ensure the correct output level in the sound field. During dual-task testing, the visual probes were displayed on a touchscreen computer (Dell OPTIPLEX 7460 AIO) placed directly in front of a participant. The SNRs were chosen based on pilot testing with naïve participants to target triplet recognition performance levels between 50% and 80% correct.

4.3.6 Procedure

Before data collection, informed consent was obtained from each participant's parent/guardian and assent was obtained from the participants themselves. Standard audiometric procedures followed (otoscopic examination, tympanometry, pure-tone audiometry, and speech audiometry) to confirm normal bilateral hearing sensitivity. A visual screening test was also conducted. Listening effort measures were conducted in a sound-attenuating booth as described earlier. Training rounds were conducted prior to data collection to ensure that the participant understood the listening task. Training rounds consisted of the following: primary task in quiet and in noise, secondary task in quiet and in noise, and dual-task in quiet and in noise. Participants then performed only the secondary task again. Training lists (10-digit triplets) were not repeated during the experimental testing. After the training rounds, participants were prepared to start with data collection testing for the single- and dual-task paradigms. For data collection of both paradigms, a single 20-digit triplet list was used in each condition. Twenty-five lists consisting of 20 digit triplets each were created in order to ensure no repetition of a digit triplet list in the various test conditions. The order of the test conditions and digit triplet list were randomized across participants.

4.3.7 Data Analysis

Outcomes from both single- and dual-task paradigms consisted of triplet recognition scores and RT. For the single-task paradigm, the verbal RTs were taken as the measure of listening effort. RTs to visual stimuli (dual-task visual RT) were the main listening effort measure during the dual-task paradigm. For both tasks, RTs were included in the analysis if they were within ± 2.5 SDs of the mean for the participant in a given digit triplet list. As suggested by Hsu et al. (2017), RT data were included from both correct and incorrect primary task trials as it would result in better representation of the varying levels of listening effort that children might experience in real-life, noisy classroom situations. The approach of including of the full data set for analyses (i.e., results based on both correct and incorrect responses for single- and dual-task paradigms) was also followed by McGarrigle et al. (2019). Outcomes were analyzed separately for each task. Each analysis of variance (ANOVA) included a single within-participant factor (SNR; quiet, −10 dB, −15 dB) and a single between-participant factor (Language Group; English as nonnative language, English as native language). Significant interactions were explored with follow-up ANOVAs, and significant main effects were analyzed with pairwise comparisons controlling for familywise error rate with Bonferroni adjustments. Greenhouse–Geisser correction for sphericity violations were used when necessary. To explore the effects of age on single- and dual-task performance, Pearson correlation analyses were conducted between age and each outcome (triplet recognition, RTs), collapsed across Task, SNR, and Language Group, unless otherwise indicated by significant interactions in the ANOVA. Prior to analysis, triplet recognition scores were converted to rationalized arcsine units to normalize the variance near the extremes, according to the equations in Studebaker (1985). Analyses were conducted in IBM SPSS (Version 26).

4.4 RESULTS

4.4.1 Single-task Paradigm

Figure 4.1 displays triplet recognition (Panel A) and RTs (Panel B) obtained during the single-task paradigm for each SNR and language group. Analysis of digit triplet recognition revealed a significant main effect of SNR, ($F_{2, 116} = 450.34$, $p < .001$, $\eta_p^2 = .89$) and no significant effects of Language Group or Language Group × SNR interaction ($p > .40$, $\eta_p^2 = .02$). Analysis of RTs revealed a significant main effect of SNR ($F_{1.68, 97.53,} = 80.20$, $p < .001$, $\eta_p^2 = .58$) and no significant effects of Language Group ($p > .45$, $\eta_p^2 = .01$) or Language Group × SNR interaction ($p > .29$, $\eta_p^2 = .02$). Pairwise comparisons, displayed in Table 4.1, reveal digit triplet recognition performance was significantly worse, and RTs were significantly slower, with the addition of, or increase in, background noise.

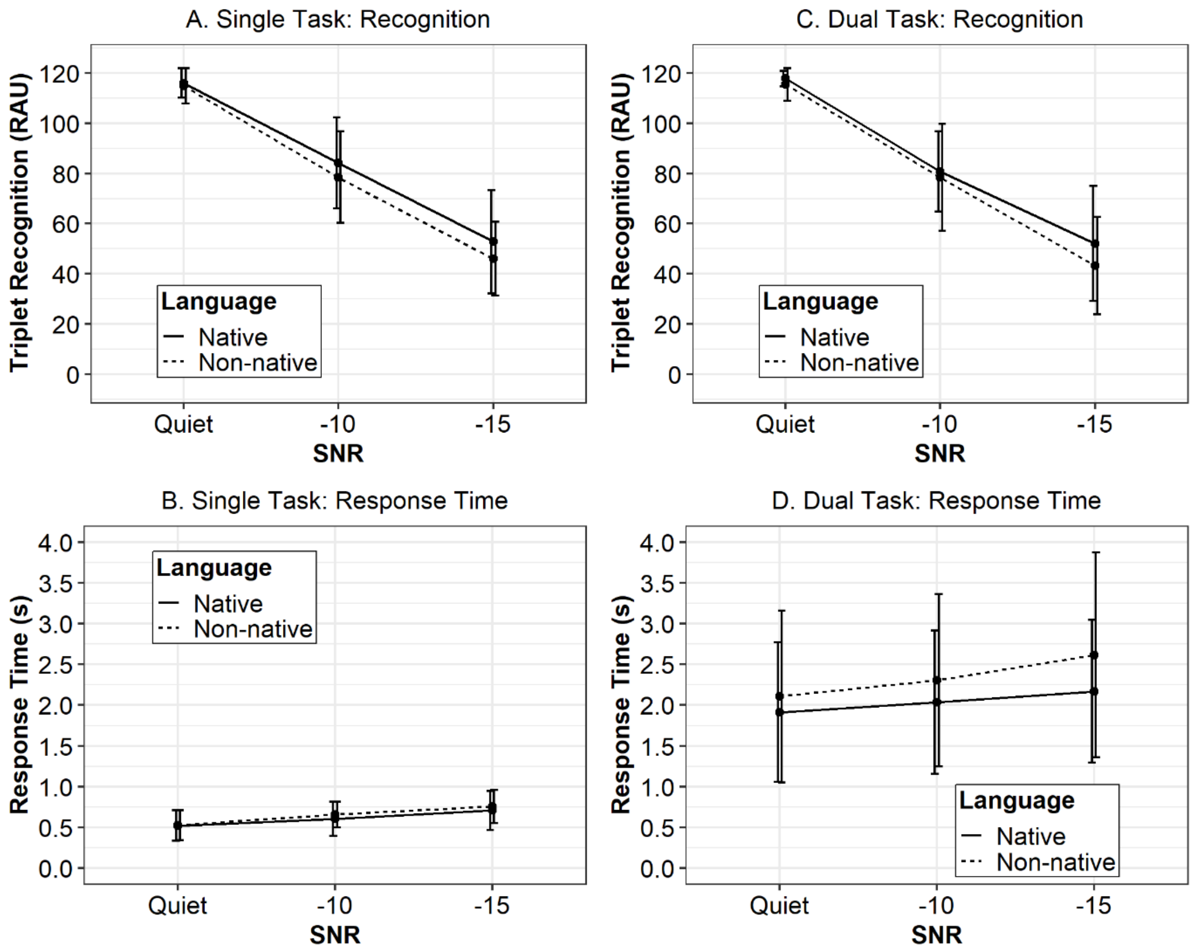

Figure 4.1 Panel A: Mean triplet recognition scores (RAU) for each signal-to-noise ratio (SNR) condition and language group during the single-task paradigm. Panel B: Mean response times during the single-task paradigm for each signal-to-noise ratio (SNR) and each language group. Panel C: Mean triplet recognition scores (RAU) for each SNR condition and language group during the dual-task paradigm. Panel D: Mean response times during the dual-task paradigm for each SNR and each language group. RAU = rationalized arcsine units.

Table 4.1 Results of pairwise comparisons of triplet recognition performance (rationalized arcsine units) and response times (ms) for the single-task paradigm, collapsed across language groups. Significant differences are indicated by bold typeface.

Outcome	Comparison	*M* difference	Std Error	95% CI	*p*
Triplet Recognition	**Quiet to -10 dB**	**43.15**	**2.31**	**28.46 to 39.83**	**<.001**
	Quiet to -15 dB	**66.07**	**2.27**	**60.47 to 71.67**	**<.001**
	-10 to -15 dB	**31.92**	**2.02**	**26.96 to 36.89**	**<.001**
Response Times	**Quiet to -10 dB**	**-106**	**12**	**-137 to -76**	**<.001**
	Quiet to -15 dB	**-207**	**17**	**-249 to -164**	**<.001**
	-10 to -15 dB	**-100**	**19**	**-146 to -55**	**<.001**

Correlation analyses, displayed in Figure 4.2, revealed a significant relationship between age and triplet recognition ($r = .24$, $p < .001$), demonstrating that triplet recognition performance improved with age. There was no significant association between age and RT during the single task ($r = -.08$, $p = .26$). Together, these data indicate that the triplet recognition scores and RTs were sensitive to the effects of SNR, but not to language background. In addition, older children tended to demonstrate better triplet recognition performance than younger children, although RTs did not demonstrate such a pattern.

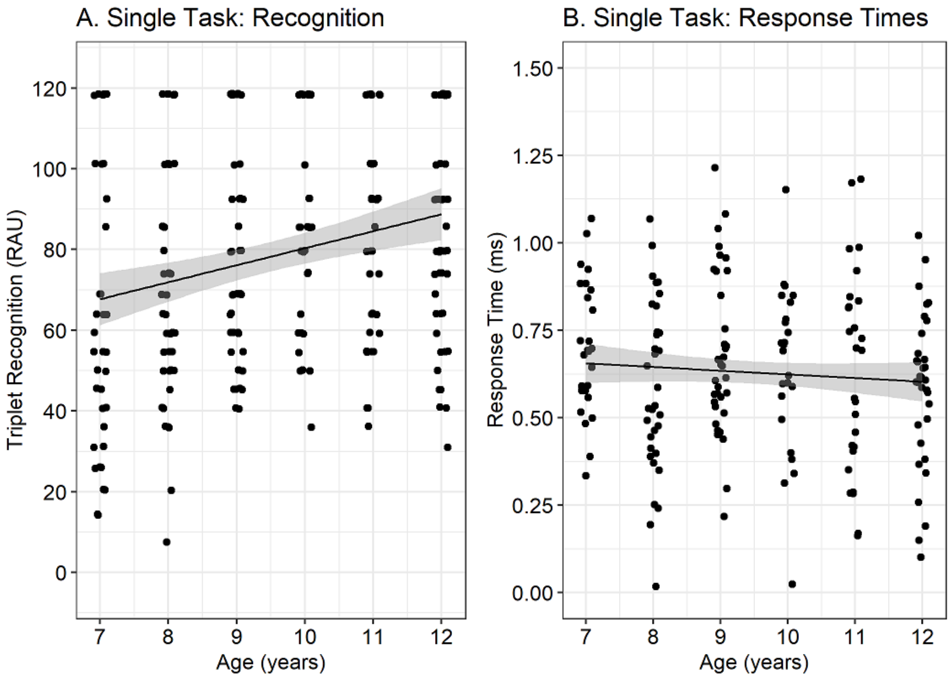

Figure 4.2 Triplet recognition performance and response times across participants' ages for the single-task paradigm. RAU = rationalized arcsine units.

4.4.2 Dual-task Paradigm

Figure 4.1 displays triplet recognition (Panel C) and RTs (Panel D) obtained during the dual-task paradigm for each SNR and Language Group. Analysis of digit triplet recognition revealed a significant main effect of SNR, ($F_{2, 116}$ = 332.69, $p < .001$, η_p^2 = .85), and no significant effects of Language Group ($p > .13$, η_p^2 = .04) or Language Group × SNR interaction ($p > .38$, η_p^2 = .02). Analysis of dual-task visual RTs revealed a significant main effect of SNR, ($F_{1.77, 102.73}$ = 17.22, $p < .001$, η_p^2 = .23), and no significant effects of Language Group ($p > .22$, η_p^2 = .03) or Language Group × SNR interaction ($p > .14$, η_p^2 = .03). Pairwise comparisons, displayed in Table 4.2, reveal digit triplet recognition performance, and dual-task visual RTs were significantly worse with the addition of, or increase in, background noise.

Table 4.2 Results of pairwise comparisons of triplet recognition performance (rationalized arcsine units) and response times (ms) for the dual-task paradigm, collapsed across language groups. Significant differences are indicated by bold typeface.

Outcome	Comparison	*M* difference	Std Error	95% CI	*p*
Triplet Recognition	**Quiet to -10 dB**	**37.06**	**2.48**	**30.94 to 43.17**	**<.001**
	Quiet to -15 dB	**68.94**	**2.69**	**62.31 to 75.57**	**<.001**
	-10 to -15 dB	**31.88**	**2.84**	**24.88 to 38.90**	**<.001**
Response Times	**Quiet to -10 dB**	**-162**	**54**	**-295 to -30**	**.011**
	Quiet to -15 dB	**-383**	**75**	**.567 to -199**	**<.001**
	-10 to -15 dB	**-221**	**54**	**-385 to -57**	**.005**

Correlation analysis, displayed in Figure 4.3, revealed a significant relationship between age and digit triplet recognition (r = .20, $p < .002$), in addition to significant relationship between age and dual-task visual RTs (r = −.39, $p < .0001$) with dual-task visual RTs generally decreasing and triplet recognition increasing with increasing age.

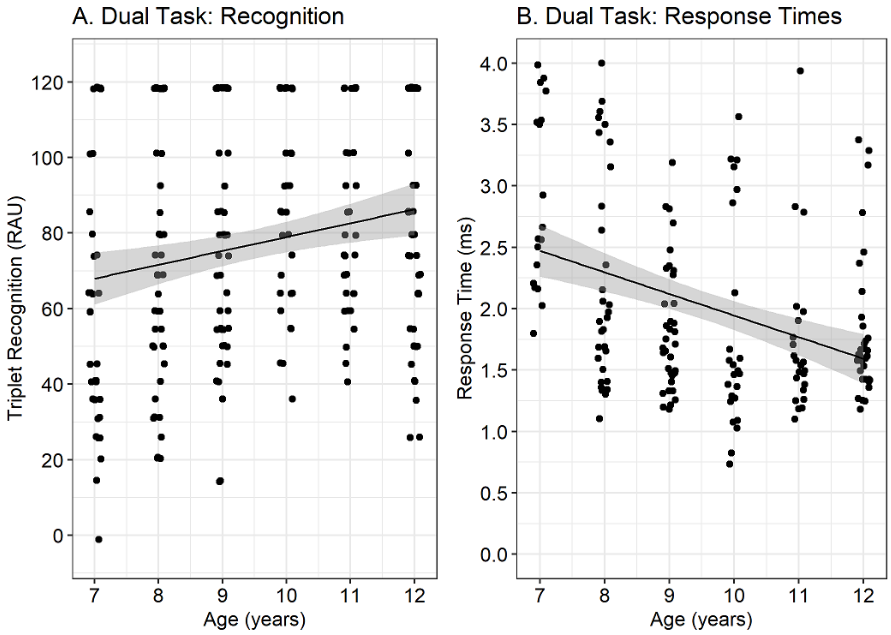

Figure 4.3 Triplet recognition performance and response times across participants' ages for the dual-task paradigm. RAU = rationalized arcsine units.

Taken together, these data demonstrate that both single- and dual-task paradigms were sensitive to changes in the background noise. However, language background (native English, nonnative English) did not affect the pattern of RTs. The data also demonstrate a maturation effect for RTs during the dual-task, but not the single-task paradigm.

4.5 DISCUSSION

The objective of this study was to explore the effects of SNR on listening effort in normal-hearing school-aged children with English native language and English as nonnative language as measured with a novel, low linguistic single- and dual-task paradigms. The effects of SNR, age, and language groups on digit triplet recognition and RTs will be considered separately below. It was hypothesized that speech recognition would decrease, and RTs would increase as SNR decrease and that the single-task paradigm would be more sensitive to the effects of SNR. It was also hypothesized that older children would have better speech-recognition-in-noise performance and that their RTs would be shorter than younger children. In addition, it was hypothesized that both low linguistic single- and dual-task paradigms would be unaffected by the possible effect of language differences on speech recognition as well as on RTs.

4.5.1 Effect of SNR on Digit Triplet Recognition and RTs

Recognition of digit triplets followed the expected pattern of poorer performance with decreasing SNR even for children with normal hearing (e.g. Bess et al., 1986; Crandell & Smaldino, 2000b). The effects of SNR on RTs were evident with both the single- and dual-task paradigms. With both paradigms, increased RTs were evident between quiet and noise conditions as well as when the noise was increased from −10 dB SNR to −15 dB SNR. This pattern of results is consistent with previous reports, which indicate that increasing background noise increases RTs (dual task and/or single task), reflecting an in increase in listening effort in adults (Fraser et al., 2010; Picou et al., 2017; Picou & Ricketts, 2014; Picou et al., 2011; Sarampalis et al., 2009) and children (Gustafson et al., 2014; Howard et al., 2010; Hsu et al., 2017; Lewis et al., 2016; McGarrigle et al., 2019; Picou et al., 2019a; Picou et al., 2017). The findings of this study are somewhat inconsistent with recent findings by McGarrigle et al. (2019) who demonstrated that verbal RTs (as a single-task measure) were more sensitive to changes in SNR than RTs during a dual-task paradigm in school-aged children.

Discrepancy in dual-task paradigm results across studies can be attributed to substantial methodological differences. The performance level achieved in the primary task may be a potential explanation of discrepancy in results among studies regarding the effect of SNR on listening effort as measured by dual-task paradigms (McGarrigle et al., 2019). According to Pichora-Fuller et al. (2016), a listening effort threshold exists, referring to the trend where RTs will generally increase until a speech recognition task becomes too difficult at which level listening effort will likely decrease as evident in faster RTs. This is also described as a point of cognitive overload (Wu et al., 2016). As noted by McGarrigle et al. (2019), the more challenging SNRs employed in their study (particularly for children with a hearing loss, resulting in < 50%-word recognition) may have resulted in more frequent incidences of cognitive overload. In contrast with the findings of McGarrigle et al. (2019) of insignificant effects on listening effort with decreasing SNRs, the results of Howard et al. (2010) correspond with the current study results where significant effects of SNR on secondary task RTs were found. Interestingly, the targeted speech recognition scores of 50%–80% correct in the current study corresponded to scores found in the study by Howard et al. (2010) who also reported significant effects of SNR on listening effort in children with normal hearing. Thus, it is possible that a dual-task paradigm could be as sensitive to changes in SNR as a single-task measure if the targeted speech recognition performance is higher. However, in the study by Hicks and Tharpe (2002), the average word recognition performance of 85% resulted in nonsignificant effects of SNR in listening effort. Thus, the targeted speech recognition performance, SNRs, and type of material used in the primary and secondary tasks should be viewed as important methodological considerations for dual-task paradigms used in school-aged children. Furthermore, factors such as cognitive resource allocation and attention allocation abilities are associated with the interpretation of dual-task results, and these abilities are still developing in school-aged children and thus could contribute to the general variance in dual-task performance (McGarrigle et al., 2019).

4.5.2 Effect of Age on Digit Triplet Recognition and RTs

The effect of age on speech-recognition-in-noise abilities is evident in this study's results. These findings support results demonstrating speech-in-noise-recognition abilities for children with normal hearing continue to develop and improve into late childhood and adolescent years (Elliott, 1979; Koopmans et al., 2018). Adultlike performance for speech perception in noise can be reached between the ages of 10 and 12 years of age (Buss et al., 2006; Hall et al., 2004; Holder et al., 2016; Koopmans et al., 2018). This effect of age on speech perception in noise is also apparent in the current study with improved digit triplet recognition performance during both tasks as the children get older.

Age effects for RTs seen in the results were task specific as it was only evident during dual-task measures. It should be noted that the dual-task visual RTs demonstrated more variability than verbal RT from the single-task paradigm. The dual-task method relies on assumptions of cognitive resource allocation (Kahneman, 1973). However, as school-aged children could still show unpredictable attention or cognitive resource allocation, this may contribute to the overall performance variability as seen in the dual-task conditions that requires high-level attentional and cognitive processing compared with a simpler task of speech recognition alone (McGarrigle et al., 2019). The dual-task paradigm has ecological validity as multitasking is a common required skill in everyday classrooms situations and thus may be an important skill to be developed for academic progress. During dual-task measures, the faster RTs to visual stimuli that were evident with an increase in the age of the participants can be due to improved multitasking ability with age. This can reflect that dual-task measures are more sensitive to maturation effects whereas single-task measures appeared to be immune to the effect that age could possibly have on RTs. This is an important aspect that should be considered in study design in the pediatric population. Therefore, a single-task paradigm such as verbal RT measures could be used in school-aged children from the age of 7 years, whereas participant age needs to be accounted for with dual-task paradigms if participants are younger than 13 years old.

4.5.3 Effect of Language Group on Digit Triplet Recognition and RTs

The aim of the study was not to compare listening effort between native and nonnative English-speaking school-aged children but rather to explore stimuli that can be useful in behavioral measures of listening effort in children from multilingual backgrounds. In terms of language group differences between the participants, there was no systematic effect of language group on triplet recognition or RTs, as hypothesized. These findings are inconsistent with behavioral measures of listening effort in adults who are nonnative listeners (Peng & Wang, 2019). This may relate to the fact that digits, used as speech stimuli, are universal concepts, have a low linguistic load, and are often even familiar to persons who do not speak the language (Potgieter et al., 2016). Furthermore, digit recognition stems from a closed set speech recognition task that is easier than an open-set speech recognition task that involves monosyllabic words. The results of this study indicate that the novel low linguistic single-task and dual-task paradigms can be performed on young school-aged children from a multilingual context.

4.6 CONCLUSION

In total, the results of this study demonstrate that the single- and dual-task paradigms with low linguistic speech material can be sensitive to changes in listening condition (quiet vs. noisy conditions) for school-aged children between 7 and 12 years of age. Language background (English as native language vs. English nonnative language) had no significant effect on triplet recognition or RTs. Thus, these novel listening effort measures could be useful for evaluating listening effort in children from multilingual contexts. Furthermore, a maturation effect for speech recognition in noise and RTs (only with dual-task paradigm) is evident. The latter indicates that speech-in-noise recognition abilities improve with age for school-aged children, as expected. Furthermore, as multitasking skills develop, older children tend to exert less listening effort as reflected in shorter RTs during dual-task measures. Children have to develop important cognitive, language, and academic skills in the classroom. Therefore, the results also suggest that due consideration should be given to the negative effects of increased listening effort in acoustic challenging situations (e.g., classrooms with high noise levels) even for young school-aged children with normal hearing as it increases listening effort, which could deter academic learning.

4.7 ACKNOWLEDGEMENTS

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CHAPTER 5

LISTENING EFFORT IN SCHOOL-AGED CHILDREN WITH NORMAL HEARING COMPARED TO CHILDREN WITH LIMITED USEABLE HEARING UNILATERALLY

Authors: Ilze Oosthuizen, Erin M. Picou, Lidia Pottas, Hermanus C. Myburgh, and De Wet Swanepoel

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5.1 ABSTRACT

Objectives: Children with limited hearing unilaterally might experience more listening effort than children with normal hearing, yet previous studies have not confirmed this. This study compared listening effort in school-aged children with normal hearing and limited hearing unilaterally using behavioral and subjective listening effort measures.

Design: Two groups of school-aged children (aged 7-12 years) participated: 19 with limited hearing unilaterally and 18 with normal hearing bilaterally. Participants completed digit triplet recognition tasks in quiet and in noise (-12 dB signal-to-noise ratio) in three loudspeaker conditions: midline, direct, and indirect. Verbal response times during the recognition task were interpreted as behavioral listening effort. Subjective ratings of "task difficulty" and "hard to think" were interpreted as subjective listening effort. Participant age was included as a covariate in analysis of behavioral data.

Results: Noise negatively affected digit triplet recognition for both groups in the midline loudspeaker, and for participants with limited hearing unilaterally in the direct and indirect conditions. Relative to their peers with normal hearing, children with limited hearing unilaterally exhibited significantly longer response times and higher ratings of effort only in the noisy indirect condition. Differences between groups were evident even when age differences were controlled for statistically.

Conclusions: Using behavioral and subjective indices of listening effort, children with limited unilateral hearing demonstrated significantly more listening effort relative to their peers with normal hearing during the difficult indirect listening condition. Implications include classroom accommodations to limit indirect listening situations for children with limited useable hearing unilaterally and consideration of intervention options.

5.2 INTRODUCTION

School-aged children develop important cognitive and academic language proficiencies in classrooms. Yet, these contexts are often acoustically challenging due to background noise and/or reverberation (Berg, 1993; Bistafa & Bradley, 2000; Crandell & Smaldino, 2000b). The consequences of listening in such challenging environments include reduced speech perception, increased listening effort, and possibly fatigue (Prodi et al., 2010). Listening effort is described as the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a task that involves listening in order to understand speech (Pichora-Fuller et al., 2016). Considering the negative impact that listening effort and resultant fatigue can have on academic performance and general quality of life (Bess & Hornsby, 2014a, 2014b), it is important to understand the listening conditions and individual factors that might increase listening effort. Examining listening effort in addition to speech understanding in school-aged children with limited hearing unilaterally may be of clinical importance as this population continue to present with academic and behavioral difficulties (Culbertson & Gilbert, 1986; Lieu et al., 2013), despite improved and earlier identification and intervention (Bagatto et al., 2019).

5.2.1 Listening Effort

The Framework for Understanding Effortful Listening (FUEL; Pichora-Fuller et al., 2016) and the Ease of Language Understanding model (ELU; Rönnberg et al., 2013; Rönnberg et al., 2008) provide frameworks for understanding the factors that might affect listening effort. According to the FUEL and the ELU model, cognitive demand is a pivotal factor contributing to listening effort and various factors can increase the cognitive demand by interfering with the match between the incoming signal and long-term memory stores. Thus, factors which distort or degrade an auditory signal, such as reduced hearing acuity or background noise, would be expected to result in more listening effort. Indeed, existing evidence supports these hypotheses, demonstrating that, for school-aged children, listening effort is higher in background noise (Hsu et al., 2017; McGarrigle et al., 2019; Picou et al., 2019a) and for children with hearing loss (Hicks & Tharpe, 2002). However, existing evidence is primarily focused on children with bilateral hearing loss (e.g., Hicks & Tharpe, 2002; Hughes & Galvin, 2013; McGarrigle et al., 2019; Stelmachowicz et al., 2007). Much less is known about listening effort in children with unilateral hearing loss (UHL), specifically the sub-group of severe-profound sensorineural unilateral hearing loss, compared to children with normal hearing. If children with UHL experience difficulties in listening to and understanding speech (discussed below), one might also expect them to exhibit more listening effort compared to children with bilateral normal hearing.

5.2.2 Listening Difficulties With Unilateral Hearing Loss

UHL is detrimental to the benefit of binaural listening skills due to the loss of binaural cues, such as interaural time difference and interaural level difference cues. These interaural cues are considered the primary cues used in binaural hearing and assist the auditory system with sound source localization as well as to separate relevant from irrelevant signals (Arndt et al., 2014; Loiselle et al., 2016). The loss of binaural hearing for children with UHL has a negative impact on localization (Johnstone et al., 2010) as well as speech perception (Bess et al., 1986), especially in noise (Bess & Tharpe, 1986b; Bess et al., 1986; Ruscetta et al., 2005). Consequently, children with UHL have a greater risk of poorer speech, language, and cognition outcomes compared to normal hearing peers (Ead et al., 2013; Lieu, 2013). This could lead to academic difficulties such as increased need for additional academic assistance (Bess et al., 1986; Lieu, 2004; Oyler et al., 1988) or behavioral problems (Lieu, 2004). The risks can even be more pronounced for children with unaidable unilateral hearing loss (Bess et al., 1986; Culbertson & Gilbert, 1986; Lieu et al., 2013), which is defined as greater than severe unilateral sensorineural hearing loss with poor word recognition. Unaidable unilateral hearing loss has been referred to as "single-sided deafness" (SSD) or "limited useable hearing unilaterally" (LUHU; Picou et al., 2020a; Picou et al., 2020b; Picou et al., 2019b). The term LUHU will be used hereafter because it is more specific in terms of the expected auditory abilities than the term "single-sided deafness".

