Listening Effort in School-Aged Children With Normal Hearing Compared to Children With Limited Useable Hearing Unilaterally

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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.

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, 2000). 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 continues 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).

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 normal hearing bilaterally.

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, 1986; 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 (i.e., speech directed to the ear with normal hearing; Bess et al., 1986).

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).

MATERIALS AND METHODS

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, 1966)* 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 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 1. Participant demographic information

Number	Age	Gender	Native (N) or nonnative (NN) English	Ear with LUHU	Age at diagnosis	Etiology	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 the age of 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	Perinatal period	Congenital: suspect Goldenhar syndrome	Profound
12	10	M	NN	R	6 years	Unknown	Profound
13	12	F	NN	R	5 years	Unknown	Profound
14	12	M	N	R	10 years	Acquired: viral infection	Severe–profound
15	7	F	N	L	4 years	Acquired: prematurity and ototoxic medication	Profound
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 the age of 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 useable hearing unilaterally; M = male; L = left; R = right; F = female; OM = otitis media; NH = normal hearing.

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 headworn 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.

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.

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).

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.

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 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.

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 (see the Appendix for a description of this RT calculation procedure). 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).

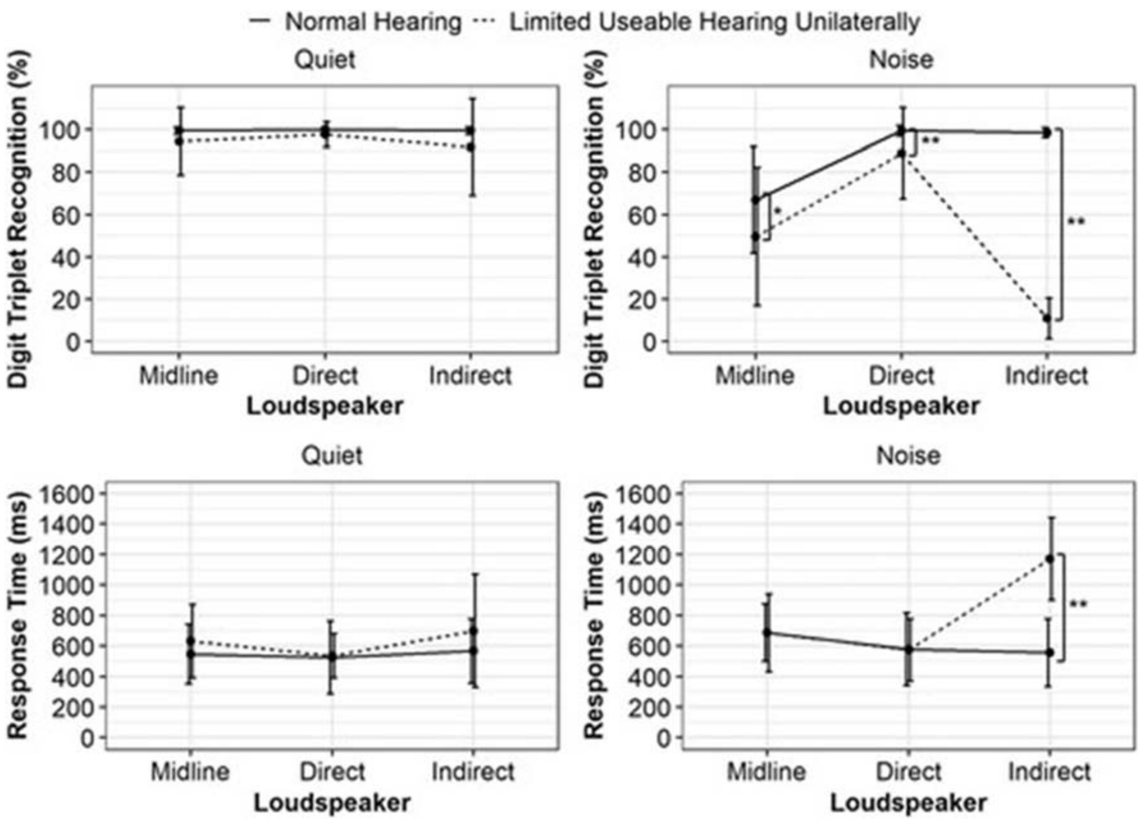

Figure 1. Mean digit triplet recognition scores (percent correct) in quiet (top left panel) and in noise (top right panel) and mean response times (ms) in quiet (bottom left panel) and in noise (bottom right panel). Solid lines indicate participants with normal hearing. Dashed lines indicate participants with limited useable hearing unilaterally. Error bars indicate standard deviation. Significant differences are indicated by * ($p < .05$) or ** ($p < .001$).

RESULTS

Digit Triplet Recognition

Figure 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 2.

Table 2. Results of ANCOVA analyses for digit triplet recognition (in rationalized arcsine units) conducted separately for each loudspeaker location.