In addition to being dependent on the degree of UHL, speech recognition difficulties are expected to be specific to the talker's location. For example, Corbin et al. (2017) and also Kenworthy et al. (1990) demonstrated that children with LUHU have the most difficulty understanding indirect speech (speech directed towards the ear with LUHU and noise directed towards the ear with normal hearing). In classroom environments, this has implications for a variety of routine academic experiences, such as during group work if a peer is seated near a student's side with LUHU. Although the differences in performance between children with LUHU and normal hearing might be smaller, some deficits have also been noted for midline conditions, e.g. frontal instruction in a classroom (Ruscetta et al., 2005), and direct listening situations (i.e., speech directed to the ear with normal hearing; Bess et al., 1986).

5.2.3 Listening Effort in the UHL Population

Combined, these data demonstrate that children with UHL, and especially with LUHU, exhibit more listening difficulty than their peers with normal hearing, due to the loss of audibility in one ear and the loss of binaural information. From the FUEL and the ELU model, if the loss of unilateral audibility and loss of binaural cues impede a match between the incoming signal and long-term memory stores, children with LUHU would also be expected to exhibit more listening effort than peers with normal hearing. However, the conclusions about listening effort for children with UHL might depend on the type of methodology used to evaluate listening effort, as some of the listening effort methodologies might reflect unique sub-constructs of listening effort (c.f., McGarrigle et al., 2014; Strand et al., 2018). Two general categories of listening-effort methodologies include behavioral and subjective measures.

Behavioral listening effort methodologies involving a timed response, for example verbal response time measures (i.e. speed of speech repetition) or timed secondary task, are commonly used in adult and pediatric populations (Gagne et al., 2017). In a verbal response time paradigm, participants repeat speech and the time between stimulus presentation and the participant's verbal response is recorded. As a result, outcomes from a verbal response time paradigm include both speech recognition performance and response times. Verbal response times have been used in the pediatric population, with longer response times interpreted as more listening effort (Gustafson et al., 2014; Houben et al., 2013; Lewis et al., 2016; McGarrigle et al., 2019; Oosthuizen et al., 2020; Pals et al., 2015; Prodi et al., 2019). Lewis and colleagues (2016) used a single-task paradigm to evaluate the effect of SNR (-5 to +5 dB) in three groups of school-aged children (5-12 years), namely children with normal hearing, children with mild bilateral hearing loss, and children with UHL. Results showed a significant effect of SNR (increased response times in less favorable SNRs), but no differences between groups.

In addition to behavioral measures of effort, subjective ratings have been used to evaluate listening effort. Although limited, the results of previous studies that have reported subjective effort with children suggest that, as with adults (Moore & Picou, 2018; Strand et al., 2018), results of behavioral listening effort measures and subjective ratings can be discrepant (Gustafson et al., 2014; Picou et al., 2019a). These results suggest that subjective ratings provide information about different dimensions of listening effort when compared to other listening effort measures, e.g., behavioral response time measures (e.g., Alhanbali et al., 2019; Lemke & Besser, 2016; Pichora-Fuller et al., 2016). Consequently, it is possible that children with UHL could demonstrate more listening effort than their peers with normal hearing on a behavioral measure, but not a subjective measure, or vice versa.

Although the existing evidence suggests children with UHL would exhibit more listening effort than their peers with NH, especially based on the FUEL and ELU model, demonstration of group differences has been elusive so far in the literature. For example, McFadden and Pittman (2008) evaluated dual-task performance in 8- to 10-year-old children with normal hearing, or with mild bilateral hearing loss, or UHL. Participants performed a primary task (word categorization) and a secondary task simultaneously (dot-to-dot games). Performance degradations on the secondary task are thought to reflect changes in cognitive effort (e.g., Gagne et al., 2017) because human cognitive capacity is finite (Kahneman, 1973). Participants in the McFadden and Pittman study (2008) completed dual-task testing in quiet and noise (0 to + 6 dB). Overall, the primary task was sensitive to changes in signal-to-noise ratio (SNR) for children with hearing loss. However, the secondary task performance was not affected by changes in SNR or hearing status, contrary to expectations set forth by the FUEL and ELU model. A possible explanation is that the secondary task was too engaging, which negatively affected the primary task, as has been demonstrated for other types of dual-task paradigms in the pediatric population (Choi et al., 2008). Consistent with the results of the dual-task study of McFadden and Pittman (2008), the study by Lewis et al. (2016) resulted in no significant listening effort differences among children with normal hearing, children with mild bilateral hearing loss, and children with UHL. Another explanation for the non-significant finding across participant groups may be the heterogeneity in degree of hearing loss included in the previous studies. That is, children with only mild-moderate UHL were included and they might not have experienced more listening effort than children with normal hearing. Lewis et al. (2016) suggested that children with more severe degrees of UHL would demonstrate more listening effort, which would be consistent with the aforementioned evidence of increased speech recognition difficulties exhibited by children with LUHU than by those with mild-moderate UHL (Bess et al., 1986; Lieu et al., 2013).

The purpose of this study was to determine if school-aged children with LUHU experience more listening effort than similarly-aged peers with normal hearing, as measured behaviorally (verbal response times) and subjectively (subjective ratings) in quiet and in noise. Three listening conditions were used to reflect some of the scenarios that might be found in a classroom (i.e., midline signal, direct, and indirect). A multilingual sample from diverse language backgrounds (native English and non-native English speakers), typical of classroom compositions, was included. This study did not aim to examine multilingualism but listening to non-native speech could affect listening effort (Peng & Wang, 2016; Peng & Wang, 2019; Pichora-Fuller et al., 2016). Therefore, speech stimuli of digit triplets were used as it has previously been shown to be insensitive to listeners' language backgrounds (Oosthuizen et al., 2020). It was expected that, relative to their peers with NH, children with LUHU would exhibit lower digit triplet recognition scores and more listening effort, as measured behaviorally and subjectively. Specifically, greater listening effort for children with LUHU was expected in a noisy, indirect listening situation based on previous studies identifying this situation as the most challenging for children with LUHU with regards to speech understanding (Corbin et al., 2017; Kenworthy et al., 1990). Age was included as a covariate since previous studies demonstrated significant effects of age on response time measures for children in this age range (e.g., Key et al., 2017; Lewis et al., 2016; Oosthuizen et al., 2020).

5.3 MATERIALS AND METHODS

5.3.1 Participants

Two groups of similarly-aged school-aged children from multilingual backgrounds (native English and non-native English speakers) participated in the study: 19 children with LUHU (*M* = 9.9 years, *SD* = 1.7, range 7-12 years) and 18 children with normal hearing bilaterally (NH; *M* = 10.2 years, *SD* = 1.5, range 7-12 years). All participants had normal middle ear function, verified by tympanometry measures and normal otoscopic examination findings on the day of testing. Participants with NH presented with normal hearing sensitivity in both ears (≤ 15 dB HL for octave frequencies from 250 to 8000 Hz). Participants with LUHU presented with normal hearing sensitivity in one ear and a severe-profound sensorineural unilateral hearing loss in the opposite ear. Hearing loss was characterized by: a) air conduction thresholds greater than 70 dB HL from 250 Hz to 8000 Hz, (b) an average air-bone gap no greater than 10 dB at

1000 Hz, 2000 Hz, and 4000 Hz, (c) and poor phonetically-balanced monosyllabic word recognition (<70%; using the *Afrikaanse Foneties Gebalanseerde Woordelys (Laubscher & Tesner, 1966a)* or the *University of Pretoria, English Phonetically Balanced Word List)* at a comfortable presentation level in the impaired ear (Madell et al., 2011). Participants with LUHU completed all the testing unaided. No participant had other otologic or cognitive disorders, as evident from parental and/or teacher report. All participants had typical speech, language, and motor development as confirmed by parental report. Table 5.1 summarizes the demographic information of the participants. Institutional review board approval was granted for this study by the Research Ethics Committee of the Faculty of Humanities, University of Pretoria.

Table 5.1: Participant demographic information

Number	Age	Gender	Native (N) or Non-native (NN) English	Ear with LUHU	Age at diagnosis	Aetiology	Degree of hearing loss
PARTICIPANTS WITH LUHU							
1	7	M	N	L	5 years	Acquired: Mumps (on the left)	Severe-profound
2	10	M	NN	R	6 years	Acquired: Meningitis at 2 weeks of age	Profound
3	11	F	NN	L	3 years	Unknown	Profound
4	11	F	NN	R	8 years	Congenital: cochlear malformation	Profound
5	10	F	N	L	6 years	Unknown	Profound
6	10	M	N	L	4 years, 11 months	Congenital: Dysmorphia of cochlea and hypoplastic auditory nerve	Profound
7	11	M	NN	L	6 years	Acquired: Suspect viral infection	Severe-profound
8	9	M	N	R	5 years	Acquired: Meningitis at age 4 years	Profound
9	9	F	NN	L	2 years	Acquired: Suspect due to chronic OM	Profound
10	10	M	NN	L	2 years	Acquired: Tuberculosis at 6 months of age	Profound
11	12	F	N	R	Peri-natal period	Congenital: Suspect Golden-Har Syndrome	Profound
12	10	M	NN	R	6 years	Unknown	Profound
13	12	F	NN	R	5 years	Unkown	Profound
14	12	M	N	R	10 years	Acquired: Viral infection	Severe-profound
15	7	F	N	L	4 years	Acquired:	Profound

						Prematurity and ototoxic medication	
16	7	F	NN	R	5 years, 4 months	Unknown	Severe-profound
17	11	M	NN	R	10 years	Acquired: Labyrinthitis	Profound
18	12	F	NN	R	6 years	Congenital	Profound
19	8	F	NN	L	5 years	Mumps at age 5 years	Severe-profound
PARTICIPANTS WITH NH							
1	7	M	N				
2	10	M	NN				
3	11	F	NN				
4	11	F	NN				
5	10	F	N				
6	10	F	N				
7	11	M	NN				
8	9	F	N				
9	9	M	NN				
10	10	F	NN				
11	12	M	N				
12	10	F	NN				
13	12	F	NN				
14	12	M	N				
15	7	F	N				
16	7	F	NN				
17	11	M	NN				
18	12	M	NN				

Note: Participant 8 in the LUHU group was deemed unreliable during testing and his data were not included in analyses.

LUHU = limited usable hearing unilaterally; NH = normal hearing

5.3.2 Verbal Response Time Paradigm

The behavioral listening effort paradigm was previously used in a study of listening effort with school-aged children (Oosthuizen et al., 2020). The speech stimuli were digit triplets from the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018). The use of digit triplets from an English-based digits-in-noise test has several advantages over open-set word or sentence recognition stimuli that make it more applicable for use in a multilingual context, which is typical of children in South Africa. First, digits-in-noise stimuli are low in linguistic demands and secondly, the speech materials are presented in a closed set (Kaandorp et al., 2016; Potgieter et al., 2018). That is, mono- and bi-syllabic digits (0-9) are used in the triplets because the recognition probabilities of all the digits are equalized so that a potential difference in recognition probabilities is eliminated (Smits, 2016). Thirdly, English digits are mostly familiar and often used by speakers of other languages (Branford & Claughton, 2002). In addition, as evidenced by Oosthuizen et al. (2020), these stimuli were insensitive to the language background of school-aged listeners; listeners who spoke English as an additional language or as a first language repeated a similar number of digit triplets and responded similarly quickly across a variety of SNRs.

During testing, participants were required to listen to, and repeat digit triplets presented in quiet and in noise. Digit triplets were presented at 60 dB(A). Noise, when present, was at 72 dB(A) for a -12 dB SNR. The noise was steady-state noise with the same long-term average speech spectrum as the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018). Pilot testing with naïve participants with normal hearing indicated the -12 dB SNR in this study would result in approximately 50 – 80% correct digit triplet recognition performance with a midline signal. Based on the work of Wu and colleagues (2016), this approximate performance level is expected to be sensitive to changes in listening effort.

Prior to testing, participants were instructed to listen to and repeat the digit triplets. Participants were encouraged to guess if they were unsure of the digit triplet that was presented. Participants were unaware that the tasks were timed and therefore not instructed to give their responses as quickly as possible. Furthermore, participants were instructed to keep their head still and face forward for the duration of the testing. Participants' verbal responses were recorded by a head-worn microphone and saved by a custom software program (MATLAB R2015a). The experimenter scored the verbal responses to the digits and calculated a percent correct digit triplet recognition score for each participant in each condition. The verbal response times (RTs) were automatically calculated by a custom MATLAB program that measured the time elapsed from the end of the digit triplet to the onset of the participant's response. Thus, this reaction time measure indicated how quickly the participant began to speak once the stimulus ended. Digit length varied between 420 – 740 ms with 100 ms intervals between digits in a triplet. The average length of a digit triplet was ~ 2000ms. Therefore, it can be assumed that the participant has begun processing of the stimulus before beginning to respond. The RTs were saved in specific files for each participant.

5.3.3 Subjective Ratings

Immediately after completion of a listening effort task in each condition, participants provided subjective ratings by answering three questions: 1) “How did you find the listening task?” (task difficulty); 2) “How many numbers do you think you got right?” (recognition performance); 3) “Was it hard to think when you were listening?” (hard to think). Participants answered the three questions on a questionnaire by marking their subjective opinion on a 5-point emoji rating scale, where 1 meant “very easy/everything/very easy” (big smile) and 5 meant “very hard/nothing/very hard” (big frown). The questions were typed on a piece of paper with the five emojis below each question.

5.3.4 Test Environment

Testing was conducted in a double-walled, sound-attenuating audiometric test booth (2.13m x 2.03m x 2.43m). Three (3) loudspeakers (GSI 90 dB) were located at 0°, 90°, and 270°. Participants were seated in the booth, 1 meter from the loudspeakers, at a school desk. Handprints were placed on the desk’s surface showing participants where to place their hands during testing to help eliminate noise from possible hand movements. Digit triplets were presented through custom programming of MATLAB software, routed to an audiometer (GSI AudioStar Pro), and then to a loudspeaker. Noise files were stored on the audiometer and selected from the internal files. The noise, when present, was routed from the audiometer to loudspeaker(s). Prior to testing, output levels for digit triplets and digit noise were measured by means of a sound level meter to ensure the correct output level in the sound field. The microphone of the sound level meter was at a position equivalent to center of the participant’s head. The digit noise was used during the measurement of output levels because it matches the long-term average speech spectrum of the digits (Potgieter et al., 2016).

5.3.5 Test Conditions

Participants were tested in a total of 6 conditions, which varied by SNR (quiet, -12 dB) and loudspeaker conditions (midline, direct, and indirect). In the *midline condition* the digit triplets were played through the loudspeaker directly in front of the participant (0°) and correlated noise was routed synchronously from the audiometer to the two loudspeakers placed at 90° and 270° azimuths. In the *direct listening condition,* the digits were presented through the loudspeaker directed towards the ear with normal hearing and noise was presented through a loudspeaker directed towards the ear with LUHU. For a participant with LUHU in the left ear, digit triplets were presented from 90° and noise from 270°. In the *indirect listening condition* digit triplets were presented through the loudspeaker directed towards the ear with LUHU and noise was presented through a loudspeaker directed towards the ear with normal hearing. For example, for a participant with LUHU in the left ear, digit triplets were presented from 270° and noise from 90°. To facilitate comparisons between groups for the direct and indirect conditions, the 90° loudspeaker was always designated as the "direct" loudspeaker (i.e., digit triplets presented from 90° and noise presented from 270°), whereas the 270° loudspeaker was always designated as the "indirect" loudspeaker (i.e., digit triplets presented from 270° and noise presented from 90°) for participants with NH.

5.3.6 Procedures

Before data collection commenced, informed consent was obtained from each participant's parent/guardian and assent was obtained from the participants. Standard audiometric procedures confirmed normal bilateral hearing sensitivity for participants with NH and confirmed normal hearing in one ear and a severe-profound sensorineural hearing loss in the opposite ear for participants with LUHU. Also prior to data collection, training rounds were conducted to ensure that the participants understood the instructions. Training rounds consisted of verbal response time tasks in quiet and in noise. Training lists (lists containing ten digit triplets) were not repeated during the experimental testing. After the training rounds, data collection commenced. A single list with 20 digit triplets was used in each condition. Twenty-five (25) lists consisting of 20 digit triplets each were created in order to ensure no repetition of a digit triplet list in the various test conditions. The order of the loudspeaker conditions (midline, direct, indirect) and SNR condition (quiet, -12 dB) and digit triplet lists were randomized across participants. Directly after each digit triplet list was presented, participants answered the three rating scale questions.

5.3.7 Data Analysis

During testing, one participant with LUHU (9-year-old male) was noticeably distracted. Consequently, his results were deemed unreliable and his data were excluded from the study. Analyses for the different outcomes (digit triplet recognition, response times, subjective ratings) were based on the remaining 36 participants (18 in each group). Prior to analysis, digit triplet recognition data were converted to rationalized arcsine units (rau) to normalize the variance near the extremes with the equations found in Studebaker (1985). Results on digit triplet recognition performance are presented in percent correct in figures with rau scores in the text to assist interpretation of results.

Verbal response times were taken as the measure of listening effort. As suggested by Hsu and colleagues (2017), response time (RT) data from both correct and incorrect digit triplet recognition trials were included as it results in better representation of the varying levels of listening effort that children might experience in real-life, noisy situations. However, there were some exceptions. RTs for verbal responses not containing digits (e.g., "I don't know/I didn't hear") were excluded from analysis (a total of 46 RTs from 9 participants with LUHU). Subjective checks of all recordings were done to identify occurrences of speech fillers such as "umm" and "uh", stutters, and nonspeech sounds (e.g., breathing, yawns) that occurred before a digit triplet was spoken as well for trials with self-corrections. In these cases, fillers and false starts were replaced with silence and the verbal response onset-time was marked as the onset of the self-corrected, second utterance (a total of 9 and 25 RTs were manually corrected for participants with NH and those with LUHU, respectively). Furthermore, to ensure the RTs were calculated correctly by the MATLAB program, the responses of each participant to a single digit triplet were analysed. The resultant RT was compared to that produced by the MATLAB program. In addition, RTs were included in the analysis only if they were within +/- 2.5 standard deviations of the mean RT for the participant in a given digit triplet list. A total of 113 RTs (54 from the NH group; 59 from the LUHU group) were eliminated in this process. In total, 159 of 4320 RTs were excluded for all participants and conditions (3.7%).

Digit triplet recognition and verbal response times were analyzed separately using analysis of co-variance (ANCOVA) with two between-participant factors, Group (NH, LUHU) and Language group (native English, non-native English), and two within-participant factors, Loudspeaker (midline, indirect, direct) and Condition (quiet, noise). Age (in years, centered at 0 via linear transformation) was included as a covariate. Data analyses were done using both ANCOVA and linear mixed effects modelling. Results were similar for both methods. Due to the relative simplicity of the approach, only ANCOVA results are reported. Significant interactions were explored using follow-up ANCOVAs and multiple pairwise comparisons with false discovery rate corrections for family-wise error rate (Benjamini & Hochberg, 1995). Significant effects of the covariate were explored using Pearson correlation analysis. Greenhouse-Geisser corrections for sphericity violations were used when necessary. Data for response times were normally distributed as assessed via visual inspection of the Q-Q plots. Data for the digit triplet recognition performance violated the assumption of normality due to expected excellent performance in some conditions (e.g., direct condition, quiet). Despite non-normal distributions, ANCOVAs were used because they are considered to be robust to deviations from normality as well as to Type I errors (Blanca et al., 2017; Maxwell & Delaney, 2004). Where outliers were detected, ANCOVAs were re-run with and without the outliers included in the analysis. Analyses showed the same significant results for both instances and therefore outliers were included in all analyses. Analyses were conducted in R (v 3.6.1; R Core Team, 2019). ANCOVAs were completed using the aov_ez function in the afex package (Singmann et al., 2020). Pairwise comparisons were calculated using the emmeans function in the emmeans package (Lenth, 2019). Correlations were calculated using the cor.test function in base R.

Subjective ratings were analyzed using non-parametric, Mann-Whitney U analyses as the data were ordinal in nature. Analyses included one between-participant factor (Group) for each Loudspeaker and Condition combination. Significance values were corrected for the number of comparisons (6), leading to a significance criterion value of $p < .0083$. Responses to all three questions were analyzed separately. Mann-

Whitney U analyses were conducted using the wilcox.test function in base R (Singmann et al., 2020).

5.4 RESULTS

5.4.1 Digit Triplet Recognition

Figure 5.1 displays mean digit triplet recognition (in percent correct) in quiet (top left panel) and in noise (top right panel) for each group in each loudspeaker condition. Analysis of digit triplet recognition revealed significant main effects of Condition, Loudspeaker, and Group as well as significant two-way interactions of Condition x Group, Loudspeaker x Group, and Condition x Loudspeaker. In addition, there were significant three-way interactions of Condition x Loudspeaker x Group ($F_{1.64,\ 50.92}$ = 56.67, $p < .001$, $\eta_p^2 = 0.65$) and Age x Condition x Loudspeaker ($F_{1.64,\ 50.92}$ = 5.16, $p < .05$, $\eta_p^2 = 0.14$). The main effect of Language group and all interactions with Language group were non-significant ($p > .50$, $\eta_p^2 < 0.06$). Consequently, the significant interactions were explored using separate ANCOVAs for each Loudspeaker with a single within-participant factor (Condition), a single between-participant factor (Group), and Age as a covariate. Results are displayed in Table 5.2.

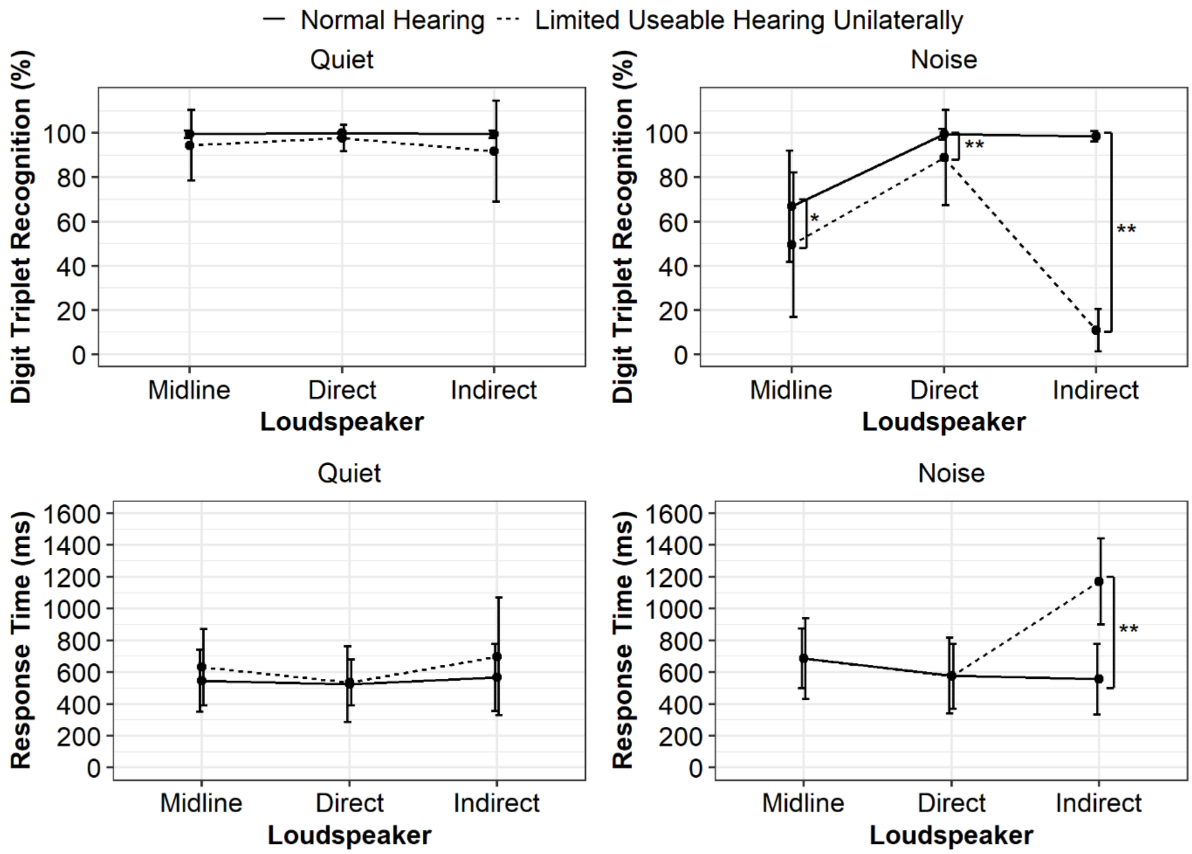

Figure 5.1. Mean digit triplet recognition scores (percent correct) in quiet (top left panel) and in noise (top right panel) and mean response times (ms) in quiet (bottom left panel) and in noise (bottom right panel). Solid lines indicate participants with normal hearing. Dashed lines indicate participants with limited useable hearing unilaterally. Error bars indicate standard deviation. Significant differences are indicated by * (*p* < .05) or ** (*p* < .001).

Table 5.2. Results of ANCOVA analyses for digit triplet recognition (in rau) conducted separately for each loudspeaker location. Significant effects or interactions are indicated by bold type face. Corrected *p* values are displayed.

Loudspeaker	Effect	F	*df*	*p*	η_p^2
Midline					
	Age	2.92	1, 33	.097	0.08
	Group	**4.73**	**1, 33**	**.037**	**0.13**
	Condition	**113.33**	**1, 33**	**<.001**	**0.77**
	Group x Condition	3.98	1, 33	.054	0.11
	Condition x Age	**7.95**	**1, 33**	**.008**	**0.19**
Direct					
	Age	0.04	1, 33	.835	0.001
	Group	**6.93**	**1, 33**	**.013**	**0.17**
	Condition	**8.9**	**1, 33**	**.005**	**0.21**
	Group x Condition	**6.87**	**1, 33**	**.013**	**0.17**
	Condition x Age	0.56	1, 33	.459	0.02
Indirect					
	Age	0.04	1, 33	.846	0.001
	Group	**115.64**	**1, 33**	**<.001**	**0.78**
	Condition	**348.94**	**1, 33**	**<.001**	**0.91**
	Group x Condition	**305.62**	**1, 33**	**<.001**	**0.90**
	Condition x Age	0.15	1, 33	.705	0.004

For the midline loudspeaker, analysis revealed significant main effects of Condition and Group, indicating performance was better in quiet than in noise (*M* difference = 37.79 rau, 95% CI: 30.57 to 45.01 rau, $p < .0001$) and was better for the group with NH than the group with LUHU (*M* difference = 11.85 rau, 95% CI: 0.76 to 22.93 rau, $p = .037$). Correlation analysis between the covariate (age) and digit triplet recognition for each condition were conducted to follow-up on the significant Condition x Age interaction (see Figure 5.2). Results revealed age was significantly related to digit triplet recognition only for participants with NH and only in noise (r = 0.58, $p = .011$). Age was not correlated with performance in noise for listeners with LUHU (r = 0.28, $p = .260$) or in quiet for either group (r = -0.20, $p = .420$ and r = -0.006, $p = .981$ for participants with NH and LUHU, respectively; not displayed).

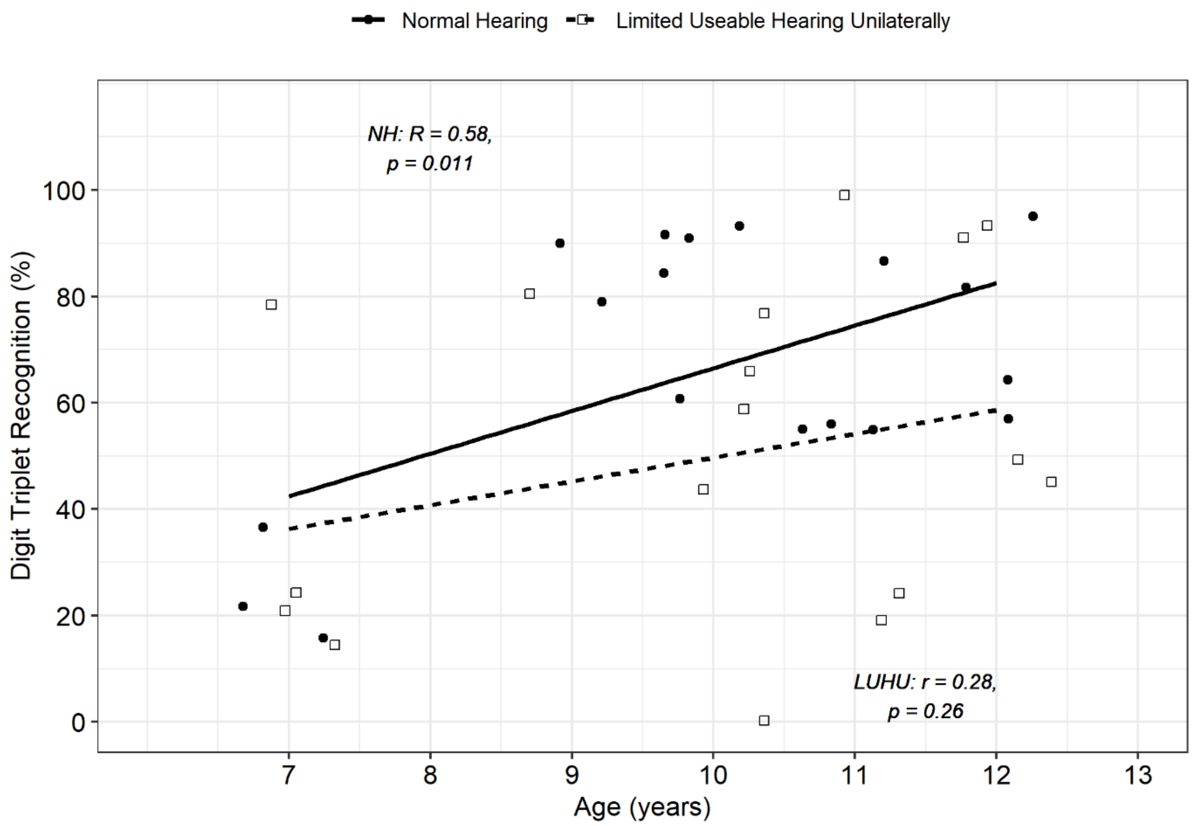

Figure 5.2. Relationship between age and digit triplet recognition for the midline loudspeaker condition in noise. Solid lines and circles indicate participants with normal hearing. Dashed lines and squares indicate participants with limited useable hearing unilaterally.

For the direct loudspeaker, results indicated significant effects of Condition and Group, as well as a significant interaction of Condition X Group. Pairwise comparisons revealed children with NH had higher digit triplet recognition performance than children with LUHU in noise (*M* difference = 14.50 rau, 95% CI: 6.46 to 22.54 rau, $p < .001$), but performance between the two groups was similar in quiet (*M* difference = 3.51 rau, 95% CI: -4.53 to 11.55 rau, $p = .385$). A similar pattern was evident for the indirect loudspeaker, where analysis revealed significant effects of Condition and Group as well as a significant Condition X Group interaction (see Table 5.2). Pairwise comparisons revealed children with NH had higher digit triplet recognition performance than children with LUHU in noise (*M* difference = 79.90 rau, 95% CI: 70.79 to 89.00 rau, $p < .001$), but performance between the two groups was similar in quiet (*M* difference = 6.46 rau, 95% CI: -2.64 to 15.56 rau, $p = .160$). Combined, these data indicate that children with LUHU exhibited lower digit triplet recognition performance in noise than their peers with NH, even when accounting statistically for age.

5.4.2 Response Times

The bottom panels of Figure 5.1 display mean response times in quiet and in noise in each loudspeaker setup. Analysis of RTs revealed a significant Condition x Loudspeaker x Group interaction ($F_{1.81,\ 56.25} = 22.23$, $p < .001$, $\eta_p^2 = 0.42$). There was also a significant main effect of Condition as well as significant two-way interactions of Group x Condition, and Loudspeaker x Group. There were no main effects or interactions with Language Group ($p > 0.05$). As a result, follow-up ANCOVAs were conducted for each Loudspeaker position, separately. Each ANCOVA included a between-participant factor (Group) and a within-participant factor (Condition). To be consistent with the digit triplet recognition scores, the ANCOVAs also included age as a covariate. Results of the follow-up ANCOVAs are displayed in Table 5.3.

Table 5.3. Results of ANCOVA analyses for response time conducted separately for each loudspeaker location. Significant effects or interactions are indicated by bold type face. Corrected *p* values are displayed.

Loudspeaker	Effect	F	*df*	*p*	η_p^2
Midline					
	Age	0.98	1, 33	.330	0.03
	Group	0.35	1, 33	.557	0.01
	Condition	**8.08**	**1, 33**	**.008**	**0.20**
	Group x Condition	1.63	1, 33	.210	0.05
	Condition x Age	0.72	1, 33	.401	0.02
Direct					
	Age	0.01	1, 33	.934	<.001
	Group	<0.01	1, 33	.963	<.001
	Condition	**4.82**	**1, 33**	**.035**	**0.13**
	Group x Condition	0.20	1, 33	.659	0.01
	Condition x Age	2.32	1, 33	.137	0.07
Indirect					
	Age	0.02	1, 33	.883	<.001
	Group	**21.24**	**1, 33**	**<.001**	**0.39**
	Condition	**26.13**	**1, 33**	**<.001**	**0.44**
	Group x Condition	**28.36**	**1, 33**	**<.001**	**0.46**
	Condition x Age	0.6	1, 33	.445	0.02

Results revealed only a significant effect of noise on RTs in the midline and direct loudspeaker conditions. Pairwise comparison testing indicated noise increased RTs for both groups in the midline (*M* difference = 98 ms, 95% CI: 28 to 167 ms, $p < .01$) and direct conditions (*M* difference = 47 ms, 95% CI: 3 to 91 ms, $p < .05$). For the indirect condition, results revealed significant main effects of Condition and Group as well as a significant interaction of Condition X Group. Pairwise comparison testing of the interaction revealed that participants with NH responded faster than participants with LUHU in the noise condition (*M* difference = 624 ms, 95% CI: 428 to 801 ms, $p < .001$), but not in the quiet condition (*M* difference = 133 ms, 95% CI: -53 to 320 ms, $p = .156$). Combined, these data indicate that, when accounting for age statistically, noise increased response times for both groups of participants in the midline and direct loudspeaker conditions. In addition, participants with LUHU exhibited slower response times than participants with NH, but only in the indirect loudspeaker condition with noise. Age was not statistically related to response times in any condition.

5.4.3 Subjective Ratings

Analysis revealed the distributions of subjective ratings were generally similar across listeners with NH and LUHU for all three questions. The notable exception is that listeners with LUHU rated all three questions significantly higher than listeners with NH in the indirect condition with noise (see Table 5.4). These data indicate that children with NH and LUHU rated the task difficulty, their recognition performance, and how hard it was to think similarly in the midline and direct conditions. On the contrary, in the indirect noise conditions, participants with LUHU rated task difficulty as higher, their recognition performance as lower, and listening effort as higher than children with NH.

Table 5.4. Results of mean rank differences of the subjective ratings for each Loudspeaker and Condition combination. Significant differences between the NH (normal hearing) participant and LUHU (limited useable hearing unilaterally) participant groups are indicated in bold type face (*p* < .0083).

Question	Loudspeaker	Condition	Mann-Whitney U	Asymptotic Sig
Task Difficulty	Midline	Quiet	133.5	.240
Task Difficulty	Midline	Noise	143	.543
Task Difficulty	Direct	Quiet	135	.162
Task Difficulty	Direct	Noise	231	.016
Task Difficulty	Indirect	Quiet	114	.047
Task Difficulty	**Indirect**	**Noise**	**56.5**	**<.001**
Recognition Performance	Midline	Quiet	168	.828
Recognition Performance	Midline	Noise	172	.742
Recognition Performance	Direct	Quiet	252	.617
Recognition Performance	Direct	Noise	180	.524
Recognition Performance	Indirect	Quiet	132	.217
Recognition Performance	**Indirect**	**Noise**	**33**	**<.0001**
Hard to Think	Midline	Quiet	143.5	.380
Hard to Think	Midline	Noise	181.5	.534
Hard to Think	Direct	Quiet	144	.476
Hard to Think	Direct	Noise	186	.426
Hard to Think	Indirect	Quiet	113.5	.081
Hard to Think	**Indirect**	**Noise**	**72**	**.004**

5.4.4 Relationship Between Outcomes

Exploratory Spearman's rank-order correlation analyses between age, behavioral, and subjective measures were conducted for the indirect condition with noise as it was the only listening condition where participants with LUHU had significantly increased RTs relative to NH peers. Correlations were conducted separately for participants with NH and with LUHU (see Table 5.5). Figure 5.3 displays the relationships between age and subjective ratings for both groups of participants. For participants with NH, there were few significant correlations. The outcomes (digit triplet recognition performance, response times, subjective ratings) were not generally correlated with each other nor were they correlated with age. This result is likely due to the generally high digit triplet recognition performance and fast response times in this condition for participants with

NH (see right panels of Figure 5.1). For participants with LUHU, where there was more variability in scores, analysis revealed digit triplet recognition performance and response times were correlated with each other, but not with subjective ratings. Instead, the subjective ratings were correlated with each other and with age. As displayed in Figure 5.3, older children with LUHU were more likely than younger children to provide high ratings, indicating the task was more difficult, their performance was worse, and it was harder to think during testing.

Table 5.5. Results from exploratory Spearman's rank-order correlation analyses between age, behavioral and subjective measures for the different participants groups in the indirect condition with noise. Significant correlations are indicated in bold type face.

	Triplet recognition (rau)	Response times (ms)	Rating of Task Difficulty	Rating of Recognition Performance	Rating of Hard to Think
Participants with NH					
Age (years)	0.27 (.273)	-0.25 (.323)	-0.04 (.866)	0.23 (.355)	-0.08 (.751)
Triplet recognition (rau)		-0.15 (.555)	0.13 (.614)	-0.23 (.354)	0.05 (.844)
Response times (ms)			0.04 (.877)	**-0.52* (.028)**	-0.13 (.604)
Rating of Task Difficulty				0.18 (.487)	**0.64*** (<.0001)**
Rating of Recognition Performance					0.27 (.272)
Participants with LUHU					
Age (years)	0.03 (.907)	0.01 (.960)	**0.68*** (<.0001)**	**0.52* (.026)**	**0.78*** (<.0001)**
Triplet recognition (rau)		**-0.63* (.005)**	-0.06 (.827)	-0.32 (.198)	-0.27 (.286)
Response times (ms)			0.13 (.595)	0.17 (.490)	0.25 (.324)
Rating of Task Difficulty				**0.81*** (<.0001)**	**0.91*** (<.0001)**
Rating of Recognition Performance					**0.76*** (<.0001)**

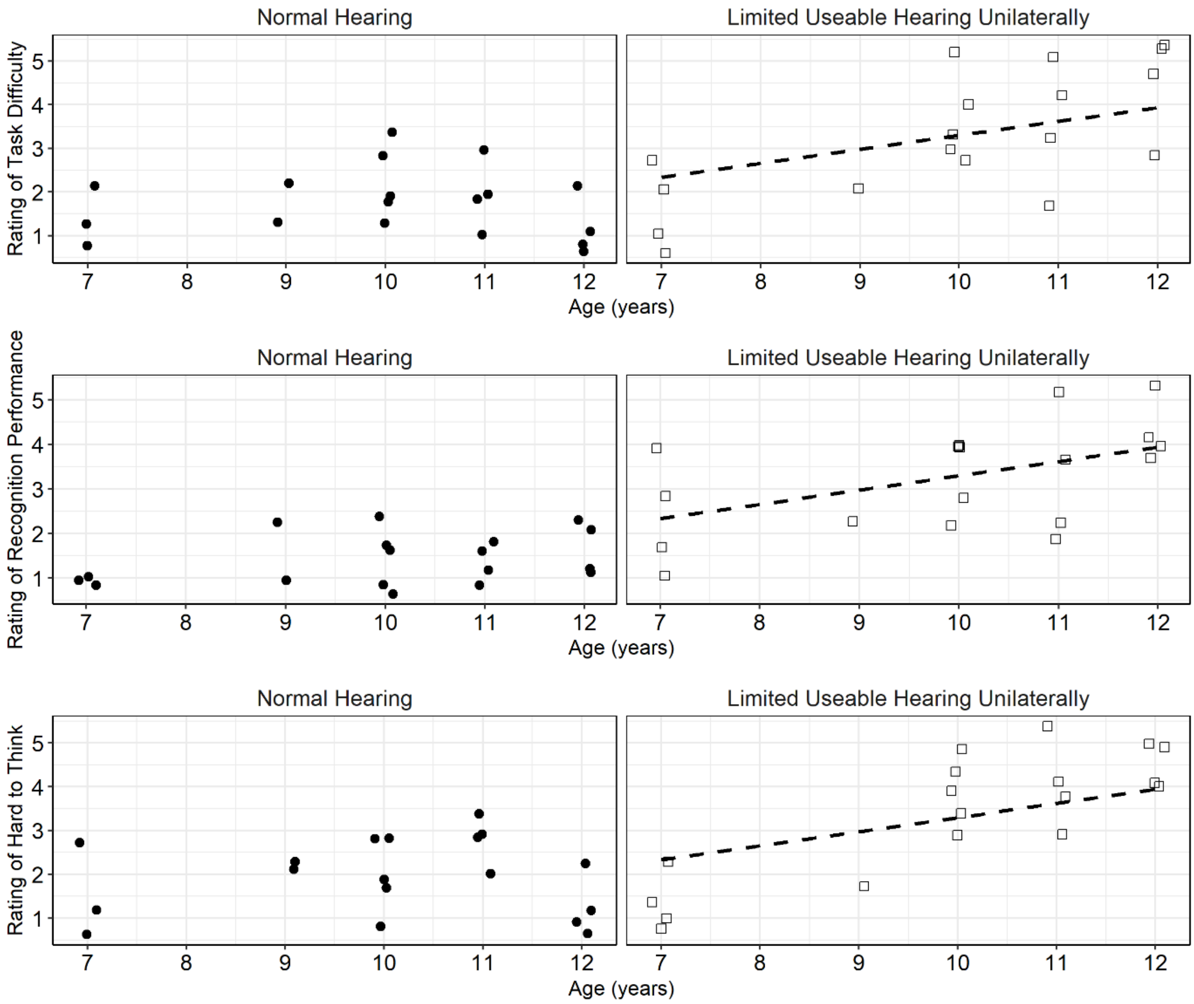

Figure 5.3. Relationship between age and subjective measures for both participant groups in the indirect condition with noise. Solid circles indicate participants with normal hearing. Dashed lines and squares indicate participants with limited useable hearing unilaterally.

5.5 DISCUSSION

The purpose of this study was to evaluate if school-aged children with LUHU experience more listening effort than similarly-aged peers with normal hearing in a variety of loudspeaker configurations (midline, direct, and indirect). Based on the FUEL and the ELU model, children with LUHU would exhibit more listening effort relative to their peers with normal hearing, as a result of reduced audibility and loss of binaural cues. Consistent with previous work demonstrating that speech recognition, behavioral listening effort, and subjective listening effort are three unique constructs (e.g., Alhanbali et al., 2019; McGarrigle et al., 2014; Strand et al., 2018), the current study revealed a distinct pattern of results for digit triplet recognition scores, response times, and subjective ratings. Each outcome will be discussed in turn.

5.5.1 Digit Triplet Recognition

Both groups had poorer digit triplet recognition in the midline loudspeaker condition with noise compared to the quiet midline loudspeaker condition. Although the speech and noise signals were presented from spatially separated loudspeakers in the midline loudspeaker condition, the fact that the noise presented from the side loudspeakers were correlated, could have led to the perception of a centrally-localized single noise source (Kendall, 2010), resulting in poorer performance for midline than direct speech stimuli. Consistent with the previous findings of poorer speech recognition in noise performance for children with LUHU in a midline condition (Ruscetta et al., 2005), the results of the current study also demonstrate group differences in recognition performance for midline signals in noise. Children with normal hearing outperformed children with LUHU for the midline loudspeaker conditions with noise, achieving ~18 average percentage points more correct digit triplet recognition. This finding is expected because, even in such a listening condition where similar speech and noise information is received in both ears, children with NH benefit from binaural redundancy (i.e., having access to two neural representations of the speech and noise stimuli) to improve speech recognition performance in noise (Ching et al., 2005; McArdle et al., 2012). Conversely, children with LUHU are unable to benefit from binaural redundancy.

Furthermore, children with LUHU appeared to be more sensitive to the effects of noise on digit triplet recognition than children with NH for both direct and indirect loudspeaker locations. Participants with LUHU performed ~10 and ~88 average percentage points worse than their peers with NH in the direct noise and indirect noise conditions, respectively. Consistent with the existing literature, the negative effects of noise on speech recognition would be expected for participants with LUHU in indirect as well as in direct listening situations (Bess et al., 1986; Kenworthy et al., 1990) due the loss of the benefits of binaural listening advantages of the head-shadow effect, summation, and binaural squelch (i.e. binaural release from masking; Colburn & Latimer, 1978; Van Deun et al., 2010).

The effect of age on speech perception in noise is evident in the current study, but only for participants with NH in the midline loudspeaker condition with noise; digit triplet recognition performance was higher for older children than younger children. This finding is consistent with published literature demonstrating speech in noise recognition abilities for children with normal hearing continue to develop and improve into late childhood and adolescent years (Elliott, 1979; Koopmans et al., 2018). The non-significant relationship between digit triplet recognition in noise and age for the LUHU participant group may be due to the variability of the data for this group. Future work is warranted to evaluate the developmental trajectory for children with LUHU, as this cross-sectional study only suggests group differences in auditory maturation.

5.5.2 Response Times

The results of this study also demonstrated the addition of noise increased response times for the midline and direct loudspeaker conditions (98 and 47 ms, respectively). This is expected based on the FUEL and ELU models which suggest that the presence of background noise is associated with more listening effort as it increases listening difficulty and consequently cognitive demand. Therefore, the pattern of results of increased response times in noisy conditions is consistent with previous reports, which indicate that increasing background noise increases listening effort in general in children (Gustafson et al., 2014; Howard et al., 2010; Lewis et al., 2016; McGarrigle et al., 2019; Picou et al., 2019a; Picou et al., 2017).

Also consistent with expectations, the study results confirmed that children with LUHU experienced the most evident increases in listening effort in the indirect condition with noise. Specifically, children with LUHU exhibited 624 ms longer average RTs than their NH peers, indicating more listening effort, in the noisy, indirect listening condition. In fact, all the LUHU participants had slower RTs than the mean RT of NH participants in the indirect noise condition. Although no study has previously reported more listening effort for children with LUHU compared to peers with NH, the results of the current study are generally consistent with existing work evaluating listening effort for children with bilateral hearing loss. For example, McGarrigle et al. (2019) compared verbal RTs between children with NH and children with mild-to-moderate bilateral sensorineural hearing loss. Their results indicated that children with hearing loss had significantly slower RTs relative to children with NH (~ 400 ms).

This study's findings that children with LUHU experience greater amounts of listening effort in certain conditions suggests that non-significant group differences between children with UHL and children with NH reported in previous studies (Lewis et al., 2016; McFadden & Pittman, 2008) might be the result of methodological choices. For example, the current study focused on children with LUHU. Participants with greater degrees of hearing loss could possibly be exhibiting more listening effort that is not seen in participants with a mild degree of hearing loss. By focusing on the sub-group of sensorineural unilateral hearing loss of a severe-profound degree, this study clearly demonstrates that children with LUHU experience significantly more listening effort compared to children with NH in a noisy, indirect listening scenario. This suggests that additional cognitive processing is required by children with LUHU when listening in such adverse acoustic conditions. Combined with the non-significant group differences reported by the previous studies (Lewis et al., 2016; McFadden & Pittman, 2008), the results of the current study suggest that children with milder degrees of UHL might not be at similar risk of significantly greater listening effort as children with LUHU. Future studies should investigate listening effort across different degrees of UHL.

Furthermore, the targeted speech recognition performance in the current study could account for the significant group differences in listening effort. During the dual-task paradigm, McFadden and Pittman (2008) reported word categorization performance of at least 90%. However, according to Wu and colleagues (2016), listening effort peaks around 30-50% speech recognition performance. For higher or lower performance levels, changes in speech recognition performance or SNR might result in smaller changes in effort because the task is too easy, or participants have disengaged due to possible cognitive overload. Consequently, the poorer performance in the current study (66.94 and 49.44 percentage points for listeners with NH and LUHU in the midline noise condition, respectively) relative to the work by McFadden and Pittman (2008), could have also contributed to the revelation that children with LUHU exhibit more listening effort than their peers.

Age effects for response times were not significant for either participant group in any of the loudspeaker conditions. This finding is consistent with previous work demonstrating non-significant effects of age on verbal response times with similarly-aged children (e.g., Lewis et al., 2016; Oosthuizen et al., 2020). For example, Lewis et al. (2016) reported no significant difference in verbal response times from 8- and 12-year-old children with mild bilateral hearing loss or UHL to peers with NH. In both the current study and the study by Lewis et al. (2016), the participant age ranges were large, but the number of participants per age group was limited, which might limit the possibility of demonstrating significant effects of age on verbal RTs. Future studies with larger number of participants with NH and LUHU per age group, across a range of ages, will be necessary to clarify a potential effect of age on verbal response times.

5.5.3 Subjective Ratings

Results of the subjective rating questionnaires were compared between the two participant groups in order to evaluate subjective listening effort. As hypothesized, children with LUHU reported greater task difficulty, poorer recognition performance, and that it was harder to think compared to similarly-aged peers with NH. The group differences were significant only in the indirect loudspeaker condition with noise. Thus, results from the subjective measures correspond to the behavioral listening effort measure (RTs), as both measures demonstrate that children with LUHU experience significantly more listening effort than peers with NH in a noisy, indirect condition. These results suggest that subjective ratings might be a useful indicator of listening effort in different listening situations for school-aged children with LUHU that is not directly assessed by traditional hearing assessments. Further research is needed to develop a reliable listening effort subjective rating scale for school-aged children.

Correlation analyses for the indirect condition with noise, showed no relationship between digit triplet recognition performance, response times, subjective ratings, and age for participants with NH. However, for participants with LUHU, analysis revealed subjective ratings were related to age, rather than digit triplet recognition performance or RTs in the indirect, noise condition. The non-significant correlation between behavioral and subjective measures of listening effort is consistent with previous work that also revealed no significant relationship between behavioral and subjective indices (e.g., Gustafson et al., 2014; Picou et al., 2019a). The significant effect of age on subjective ratings provided by the children with LUHU indicate that, compared to younger children with LUHU, older children with LUHU rated the task as more difficult, their performance as worse, and that it was harder to think during testing in the noisy, indirect condition. These findings support the use of subjective questions for describing perceived listening effort, as results from both RTs and subjective measures indicated greater listening effort in an indirect condition with noise. However, caution should be taken when interpreting results for individual participants as a result of the significant contribution of age to ratings.

5.6 CONCLUSION

By focusing on children with limited useable hearing in one ear and using sensitive measures of listening effort, this study is the first to demonstrate that children with LUHU can experience more listening effort, specifically in a listening condition where speech is directed to the ear with LUHU and noise towards the ear with normal hearing. Therefore, classroom placement should be considered for children with LUHU to avoid situations that may cause more listening effort. For example, preferential seating could be arranged to maximize direct and midline listening scenarios to support academic performance in the classroom by reducing the cognitive demands associated with indirect listening. In addition, the study results replicated the extant literature and demonstrated that children with LUHU exhibit poorer digit triplet recognition performance in noisy midline, direct, and indirect listening conditions, relative to similarly-aged peers with NH. Therefore, in addition to all the other known risk factors related to the academic environment for children with LUHU, it is important to consider the increased listening effort that can be experienced by this population and the possible detrimental effects it may pose on their academic performance. The use of self-report questionnaires may be useful to document subjective ratings of perceived listening effort in school-aged children and should be considered for inclusion in the management plan in the case of a child with LUHU.

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CHAPTER 6

LISTENING EFFORT IN SCHOOL-AGED CHILDREN WITH LIMITED USEABLE HEARING UNILATERALLY: EXAMINING THE EFFECTS OF A PERSONAL, DIGITAL REMOTE MICROPHONE SYSTEM AND A CONTRALATERAL ROUTING OF SIGNAL SYSTEM

Authors: Ilze Oosthuizen, Erin M. Picou, Lidia Pottas, Hermanus C. Myburgh, and De Wet Swanepoel

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6.1 ABSTRACT

Technology options for children with limited hearing unilaterally that improve the signal-to-noise ratio are expected to improve speech recognition and also reduce listening effort in challenging listening situations, although previous studies have not confirmed this. Employing behavioral and subjective indices of listening effort, this study aimed to evaluate the effects of two intervention options, remote microphone system and contralateral routing of signal system, in school-aged children with limited hearing unilaterally. Nineteen (19) children (aged 7-12 years) with limited hearing unilaterally completed a digit triplet recognition task in three loudspeaker conditions: midline, monaural direct, and monaural indirect with three intervention options:

unaided, remote microphone system, and contralateral routing of signal system. Verbal response times was interpreted as a behavioral measure of listening effort. Participants provided subjective ratings immediately following behavioral measures. The remote microphone system significantly improved digit triplet recognition across loudspeaker conditions and reduced verbal response times in the midline and indirect conditions. The contralateral routing of signal system improved speech recognition and listening effort only in the indirect condition. Subjective ratings analyses revealed significantly more participants indicated that the remote microphone made it easier for them to listen and to stay motivated. Behavioral and subjective indices of listening effort indicated that a remote microphone system provided the most consistent benefit for speech recognition and listening effort for children with limited unilateral hearing. Remote microphone systems could therefore be a beneficial technology option in classrooms for children with limited hearing unilaterally.

Keywords: unilateral hearing loss, speech-in-noise, classroom, hearing aid

6.2 INTRODUCTION

Approximately 2.5–3% of school-aged children are reported to present with unilateral hearing loss (UHL) with an increase in prevalence of up to 14% in adolescents (Bess et al., 1998; Shargorodsky et al., 2010). There is mounting evidence that these children have a greater risk of poorer speech, language, and cognitive outcomes compared to normal hearing peers (Ead et al., 2013; Lieu, 2013), in addition to more behavioral problems (Lieu, 2004) and academic difficulties (Bess et al., 1986; Lieu, 2004; Oyler et al., 1988). The risks can even be more prominent for children with unaidable unilateral hearing loss (Bess et al., 1986; Culbertson & Gilbert, 1986; Lieu et al., 2013), defined as greater than severe unilateral sensorineural hearing loss and/or poor word recognition. Unaidable unilateral hearing loss has been referred to as “single sided deafness” (SSD) or “limited useable hearing unilaterally” (LUHU) (Oosthuizen et al., In Press; Picou et al., 2020a; Picou et al., 2020b; Picou et al., 2019b). The term LUHU will be used hereafter to refer to the specific population under study. Compared to children with milder unilateral hearing loss, children with LUHU are at greater risk of poorer speech recognition performance (Bess et al., 1986; Lieu et al., 2013) and an increased need for academic assistance (Culbertson & Gilbert, 1986; Lieu et al., 2013). More recently, results from a previous study also indicated that children with LUHU experience significantly more listening effort in indirect, noisy listening situations relative to their peers with normal hearing bilaterally (Oosthuizen et al., In Press).

6.2.1 Listening Effort

Listening effort is defined as "the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a task that involves listening in order to understand speech" (Pichora-Fuller et al., 2016 , 11S). The FUEL (Framework for Understanding Effortful Listening; Pichora-Fuller et al., 2016) and the ELU model (Ease of Language Understanding; Rönnberg et al., 2013; Rönnberg et al., 2008) clearly describe that cognitive demand is a key factor to listening effort. Several factors can increase the cognitive demand of a listening task, for example, the hearing ability of a listener (e.g., the presence of hearing loss), and task demands (e.g., presence of noise or reverberation in the listening situation). Furthermore, the listener's motivation to achieve the goal of understanding what is said as well as to complete a listening task also affects listening effort. Speech understanding and listening effort are related, yet distinct concepts as people with hearing loss often complain that listening is tiring and effortful even when speech is audible, and words are recognized correctly (Pichora-Fuller et al., 2016). Furthermore, some factors affect listening effort and not speech recognition (e.g., digital noise reduction; Sarampalis et al., 2009) or affect recognition but not listening effort (e.g., reverberation; Picou et al., 2019a). Therefore, examining listening effort in addition to speech understanding can be of clinical importance, especially for school-aged children.

Recent evidence suggests that school-aged children spend 70% to 80% of their time in school listening in the presence of background noise (Crukley et al., 2011; Ricketts et al., 2017). Based on the FUEL and ELU models, increased listening effort is expected with increased background noise, as reflected in numerous previous studies in adults (Desjardins & Doherty, 2013; Picou et al., 2017; Picou & Ricketts, 2014; Picou et al., 2013; Sarampalis et al., 2009; Tun et al., 2009) and children (Gustafson et al., 2014; Howard et al., 2010; Lewis et al., 2016; McGarrigle et al., 2019; Picou et al., 2019a;

Picou et al., 2017). Within the context of the FUEL and ELU model, it can be expected that intervention options that reduce cognitive demand while maintaining or improving speech recognition performance may be anticipated to also reduce the listening effort experienced in situations with high task demands. Given the increased academic difficulties that children with LUHU might experience together with the detrimental effects that listening effort and the resultant fatigue can have on academic performance and quality of life (Bess & Hornsby, 2014a, 2014b), it is important to examine the efficacy that intervention options for children with LUHU might have on reducing the listening effort experienced in classroom situations.

6.2.2 Non-Surgical Intervention Options for Children With LUHU

Current non-surgical intervention options for children with LUHU include preferential seating alone or in combination with either a remote microphone system (RMS) or contralateral routing of signal (CROS) system. Remote microphone system (RMS) refers to a wireless system that converts audio signals from a remotely placed microphone into radio or digital signals and transmits them via frequency modulation (FM) or digital modulation (DM) to a receiver near the listener (Bagatto et al., 2019). Remote receiver options include a personal ear level RMS, a classroom audio distribution system (single or multiple loudspeakers), or a personal desktop loudspeaker. RMSs improve the signal-to-noise ratio for the listener by overcoming noise, distance, and reverberation because a microphone (transmitter) is close to the mouth of a talker (Thibodeau, 2014; Wolfe et al., 2016). Current guidelines state that RMSs are the preferred choice of intervention recommended for school-aged with LUHU in classrooms as they offer the most consistent speech recognition benefits (e.g., American Academy of Audiology, 2013) .

In a Contralateral routing of signal (CROS) system, which includes two ear-level devices, sound is transmitted from the ear with limited useable hearing to the ear with better hearing. The purpose of CROS fittings is to re-route indirect speech to the ear with better hearing. However, CROS can be detrimental with direct speech and indirect noise; the CROS would enable the presentation of interfering noise to the ear with normal hearing when the noise would previously have been reduced due to head shadow effects. Therefore, CROS aids have not previously been recommended for young children (McKay et al., 2008).

These recommendation are based in part on work by Kenworthy and colleagues (1990), who evaluated speech recognition in noise for 6 children (8-12 years of age) with moderate to profound unilateral hearing loss. The authors evaluated three interventions (none, CROS, RMS) used in three listening configurations: monaural direct (speech presented at 45˚ relative to ear with normal hearing; noise presented at 45˚ relative to ear with unilateral hearing loss), monaural indirect (speech presented at 45˚ relative to ear with unilateral hearing loss; noise presented at 45˚ relative to ear with normal hearing), and midline signal (speech presented at 0˚; noise presented at 135, 180, 225˚ relative to midline). The remote microphone was always placed near the speech loudspeaker. Results revealed RMS benefits for improved speech recognition in noise in the midline and indirect loudspeaker conditions, and CROS benefits only in the indirect condition. CROS detriments were evident in the midline and direct loudspeaker conditions. The consistent benefits of RMS use were confirmed by Updike (1994), whose findings also support RMS benefits for children with unilateral hearing loss and whose work also informed current recommendations for management of unilateral hearing loss.

However, as Kenworthy and colleagues (1990) and Updike (1994) focused on speech recognition performance, the effect of non-surgical intervention options on listening effort for children with LUHU is less clear. In the adult and pediatric populations, listening effort is often measured by means of behavioral methodologies involving a timed response, for example speed of speech repetition, also known as verbal response time (Gagne et al., 2017). Cowan and colleagues (2003) suggested that increases in verbal response times in nonword recognition tasks reflect an increase in the amount of time that children need to process a signal, with longer verbal response times reflecting greater processing effort. Previous studies employing verbal response times in the pediatric population support the use of such a single-task paradigm as a listening effort measure for school-aged children (Gustafson et al., 2014; Houben et al., 2013; Lewis et al., 2016; McGarrigle et al., 2019; Oosthuizen et al., 2020; Pals et al., 2015; Prodi et al., 2019).

Subjective ratings have also been used in a few studies to evaluate listening effort, primarily by means of study-specific questionnaires (e.g., Gustafson et al., 2014; Picou et al., 2019a). Emerging evidence suggests results of behavioral and subjective indices might reflect different aspects of listening effort, especially in children (Gustafson et al., 2014; Hicks & Tharpe, 2002; Picou et al., 2019a). However, recent evidence suggests that self-report measures of listening effort can be used in school-aged children to document perceived listening effort (Oosthuizen et al., In Press). Moreover, considering subjective ratings of the effect that specific intervention options for children with LUHU might have on their listening effort would be of value for child-specific management plans. Including considerations of how intervention options affect the child's motivation to sustain listening can be included because motivation also affects experienced listening effort (Peelle, 2018; Pichora-Fuller et al., 2016).

6.2.3 Purpose

The purpose of this study was to evaluate the effects of RMS and CROS on speech recognition and listening effort in three different loudspeaker conditions reflecting listening situations that can be encountered in the classroom scenario, namely midline, monaural direct, and monaural indirect. Employing a single-task paradigm and listening scenarios with similar loudspeaker configurations as Kenworthy and colleagues (1990), this study has the potential to replicate earlier findings on the effects of RMS and CROS on speech recognition and to extend these findings to listening effort. A second purpose of this study was to explore subjective ratings of RMS and/or CROS benefits in terms of ease of listening and listening motivation. As the three loudspeaker conditions followed a similar configuration to previous laboratory studies (Kenworthy et al., 1990), the investigators expected that listening with the RMS would result in improved digit triplet recognition relative to the unaided condition and listening with a CROS system. A decrease in verbal response times also was expected (i.e., less listening effort) when participants listened with the RMS in comparison to the CROS condition. It was further hypothesized that the CROS benefit for speech recognition and listening effort mainly would be evident in the indirect loudspeaker condition, based on the findings of Kenworthy et al. (1990).

6.3 MATERIALS AND METHOD

6.3.1 Participants

Nineteen (19) school-aged children with LUHU, from diverse language backgrounds, participated in the study (*M* = 9.9 years, *SD* = 1.7, range 7-12 years). All participants had normal middle ear function, verified by tympanometry measures and normal otoscopic examination findings on the day of testing. Participants presented with normal hearing sensitivity in one ear (≤ 15 dB HL for octave frequencies from 250 to 8000 Hz) and a severe-profound sensorineural unilateral hearing loss in the opposite ear. Hearing loss was characterized by air conduction thresholds greater than 70 dB HL from 250 Hz to 8000 Hz; an average air-bone gap no greater than 10 dB at 1000 Hz, 2000 Hz and 4000 Hz; and poor phonetically-balanced monosyllabic word recognition at a comfortable presentation level (< 70%) in the impaired ear (Madell et al., 2011). No participant had other otologic or cognitive disorders, as reported by parents/guardians. Participants had typical speech, language, and motor development as confirmed by parental report. Table 6.1 summarizes the demographic information of study participants. Children participated in this study as part of a larger protocol, the remainder of which is published elsewhere (Oosthuizen et al., In Press). Institutional review board approval was granted for this study by the Research Ethics Committee of the Faculty of Humanities, University of Pretoria.

Table 6.1. Participants' demographic information

ID	Age	Gender	Native (N) or Non-native (NN) English	Ear with LUHU	Age at diagnosis	Aetiology	Degree of hearing loss	Age at and type of intervention
1	7	M	N	L	5 years	Acquired: Mumps (on the left)	Severe-profound	6 years: Personal RMS
2	10	M	NN	R	6 years	Acquired: Meningitis at 2 weeks of age	Profound	6 years: Personal RMS
3	11	F	NN	L	3 years	Unknown	Profound	Bone-conduction device on soft band: 3 years HA: 4 years CI + RMS: 8 years
4	11	F	NN	R	8 years	Congenital: cochlear malformation	Profound	9 years: HA 9 years, 7 months: CI
5	10	F	N	L	6 years	Unknown	Profound	8 years: Personal RMS
6	10	M	N	L	4 years, 11 months	Congenital: Dysmorphia of cochlea and hypoplastic auditory nerve	Profound	5 years: CI
7	11	M	NN	L	6 years	Acquired: Suspect viral infection	Severe-profound	6 years: Personal RMS
~~8~~	~~9~~	~~M~~	~~N~~	~~R~~	~~5 years~~	~~Acquired: Meningitis at age 4 years~~	~~Profound~~	~~5 years: Personal RMS~~
9	9	F	NN	L	2 years	Acquired: Suspect due to chronic OM	Profound	4 years: Personal RMS
10	10	M	NN	L	2 years	Acquired: Tuberculosis at 6 months of age	Profound	7 years: Personal RMS
11	12	F	N	R	Peri-natal period	Congenital: Suspect Golden-Har Syndrome	Profound	6 years: HA + RMS 11 years: CROS + RMS
12	10	M	NN	R	6 years	Unknown	Profound	6 years: Personal RMS
13	12	F	NN	R	5 years	Unkown	Profound	11 years: CROS 12 years: CI
14	12	M	N	R	10 years	Acquired: Viral infection	Severe-profound	No intervention yet

15	7	F	N	L	4 years	Acquired: Prematurity and ototoxic medication	Profound	4 years: Bone-conduction device on soft band
16	7	F	NN	R	5 years, 4 months	Unknown	Severe-profound	5 years, 5 months: HA + RMS
17	11	M	NN	R	10 years	Acquired: Labyrinthitis	Profound	10 years: CI
18	12	F	NN	R	6 years	Congenital	Profound	6 years: Personal RMS
19	8	F	NN	L	5 years	Mumps at age 5 years	Severe-profound	5 years: HA

Note: Participant ID 8 was deemed unreliable during testing and his data were not included in analyses. For participants wearing a CI, the sound processor was removed during data collection.

LUHU = limited usable hearing unilaterally; RMS = remote microphone system; HA = hearing aid; CI = cochlear implant; CROS = contralateral routing of signal hearing aid

6.3.2 Behavioral Listening Effort: Verbal Response Time

The listening effort measure was a behavioural methodology involving a timed response, namely a single-task paradigm of verbal response time (VRT). This paradigm was used previously in studies of listening effort with school-aged children with normal hearing (Oosthuizen et al., 2020) as well as school-aged children with LUHU (Oosthuizen et al., In Press). Outcomes from this single-task paradigm include both speech recognition performance and verbal response times. The speech stimuli consisted of digit triplets from the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018). The recognition probabilities of all the digits are equalized so that a potential difference in recognition probabilities is eliminated (Smits, 2016). Therefore, mono- and bi-syllabic digits (0-9) were used in the triplets. In comparison to the use of open-set word or sentence recognition stimuli, digit triplets from an English-based digits-in-noise test present several advantages, for example digits-in-noise stimuli are low in linguistic demands. Secondly, the speech material is presented in a closed set, including only digits between 0 and 9 (Kaandorp et al., 2016; Potgieter et al., 2018). Thirdly, English digits are mostly familiar and often used by speakers of other languages (Branford & Claughton, 2002), making it a more appropriate choice of stimuli for use in a multilingual population. In addition, as evidenced by Oosthuizen et al. (2020), performance on single- and dual-task measures of listening effort were unaffected by language background of school-age children using these stimuli. As multilingualism is a universal reality in classrooms, both native and non-native speakers of English were included in this study.

Participants were instructed to listen to, and repeat digit triplets presented in noise. Participants were encouraged to guess if they were unsure of the digit triplet that was presented. Digit triplets were presented at 60 dB(A) and noise was presented at 72 dB(A) for a -12 dB SNR. The noise was steady state noise with the same long-term average spectrum as the South African English digits-in-noise hearing test (Potgieter et al., 2016; Potgieter et al., 2018). The SNR was chosen based on pilot testing with naïve participants to target digit triplet recognition performance levels between 50 and 80% correct in a midline loudspeaker condition. In addition, the background noise level reflects possible noise levels that might be encountered in classrooms. Noise levels in occupied classrooms range from 56-76 dB(A) (Shield & Dockrell, 2004), and often exceed 70 dB(A) in South African primary school classrooms (Van Tonder et al., 2015). With moderate level speech (60 dBA), the resultant SNRs would range from +4 to -16 dB (Shield & Dockrell, 2004; Van Tonder et al., 2015).

Participants' verbal responses were recorded by a head-worn microphone and saved by a custom software program (MATLAB R2015a). The experimenter scored the verbal responses of the digit triplets and calculated a percent correct digit triplet recognition score for each participant in each condition. Verbal response times (VRT) were calculated as the time elapsed from the end of the digit triplet to the onset of the participant's verbal response in the MATLAB software. Subjective checks of all recordings were done to identify occurrences of speech fillers such as "umm" and "uh", stutters, and nonspeech sounds (e.g., breathing, yawns) that occurred before a digit triplet was spoken as well for trials with self-corrections. In these cases, fillers and false starts were removed. The verbal response onset-time was marked as the onset of the self-corrected, second utterance.

6.3.3 Subjective Ratings

Directly after completion of a listening effort task in each condition with either the personal RMS or the CROS system, participants provided subjective ratings. Questions asked were: 1) "Did the remote microphone system (FM system)/hearing aids make it easier for you to listen when it was noisy?" (ease of listening); 2) "Did the remote microphone system (FM system)/hearing aids help you to keep trying?" (motivation to complete listening task). Participants answered the two questions on a questionnaire by marking their subjective opinion on a binary (yes/no) emoji scale [1) yes = big smile, thumb up; 2) no = big frown, thumb down]. The questions were typed on a piece of paper with the emoji options scale below each one. No questions were asked after unaided conditions.

6.3.4 Test Conditions

Three loudspeaker configurations, displayed in Figure 6.1, were used during testing. In the *midline condition* the digit triplets were played through the loudspeaker directly in front of the participant (0°), and identical noise was routed synchronously from the audiometer to the two loudspeakers placed at 90° and 270° azimuths. In the *monaural direct listening condition,* the digit triplets were presented through the loudspeaker which was at 90° azimuth to the participant's ear with normal hearing and noise was presented through a second loudspeaker positioned perpendicular to the participant's ear with hearing loss. In the *monaural indirect listening condition* speech was presented through a loudspeaker directed at 90° azimuth toward the ear with hearing loss of the participant, and noise was directed through a loudspeaker positioned directly towards the ear with normal hearing.

In each of the three loudspeaker conditions, participants performed the single-task paradigm in three intervention conditions, namely unaided, with the use of a digital ear-level, personal remote microphone system (RMS) and a contralateral routing of signal (CROS) hearing aid. Participants with a cochlear implant removed their speech processor during all conditions. The remote microphone was always placed at the single-coned loudspeaker of interest, as displayed by a rectangle labelled 'remote mic' in Figure 6.1.

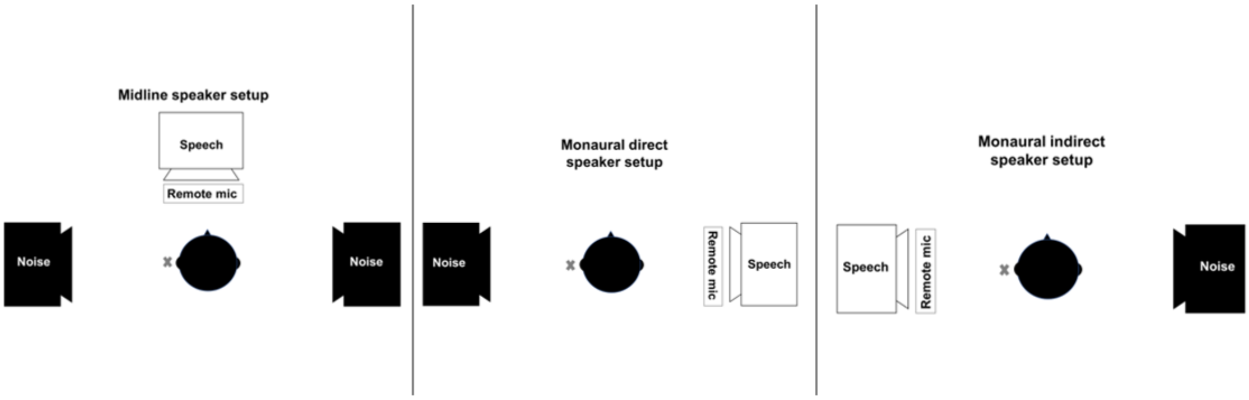

Figure 6.1. Schematic diagram representing loudspeaker locations in the midline, monaural direct, and monaural indirect configurations. Black loudspeakers indicate noise loudspeakers. White loudspeakers indicate speech loudspeakers. The LUHU ear is indicated by an "X".

Note: Figure is not to scale.

6.3.5 Intervention Options

Prior to data collection, fitting and verification procedures for the RMS and CROS hearing aid were conducted on each participant. A digital ear-level, personal RMS receiver (Phonak Roger™ Focus) was fitted on the normal hearing ear of each participant. Acoustic coupling was a standard slim tube and a small, non-occluding, non-custom eartip. Slim tube length was measured and changed accordingly for each participant. The ear-level RMS receiver was paired to a remote microphone (Phonak Roger™ Touchscreen). Real-ear measurements were conducted on the Audioscan Verifit Real Ear System (Audioscan, Dorchester, Ontario) as recommended by the American Academy of Audiology (2011) and Schafer et al. (2014) to verify that estimated uncomfortable loudness levels (UCLs) were not exceeded and prescriptive targets were met. During these measurements, the remote microphone was placed in the test box and the real-ear microphone was placed in the participant's ear. Specifically, the maximum power output (MPO) stimulus was selected on the Verifit. The examiner visually compared the MPO (based on the default volume setting) with the estimated UCL from the Desired Sensation Level (DSL) v5.0 software (Scollie et al., 2005) to ensure that the MPO did not exceed predicted UCL levels. Next, the output from the RMS receiver was compared to DSL v5.0 targets (Scollie et al., 2005) using the Verifit's "standard speech signal" presented in the test box at an intensity appropriate for a chest-level transmitter microphone (i.e., 84 dB SPL) to ensure that the output from the child's ear met the DSL v5.0 prescriptive targets at 1000, 2000, and 4000 Hz. If volume-adjustments were done, the MPO measurement was repeated at the volume adjusted level.

Subsequently, a CROS hearing aid (Phonak CROS B-312) was fitted to the ear with the severe-profound sensorineural hearing loss with a helix hook for stability and retention. A receiver hearing aid (Phonak Sky B70-M, open fitting) was fitted to the normal hearing ear of each participant. Acoustic coupling was a standard slim tube and a small, non-occluding, non-custom eartip. Slim tube length was measured and changed accordingly for each participant. The automatic features in the receiver hearing aid were deactivated, including automatic program selection, digital noise reduction, and wind noise reduction. The microphone was set to mild, fixed-directional. The CROS microphone was set to be a "real-ear" microphone. Real-ear measurements were conducted on the Audioscan Verifit Real Ear System (Audioscan, Dorchester, Ontario) prior to data collection to ensure that the receiver hearing aid of the CROS system was acoustically appropriate for each participant's individual hearing thresholds. The CROS receiver hearing aid output in the participant's ear, at octave frequencies, was compared to Desired Sensation Level (DSL) (Scollie et al., 2005) v5.0 targets using the Verifit's "standard speech signal" (the carrot passage) presented at 65 dB SPL.

Furthermore, real ear unaided responses (REUR) were measured and compared to real ear occluded responses (REOR) with the ear-level RMS receiver and the CROS receiver hearing aid turned off to ensure that there was minimal insertion loss. Because the ear-level RMS receiver and the receiver hearing aid of the CROS system were fitted to a normal hearing ear, it is important that use of such a device does not degrade environmental hearing.

6.3.6 Test Environment

Listening effort measures were conducted in a double-walled, sound-attenuating audiometric test booth (2.13m x 2.03m x 2.43m). Three (3) loudspeakers (GSI 90 dB) were located at 0°, 90° and 270° at 1 meter from the participant, who was seated at a school desk. Handprints were placed on the desk's surface showing participants where to place their hands during testing to help eliminate possible noise from hand movements. Furthermore, participants were instructed to keep their head still and face forward for the duration of the testing. Digit triplets were presented through custom programming of MATLAB software, routed to an audiometer (GSI AudioStar Pro) and to a loudspeaker. Noise files were stored on the audiometer and selected from the internal files. The noise was routed from the audiometer to loudspeaker(s). Output levels for digit triplets and digit noise were measured by means of a sound level meter to ensure the correct output level in the sound field.

6.3.7 Procedures

Before data collection commenced, informed consent was obtained from each participant's parent/guardian and assent was obtained from the participants. Standard audiometric procedures confirmed normal hearing in one ear and a severe-profound sensorineural hearing loss in the opposite ear. After fitting and verification procedures, training rounds were conducted to ensure that the participants understood the listening task. Training rounds consisted of verbal response time tasks in quiet and in noise. Training lists (consisting of 10 digit triplets) were not repeated during the experimental testing. After the training rounds, participants were prepared to start with data collection testing. A single list with 20 digit triplets was used in each loudspeaker and intervention condition. Twenty-five (25) lists consisting of 20 digit triplets each were created in order to ensure no repetition of a digit triplet list in the various test conditions. The order of the loudspeaker conditions (midline, monaural direct, monaural indirect), intervention conditions (unaided, RMS, CROS hearing aid) and digit triplet lists were randomized across participants. Directly after each list was presented when listening in either the RMS or the CROS condition, participants completed a short questionnaire with the two binary rating questions.

6.3.8 Data Analysis

During testing, one participant (ID 8 = 9-year-old male) was noticeably distracted. As a result, his results were deemed unreliable, and his data were excluded from the study in general. Prior to analysis, digit triplet recognition data were converted to rationalized arcsine units (rau) to normalize the variance near the extremes with the equations found in Studebaker (1985). This transformation was necessary due to excellent digit triplet recognition performance by many participants with the RMS in all loudspeaker conditions. Verbal response times (VRT) were taken as the measure of listening effort. As suggested by Hsu and colleagues (Hsu et al., 2017), verbal response time data from both correct and incorrect digit triplet recognition trials were included as it would result in better representation of the varying levels of listening effort that children might experience in real-life, noisy classroom situations. However, there were some exceptions. VRTs for verbal responses not containing digits (e.g., “I don’t know/I didn’t hear”) were excluded from analysis (a total of 93 VRTs from 9 participants). In addition, VRTs were included in the analysis only if they were within +/- 2.5 standard deviations of the mean VRT for the participant in a given digit triplet list as in previous studies of response time in children (Ratcliff, 1993). A total of 96 VRTs were eliminated in this process. In total, 189 of 3240 VRTs were excluded for all participants and conditions (5.8%).

Data were analyzed separately for each outcome (digit triplet recognition, verbal response times) using repeated measures analysis of variance (RM-ANOVA) with two within-participant factors, Loudspeaker (midline, direct, indirect) and Intervention (unaided, RM, CROS). Significant interactions were explored using follow-up ANOVAs and multiple pairwise comparisons controlling for family-wise error rate with Bonferroni adjustments for the number of comparisons (Dunn, 1961). Greenhouse-Geisser corrections for sphericity violations were used when necessary. Data for verbal response times was normally distributed as assessed by Shapiro Wilk’s test of normality on the studentized residuals with significance values corrected for the number of comparisons within a paradigm. Data for the digit triplet recognition performance violated the assumption of normality due to expected excellent performance in some conditions (e.g. digit triplet recognition with the RMS in the direct loudspeaker condition). Data for digit triplet recognition had one outlier. Repeated measures ANOVA were re-run with and without the outlier included in the analysis. Analyses resulted in similar significant results and it was therefore decided to include the outlier in the digit triplet recognition analyses. Despite non-normal distributions for digit triplet recognition in some conditions, ANOVAs were used because they are considered to be robust to deviations from normality (Maxwell & Delaney, 2004). Subjective ratings were analyzed using non-parametric, exact McNemar's tests as the data was dichotomous in nature. All analyses were completed in SPSS (IBM Corporation, v 26).

6.4 RESULTS

6.4.1 Digit Triplet Recognition

Mean digit triplet recognition scores (rau) for the different intervention conditions (unaided, RMS, CROS) across the different loudspeaker configurations are displayed in Figure 6.2.

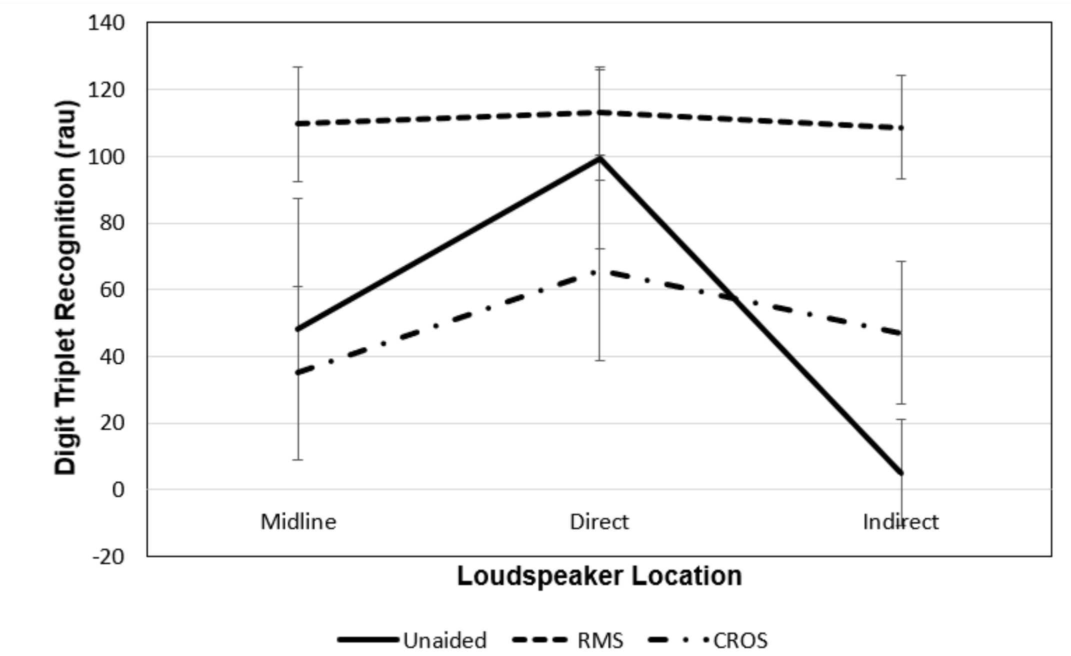

Figure 6.2. Mean digit triplet recognition scores (rau) for the different intervention conditions (unaided, RMS, CROS) across the different loudspeaker configurations. Vertical bars indicate standard deviation.

RMS = remote microphone system; CROS = contralateral routing of signal system.

Analysis revealed significant main effects of Loudspeaker ($F_{2, 16}$ = 101.63, $p < .001$, η_p^2 =0.93) and Intervention ($F_{2, 16}$ = 159.25, $p < .001$, η_p^2 =0.95) as well as a significant two-way interaction of Loudspeaker x Intervention ($F_{4, 14}$ = 60.68, $p < .001$, η_p^2 =0.94). Consequently, the significant interaction was explored using separate RM-ANOVAs for each Loudspeaker with a single within-participant factor (Intervention). Results are displayed in Table 6.2.

Table 6.2. Results of pairwise comparisons of digit triplet recognition performance (rau) in different loudspeaker conditions for different intervention options. Significant differences are indicated by bold typeface.

Loudspeaker	Comparison	*M* difference	Std Error	*p*	95% CI
Midline	**RMS vs Unaided**	**61.50**	**8.44**	**<. 001**	**39.09 to 83.91**
	CROS vs Unaided	-13.19	6.90	.219	-31.50 to 5.13
	RMS vs CROS	**74.69**	**6.39**	**<. 001**	**57.72 to 91.65**
Direct	**RMS vs Unaided**	**13.58**	**4.82**	**.035**	**0.79 to 26.38**
	CROS vs Unaided	**-33.76**	**5.46**	**<. 001**	**-48.26 to -19.27**
	RMS vs CROS	**47.35**	**5.42**	**<. 001**	**32.96 to 61.73**
Indirect	**RMS vs Unaided**	**103.45**	**4.29**	**<. 001**	**92.06 to 114.84**
	CROS vs Unaided	**41.95**	**4.68**	**<. 001**	**29.51 to 54.39**
	RMS vs CROS	**61.50**	**4.81**	**<. 001**	**48.74 to 74.26**

Taken together, these data indicate the RMS significantly improved digit triplet recognition in all loudspeaker configurations, whereas the CROS significantly improved recognition only in the indirect condition and significantly impaired recognition in the direct condition.

6.4.2 Verbal Response Times

Figure 6.3 displays the mean verbal response times for the different intervention options (unaided, RMS, CROS) for each loudspeaker configuration.

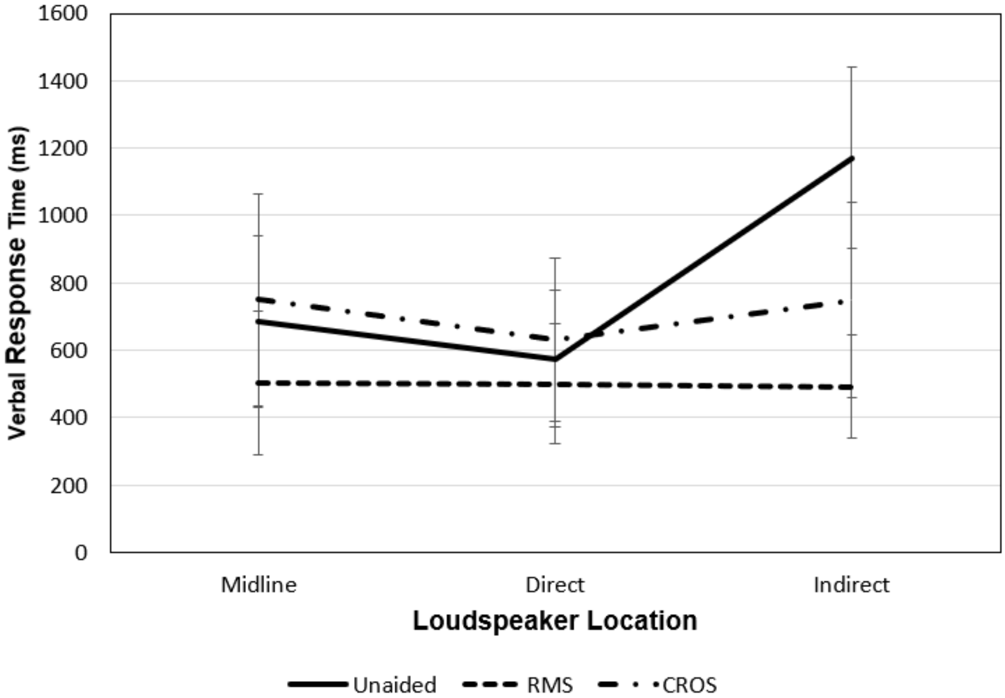

Figure 6.3. Mean verbal response times for the different intervention options (unaided, RMS, CROS) for each loudspeaker configuration. Vertical bars indicate standard deviation.

RMS = remote microphone system; CROS = contralateral routing of signal system

Analysis revealed significant main effects of Loudspeaker ($F_{2, 16}$ = 14.43, p < .001, η_p^2 =0.64) and Intervention ($F_{2, 16}$ = 40.20, p < .001, η_p^2 =0.83) as well as a significant two-way interaction of Loudspeaker x Intervention ($F_{4, 14}$ = 12.07, p < .001, η_p^2 =0.78). Consequently, the significant interaction was explored using separate RM-ANOVAs for each Loudspeaker with a single within-participant factor (Intervention). Results are displayed in Table 6.3. Collectively, the data reveal that RMS significantly reduced VRTs in the midline and indirect loudspeaker conditions. A significant effect of the CROS to reduce VRTs was only evident in the indirect loudspeaker configuration.

Table 6.3. Results of pairwise comparisons of verbal response times (ms) in different loudspeaker conditions for different intervention options. Significant differences are indicated by bold typeface.

Loudspeaker	Comparison	*M* difference	Std Error	*p*	95% CI
Midline	**RMS vs Unaided**	**-182**	**0.07**	**.038**	**-356 to -9**
	CROS vs Unaided	64	0.09	1.000	-178 to 307
	RMS vs CROS	**-247**	**0.08**	**.014**	**-447 to -46**
Direct	RMS vs Unaided	-75	0.03	.088	-158 to 9
	CROS vs Unaided	58	0.04	.425	-42 to 158
	RMS vs CROS	**-133**	**0.03**	**.001**	**-211 to -54**
Indirect	**RMS vs Unaided**	**-680**	**0.08**	**< .001**	**-892 to -468**
	CROS vs Unaided	**-422**	**0.08**	**< .001**	**-626 to -218**
	RMS vs CROS	**-258**	**0.07**	**.003**	**-431 to -85**

6.4.3 Subjective Ratings

An exact McNemar's test was run for the two subjective questions: (1) "ease of listening" and 2) "motivation" in each loudspeaker configuration. Results are displayed in Table 6.4.

Table 6.4. Results of the McNemar's tests of the subjective ratings for each question in each loudspeaker condition. Significant differences between the RMS and CROS system are indicated in bold type face.

Question	Loud-speaker	*p*	Mean count of participants who selected option 1 (yes): RMS	Mean count of participants who selected option 1 (yes): CROS
1	**Midline**	**.016**	**18**	**11**
1	Direct	.250	18	15
1	**Indirect**	**.016**	**18**	**11**
2	**Midline**	**.008**	**18**	**10**
2	Direct	.625	17	15
2	**Indirect**	**.013**	**18**	**12**

For question 1, analysis revealed that significantly more participants indicated that the use of an RMS made listening easier in the midline and monaural indirect conditions. In the direct loudspeaker condition, no significant difference was found between the two intervention options in question regarding ease of listening. Similar to the findings of question 1, results for question 2 showed that in the midline and monaural indirect loudspeaker conditions, participants indicated the use of an RMS significantly improved their motivation to listen compared to the use of a CROS system. In the monaural direct condition, results indicate no significant difference between the effect of the RMS and the CROS system on participants' motivation to complete the listening task.

6.5 DISCUSSION

This study aimed to evaluate the effects of an RMS and CROS systems on digit triplet recognition and listening effort in school-aged children with LUHU in a number of different listening conditions that might be encountered in a classroom (i.e. midline signal, monaural direct, and monaural indirect). Existing research has not yet demonstrated whether the use of a personal, ear-level RMS and/or a CROS system can reduce listening effort for children with LUHU. A second objective of this study was to explore subjective ratings of RMS and/or CROS benefits in terms of listening ease and motivation to complete a listening task. Results for each outcome will be discussed separately.

6.5.1 Effect of RMS and CROS Intervention Options: Digit triplet recognition

As expected, results suggest that the use of a personal RMS significantly improved digit triplet recognition in noise for all three loudspeaker conditions relative to the unaided condition. Specifically, 94%, 56%, and 100% of participants demonstrated digit triplet recognition benefit with the RMS relative to unaided listening in the midline, direct, and indirect loudspeaker conditions respectively (see Appendix K for intervention benefit scores for each participant). These findings are consistent with results of previous laboratory studies with similar loudspeaker configurations which indicated that RMS provided the most consistent speech-in-noise recognition benefits (Kenworthy et al., 1990; Updike, 1994). Also consistent with earlier work, the CROS system impaired digit triplet recognition in the direct condition and improved it in the indirect condition. The CROS benefits in the indirect condition and the detriments in the direct condition were evident for 100% and 94% of participants, respectively (see Appendix K).

Combined, it can be concluded that the findings for speech recognition from Kenworthy et al., (1990) generalized to the results from a larger pool of multilingual participants in the current study, indicating that the use of RMS and/or CROS intervention options can be beneficial to support speech recognition in noise for children with LUHU in different listening situations.

6.5.2 Effect of RMS and CROS Intervention Options on Listening Effort: Verbal Response times

Children with LUHU experience increased listening effort relative to their peers with normal hearing in indirect listening (Oosthuizen et al., in review). In order to alleviate this increased listening effort, the FUEL and ELU models suggest audibility needs to be increased. Therefore, intervention options that are able to improve the SNR for the listener and thus improve audibility, have the potential to reduce listening effort. For children with LUHU, an RMS could improve audibility by overcoming noise, distance, or reverberation; a CROS system could improve audibility by overcoming the consequences of the head shadow for the ear with hearing loss.

Results of this study indicate that the use of both intervention options of the RMS and the CROS hearing aid had a significant effect on reducing VRTs during the indirect loudspeaker condition when compared to the unaided condition. Specifically, 100% and 89% of participants demonstrated a benefit in terms of listening effort (i.e., faster verbal response times) relative to the unaided condition with the RMS and CROS, respectively (see Appendix K). In addition, the mean VRT achieved with the RMS in the indirect condition (492 ms) in this study is less than the mean VRTs from peers with normal hearing in an indirect condition (556 ms) reported in a recent study by the authors (Oosthuizen et al., In Press). This suggests that the use of an RMS has the potential to effectively alleviate the significant increased listening effort experienced by children with LUHU in an indirect, noisy condition.

The benefit of the RMS to reduce listening effort relative to the unaided condition is also evident in the midline loudspeaker condition. Specifically, with the RMS, 72% of participants had a VRTs that were 182 ms faster on average compared to the unaided condition in the midline loudspeaker condition. In the direct loudspeaker condition, listening with the RMS and CROS system did not result in significant reduction of VRTs compared to the unaided condition.

When comparing the effect of RMS to a CROS system to reduce listening effort (i.e. faster VRTs), results revealed that verbal response times were faster with the RMS compared to the CROS in all three loudspeaker conditions. Specifically, 89% of participants had reduced VRTs by an average of 247 ms compared to the CROS system in the midline condition. In the direct condition, listening with a personal RMS resulted in significantly less listening effort as indicated by shorter VRTs for 89% of participants compared to listening with a CROS system (*M* difference = -133 ms). In the indirect condition, 89% of participants had VRTs that were significantly faster with the use of a personal RMS compared to the CROS (*M* difference = -258 ms).

6.5.3 Effect of RMS and CROS Intervention Options on Listening Effort: Subjective Ratings

From the FUEL model (Pichora-Fuller et al., 2016), it is clear that an individual's motivation also affects listening effort. If a listener has little motivation to understand what they are hearing, increasing cognitive demands may result in little or no change in effort. However, if an intervention option can increase a listener's motivation to continue listening, even if the listening situation poses a high cognitive demand with increased listening effort, it might help the listener to maintain the effort and complete the listening task (e.g., continue listening and participating in discussions in in a noisy classroom situation and not disengage). Consistent with the findings of digit triplet recognition and VRTs, results of the subjective measures indicate that the RMS yielded consistent benefits in terms of 1) ease of listening and 2) motivation to complete the listening task for most participants in this study. However, results could have been influenced by the fact that only 2 participants were experienced CROS users and that more than half of participants had experience listening with an RMS, whether personal or in combination with another intervention option. Furthermore, the findings might be limited by a social desirability response bias (King & Bruner, 2000). That is, participants want to give researchers answers that they think are desirable. As participants were informed of the purpose of the study before testing commenced, and as the minority had experience with CROS, it is possible they wanted to increase their social appropriateness by indicating in the subjective ratings that the RMS was more beneficial. Therefore, future studies should take into consideration potential social desirability response biases (King & Bruner, 2000). Considering subjective measures in the pediatric population is important towards implementing child-specific and responsive management plans. However, more research is needed in this area in order to develop reliable and valid subjective listening effort questionnaires.

6.6 CONCLUSION

As children with LUHU are at risk for decreased speech recognition and increased listening effort in noisy conditions, this study aimed to investigate the effect of two intervention options on speech recognition and listening effort for this population. Digit triplet recognition results with the RMS and CROS, replicated the extant literature and indicated that, when the microphone was placed near the loudspeaker of interest, the RMS provided the most consistent benefit, with significant positive effects in all loudspeaker conditions (midline, direct, indirect). A significant benefit of the CROS system relative to unaided digit triplet recognition was only evident in an indirect loudspeaker condition. Verbal response time results suggest that the use of a personal RMS effectively alleviated the increased listening effort experienced by children with LUHU in midline and indirect loudspeaker conditions. Conversely, relative to unaided listening the CROS reduced listening effort only in an indirect condition. The use of self-report questionnaires can be useful to determine perceived benefit of intervention options for lessening listening effort in school-aged children. Reducing listening effort by means of intervention options may enable children with LUHU to achieve successful participation in academic and social situations.

6.7 ACKNOWDLEDGEMENTS

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CHAPTER 7

GENERAL DISCUSSION, CLINICAL IMPLICATIONS AND CONCLUSIONS

Listening is imperative in the educational setting as 45% to 75% of a school day is dedicated to listening activity (Crandell & Smaldino, 2000a; Dahlquist, 1998). However, listening and learning often occur in acoustically disadvantaged environments, due to the presence of background noise and/or reverberation (Berg, 1993; Bistafa & Bradley, 2000; Crandell & Smaldino, 2000b). The consequences of sustained listening in such acoustically challenging environments includes reduced speech perception, increased listening effort, and possible fatigue (Prodi et al., 2010).

One population that might be at risk of experiencing increased listening effort is children with unilateral hearing loss (UHL). The recently published consensus practice parameter of UHL in children by Bagatto and colleagues (2019), brings a renewed focus on this specific population in terms of audiological assessment and management. Despite improved early identification and intervention, children with UHL still experience academic, speech and language, and social and/or behavioral difficulties (e.g. Bess & Tharpe, 1986a; Bess et al., 1986; Lieu, 2013; Lieu, 2004). Moreover, the difficulties of poorer speech recognition and increased need for academic assistance associated with UHL are more pronounced for children with LUHU compared to children with milder degrees of UHL (Bess et al., 1986; Lieu et al., 2013). From the FUEL model (Pichora-Fuller et al., 2016), it can be expected that children with LUHU experience more listening effort relative to peers with normal hearing although research evidence to date has not yet confirmed this.

Research in the UHL population should distinguish between degrees of severity to make more accurate management recommendations (Bagatto et al., 2019). Therefore, the main aim of this study was to investigate listening effort in school-aged children with LUHU. Given the global reality of learners for multilingual backgrounds in educational contexts, this research project first aimed at developing listening effort paradigms with low linguistic content that would be suitable to use in a multilingual context. These novel low linguistic listening effort paradigms were subsequently used to investigate listening effort experienced specifically by school-aged children with LUHU, relative to peers with bilateral normal hearing. Furthermore, the effect of two non-surgical intervention options for children with LUHU (RMS and CROS) on listening effort were explored.

7.1 OVERVIEW OF RESEARCH FINDINGS

Results from Study I indicated that the novel listening effort measures of single- and dual task paradigms with low linguistic speech material were both sensitive to the effects of SNR (single-task: $p < .001$, $\eta_p^2 = 0.58$; dual-task: $p < .001$, $\eta_p^2 = 0.23$) with decreasing SNRs resulting in increased RTs. The finding that language background (English as native language versus English as non-native language) had no significant effect on triplet recognition performance (single-task: $p > .40$, $\eta_p^2 = 0.02$; dual-task: $p > .13$, $\eta_p^2 = 0.04$) or response times (single-task: $p > .45$, $\eta_p^2 = 0.01$; dual-task: $p > .22$, $\eta_p^2 = 0.03$) indicate that both these behavioral listening effort measures can be used for evaluating listening effort in school-aged children, between 7 and 12 years of age, from multilingual contexts. A significant relationship between age and dual-task visual RTs (r = -0.39, $p < .0001$) was evident, indicating a maturation effect for response times, similar to the developmental effect for speech recognition in noise. This indicates that as speech-in-noise recognition abilities and multitasking skills improve with age for school-aged children, older children tend to exert less listening effort as reflected in shorter response times during dual-task measures. Therefore, consideration should be given even to young school-aged children with normal hearing as they can experience increased listening effort in acoustic challenging situations (e.g., classrooms with high noise levels), which could deter academic learning.

By focusing on children with limited useable hearing in one ear and normal hearing sensitivity in the opposite ear, results from verbal response time measures in Study II indicated that school-aged children with LUHU experienced significantly more listening effort relative to their peers with normal hearing, specifically in a noisy, indirect listening condition ($p < .001$, *M* difference = 624 ms, 95% CI: 428 to 801 ms). In addition, the study results replicated the extant literature and indicated that children with LUHU are at risk for poorer digit triplet recognition in noisy midline, direct, and indirect listening conditions. Correlation analyses revealed a significant relationship between age and triplet recognition only in the midline condition with noise and only for the participants with NH (r = 0.58, $p = .011$). However, no significant correlation between age and RTs for neither participants with NH nor participants with LUHU in any of the loudspeaker conditions were found. Significant differences in subjective ratings between the two groups were also only evident in the noisy, indirect condition with participants with LUHU rating task difficulty as significantly higher ($p < .001$), recognition performance as significantly lower ($p < .0001$), and that it was harder to think ($p = .004$) compared to children with NH. Results from correlation analyses for the indirect condition with noise revealed that subjective ratings were related to age (r = 0.68, $p < .0001$; r = 0.52, $p = .026$; r = 0.78, $p < .0001$ for ratings of task difficulty, recognition performance, and hard to think, respectively), rather than digit triplet recognition performance or RTs, but only for participants with LUHU.

Non-surgical intervention options for children with limited hearing unilaterally that improve the SNR are expected to improve speech recognition and also reduce listening effort in challenging listening situations, although previous studies have not confirmed this. Employing behavioral and subjective indices of listening effort, Study III aimed to evaluate the effects of two intervention options, remote microphone system and contralateral routing of signal system, on listening effort in school-aged children with LUHU. Results indicated that relative to the unaided condition, the RMS significantly improved digit triplet recognition in the midline ($p < .001$, *M* difference = 61.50 rau, 95% CI = 39.09 to 83.91 rau), monaural direct ($p = .035$, *M* difference = 13.58 rau, 95% CI = 0.79 to 26.38 rau) and monaural indirect ($p < .001$, *M* difference = 103.45 rau, 95% CI = 92.06 to 114.84 rau) loudspeaker conditions and significantly reduced verbal response times in the midline ($p = .038$, *M* difference = -182 ms, 95% CI = -356 to -9 ms) and monaural indirect ($p < .001$, *M* difference = -680 ms, 95% CI = -892 to -468 ms) conditions. The CROS system significantly improved digit triplet recognition ($p < .001$, M difference = 41.95 rau, 95% CI = 29.51 to 54.39 rau) and reduced verbal response times ($p < .001$, M difference = -422 ms, 95% CI = -626 to -218 ms) only in the monaural indirect condition, relative to the unaided condition. Consistent with the findings of digit triplet recognition and VRTs, analyses of the subjective ratings indicated that the RMS yielded more consistent benefits in terms of 1) ease of listening and 2) motivation to complete the listening task for most participants.

7.2 CLINICAL IMPLICATIONS

As language background (English as native language vs English non-native language) had no significant effect on digit triplet recognition or response times (verbal response times and dual-task visual response times), these novel low-linguistic listening effort measures can be useful for evaluating listening effort in school-aged children from multilingual backgrounds. Result from study I revealed a maturation effect for response times, as older children tended to exert less listening effort as reflected in shorter response times during dual-task measures. This could be due to improved development of multitasking skills in older school-aged children. Children have to develop important cognitive, language, and academic skills in the classroom. Results from Study I indicated that even young school-aged children with normal hearing can experience increased listening effort in acoustic challenging situations (e.g., classrooms with high noise levels). Sustained increased listening effort may result in stress, fatigue, inattentiveness, irritability, less participation in classroom activities and/or discussions. As a result, children's academic performance may be negatively affected. Therefore, it will be important to raise awareness of professionals in the educational context regarding the increased listening effort that can be experienced by learners in noisy classroom environments. In addition, due consideration should be given to management of classroom noise levels to support learners and to help ensure optimal classroom acoustics for all school-aged children. Several guidelines on improving room acoustics exist that can be followed to improve listening and communication (e.g., Rosenberg, 2002; Smaldino et al., 2015).

Results from both behavioral and subjective indices of listening effort used in Study II clearly indicated that another pediatric population that can be at risk for exhibiting more listening effort is children with LUHU, specifically in indirect, noisy listening scenarios. Therefore, classroom placement should be considered for children with LUHU to avoid situations that may cause more listening effort. For example, preferential seating could be arranged to maximize direct and midline listening scenarios to support academic performance in the classroom by reducing the cognitive demands associated with indirect listening. Subjective ratings can be used to index the perceived listening effort in different listening situations for school-aged children with LUHU that is not directly assessed by standard audiometric procedures. Considering subjective ratings of perceived listening effort in school-aged children can contribute to a management plan for a child with LUHU. Therefore, in addition to all the other known risk factors related to the academic environment for children with LUHU, it will be of importance that professionals involved in the assessment and management of children with LUHU consider the increased listening effort that can be experienced by this population and the possible negative effects it may have on their academic performance and quality of life. Moreover, it will be important to raise awareness of parents/caregivers of children with LUHU about increased listening effort that these children can experience and the effects thereof (e.g., fatigue) as well as how they can assist in the management thereof (e.g., ensuring their child gets sufficient sleep/rest, reducing noise when studying or doing academic related tasks). Furthermore, it will be important to teach children with LUHU assertiveness and self-advocacy skills to ensure their active and successful participation in different listening scenarios/especially in difficult listening scenarios (e.g., noisy, indirect listening scenarios). The FUEL and ELU models suggest audibility needs to be increased to help reduce this increased listening effort. Therefore, intervention options that can improve the SNR for the listener and thus improve audibility, have the potential to reduce listening effort and should be considered.

Results from Study III provide evidence that RMS and CROS systems have the potential to improve speech recognition in noise and to reduce the increased listening effort experienced by school-aged children with LUHU. Consequently, it will be important to consider and trial options on an individual basis in academic, home, and social contexts for reducing listening effort and enabling children with LUHU to achieve increased participation in academic and social situations. Audiologists can also conduct aided assessments of speech recognition and listening effort after trial periods with specific intervention options as part of a validation component of audiological management of children with LUHU. Furthermore, the use of self-report questionnaires can be useful to determine the perceived benefit of an intervention option(s) for reducing listening effort in school-aged children with LUHU and thus further support a patient-centered management plan. Subjective reports of listening effort experienced by children with LUHU and of the effect of intervention options on listening effort can also be requested from parents and teachers during the validation stage.

Based on this research project's findings and clinical implications a continuous management plan for listening effort in school-aged children with LUHU is proposed in Figure 7.1. Continuous management and monitoring of children with LUHU entail the ongoing need for assessment of these children's hearing abilities and listening needs throughout childhood and adolescent years. This is important as the listening needs of children with LUHU may change according to the various listening environments they find themselves in within academic and social contexts. Individual variability in terms of listening needs should also be considered. Therefore, the listening needs of children with LUHU specific to their listening environments should be continuously evaluated and addressed in a patient-centered approach.

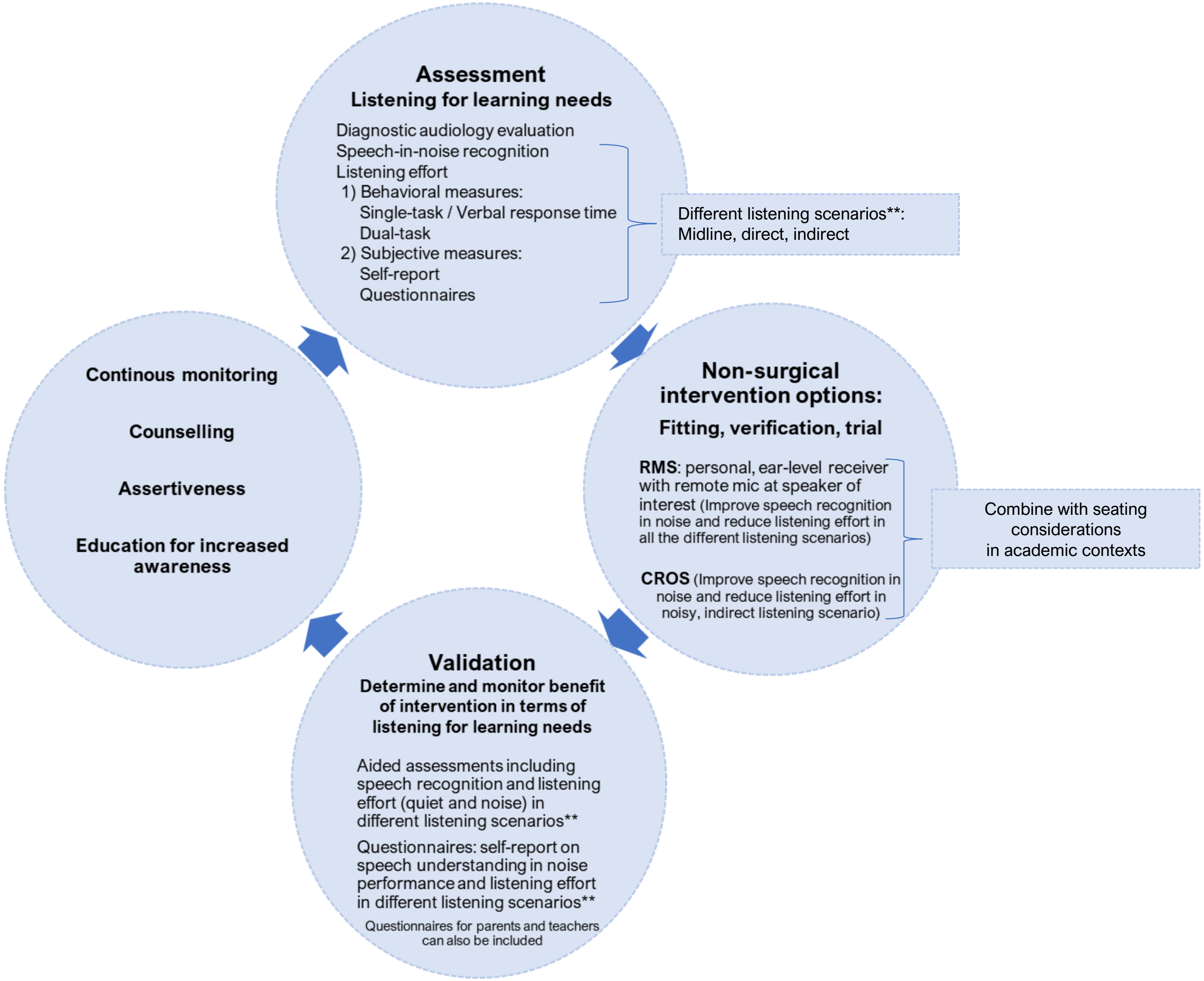

Figure 7.1 Proposed management of listening effort in school-aged children with LUHU

7.3 STUDY STRENGHTS AND LIMITATIONS

A critical evaluation of this research project was conducted to evaluate its strengths and limitations.

7.3.1 Study strengths

- The choice of speech stimulus is an important methodological consideration when considering outcomes in modern classrooms with children from diverse language backgrounds. The typical speech materials used for listening effort testing are age-appropriate, standardized, pre-recorded word lists. In a multilingual context, the use of word lists, with a high linguistic demand, could pose a challenge for younger children and for children who may not be native speakers of the language of the word lists. Therefore, digit triplets from an English-based digits-in-noise test was used to develop listening effort paradigms (single- and dual-task) with low linguistic load. The use of digits has several advantages compared to using open-set word or sentence recognition stimuli that makes it more applicable for use in a multilingual context, which is typical of children in South Africa. First, digits-in-noise stimuli is low in linguistic demands and secondly, the speech material is presented in a closed set (Kaandorp et al., 2016; Potgieter et al., 2018). Thirdly, English digits are mostly familiar and often used by speakers of other languages (Branford & Claughton, 2002). Results from Studies I and II provide evidence that digit triplets as speech stimuli were insensitive to the language background of school-aged listeners with normal hearing as well as school-aged children with LUHU. As a result, the use of digit triplets had no effect on digit triplet recognition performance or response times when used in a single- or dual-task listening effort paradigm. This clearly indicates that these effort paradigms with low-linguistic load are viable options to assess listening effort in young school-aged children with normal hearing and children with LUHU from multilingual backgrounds.
- Study II was the first to explore and compare listening effort in school-aged children with LUHU relative to peers with bilateral normal hearing by means of behavioral and subjective listening effort measures.

- Study III was to first study to examine the effect of a personal RMS and CROS system on the increased listening effort that can be experienced by school-aged children with LUHU, using behavioral and subjective indices of listening effort.
- Results from behavioural (VRTs) and subjective (study-specific subjective questionnaires) measures of listening effort aligned as both these measures revealed that school-aged children with LUHU can experience significantly more listening effort than peers with normal hearing in noisy, indirect listening conditions. This indicates the feasibility and value of the use of subjective ratings of perceived listening effort complementary to more objective, behavioural measures. Including reports of subjective ratings of perceived listening effort in school-aged children with LUHU as well as subjective ratings of the effect of intervention options on listening effort, can help to support a management plan in the case of a child with LUHU.

7.3.2 Study limitations

- Generalizability of the findings of studies may be limited by the specific test conditions used during this study as it was a laboratory study with a single talker (from different directions for Studies II and III) and relatively directional noise sources. Such laboratory setups do not reflect typical contemporary classrooms that have primarily diffused noise (Crukley et al., 2011; Ricketts et al., 2017).
- Although the speech and noise signals were presented from spatially separated loudspeakers in Study I and for the midline conditions for Studies II and III, the fact that the noise presented from the side loudspeakers were identical, the perception might have been that of a centrally localized single noise source. Thus, participants could have perceived the speech and noise signals to be spatially coincident (Kendall, 2010). This could have affected participants' performance in terms of digit triplet recognition and RTs.
- The digit noise used was steady state and speech-shaped. It did not contain temporal modulations or informational masking, both of which might affect listening effort (Desjardins & Doherty, 2013; Koelewijn et al., 2014).
- The relatively directional noise sources also might have underestimated the possible benefits of a CROS system as results of recent work with unilateral

cochlear implants and CROS systems indicated that the limitations of CROS systems can be larger with directional noise than diffuse noise (Taal et al., 2016).

- The remote microphone was always placed near the talker (loudspeaker) of interest, similar to setup used by Kenworthy and colleagues (1990). This might overestimate the benefits of an RMS for speech recognition in a classroom environment with multiple talkers of interest, resulting in a remote microphone that is not always near the talker of interest (Ricketts et al., 2017; Ricketts et al., 2010).
- Participants were explicitly instructed to keep their heads still and face the front loudspeaker. The limitation of head turning could have reduced participants' abilities to manage the listening environment to help improve speech recognition, especially with the use of a CROS system in Study III.

7.4 RECOMMENDATIONS FOR FUTURE RESEARCH

The results obtained and the conclusions drawn from this project revealed several significant aspects that require further investigation as the limitations in the generalizability and applicability of the results are recognized. These are presented below to provide suggestions for future research.

- Digit recognition in noise abilities can emerge as young as the age of 4 (Koopmans et al., 2018). Therefore, future studies should consider including children with normal hearing younger than 7 years of age to target a more comprehensive investigation on age related changes in listening effort in the pediatric population.
- Future research should consider the impact of different types of masker noise with these novel low-linguistic listening effort paradigms (e.g., steady state, speech shaped noise versus informational masking noise) as the digit noise that was used was steady state, speech-shaped and did not contain temporal modulations or informational masking, which might affect listening effort (Desjardins & Doherty, 2013; Koelewijn et al., 2014).
- Typical contemporary classrooms have primarily diffuse noise that is present at least 70% of the time (Crukley et al., 2011; Ricketts et al., 2017). Future studies should consider the use of more diffuse background noise together with different

types of masker noise (e.g., speech-like background noise) in evaluating listening effort in school-aged children with normal hearing and school-aged children with LUHU in order to better resemble a realistic classroom situation.

- In the midline loudspeaker condition identical noise was presented simultaneously from the side loudspeakers. Therefore, the noise might have been perceived as originating from a central point, and thus coincident with the speech source (Kendall, 2010). Although this setup is easy to implement in most clinic test booths, it does not generalize to most natural listening situations. Therefore, future studies should explore the effects on speech recognition and listening effort where noise from side loudspeakers are uncorrelated.
- The use of digit triplets as stimuli might under-estimate the increases in listening effort experienced by children with LUHU. Results from a study by Stiles and colleagues (2012) indicated that the use of digits as speech stimuli is not sensitive to depict differences between children with NH and bilateral mild-to-moderate sensorineural hearing loss. Although results from the current study indicate that the use of digit triplets was successful to show clear differences in speech recognition and in measures of listening effort between school-aged children with NH and LUHU, the effects might be larger with more linguistically complex stimuli. The low linguistically loaded stimuli (digit triplets) used in this study might overestimate speech recognition performance as it is stemming from a closed set, highly-familiar corpus. Children with UHL may have poorer language abilities compared to peers with NH (Lieu et al., 2010), and according to FUEL, language ability is thought to affect listening effort (Pichora-Fuller et al., 2016). Results from Study II showed that home language had no significant effect on digit triplet recognition performance or responses times. Future studies with higher linguistic load (e.g., age-appropriate open set word or sentence material) and including language abilities as a variable are warranted to determine the possible effect that language abilities may have on listening effort in children with LUHU. In addition, with regards to the choice of speech stimulus, future studies could investigate the effect of using speech stimuli with different linguistic loads (i.e., low linguistically loaded versus high linguistically loaded) in listening effort measures in the pediatric population.

- The finding that participants with LUHU had significantly longer VRTs relative to the VRTs of peers with normal hearing in the difficult indirect listening condition with noise (Study II) should be investigated in more detail future research. Specifically, an alternative interpretation that the significantly slower VRTs of participants with LUHU in an indirect listening condition with noise was due to a failure to respond rather than increased listening effort may be explored in future studies.
- Modern classroom situations are characterized by multiple talkers of interest speaking simultaneously (e.g., oral group reading) or in quick succession (e.g., question and answer sessions; Ricketts et al., 2017; Ricketts et al., 2010). This may result in a remote microphone that is not always near the talker of interest. In these situations, the remote microphone is more likely to remain with a single talker (e.g., the teacher) who is not always the talker of primary interest (e.g., during group discussions). The test setup used in a recent study by Picou and colleagues (Picou et al., 2020a; Picou et al., 2019b) applied the aforementioned factors of diffused noise, dynamic talker location but with a single location for the remote microphone. The results suggested that a CROS system has the potential to improve speech recognition in dynamic, classroom listening situations, more than what was found in Study III and previous studies (e.g., Kenworthy et al., 1990; Updike, 1994). Future work should therefore focus on using such a test setup that resembles a multitude of realistic classroom situations to determine the effect that an RMS and CROS system may have on the listening effort experienced by children with LUHU in everyday learning environments.
- The limitation of head turning could have reduced participants' abilities to manage the listening environment to help improve speech recognition, especially with the use of a CROS system (Study III). Direct measurement of head orientation and the effect on speech recognition and possibly listening effort, warrants future research.
- Only non-surgical interventions options were considered in Study III. However, bone anchored implants and cochlear implants can be intervention options for children with LUHU. Bone-anchored implants have the potential to improve speech recognition in monaural indirect listening scenarios by rerouting signals to overcome the head shadow (Bosman et al., 2003; Hol et al., 2005). A cochlear implant might offer children with LUHU the potential for bilateral hearing (Bernstein

et al., 2017) and improved speech recognition in noise (Arndt et al., 2015; Hassepass et al., 2013). Therefore, future studies should consider examining the effect of surgical intervention options of bone-anchored hearing devices and cochlear implants on listening effort in children with LUHU. In addition, the effect of independent variables of age of intervention and type of prior intervention on listening effort should be considered in future studies with larger participant samples to examine the effect of surgical and non-surgical intervention options for children with LUHU. Furthermore, the long-term effect of various intervention options (surgical and non-surgical) on listening effort in children with LUHU should be determined by future longitudinal studies.

- As the digit noise was steady-state noise, the digital noise reduction in the receiver hearing aid of the CROS system was de-activated to prevent possible interference of the digital noise reduction technology with processing of the speech signal in noise (Study III). Hence, determining the effect of activated digital noise reduction technology in the receiver hearing aid use of a CROS system on listening effort in children with LUHU should be explored in future studies. Also, the combination of a CROS hearing aid system together with an RM system (RM receiver coupled to the CROS hearing aid system) should be considered in future studies concerning listening effort in school-aged children with LUHU.
- The subjective rating questions of Study II were not significantly correlated with VRTs. Therefore, the results of Study II do not provide insight into optimization of language used to elicit subjective ratings of listening effort. In addition, only for participants with LUHU, subjective ratings were correlated with each other and with age in the indirect condition with noise. Therefore, interpretation of individual participants' subjective rating results should be done with caution due to the significant contribution of age to ratings. Results from the subjective indices used in Study III indicated that self-report questionnaires can also be useful to determine the perceived benefit of intervention options in terms of reducing listening effort experienced by school-aged children. Considering subjective measures in the pediatric population is important towards implementing specific and responsive management plans. Self-report measures of listening effort also have the advantages of low technological demands and high face validity. However, more

research is needed in this area in order to develop reliable and valid subjective listening effort questionnaires for children.

- Future studies comparing listening effort between native and non-native children should consider bigger participant numbers and using speech material with a higher linguistic load if the effect of language background on listening effort in school-aged children wants to be examined. This might result in more significant group differences between children with a native language background versus children with a non-native language background.
- In the clinical and research domains of Pediatric Audiology, the reliability of behavioral testing and behavioral responses obtained from children is important. Future studies employing behavioral measures of listening effort in the pediatric population should consider including rating or documentation of the reliability of behavioral responses.

7.5 CONCLUSION

Study I aimed to explore the effects of SNR on listening effort in multilingual school-aged children (native English; non-native English) as measured with a single- and a dual-task paradigm with low-linguistic speech stimuli (digit triplets). The study also aimed to explore age effects on digit triplet recognition and response times. Significant effects of SNR on response times were evident during both single- and dual-task paradigms. As expected, language background did not affect speech recognition performance or the pattern of response times. The data also revealed a maturation effect for triplet recognition during both tasks and for response times during the dual-task only.

The aim of Study II was to compare listening effort in school-aged children with normal hearing and limited useable hearing unilaterally in a number of different listening conditions that might be encountered in a classroom (i.e., midline signal, direct, and indirect). The focus was on comparing children with LUHU to children with NH across behavioral and subjective indices of listening effort (single-task paradigm, subjective ratings) in quiet and noise conditions. Both groups had poorer digit triplet recognition in the midline loudspeaker condition with noise compared to the quiet midline loudspeaker condition. Furthermore, children with LUHU appeared to be more sensitive to the effects of noise on digit triplet recognition than children with NH for both direct and indirect loudspeaker locations. Participants with LUHU exhibited significantly slower response times only in the noisy, indirect loudspeaker condition, relative to their peers with normal hearing. Significant differences in subjective ratings of task difficulty, recognition performance and how hard it was to think between the two groups were also only evident in the indirect condition with noise.

Study III aimed to evaluate the effects of two intervention options, RMS and CROS system, on listening effort in school-aged children with limited hearing unilaterally. Behavioral and subjective indices of listening effort indicated that an RMS provided the most consistent benefit for speech recognition and listening effort for children with LUHU. Specifically, the RMS significantly improved digit triplet recognition across loudspeaker conditions and reduced verbal response times in the midline and indirect conditions. The CROS system improved digit triplet recognition and listening effort only in the indirect condition. Results from subjective ratings revealed significantly more participants indicated that the RMS made it easier for them to listen and to stay motivated to complete the listening task.

This work contributes to a better understanding of possible listening effort that even young school-aged children with normal hearing can experience in noisy classroom situations. Furthermore, the results provide valuable baseline data on increased listening effort that can be experienced by school-aged children with LUHU. Therefore, this work contributes to an improved understanding of listening effort difficulties that school-aged children with LUHU can experience in addition to decreased speech-in-noise recognition performance in noisy listening situations. Due consideration should be given to the greater listening effort that children with LUHU can exhibit as it may negatively affect their performance in academic and social contexts. By exploring the effect of two non-surgical intervention options for children with LUHU on listening effort, in addition to speech-in-noise recognition improvement, this work can support evidence-based recommendations for the type of intervention options for school-aged children with LUHU.

Results from multiple indices of listening effort from this research project can support clinicians working with the school-aged LUHU population in terms of counselling regarding the possibility of more listening effort and the effects thereof, recommendations of non-surgical intervention options based on individual needs of the child, and in terms of continued monitoring of children with LUHU to increase these children's successful participation in academic and social situations.

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APPENDICES

APPENDIX A

Ethical approval letter

Postgraduate Research Ethics Committee

Faculty of Humanties

University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Humanities 100.
1919 - 2019

Research Ethics Committee

1 March 2019

Dear Mrs I Oosthuizen

Project Title:	Listening effort in children with severe-profound sensorineural unilateral hearing loss
Researcher:	Mrs I Oosthuizen
Supervisor:	Prof L Pottas
Department:	Speech Language Path and Aud
Reference number:	HUM005/0219
Degree:	Doctoral

I have pleasure in informing you that the above application was **approved** by the Research Ethics Committee on 28 February 2019. Data collection may therefore commence.

Please note that this approval is based on the assumption that the research will be carried out along the lines laid out in the proposal. Should the actual research depart significantly from the proposed research, it will be necessary to apply for a new research approval and ethical clearance.

We wish you success with the project.

Sincerely

Prof Maxi Schoeman
Deputy Dean: Postgraduate and Research Ethics
Faculty of Humanities
UNIVERSITY OF PRETORIA
e-mail: PGHumanities@up.ac.za

Fakulteit Geesteswetenskappe
Lefapha la Bomotho

APPENDIX B

Information letter and consent slip from

The principal of the Eduplex Primary School: Study I

The principal of the Carel du Toit School: Studies II and III

8 February 2019

Dear Principal, Mr J. De Goede

Invitation for learners of your school to participate in a research study

We would like to kindly invite learners of your school to participate in a research study from the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

Information about the research study
The purpose of the study is to determine the listening effort experienced by normal hearing school-aged children with English as first language (L1) compared to normal hearing school-aged children with English as additional language (EAL). Listening effort can be described as the amount of mental effort (the attention and cognitive resources) a person uses to understand speech. Results from this study may help to determine the sensitivity of a low linguistic test method to assess listening effort in school aged children and may also enhance awareness of the listening effort experienced by children with English as additional language in an academic context.

Participant candidacy
For this study, school-aged children aged 7 to 12 years with normal hearing in both ears and with English as a first language and school-aged children aged 7 to 12 years with normal hearing in both ears with English as additional language will be included. Furthermore, participants should have age-appropriate speech, language, and motor development and no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. With the parents'/caregivers' consent, access to the child's educational file will be requested to confirm the child's developmental and medical history as documented in the child's educational file.

Requirements from participants
The child will be seated in a soundproof booth and will be required to do two listening effort tests. The one test procedure will require the child to do two tasks simultaneously – listening to and repeating a sequence of three numbers and at the same time look at a computer screen, situated in front of the child, and touch the screen whenever a shape (for example a red circle) appears on the screen. The other test procedure will only require that the child listen to and repeat a sequence of three numbers and the child's verbal responses will be recorded by the

Communication Pathology Building
University of Pretoria, Private Bag X20
Hatfield 0028, South Africa
Tel +27 (0)12 420 4280
Fax +27 (0)12 420 3517
dewet.swanepoel@up.ac.za
www.up.ac.za

computer. Before the listening effort tests, the researcher will conduct a visual screening test to confirm normal visual acuity and a standard hearing test on the child to confirm that the child has normal hearing in both ears. The test battery will include an otoscopic examination (to look at the outer ear, ear canal and eardrum), a tympanogram (to determine the functioning of the middle ear systems) as well a pure-tone audiometric hearing test.

Test duration and venue
The testing will take place at the Audiology Department at Eduplex School, in Pretoria. The test will take approximately 1 hour. Testing will be arranged so that the child's school work will not be affected negatively.

Possible risks and benefits associated with this study
Participants will not be exposed to any risk or experience any discomfort during this test. No reimbursement will be given to the principal or the school. Information obtained from this study will assist in determining a valid and reliable low linguistic test method to assess listening effort in primary school-aged children as well as increasing awareness of the listening effort experienced by normal hearing school-aged children with English as a first language compared to children with English as additional language.

Confidentiality
All the results will be recorded under an anonymous research code, therefore, all identifying information and results will be kept confidential. Only the researcher and audiologist will have access to the information. The results of the research study will be archived at the Department of Speech-Language Pathology and Audiology for 15 years.

Sharing of results
The results obtained from this research study will be reported in the form of a scientific article which will be available to professionals in the field of audiology. The results from the research study may be used by future researchers. If data is to be used for further research, participants' permission will be obtained through an informed consent form. The results of the research will also be shared with the child's parents/caregivers.

Refusal or withdrawal from the research
Participation by learners from your school in this research study is entirely voluntary, therefore, the child may withdraw from the study at any point, should he/she wish to do so, without having to explain why. There will be no penalty or loss of benefit if they decide not to take part. Participants and their parents/caregivers will have the opportunity to ask questions about the proposed study before signing verbal assent or consent, respectively.

Contact information
If you would like further information on the research study, please contact us on:

Ilze Oosthuizen *Researcher / Audiologist*	072 288 4209 ilze.oosthuizen@earinstitute.co.za
Prof De Wet Swanepoel *Supervisor*	012 420 4280 dewet.swanepoel@up.ac.za
Prof Lidia Pottas *Supervisor*	012 420 2357 lidia.pottas@up.ac.za

Yours sincerely

Ilze Oosthuizen **Researcher/Audiologist**	**Prof De Wet Swanepoel** **Supervisor**	**Prof Lidia Pottas** **Supervisor**

Dr Jeannie van der Linde
Head: Department of Speech-Language Pathology and Audiology

INFORMED CONSENT FOR THE PRINCIPAL

I, [illegible], hereby consent that my school, [illegible], may be used as research site to access participants to participate in the research study entitled *Listening effort in normal hearing English first language (L1) speaking and English additional language (EAL) speaking school-aged children using dual task and verbal response time paradigms.*

I understand that neither I nor the school will receive any reimbursement if the learners participate in this research study. I am aware that the learners may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that the learners are not harmed in this research study.

Principal Signature: ____________________

Date: 11/2/2019

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

8 February 2019

Dear Principal, Mrs. Adri Hodgson

Invitation for paediatric patients of your school to participate in a research study

We would like to kindly invite paediatric patients from your school to participate in a research study from the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

Information about the research study
The purpose of the study is to determine the listening effort that children with severe-profound sensorineural unilateral hearing loss experience compared to children with normal hearing. Listening effort can be described as the amount of mental effort (the attention and cognitive resources) a person uses to understand speech. Results from this study may help to increase awareness of the listening effort experienced by children with severe-profound sensorineural unilateral hearing loss and the subsequent effects of this listening effort in order the optimise intervention guidelines for children with severe-profound sensorineural unilateral hearing loss. Furthermore, enhanced classroom management guidelines can be proposed to support these learners and to help ensure good classroom acoustics for all children in primary schools.

Participant candidacy
For this study, school-aged children aged 7 to 12 years with a severe-profound sensorineural unilateral hearing loss and school-aged children aged 7 to 12 years with normal hearing in both ears, will be included. Furthermore, participants should have age-appropriate speech, language, and motor development and no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. With the parents'/caregivers' consent, access to the child's audiological file will be requested to confirm the child's developmental and medical history as documented in the child's file.

Requirements from participants
The child will be seated in a soundproof booth and will be required to do two listening effort tests. The one test procedure will require the child to do two tasks simultaneously – listening to and repeating a sequence of three numbers and at the same time look at a computer screen, situated in front of the child, and touch the screen whenever a shape (for example a red circle)

Communication Pathology Building
University of Pretoria, Private Bag X20
Hatfield 0028, South Africa
Tel +27 (0)12 420 4280
Fax +27 (0)12 420 3517
dewet.swanepoel@up.ac.za
www.up.ac.za

Fakulteit Geesteswetenskappe
Departement Spraak-Taalpatologie en Oudiologie
Lefapha la Bomotho
Kgoro ya Phatholotši ya Polelo-Maleme le Go kwa

appears on the screen. The other test procedure will only require that the child listen to and repeat a sequence of three numbers and the child's verbal responses will be recorded by the computer. Before the listening effort tests, the researcher will conduct a visual screening test to confirm normal visual acuity and a standard hearing test on the child to confirm the child's hearing status. The test battery will include an otoscopic examination, tympanometry as well a pure-tone audiometric hearing test.

Test duration and venue
The testing will take place at a private audiology practice in Belville, in close proximity of the school. Parents will be requested to bring their child to the practice. The test will take approximately 1 hour. The researcher will provide the child with breaks so that he/she may perform optimally. Testing will be arranged so that the child's school work will not be affected negatively.

Possible risks and benefits associated with this study
Participants will not be exposed to any risk or experience any discomfort during this test. A reimbursement in the form of a monetary gift card will be given to the parent/caregiver of each participant. Furthermore, information obtained from this study will assist in increasing awareness of the listening effort experienced by school-aged children with a severe-profound sensorineural unilateral hearing loss in order to improve intervention guidelines in an academic context.

Confidentiality
All the results will be recorded under an anonymous research code, therefore, all identifying information and results will be kept confidential. Only the researcher and supervisors will have access to the information. The results of the research study will be archived at the Department of Speech-Language Pathology and Audiology for 15 years.

Sharing of results
The results obtained from this research study will be reported in the form of a scientific article and dissertation, which will be available to professionals in the field of audiology. The results from the research study may be used by future researchers. If data is to be used for further research, participants' permission will be obtained through an informed consent form.

Refusal or withdrawal from the research
Participation by paediatric patients from your practice in this research study is entirely voluntary, therefore, the child may withdraw from the study at any point, should he/she wish to do so.

Contact information
If you would like further information on the research study, please contact us on:

Ilze Oosthuizen *Researcher/Audiologist*	072 288 4209 ilze.oosthuizen@earinstitute.co.za
Prof De Wet Swanepoel *Supervisor*	012 420 4280 dewet.swanepoel@up.ac.za
Prof Lidia Pottas *Supervisor*	012 420 4280 lidia.pottas@up.ac.za

Yours sincerely

Ilze Oosthuizen
Researcher

Prof De Wet Swanepoel
Supervisor

Prof Lidia Pottas
Supervisor

Dr Jeannie van der Linde
Head: Department of Speech-Language Pathology and Audiology

INFORMED CONSENT FROM THE PRINCIPAL

I, **Adri Hodgson**, hereby consent that my school, **Carel du Toit Centre**, may be used as research site to access participants to participate in the research study entitled *Listening effort in school-aged children with normal hearing compared to school-aged children with severe-profound sensorineural unilateral hearing loss.*

I understand that neither I nor the school will receive any reimbursement if the learners participate in this research study. I am aware that the learners may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that the learners are not harmed in this research study.

Principal Signature: ___________________________

Date: 18 February 2019

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

8 February 2019

Dear Principal, Mrs Adri Hodgson

Invitation for paediatric patients of your school to participate in a research study

We would like to kindly invite paediatric patients from your school to participate in a research study from the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

Information about the research study
The purpose of the study is to determine the effect of using a digital RM (remote microphone) system compared to using a CROS (contralateral routing of signal) hearing system on the listening effort that school-aged children with a severe-profound sensorineural unilateral hearing loss experience. Listening effort can be described as the amount of mental effort (the attention and cognitive resources) a person uses to understand speech. Results from this study may help to increase awareness of the listening effort experienced by children with a severe-profound unilateral hearing loss and the subsequent effects of this listening effort in order the optimise intervention guidelines for children with a severe-profound unilateral hearing loss. Furthermore, the results may indicate the effectiveness of a digital RM system and CROS system to possibly reduce the listening effort exerted by school-aged children with a severe-profound unilateral hearing loss.

Participant candidacy
For this study, school-aged children aged 7 to 12 years with a severe-profound sensorineural unilateral hearing loss will be included. Furthermore, participants should have no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. With the parents'/caregivers' consent, access to the child's audiological file will be requested to confirm the child's developmental and medical history as documented in the child's file.

Requirements from participants
The child will be seated in a soundproof booth and required to do two listening effort tests. The one test procedure will require the child to do two tasks simultaneously – listening to and repeating a sequence of three numbers and at the same time look at a computer screen, situated in front of the child, and touch the screen whenever a shape (for example a red circle)

Communication Pathology Building
University of Pretoria, Private Bag X20
Hatfield 0028, South Africa
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dewet.swanepoel@up.ac.za
www.up.ac.za

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Departement Spraak-Taalpatologie en Oudiologie
Lefapha la Bomotho
Kgoro ya Phatholotši ya Polelo-Maleme le Go kwa

appears on the screen. The other test procedure will only require that the child listen to and repeat a sequence of three numbers and the child's verbal responses will be recorded by the computer. The listening effort test procedures will be done without the use of a digital RM system and a CROS system and again with the use of a digital RM system and a CROS system. When the digital RM system will be used, the child will be fitted with an ear-level receiver and he/she will wear it only for the duration of the test. When the CROS system will be used, the child will be fitted with a CROS hearing aid on the ear with the hearing loss and a receiver hearing aid on the normal hearing ear. The child will wear the CROS hearing system only for the duration of the test procedure. Evidence-based fitting guidelines will be followed when fitting the receiver and hearing aid to the child's ear to ensure optimal fitting and comfort.

Before the listening effort tests, the researcher will conduct a visual screening test to confirm normal visual acuity and a standard hearing test on the child to confirm that the child has a severe-profound sensorineural unilateral hearing loss and normal hearing in the other ear. The test battery will include an otoscopic examination, tympanometry as well a pure-tone audiometric hearing test.

Test duration and venue
The testing will take place at a private audiology practice in Belville, in close proximity of the school. Parents will be requested to bring their child to the practice.The test will take approximately 1 hour. The researcher will provide the child with breaks so that he/she may perform optimally. Testing will be arranged so that the child's school work will not be affected negatively.

Possible risks and benefits associated with this study
Participants will not be exposed to any risk or experience any discomfort during this test. A reimbursement in the form of a monetary gift card will be given to the parent/caregiver of each participant. Furthermore, information obtained from this study will assist in increasing awareness of the listening effort experienced by school-aged children with a severe-profound sensorineural unilateral hearing loss in order to improve intervention guidelines in an academic context.

Confidentiality
All the results will be recorded under an anonymous research code, therefore, all identifying information and results will be kept confidential. Only the researcher and supervisors will have access to the information. The results of the research study will be archived at the Department of Speech-Language Pathology and Audiology for 15 years.

Sharing of results
The results obtained from this research study will be reported in the form of a scientific article and dissertation, which will be available to professionals in the field of audiology. The results from the research study may be used by future researchers. If data is to be used for further research, participants' permission will be obtained through an informed consent form.

Refusal or withdrawal from the research
Participation by paediatric patients from your practice in this research study is entirely voluntary, therefore, the child may withdraw from the study at any point, should he/she wish to do so.

Contact information

If you would like further information on the research study, please contact us on:

Ilze Oosthuizen *Researcher/Audiologist*	072 288 4209 ilze.oosthuizen@earinstitute.co.za
Prof De Wet Swanepoel *Supervisor*	012 420 4280 dewet.swanepoel@up.ac.za
Prof Lidia Pottas *Supervisor*	012 420 4280 lidia.pottas@up.ac.za

Yours sincerely

Ilze Oosthuizen
Researcher

Prof De Wet Swanepoel
Supervisor

Prof Lidia Pottas
Supervisor

Dr Jeannie van der Linde
Head: Department of Speech-Language Pathology and Audiology

INFORMED CONSENT FROM THE PRINCIPAL

I, **Adri Hodgson**, hereby consent that my school, **Carel du Toit Centre**, may be used as research site to access participants to participate in the research study entitled *Listening effort in school-aged children with severe-profound sensorineural unilateral hearing loss: Examining the effects of a digital RM system and a CROS hearing system on listening effort.*

I understand that neither I nor the school will receive any reimbursement if the learners participate in this research study. I am aware that the learners may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that the learners are not harmed in this research study.

Principal Signature: ______________________________

Date: 18 February 2019

APPENDIX C

Information letter and consent slip from private audiological practices

Studies II and III

STUDY II

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

8 February 2019

Dear Audiologist/Director

Invitation for paediatric patients of your practice to participate in a research study

We would like to kindly invite paediatric patients from your practice to participate in a research study from the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

Information about the research study
The purpose of the study is to determine the listening effort that children with severe-profound sensorineural unilateral hearing loss experience compared to children with normal hearing. Listening effort can be described as the amount of mental effort (the attention and cognitive resources) a person uses to understand speech. Results from this study may help to increase awareness of the listening effort experienced by children with severe-profound sensorineural unilateral hearing loss and the subsequent effects of this listening effort in order the optimise intervention guidelines for children with severe-profound sensorineural unilateral hearing loss. Furthermore, enhanced classroom management guidelines can be proposed to support these learners and to help ensure good classroom acoustics for all children in primary schools.

Participant candidacy
For this study, school-aged children aged 7 to 12 years with a severe-profound sensorineural unilateral hearing loss and school-aged children aged 7 to 12 years with normal hearing in both ears, will be included. Furthermore, participants should have age-appropriate speech, language, and motor development and no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. With the parents'/caregivers' consent, access to the child's audiological file will be requested to confirm the child's developmental and medical history as documented in the child's file.

Requirements from participants
The child will be seated in a soundproof booth and will be required to do two listening effort tests. The one test procedure will require the child to do two tasks simultaneously – listening to and repeating a sequence of three numbers and at the same time look at a computer screen, situated in front of the child, and touch the screen whenever a shape (for example a red circle)

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appears on the screen. The other test procedure will only require that the child listen to and repeat a sequence of three numbers and the child's verbal responses will be recorded by the computer. Before the listening effort tests, the researcher will conduct a visual screening test to confirm normal visual acuity and a standard hearing test on the child to confirm the child's hearing status. The test battery will include an otoscopic examination, tympanometry as well a pure-tone audiometric hearing test.

Test duration and venue
The testing will take place at a private audiology practice in Pretoria. The test will take approximately 1 hour. The researcher will provide the child with breaks so that he/she may perform optimally.

Possible risks and benefits associated with this study
Participants will not be exposed to any risk or experience any discomfort during this test. A reimbursement in the form of a monetary gift card will be given to the parent/caregiver of each participant. Furthermore, information obtained from this study will assist in increasing awareness of the listening effort experienced by school-aged children with a severe-profound sensorineural unilateral hearing loss in order to improve intervention guidelines in an academic context.

Confidentiality
All the results will be recorded under an anonymous research code, therefore, all identifying information and results will be kept confidential. Only the researcher and supervisors will have access to the information. The results of the research study will be archived at the Department of Speech-Language Pathology and Audiology for 15 years.

Sharing of results
The results obtained from this research study will be reported in the form of a scientific article and dissertation, which will be available to professionals in the field of audiology. The results from the research study may be used by future researchers. If data is to be used for further research, participants' permission will be obtained through an informed consent form.

Refusal or withdrawal from the research
Participation by paediatric patients from your practice in this research study is entirely voluntary, therefore, the child may withdraw from the study at any point, should he/she wish to do so.

Contact information
If you would like further information on the research study, please contact us on:

Ilze Oosthuizen *Researcher/Audiologist*	072 288 4209 ilze.oosthuizen@earinstitute.co.za
Prof De Wet Swanepoel *Supervisor*	012 420 4280 dewet.swanepoel@up.ac.za
Prof Lidia Pottas *Supervisor*	012 420 4280 lidia.pottas@up.ac.za

Yours sincerely

Ilze Oosthuizen
Researcher

Prof De Wet Swanepoel
Supervisor

Prof Lidia Pottas
Supervisor

Dr Jeannie van der Linde
Head: Department of Speech-Language Pathology and Audiology

INFORMED CONSENT FROM THE AUDIOLOGIST/DIRECTOR

I, Anita vd Merwe, hereby consent to make the contact details of the parents of possible participants for the research study available to the researcher and consent that my practice, A vd Merwe Inc., may be used as research site to access participants to participate in the research study entitled entitled *Listening effort in school-aged children with normal hearing compared to school- aged children with severe-profound sensorineural unilateral hearing loss.*

I understand that I will receive no reimbursement if any of my patients participate in this research study. I am aware that the child(ren) may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that the child(ren) is not harmed in this research study.

Audiologist/Director Signature: ____________
Date: 2019/02/13

INFORMED CONSENT FROM THE AUDIOLOGIST/DIRECTOR

I, __**Nicolize Cass**_______________, hereby consent to make the contact details of the parents of possible participants for the research study entitled *Listening effort in school-aged children with normal hearing compared to school- aged children with severe-profound sensorineural unilateral hearing loss* available to the researcher.

I understand that I will receive no reimbursement if any of my patients participate in this research study. I am aware that the child(ren) may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that the child(ren) is not harmed in this research study.

Audiologist/Director Signature: _  _____________
Date: 11/02/2019

STUDY III

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

8 February 2019

Dear Audiologist/Director

Invitation for paediatric patients of your practice to participate in a research study

We would like to kindly invite paediatric patients from your practice to participate in a research study from the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

Information about the research study
The purpose of the study is to determine the effect of using a digital RM (remote microphone) system compared to using a CROS (contralateral routing of signal) hearing system on the listening effort that school-aged children with a severe-profound sensorineural unilateral hearing loss experience. Listening effort can be described as the amount of mental effort (the attention and cognitive resources) a person uses to understand speech. Results from this study may help to increase awareness of the listening effort experienced by children with a severe-profound unilateral hearing loss and the subsequent effects of this listening effort in order the optimise intervention guidelines for children with a severe-profound unilateral hearing loss. Furthermore, the results may indicate the effectiveness of a digital RM system and CROS system to possibly reduce the listening effort exerted by school-aged children with a severe-profound unilateral hearing loss.

Participant candidacy
For this study, school-aged children aged 7 to 12 years with a severe-profound sensorineural unilateral hearing loss will be included. Furthermore, participants should have no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. With the parents'/caregivers' consent, access to the child's audiological file will be requested to confirm the child's developmental and medical history as documented in the child's file.

Requirements from participants
The child will be seated in a soundproof booth and required to do two listening effort tests. The one test procedure will require the child to do two tasks simultaneously – listening to and repeating a sequence of three numbers and at the same time look at a computer screen, situated in front of the child, and touch the screen whenever a shape (for example a red circle)

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appears on the screen. The other test procedure will only require that the child listen to and repeat a sequence of three numbers and the child's verbal responses will be recorded by the computer. The listening effort test procedures will be done without the use of a digital RM system and a CROS system and again with the use of a digital RM system and a CROS system. When the digital RM system will be used, the child will be fitted with an ear-level receiver and he/she will wear it only for the duration of the test. When the CROS system will be used, the child will be fitted with a CROS hearing aid on the ear with the hearing loss and a receiver hearing aid on the normal hearing ear. The child will wear the CROS hearing system only for the duration of the test procedure. Evidence-based fitting guidelines will be followed when fitting the receiver and hearing aid to the child's ear to ensure optimal fitting and comfort.

Before the listening effort tests, the researcher will conduct a visual screening test to confirm normal visual acuity and a standard hearing test on the child to confirm that the child has a severe-profound sensorineural unilateral hearing loss and normal hearing in the other ear. The test battery will include an otoscopic examination, tympanometry as well a pure-tone audiometric hearing test.

Test duration and venue
The testing will take place at a private audiology practice in Pretoria. The test will take approximately 1 hour. The researcher will provide the child with breaks so that he/she may perform optimally.

Possible risks and benefits associated with this study
Participants will not be exposed to any risk or experience any discomfort during this test. A reimbursement in the form of a monetary gift card will be given to the parent/caregiver of each participant. Furthermore, information obtained from this study will assist in increasing awareness of the listening effort experienced by school-aged children with a severe-profound sensorineural unilateral hearing loss in order to improve intervention guidelines in an academic context.

Confidentiality
All the results will be recorded under an anonymous research code, therefore, all identifying information and results will be kept confidential. Only the researcher and supervisors will have access to the information. The results of the research study will be archived at the Department of Speech-Language Pathology and Audiology for 15 years.

Sharing of results
The results obtained from this research study will be reported in the form of a scientific article and dissertation, which will be available to professionals in the field of audiology. The results from the research study may be used by future researchers. If data is to be used for further research, participants' permission will be obtained through an informed consent form.

Refusal or withdrawal from the research
Participation by paediatric patients from your practice in this research study is entirely voluntary, therefore, the child may withdraw from the study at any point, should he/she wish to do so.

Contact information

If you would like further information on the research study, please contact us on:

Ilze Oosthuizen *Researcher/Audiologist*	072 288 4209 ilze.oosthuizen@earinstitute.co.za
Prof De Wet Swanepoel *Supervisor*	012 420 4280 dewet.swanepoel@up.ac.za
Prof Lidia Pottas *Supervisor*	012 420 4280 lidia.pottas@up.ac.za

Yours sincerely

Ilze Oosthuizen
Researcher

Prof De Wet Swanepoel
Supervisor

Prof Lidia Pottas
Supervisor

Dr Jeannie van der Linde
Head: Department of Speech-Language Pathology and Audiology

INFORMED CONSENT FROM THE AUDIOLOGIST/DIRECTOR

I, Anita vd Merwe, hereby consent to make the contact details of the parents of possible participants for the research study available to the researcher and consent that my practice, A vd Merwe Inc., may be used as research site to access participants to participate in the research study entitled, *Listening effort in school-aged children with severe-profound sensorineural unilateral hearing loss: Examining the effects of a digital RM system and a CROS hearing system on listening effort.*

I understand that I will receive no reimbursement if any of my patients participate in this research study. I am aware that the child(ren) may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that the child(ren) is not harmed in this research study.

Audiologist/Director Signature: ______________
Date: 2019/02/13

INFORMED CONSENT FROM THE AUDIOLOGIST/DIRECTOR

I, __Nicolize Cass_______________, hereby consent to make the contact details of the parents of possible participants for the research study entitled, *Listening effort in school-aged children with severe-profound sensorineural unilateral hearing loss: Examining the effects of a digital RM system and a CROS hearing system on listening effort,* available to the researcher.

I understand that I will receive no reimbursement if any of my patients participate in this research study. I am aware that the child(ren) may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that the child(ren) is not harmed in this research study.

Audiologist/Director Signature: ______ ______________________

Date: 11/02/2019

APPENDIX D

Information letter to the parents of participants

and consent slip

Studies I, II, and III

STUDY I

February 2019

Dear Parent/Caregiver

Invitation for your child to participate in a research study

We would like to kindly invite your child to participate in a research study from the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

Information about the research study
The purpose of the study is to determine the listening effort experienced by normal hearing school-aged children with English as first language (L1) compared to normal hearing school-aged children with English as additional language (EAL). Listening effort can be described as the amount of mental effort (the attention and cognitive resources) a person uses to understand speech. Results from this study may help to determine the sensitivity of a low linguistic test method to assess listening effort in school aged children and may also enhance awareness of the listening effort experienced by children with English as additional language in an academic context.

Participant candidacy
For this study, school-aged children aged 7 to 12 years with normal hearing in both ears and with English as a first language and school-aged children aged 7 to 12 years with normal hearing in both ears with English as additional language will be included. Furthermore, you as the parent/caregivers should confirm that your child has age-appropriate speech, language, and motor development and no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. With your consent, access to your child's educational file will be requested to confirm your child's developmental and medical history as documented in the child's educational file.

Requirements from participants
Your child will be seated in a soundproof booth and required to do two listening effort tests. The one test procedure will require your child to do two tasks simultaneously – listening to and repeating a sequence of three numbers and at the same time look at a computer screen, situated in front of the child, and touch the screen whenever a shape (for example a red circle)

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appears on the screen. The other test procedure will only require that your child listen to and repeat a sequence of three numbers and your child's verbal responses will be recorded by the computer. Before the listening effort tests, the researcher will conduct a visual screening test to confirm that your child has normal vision and a standard hearing test on your child to confirm that your child has normal hearing in both ears. The test battery will include an otoscopic examination (to look at the outer ear, ear canal and eardrum), a tympanogram (to determine the functioning of the middle ear systems) as well a pure-tone audiometric hearing test.

Test duration and venue
The testing will take place at the Audiology Department at Eduplex School, in Pretoria. The test will take approximately 1 hour. Testing will be arranged so that your child's school work will not be affected negatively. The researcher will provide your child with breaks so that he/she may perform optimally. During the break your child will receive a snack, for example a fruit juice or a fruit, from the researcher with your consent.

Possible risks and benefits associated with this study
Your child will not be exposed to any risk or experience any discomfort during this test. A reimbursement in the form of a monetary gift card will be given to the parent/caregiver of each participant. Information obtained from this study will assist in determining a reliable low linguistic test method to assess listening effort in primary school-aged children.

Confidentiality
All the results will be recorded under an anonymous research code, therefore, all identifying information and results will be kept confidential. Only the researcher and supervisors will have access to the information. The results of the research study will be archived at the Department of Speech-Language Pathology and Audiology for 15 years.

Sharing of results
The results obtained from this research study will be reported in the form of a scientific article which will be available to professionals in the field of audiology. The results from the research study may be used by future researchers. If data is to be used for further research, participants' permission will be obtained through an informed consent form. The results of the research will also be shared with you as parents/caregivers.

Refusal or withdrawal from the research
Participation by your child in this research study is entirely voluntary, therefore, your child may withdraw from the study at any point, should he/she wish to do so, without having to explain why. There will be no penalty or loss of benefit if they decide not to take part. Your child and you as parents/caregivers will have the opportunity to ask questions about the proposed study before signing verbal assent or consent, respectively.

Contact information
If you would like further information on the research study, please contact us on:

Ilze Oosthuizen *Researcher / Audiologist*	072 288 4209 ilze.oosthuizen@earinstitute.co.za
Prof De Wet Swanepoel *Supervisor*	012 420 4280 dewet.swanepoel@up.ac.za
Prof Lidia Pottas *Supervisor*	012 420 2357 lidia.pottas@up.ac.za

Yours sincerely

________________________ ________________________ ________________________

Ilze Oosthuizen
Researcher/Audiologist

Prof De Wet Swanepoel
Supervisor

Prof Lidia Pottas
Supervisor

____

Dr Jeannie van der Linde
Head: Department of Speech-Language Pathology and Audiology

INFORMED CONSENT FROM PARENTS / GUARDIANS (on behalf of minors under 18 years old)

I, ____, hereby consent that my child, ___________________________, aged 7-8 / 9-10 / 11-12 years of age (circle correct age for your child), may participate in the research study entitled *Listening effort in normal hearing English first language (L1) speaking and English additional language (EAL) speaking school-aged children using dual task and verbal response time paradigms.*

I understand that I will receive a monetary reimbursement if my child participates in this research study. I am aware that my child may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that my child is not harmed in this research study. I give consent that my child's results may be used anonymously in research publications from this study.

My child has age-appropriate speech, language, and motor development and no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. Furthermore, I give consent that the researcher may have access to my child's educational file to confirm my child's developmental and medical history:
YES or NO *(please circle your choice)*

My child may receive a snack from the researcher during test procedure:
YES or NO *(please circle your choice)*

Parent/Guardian Signature: _____________________________
Date: __________________

STUDY II

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

February 2019

Dear Parent/Caregiver

Invitation for your child to participate in a research study

We would like to kindly invite your child to participate in a research study from the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

Information about the research study
The purpose of the study is to determine the listening effort that children with a severe-profound sensorineural unilateral hearing loss (that is a severe-profound sensorineural hearing loss in one ear and normal hearing in the opposite ear) experience compared to children with normal hearing. Listening effort can be described as the amount of mental effort (the attention and cognitive resources) a person uses to understand speech. Results from this study may help to increase awareness of the listening effort experienced by children with a severe-profound sensorineural unilateral hearing loss and the subsequent effects of this listening effort in order the optimise intervention guidelines for children with a severe-profound sensorineural unilateral hearing loss.

Participant candidacy
For this study, school-aged children aged 7 to 12 years with a severe-profound sensorineural unilateral hearing loss and school-aged children aged 7 to 12 years with normal hearing in both ears, will be included. You as the parent/caregiver should confirm that your child has age-appropriate speech, language, and motor development and no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. With your consent, access to your child's audiological and educational files will be requested to confirm your child's developmental and medical history as documented in the child's files.

Requirements from participants
Your child will be seated in a soundproof booth and required to do two listening effort tests. The one test procedure will require your child to do two tasks simultaneously – listening to and repeating a sequence of three numbers and at the same time look at a computer screen, situated in front of the child, and touch the screen whenever a shape (for example a red circle)

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appears on the screen. The other test procedure will only require that your child listen to and repeat a sequence of three numbers and your child's verbal responses will be recorded by the computer. Before the listening effort tests, the researcher will conduct a visual screening test to confirm that your child has normal vision and a standard hearing test on your child to confirm that your child has a severe-profound sensorineural unilateral hearing loss and normal hearing in the other ear. The test battery will include an otoscopic examination (to look at the outer ear, ear canal and eardrum), a tympanogram (to determine the functioning of the middle ear systems) as well a pure-tone audiometric hearing test.

Test duration and venue
The testing will take place at a private audiology practice in Pretoria/Belville. You will be requested to bring your child to the practice. The test will take approximately 1 hour. Testing will be arranged so that your child's school work will not be affected negatively. The researcher will provide your child with breaks so that he/she may perform optimally. During the break your child will receive a snack, for example a fruit juice or a fruit, from the researcher with your consent.

Possible risks and benefits associated with this study
Your child will not be exposed to any risk or experience any discomfort during this test. A reimbursement in the form of a monetary gift card will be given to the parent/caregiver of each participant. Information obtained from this study will assist in determining a reliable low linguistic test method to assess listening effort in primary school-aged children.

Confidentiality
All the results will be recorded under an anonymous research code, therefore, all identifying information and results will be kept confidential. Only the researcher and supervisors will have access to the information. The results of the research study will be archived at the Department of Speech-Language Pathology and Audiology for 15 years.

Sharing of results
The results obtained from this research study will be reported in the form of a scientific article which will be available to professionals in the field of audiology. The results from the research study may be used by future researchers. If data is to be used for further research, participants' permission will be obtained through an informed consent form. The results of the research will also be shared with you as parents/caregivers.

Refusal or withdrawal from the research
Participation by your child in this research study is entirely voluntary, therefore, your child may withdraw from the study at any point, should he/she wish to do so, without having to explain why. There will be no penalty or loss of benefit if they decide not to take part. Your child and you as parents/caregivers will have the opportunity to ask questions about the proposed study before signing verbal assent or consent, respectively.

Contact information
If you would like further information on the research study, please contact us on:

Ilze Oosthuizen *Researcher / Audiologist*	072 288 4209 ilze.oosthuizen@earinstitute.co.za
Prof De Wet Swanepoel *Supervisor*	012 420 4280 dewet.swanepoel@up.ac.za
Prof Lidia Pottas *Supervisor*	012 420 2357 lidia.pottas@up.ac.za

Yours sincerely

________________________ _____________________ _________________

Ilze Oosthuizen
Researcher/Audiologist

Prof De Wet Swanepoel
Supervisor

Prof Lidia Pottas
Supervisor

____
Dr Jeannie van der Linde
Head: Department of Speech-Language Pathology and Audiology

INFORMED CONSENT FROM PARENTS / GUARDIANS (on behalf of minors under 18 years old)

I, ____, hereby consent that my child, ___________________________, aged 7-8 / 9-10 / 11-12 years of age (circle correct age for your child), may participate in the research study *entitled Listening effort in school-aged children with normal hearing compared to school-aged children with severe-profound sensorineural unilateral hearing loss.*

I understand that I will receive a monetary reimbursement if my child participates in this research study. I am aware that my child may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that my child is not harmed in this research study. I give consent that my child's results may be used anonymously in research publications from this study.

My child has age-appropriate speech, language, and motor development and no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. Furthermore, I give consent that the researcher may have access to my child's audiological and educational file to confirm my child's developmental and medical history:
YES or NO *(please circle your choice)*

My child may receive a snack from the researcher during test procedure:
YES or NO *(please circle your choice)*

Parent/Guardian Signature: _____________________________
Date: __________________

STUDY III

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

February 2019

Dear Parent/Caregiver

Invitation for your child to participate in a research study

We would like to kindly invite your child to participate in a research study from the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

Information about the research study

The purpose of the study is to examine the effect of using a digital RM (remote microphone) system (that is a personal, assistive listening device) compared to a CROS (contralateral routing of signal) hearing system (that is a CROS hearing aid fitted on the ear with a severe-profound sensorineural hearing loss that wirelessly sends sound input to a receiver hearing aid on the opposite normal hearing ear) on the listening effort that school-aged children with a severe-profound sensorineural unilateral hearing loss (that is a severe-profound sensorineural hearing loss in one ear and normal hearing in the opposite ear) experience. Listening effort can be described as the amount of mental effort (the attention and cognitive resources) a person uses to understand speech. Results from this study may help to increase awareness of the listening effort experienced by children with a severe-profound sensorineural unilateral hearing loss and the subsequent effects of this listening effort in order the optimise intervention guidelines for children with a severe-profound sensorineural unilateral hearing loss. Furthermore, the results may indicate the effectiveness of a digital RM system compared to a CROS system to possibly reduce the listening effort put forth by school-aged children with a severe-profound sensorineural unilateral hearing loss.

Participant candidacy

For this study, school-aged children aged 7 to 12 years with a severe-profound sensorineural unilateral hearing loss will be included. You as the parent/caregiver should confirm that your child has no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. With your consent, access to your child's audiological and educational files will be requested to confirm your child's developmental and medical history as documented in the child's files.

Communication Pathology Building
University of Pretoria, Private Bag X20
Hatfield 0028, South Africa
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www.up.ac.za

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Departement Spraak-Taalpatologie en Oudiologie
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Requirements from participants

Your child will be seated in a soundproof booth and required to do two listening effort tests. The one test procedure will require your child to do two tasks simultaneously – listening to and repeating a sequence of three numbers and at the same time look at a computer screen, situated in front of the child, and touch the screen whenever a shape (for example a red circle) appears on the screen. The other test procedure will only require that your child listen to and repeat a sequence of three numbers and your child's verbal responses will be recorded by the computer. The listening effort test procedures will be done without the use of a digital RM system and a CROS system and again with the use of a digital RM system and a CROS system. When the digital RM system will be used, your child will be fitted with an ear-level receiver and he/she will wear it only for the duration of the test. When the CROS system will be used, the child will be fitted with a CROS hearing aid on the ear with the hearing loss and a receiver hearing aid on the normal hearing ear. Your child will wear the CROS hearing system only for the duration of the test procedure. Evidence-based fitting guidelines will be followed when fitting the receiver and hearing aid to your child's ear to ensure optimal fitting and comfort.

Before the listening effort tests, the researcher will conduct a visual screening test to confirm that your child has normal vision and a standard hearing test on your child to confirm that your child has a severe-profound sensorineural unilateral hearing loss and normal hearing in the other ear. The test battery will include an otoscopic examination (to look at the outer ear, ear canal and eardrum), a tympanogram (to determine the functioning of the middle ear systems) as well a pure-tone audiometric hearing test.

Test duration and venue

The testing will take place at a private audiology practice in Pretoria/Belville. You will be requested to bring your child to the practice. The test will take approximately 1 hour. Testing will be arranged so that your child's school work will not be affected negatively. The researcher will provide your child with breaks so that he/she may perform optimally. During the break your child will receive a snack, for example a fruit juice or a fruit, from the researcher with your consent.

Possible risks and benefits associated with this study

Your child will not be exposed to any risk or experience any discomfort during this test. A reimbursement in the form of a monetary gift card will be given to the parent/caregiver of each participant. Information obtained from this study will assist in determining a reliable low linguistic test method to assess listening effort in primary school-aged children.

Confidentiality

All the results will be recorded under an anonymous research code, therefore, all identifying information and results will be kept confidential. Only the researcher and supervisors will have access to the information. The results of the research study will be archived at the Department of Speech-Language Pathology and Audiology for 15 years.

Sharing of results

The results obtained from this research study will be reported in the form of a scientific article which will be available to professionals in the field of audiology. The results from the research study may be used by future researchers. If data is to be used for further research, participants' permission will be obtained through an informed consent form. The results of the research will also be shared with you as parents/caregivers.

Refusal or withdrawal from the research

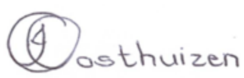
Participation by your child in this research study is entirely voluntary, therefore, your child may withdraw from the study at any point, should he/she wish to do so, without having to explain why. There will be no penalty or loss of benefit if they decide not to take part. Your child and you as parents/caregivers will have the opportunity to ask questions about the proposed study before signing verbal assent or consent, respectively.

Contact information

If you would like further information on the research study, please contact us on:

Ilze Oosthuizen *Researcher / Audiologist*	072 288 4209 ilze.oosthuizen@earinstitute.co.za
Prof De Wet Swanepoel *Supervisor*	012 420 4280 dewet.swanepoel@up.ac.za
Prof Lidia Pottas *Supervisor*	012 420 2357 lidia.pottas@up.ac.za

Yours sincerely



Ilze Oosthuizen
Researcher/Audiologist

Prof De Wet Swanepoel
Supervisor

Prof Lidia Pottas
Supervisor

Dr Jeannie van der Linde
Head: Department of Speech-Language Pathology and Audiology

INFORMED CONSENT FROM PARENTS / GUARDIANS (on behalf of minors under 18 years old)

I, ____, hereby consent that my child, ____________________________, aged 7-8 / 9-10 / 11-12 years of age (circle correct age for your child), may participate in the research study entitled *Listening effort in school-aged children with severe-profound sensorineural UHL: Examining the effects of a digital RM system and a CROS hearing system on listening effort.*

I understand that I will receive a monetary reimbursement if my child participates in this research study. I am aware that my child may withdraw from the research study at any point, should he/she wish to do so. I understand that every effort will be made to ensure that my child is not harmed in this research study. I give consent that my child's results may be used anonymously in research publications from this study.

My child has no speech or language delays not attributable to the unilateral sensorineural hearing loss and no diagnosis of a cognitive impairment, neurological disorder or learning difficulties. Furthermore, I give consent that the researcher may have access to my child's audiological and educational file to confirm my child's developmental and medical history:
YES or NO *(please circle your choice)*

My child may receive a snack from the researcher during test procedure:
YES or NO *(please circle your choice)*

Parent/Guardian Signature: ______________________________
Date: __________________

APPENDIX E

Written assent letter to participants

English and Afrikaans

Studies I, II, and III

STUDY I

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

February 2019

CHILD ASSENT FORM

(The following will be read to the child)

Dear (Child's name) ____

You have been chosen to help me do a test on your ears to see if primary school children must pay a lot of attention and think very hard to understand what someone says to them. I will first show you how the test is done. It will not hurt you at all. All you need to do is listen to some numbers and repeat the numbers and touch a shape (for example a red circle) whenever you see the shape appear on a computer screen.

You can ask me any questions you want to. You are also allowed to say that you do not want to do the listening test or point to the shapes. If you do not want to do the test I will not be angry, and you will not get in trouble.

If you want to help me and do the test, colour in the thumbs up smiley face:

If you do not want to do the test, colour in the thumbs down smiley face:

Audiologist's / Researcher's name: Ilze Oosthuizen
Audiologist's / Researcher's signature: ____________________________
Date: ____

Communication Pathology Building
University of Pretoria, Private Bag X20
Hatfield 0028, South Africa
Tel +27 (0)12 420 4280
Fax +27 (0)12 420 3517
dewet.swanepoel@up.ac.za
www.up.ac.za

Fakulteit Geesteswetenskappe
Departement Spraak-Taalpatologie en Oudiologie
Lefapha la Bomotho
Kgoro ya Phatholotši ya Polelo-Maleme le Go kwa

Februarie 2019

KINDER TOESTEMMINGSBRIEF
(Die volgende bewoording sal aan die kind gelees word)

Beste (kind se naam) ____

Jy is gekies om my te help om 'n luister-toets te doen om te kyk of laerskool kinders baie aandag moet gee en baie hard moet dink om te verstaan wat 'n persoon sê. Ek sal eers vir jou wys hoe om die toets te doen. Dit sal jou glad nie seer maak nie. Al wat jy hoef te doen is om te luister na nommers en die nommers te herhaal. Jy gaan ook voor 'n rekenaarskerm sit en jy moet aan 'n vorm raak (byvoorbeel 'n rooi sirkel) wanneer jy ookal 'n vorm op die rekenaarskerm sien.

Jy kan my enige tyd vrae oor die toets vra. Jy mag ook kies om nie die luister-toets te doen of aan die vorms op die rekenaarskerm te raak nie. As jy nie die toets wil doen nie, sal ek nie vir jou kwaad wees nie en jy sal nie in die moeilikheid kom nie.

As jy my wil help en die luister-toets wil doen, kleur die glimlag gesiggie in wat "ja" wys:

As jy nie die luister-toets wil doen nie, kleur die gesiggie in wat "nee" wys:

Oudioloog / Navorser: Ilze Oosthuizen
Oudioloog / Navorser Handtekening: ___________________________
Datum: ____

Communication Pathology Building
University of Pretoria, Private Bag X20
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STUDY II

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

February 2019

CHILD ASSENT FORM
(The following will be read to the child)

Dear (Child's name) ______________________________________

You have been chosen to help me do a test on your ears to see if primary school children with normal hearing and primary school children with a big hearing loss in only in one ear must pay a lot of attention and think very hard to understand what someone says to them. I will first show you how the test is done. It will not hurt you at all. All you need to do is listen to some numbers and repeat the numbers and touch a shape (for example a red circle) whenever you see the shape appear on a computer screen.

You can ask me any questions you want to. You are also allowed to say that you do not want to do the listening test or point to the shapes. If you do not want to do the test, I will not be angry, and you will not get in trouble.

If you want to help me and do the test, colour in the thumbs up smiley face:

If you do not want to do the test, colour in the thumbs down smiley face:

Audiologist's / Researcher's name: Ilze Oosthuizen
Audiologist's / Researcher's signature: ___________________________
Date: ____

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YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

Februarie 2019

KINDER TOESTEMMINGSBRIEF
(Die volgende bewoording sal aan die kind gelees word)

Beste (kind se naam) ____

Jy is gekies om my te help om 'n luister-toets te doen om te kyk of laerskool kinders met normale gehoor en laerskool kinders wat 'n groot gehoorverlies in net een oor het baie aandag moet gee en baie hard moet dink om te verstaan wat 'n persoon sê. Ek sal eers vir jou wys hoe om die toets te doen. Dit sal jou glad nie seer maak nie. Al wat jy hoef te doen is om te luister na nommers en die nommers te herhaal. Jy gaan ook voor 'n rekenaarskerm sit en jy moet aan 'n vorm raak (byvoorbeel 'n rooi sirkel) wanneer jy ookal 'n vorm op die rekenaarskerm sien.

Jy kan my enige tyd vrae oor die toets vra. Jy mag ook kies om nie die luister-toets te doen of aan die vorms op die rekenaarskerm te raak nie. As jy nie die toets wil doen nie, sal ek nie vir jou kwaad wees nie en jy sal nie in die moeilikheid kom nie.

As jy my wil help en die luister-toets wil doen, kleur die glimlag gesiggie in wat "ja" wys:

As jy nie die luister-toets wil doen nie, kleur die gesiggie in wat "nee" wys:

Oudioloog / Navorser: Ilze Oosthuizen
Oudioloog / Navorser Handtekening: ___________________________
Datum: ____

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STUDY III

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

February 2019

CHILD ASSENT FORM
(The following will be read to the child)

Dear (Child's name) ____

You have been chosen to help me do a test on your ears to see if primary school children with a big hearing loss in only one of their ears must pay a lot of attention and think very hard to understand what someone says to them. I will first show you how the test is done. It will not hurt you at all. All you need to do is listen to some numbers and repeat the numbers and touch a shape (for example a red circle) whenever you see the shape appear on a computer screen. I will also put hearing devices on your ears. Then you will repeat the test again while you wear the hearing devices. After the test you will take the hearing device off again.

You can ask me any questions you want to. You are also allowed to say that you do not want to do the listening test or point to the shapes. If you do not want to do the test, I will not be angry, and you will not get in trouble.

If you want to help me and do the test, colour in the thumbs up smiley face:

If you do not want to do the test, colour in the thumbs down smiley face:

Audiologist's / Researcher's name: Ilze Oosthuizen
Audiologist's / Researcher's signature: ______________________________
Date: ____

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Februarie 2019

KINDER TOESTEMMINGSBRIEF
(Die volgende bewoording sal aan die kind gelees word)

Beste (kind se naam) ____

Jy is gekies om my te help om ‘n luister-toets te doen om te kyk of laerskool kinders wat ‘n groot gehoorverlies in net een oor het baie aandag moet gee en baie hard moet dink om te verstaan wat ‘n persoon sê. Ek sal eers vir jou wys hoe om die toets te doen. Dit sal jou glad nie seer maak nie. Al wat jy hoef te doen is om te luister na nommers en die nommers te herhaal. Jy gaan ook voor ‘n rekenaarskerm sit en jy moet aan ‘n vorm raak (byvoorbeel ‘n rooi sirkel) wanneer jy ookal ‘n vorm op die rekenaarskerm sien. Ek gaan ook gehoorapparaatjies op jou ore sit. Dan gaan jy die toets weer doen terwyl jy die apparaatjies dra. Wanneer jy die toets klaar gedoen het, gaan ek weer die apparaatjies afhaal.

Jy kan my enige tyd vrae oor die toets vra. Jy mag ook kies om nie die luister-toets te doen of aan die vorms op die rekenaarskerm te raak nie. As jy nie die toets wil doen nie, sal ek nie vir jou kwaad wees nie en jy sal nie in die moeilikheid kom nie.

As jy my wil help en die luister-toets wil doen, kleur die glimlag gesiggie in wat “ja” wys:

As jy nie die luister-toets wil doen nie, kleur die gesiggie in wat “nee” wys:

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APPENDIX F

Audiogram

Universiteit van Pretoria / University of Pretoria
Spraak-Taalpatologie en Oudiologie / Speech-Language Pathology and Audiology
Tel: (012) 420-2816 / (012) 420-2491

Naam
Name: ______________________ Datum
Date: ______________________

GEB
DOB: ____________ Oudioloog
Audiologist: ____________ Student
Student: ____________

Suiwertoonoudiogram / Pure Tone Audiogram

Regteroor / Right Ear | Linkeroor / Left Ear

Frequencies (Hz): 125, 250, 500, 1000, 2000, 4000, 8000
Levels (dB): -10, 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130

Maskering / Masking

LGMC							
BGMC							

% Gehoorverlies
% Hearing Loss R _______ L _______ B _______

Pediatriese toetsprotokol/
Pediatric test protocol: | BOA | VRA | CPA |

Weber

250	500	1000	2000	4000

Rinne

R	L

Bing

R	L

Otoskopiese Ondersoek / Otoscopic Examination

R

L

Oorvormer
Transducer:

Insert oorfone / Insert earphones
Oorfone / Earphones
Vryeveld / Free field

Spraakoudiogram / Speech Audiogram

Levels (dB): 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110
Scores: 100%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, 10%, 0%

Maskering/ Masking L R

Spraak stimuli gebruik
Speech stimuli used: | Live voice | Vooraf opgeneem / Pre-recorded |

	R	L
STD / PTA		
SOD / SRT		
SOD gemasker / SRT masked		
Disk % Disc.		
MSL / MCL VP / UCL		
Spraakdeteksie / Speech Detection		

Akoestiese Immittansie / Acoustic Immittance

	R	L
Timpanogram / Tympanogram		
Middeloordruk / Middle Ear Pressure		
Statiese / Static Compliance		
Oorkanaal Volume / Ear Canal Volume		

Akoestiese Refleks / Acoustic Reflex

[illegible]						[illegible]				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
					500Hz					
					1000Hz					
					1kHz					
					2kHz					
					4kHz					
					[illegible]					

Toetsbetroubaarheid
Test reliability: | Goed / Good | Gemiddeld / Average | Swak / Poor |

Oor Ear	Ongemaskeerde lug / Unmasked air	Ongemaskeerde been / Unmasked bone	Gemaskeerde lug / Masked air	Gemaskeerde been / Masked bone	Geen respons / No response	Vry veld / Sound field	VP / UCL	Akoestiese [illegible]
R	O	<	Δ	[	↓	S	⊓	A
L	X	>	□	]				

APPENDIX G

Speech audiometry word lists

English and Afrikaans

Spondaic Words Recommended by ASHA (1988)

Easily pictured spondees for use with children (Frank, 1980)

Toothbrush
Hotdog
Baseball
Airplane
Cupcake
Popcorn
Bathtub
Fire truck
Football
Mailman
Snowman
Ice cream
Sailboat
Flashlight
Bluebird
Toothpaste
Reindeer
Shoelace
Seesaw

Frank, T. (1980). Clinical significance of the relative intelligibility of pictorially represented spondee words. *Ear and Hearing*, *1*(1), 46-49.

AFRIKAANSE SPONDEE WOORDELYS

Handsak	Roomys	Kleingeld	sonskyn
Yskas	Roosboom	Leesboek	speelgoed
Slaaibak	Seilskip	Speelgoed	leesboek
Huisvrou	Laaikas	Sonskyn	kleingeld
Spierwit	Reënboog	Roomys	voordeur
Laaikas	Sitplek	Roosboom	handsak
Reënboog	Grasgroen	Seilskip	yskas
Sitplek	beesvleis	Yskoud	slaaibak
Grasgroen	vliegtuig	Rusbank	huisvrou
Voordeur	koekblik	Boomstam	spierwit
Kleingeld	sonskyn	Beesvleis	laaikas
Leesboek	speelgoed	voetbal	reënboog
Speelgoed	leesboek	bloedrooi	sitplek
Sonskyn	kleingeld	handskoen	grasgroen
Roomys	voordeur	goudgeel	voordeur
Roosboom	handsak	roomys	Kleingeld
Seilskip	yskas	roosboom	Leesboek
Yskoud	slaaibak	seilskip	Speelgoed
Rusbank	huisvrou	laaikas	Sonskyn
Boomstam	spierwit	reënboog	Roomys
Beesvleis	laaikas	sitplek	roosboom
voetbal	reënboog	grasgroen	seilskip
bloedrooi	sitplek	beesvleis	laaikas
handskoen	grasgroen	vliegtuig	reënboog

Laubscher, A.M.U. & Tesner, H.E.C. (1966). *Afrikaanse spondee woordelyste.*
Dept Kommunikasiepatologie, Universiteit van Pretoria: Pretoria

AFRIKAANSE FONETIES-GEBALANSEERDE WOORDELYS

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Lys 1	Lys 2	Lys 3	Lys 4	Lys 5	Lys 6	Lys 7	Lys 8
vlieg	brief	brood	vryf	een	vlag	brug	vroeg
brand	eers	oop	praat	vriend	iets	eet	bril
om	fraai	vroeg	vars	volg	bruin	vel	aand
diens	vloer	volk	beurt	blou	vrag	vlam	vleis
klomp	drink	blink	dier	broer	droog	breek	draai
vra	drop	droom	klaar	deur	dank	diep	klaar
koel	kraal	klein	druk	klam	klink	krap	dink
lof	kleur	kry	leer	lyf	les	loop	kort
langs	lig	lag	krag	kloof	klim	klop	leun
hy	spring	lief	snaaks	vaal	lank	lag	lomp
staan	lei	sterf	los	skerp	skrif	swart	stert
spuit	stoom	stil	hang	groen	skoon	spreek	hoof
rak	haar	heel	hand	seep	hok	huis	self
hulp	reën	huil	noem	haal	ram	hof	hark
weet	hart	roep	streep	hier	wat	roem	res
reël	ruk	reg	traan	rug	half	wiel	woon
moet	woes	res	rond	raak	rok	ring	rant
werd	weg	mond	mark	wol	merk	meer	werk
neef	maat	nou	grap	maand	tong	wa	mos
maan	jonk	teen	trok	was	perd	nog	my
gras	neus	pos	ja	moes	prys	jaar	niks
trap	groot	pluk	reus	tree	teer	plaas	peer
tog	trek	groei	wen	plaat	jy	trou	plank
plek	plan	weef	wind	nes	nee	groet	graf
berg	paar	waar	erg	prop	golf	treur	trein

Laubscher, A.M.U. & Tesner, H.E.C. (1966). *Afrikaanse fonetiesgebalanseerde woordelyste*. Dept Kommunikasiepatologie, Universiteit van Pretoria: Pretoria

ENGLISH PHONETICALLY BALANCED WORDLISTS

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UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

List 1	List 2	List 3	List 4	List 5	List 6
shack	smart	youth	clutch	spice	fuse
us	thank	flight	romp	catch	tub
calf	than	died	chair	wig	sip
food	grace	change	jazz	flip	itch
hum	crowd	dust	glass	ask	clown
queen	chest	earth	frill	pint	gate
lift	club	cue	sky	rest	ditch
front	phone	staff	priest	bolt	spud
yeast	nerve	force	teeth	thread	odd
slide	flag	goose	lash	this	skill
till	ice	maze	depth	clod	troop
chew	tax	slug	sod	chant	birth
guess	nuts	scrub	throb	guess	nuts
chant	birth	snipe	ledge	chew	tax
clod	troop	clothe	foot	till	ice
this	skill	line	cave	slide	flag
thread	odd	champ	speed	yeast	nerve
bolt	spud	plus	cad	front	phone
rest	ditch	those	set	lift	club
pint	gate	thug	rove	queen	chest
ask	clown	spin	wage	hum	crowd
flip	itch	hurt	chap	food	grace
wig	sip	flaunt	flood	calf	than
catch	tub	rush	cling	us	thank
spice	fuse	lock	bluff	shack	smart

APPENDIX H

Questionnaires for subjective ratings of listening effort

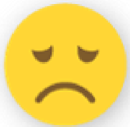
Studies II and III

English and Afrikaans

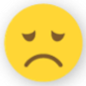
STUDY II

QUESTIONS FOR PARTICIPANTS: ***(complete after each digit triplet list)***
Participant name and number:

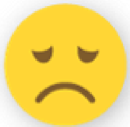
1) **How did you find the listening task?**

				
Very hard	Hard	It was okay	Easy	Very easy

2) **How many numbers do you think you got right?**

 0%	 25%	 50%	 75%	 100%
Nothing	Less than half	Only half of the numbers	More than half	Everything

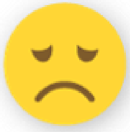
3) **Was it hard to think when you were listening?**

				
Yes, very hard	Yes, hard	It was okay	No, it was easy	No, it was very easy

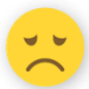
VRAE VIR DEELNEMERS ***(Voltooi vrae 1 tot 3 na elke "digit triplet" lys)***

Deelnemer naam en nommer:

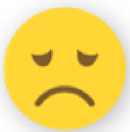
1) Hoe was die luistertoets?

				
Baie moeilik	Moeilik	Dit was "okay"	Maklik	Baie maklik

2) Hoeveel nommers dink jy het jy reg gekry?

 0%	 25%	 50%	 75%	 100%
Niks	Minder as die helfte	Die helfte	Meer as die helfte	Alles

3) Was dit moeilik om te dink toe jy die luistertoets gedoen het?

				
Ja, baie moeilik	Ja, moeilik	Dit was "okay"	Nee, dit was maklik	Nee, dit was baie maklik

STUDY III

QUESTIONS FOR PARTICIPANTS: ***(complete after each intervention option in each loudspeaker condition)***
Participant name and number:

1) **Did the remote microphone system (FM system) make it easier for you to listen when it was noisy?**

	
Yes	No

1) **Did the hearing aids make it easier for you to listen when it was noisy?**

	
Yes	No

2) Did the remote microphone system (FM system) help you to keep trying?

	
Yes, it made it easier to keep going (keep on trying).	No, I wanted to quit.

2) Did the hearing aids help you to keep trying?

	
Yes, it made it easier to keep going. (keep on trying)	No, I wanted to quit.

VRAE VIR DEELNEMERS: ***(voltooi na elke intervensie opsie in elke luidspreker opset)***
Deelnemer naam en nommer:

1) **Het die FM sisteem die makliker gemaak om in geraas te luister?**

	
Ja	Nee

1) **Het die gehoorapparate dit makliker gemaak om in geraas te luister?**

	
Ja	Nee

2) Het die FM sisteem jou gehelp om aan te hou luister?

	
Ja, dit het my gehelp om aan te hou luister.	Nee, ek wou eerder op hou.

2) Het die gehoorapparate jou gehelp om aan te hou luister?

	
Ja, dit het my gehelp om aan te hou luister.	Nee, ek wou eerder op hou.

APPENDIX I

Data storage form

Declaration for the storage of research data and/or documents

I, the principal researcher: Ilze Oosthuizen

and supervisors: Prof De Wet Swanepoel and Prof Lidia Pottas

of the following study, titled: Listening effort in children with severe-profound sensorineural unilateral hearing loss

will be storing all the research data and/or documents referring to the above-mentioned study in the following

department: Department of Speech-language Pathology and Audiology

We understand that the storage of the mentioned data and/or documents must be maintained for a minimum of 15 years from the commencement of this study.

Start date of study: March 2019

Anticipated end date of study: November 2020

Year until which data will be stored: 2034

Name of Principal Researcher	Signature	Date
Ilze Oosthuizen	Oosthuizen	2020/11/27

Name of Supervisor(s)	Signature	Date
Prof De Wet Swanepoel	[signature]	2020/11/27
Prof Lidia Pottas	LPottas	2020/11/27

Name of Head of Department	Signature	Date
Prof J van der Linde	[signature]	2020/11/27

APPENDIX J

Proof of acceptance of articles

Journal of Speech, Language, and Hearing Research (Study I)

From: em.jslhr.0.69d353.0ffe0c99@editorialmanager.com <em.jslhr.0.69d353.0ffe0c99@editorialmanager.com> **On Behalf Of** JSLHR
Sent: Monday, 09 March 2020 9:09 PM
To: Ilze Oosthuizen <ilze.oosthuizen@earinstitute.co.za>
Subject: JSLHR Manuscript Decision

CC: "Erin M. Picou" erin.picou@vumc.org, "Lidia Pottas" lidia.pottas@up.ac.za, "Hermanus Carel Myburgh" herman.myburgh@up.ac.za, "De Wet Swanepoel" dewet.swanepoel@up.ac.za

Ref.: Ms. No. JSLHR-19-00330R2
Listening effort in native and non-native English-speaking children using low linguistic single- and dual-task paradigms
Journal of Speech, Language, and Hearing Research

Dear Mrs. Oosthuizen,

I am pleased to accept your manuscript for publication in Journal of Speech, Language, and Hearing Research.

If you haven't already selected the open access option, please consider doing so now. Choosing the open access publishing option can increase readership, online attention, and citation levels. ASHA assesses an article processing charge (APC) of $2,000 for the open access option. You can find out more about Open Access by visiting https://academy.pubs.asha.org/asha-journals-author-resource-center/manuscript-submission/open-access/

Brief comments from the Editor can be found below.

Thank you for the opportunity to review and publish your work.

Sincerely,

Alexander L. Francis
Editor
Journal of Speech, Language, and Hearing Research

American Journal of Audiology (Study II)

From: em.aja.0.70d19f.17f2f925@editorialmanager.com <em.aja.0.70d19f.17f2f925@editorialmanager.com> **On Behalf Of** AJA
Sent: Friday, 22 January 2021 4:45 AM
To: Ilze Oosthuizen <ilze.oosthuizen@earinstitute.co.za>
Subject: AJA Manuscript Decision

CC: ryan.mccreery@boystown.org, aja@asha.org, "Erin M. Picou" erin.picou@vumc.org, "Lidia Pottas" lidia.pottas@up.ac.za, "Hermanus Carel Myburgh" herman.myburgh@up.ac.za, "De Wet Swanepoel" dewet.swanepoel@up.ac.za

Ref.: Ms. No. AJA-20-00082R3
Listening Effort in School-Aged Children With Normal Hearing Compared to Children With Limited Useable Hearing Unilaterally
American Journal of Audiology

Dear Mrs Oosthuizen,

I am pleased to accept your manuscript for publication in American Journal of Audiology.

If you haven't already selected the open access option, please consider doing so now. Choosing the open access publishing option can increase readership, online attention, and citation levels. ASHA assesses an article processing charge (APC) of $2,000 for the open access option. You can find out more about Open Access by visiting https://academy.pubs.asha.org/asha-journals-author-resource-center/manuscript-submission/open-access/

Comments from the Editor and Reviewers can be found below.

Thank you for the opportunity to review and publish your work.

Sincerely,

Dr. Andrea Warner-Czyz
Editor
American Journal of Audiology

Trends in Hearing
(Study III)

From: Trends in Hearing <onbehalfof@manuscriptcentral.com>
Sent: Wednesday, 02 December 2020 3:04 AM
To: Ilze Oosthuizen <ilze.oosthuizen@earinstitute.co.za>; ilzeoosthuizen8@gmail.com
Cc: firsztj@wustl.edu
Subject: Trends in Hearing - Decision on Manuscript ID TIH-20-0086.R1

01-Dec-2020

Dear Mrs. Oosthuizen:

It is a pleasure to accept your manuscript entitled "Listening effort in school-aged children with limited useable hearing unilaterally: Examining the effects of a personal, digital RM system and a CROS system" in its current form for publication in Trends in Hearing.

Thank you for your fine contribution. On behalf of the Editors of Trends in Hearing, we look forward to your continued contributions to the Journal.

Sincerely,
Dr. Andrew Oxenham
Editor in Chief, Trends in Hearing
oxenham@umn.edu

APPENDIX K

Intervention benefit score for each participant (Chapter 6)

Intervention benefit score for each participant with intervention option relative to unaided listening based on mean values for digit triplet recognition (rau) and verbal response times (VRT; in ms) in each loudspeaker condition.

Loudspeaker and Participant ID	Digit triplet recognition: RM	Digit triplet recognition: CROS	VRT: RM	VRT: CROS	Q1: Ease of listening with RM	Q1: Ease of listening with CROS	Q2: Motivation with RM	Q2: Motivation with CROS
Midline								
1	+ 38,81	-10,63	66 ms slower	86 ms slower	Yes	Yes	Yes	Yes
2	+54,35	-18,63	407 ms faster	387 ms faster	Yes	Yes	Yes	Yes
3	+72,98	+25,88	390 ms faster	160 ms faster	Yes	No	Yes	No
4	+80,69	+15,54	401 ms faster	661 ms faster	Yes	Yes	Yes	Yes
5	+136,74	+44,3	841 ms faster	611 ms faster	Yes	Yes	Yes	Yes
6	+47,1	-19,46	302 ms faster	378 ms slower	Yes	No	Yes	No
7	no effect	-59,11	412 ms slower	552 ms slower	Yes	No	Yes	No
~~8~~	~~+41,87~~	~~-77,63~~	~~603 ms slower~~	~~3 ms slower~~	~~Yes~~	~~No~~	~~Yes~~	~~No~~
9	+38,81	+6,03	188 ms faster	128 ms faster	Yes	Yes	Yes	Yes
10	+41,87	-9,26	52 ms faster	248 ms slower	Yes	Yes	Yes	No
11	+17,24	-55,74	16 ms slower	506 ms slower	Yes	No	Yes	No
12	+44,3	-59,66	98 ms faster	792 ms slower	Yes	Yes	Yes	Yes
13	+68,37	-24,07	116 ms faster	164 ms slower	Yes	No	Yes	No
14	+25,88	-23,56	62 ms slower	52 ms slower	Yes	Yes	Yes	Yes
15	+103,96	no effect	133 ms faster	79 ms slower	Yes	Yes	Yes	Yes
16	+110,86	no effect	353 ms faster	3 ms faster	Yes	No	Yes	No
17	+92,44	14,81	71 ms faster	59 ms slower	Yes	No	Yes	Yes
18	+40,2	-19,46	10 ms slower	191 ms faster	Yes	Yes	Yes	No
19	+92,44	-44,3	500 ms faster	359 ms slower	Yes	Yes	Yes	Yes
Direct								
1	-25,88	-38,81	125 ms slower	177 ms slower	Yes	Yes	Yes	Yes
2	no effect	-59,11	109 ms faster	111 ms slower	Yes	Yes	Yes	Yes
3	+66,56	-8,64	113 ms faster	87 ms slower	Yes	No	Yes	No

4	+25,88	-28,47	181 ms faster	29 ms slower	Yes	Yes	Yes	Yes
5	+17,24	-32,2	22 ms faster	8 ms slower	Yes	Yes	Yes	Yes
6	+25,88	-28,47	62 ms faster	12 ms faster	Yes	No	Yes	No
7	no effect	no effect	208 ms slower	288 ms slower	Yes	Yes	Yes	Yes
~~8~~	~~+15,54~~	~~no effect~~	~~864 ms faster~~	~~594 ms faster~~	~~Yes~~	~~No~~	~~Yes~~	~~No~~
9	no effect	-59,11	203 ms faster	277 ms slower	Yes	Yes	Yes	Yes
10	+44,3	-14,81	108 ms faster	118 ms faster	Yes	Yes	Yes	Yes
11	+17,24	-32,2	94 ms faster	6 ms slower	Yes	No	Yes	No
12	+17,24	-21,57	75 ms slower	165 ms slower	Yes	Yes	Yes	Yes
13	+17,24	-8,64	162 ms faster	232 ms faster	Yes	Yes	Yes	Yes
14	no effect	-17,24	107 ms faster	47 ms faster	Yes	Yes	Yes	Yes
15	+12,93	-34,17	47 ms faster	103 ms slower	Yes	Yes	Yes	Yes
16	+25,88	-33,23	17 ms slower	177 ms slower	Yes	Yes	Yes	Yes
17	no effect	-38,81	3 ms slower	313 ms slower	Yes	Yes	No	Yes
18	no effect	-54,35	371 ms faster	213 ms faster	Yes	Yes	Yes	Yes
19	0	-97,93	190 ms faster	67 ms faster	Yes	Yes	Yes	Yes
Indirect								
1	+110,86	+37,88	383 ms faster	263 ms faster	Yes	Yes	Yes	Yes
2	+97,93	+29,56	705 ms faster	425 ms faster	Yes	Yes	Yes	Yes
3	+97,93	+25,88	934 ms faster	754 ms faster	Yes	Yes	Yes	No
4	+97,93	+5,49	245 ms faster	185 ms faster	Yes	Yes	Yes	Yes
5	+136,74	+82,39	1136 ms faster	1016 ms faster	Yes	Yes	Yes	Yes
6	+119,5	+55,74	1129 ms faster	809 ms faster	Yes	No	Yes	No
7	+82,39	+28,04	152 ms faster	108 ms slower	Yes	No	Yes	No
~~8~~	~~+102,26~~	~~no effect~~	~~709 ms faster~~	~~21 ms slower~~	~~Yes~~	~~No~~	~~Yes~~	~~No~~
9	+84,98	+61,42	329 ms faster	139 ms faster	Yes	Yes	Yes	Yes
10	+119,5	+32,78	837 ms faster	167 ms faster	Yes	No	Yes	Yes
11	+119,5	+70,06	782 ms faster	432 ms faster	Yes	No	Yes	No
12	+92,44	+53,63	450 ms faster	520 ms faster	Yes	Yes	Yes	Yes
13	+110,86	+33,23	478 ms faster	518 ms faster	Yes	No	Yes	Yes
14	+103,96	+30,98	376 ms faster	176 ms faster	Yes	Yes	Yes	Yes
15	+75,2	+46,52	806 ms faster	786 ms faster	Yes	Yes	Yes	Yes
16	+136,74	+49,44	883 ms faster	223 ms faster	Yes	No	Yes	No

17	+103,96	+65,15	1224 ms faster	944 ms faster	Yes	Yes	Yes	Yes
18	+93,62	+18,42	1030 ms faster	26 ms slower	Yes	No	Yes	No
19	+78,08	+28,47	347 ms faster	333 ms faster	Yes	Yes	Yes	Yes

Note: Participant 8 was deemed unreliable during testing and his data were not included in analyses.

At digit triplet recognition + indicates benefit; - indicates detriment. At VRT columns, faster VRT indicates benefit (i.e. reflecting less listening effort). No effect indicates performance was similar to the unaided condition.