Loudspeaker	Effect	*F*	*df*	*p*	η_p^2
Midline	Age	2.92	1, 33	.097	.08
	Group	**4.73**	**1, 33**	**.037**	**.13**
	Condition	**113.33**	**1, 33**	**< .001**	**.77**
	Group × Condition	3.98	1, 33	.054	.11
	Condition × Age	**7.95**	**1, 33**	**.008**	**.19**
Direct	Age	0.04	1, 33	.835	.001
	Group	**6.93**	**1, 33**	**.013**	**.17**
	Condition	**8.9**	**1, 33**	**.005**	**.21**
	Group × Condition	**6.87**	**1, 33**	**.013**	**.17**
	Condition × Age	0.56	1, 33	.459	.02
Indirect	Age	0.04	1, 33	.846	.001
	Group	**115.64**	**1, 33**	**< .001**	**.78**
	Condition	**348.94**	**1, 33**	**< .001**	**.91**
	Group × Condition	**305.62**	**1, 33**	**< .001**	**.90**
	Condition × Age	0.15	1, 33	.705	.004

Note: Significant effects or interactions are indicated by bold type face. Corrected *p* values are displayed.

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 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).

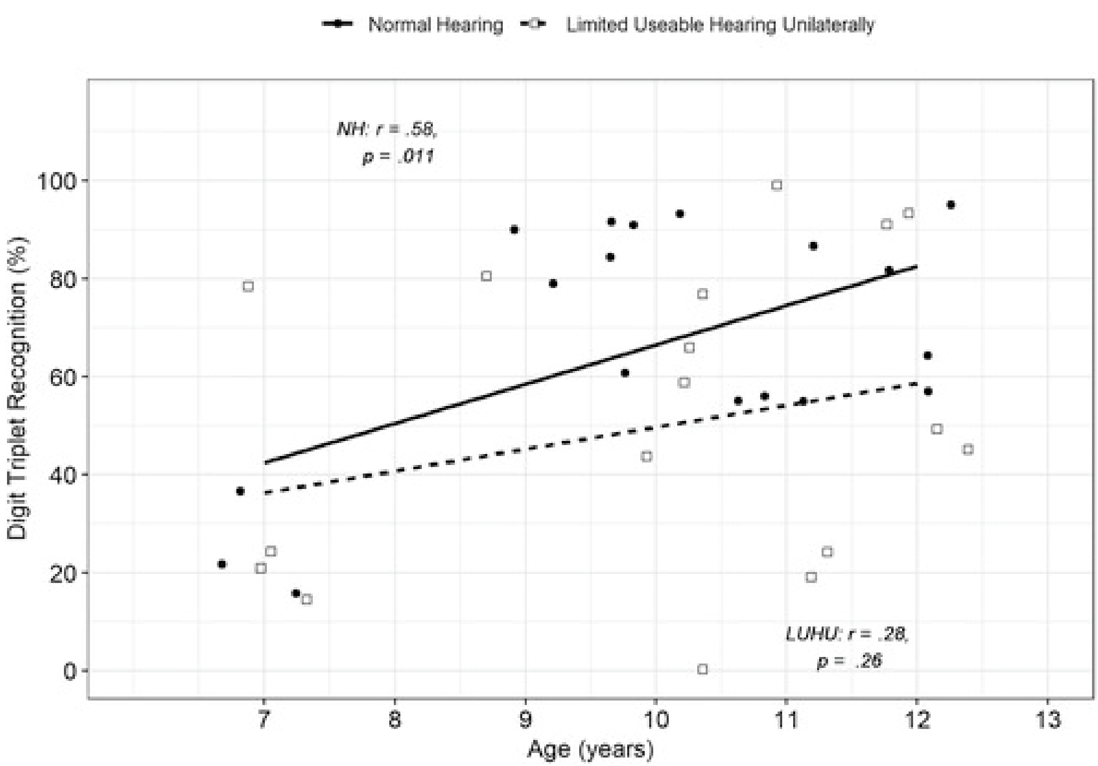

Figure 2. Relationship between age and digit triplet recognition for the midline loudspeaker condition in noise. Solid lines and circles indicate participants with normal hearing. Dashed lines and squares indicate participants with limited useable hearing unilaterally.

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 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.

Response Times

The bottom panels of Figure 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 3.

Table 3. Results of ANCOVA analyses for response time conducted separately for each loudspeaker location.

Loudspeaker	Effect	*F*	*df*	*p*	η_p^2
Midline	Age	0.98	1, 33	.330	.03
	Group	0.35	1, 33	.557	.01
	Condition	**8.08**	**1, 33**	**.008**	**.20**
	Group × Condition	1.63	1, 33	.210	.05
	Condition × Age	0.72	1, 33	.401	.02
Direct	Age	0.01	1, 33	.934	< .001
	Group	< 0.01	1, 33	.963	< .001
	Condition	**4.82**	**1, 33**	**.035**	**.13**
	Group × Condition	0.20	1, 33	.659	.01
	Condition × Age	2.32	1, 33	.137	.07
Indirect	Age	0.02	1, 33	.883	< .001
	Group	**21.24**	**1, 33**	**< .001**	**.39**
	Condition	**26.13**	**1, 33**	**< .001**	**.44**
	Group × Condition	**28.36**	**1, 33**	**< .001**	**.46**
	Condition × Age	0.6	1, 33	.445	.02

Note. Significant effects or interactions are indicated by bold type face. Corrected *p* values are displayed.

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.

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 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 4. Results of mean rank differences of the subjective ratings for each Loudspeaker and Condition combination.

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**

Note. Significant differences between the NH (normal hearing) participant and LUHU (limited useable hearing unilaterally) participant groups are indicated in bold type face ($p < 0.0083$).

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). Figure 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 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 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. 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.

	Triplet recognition (rau)	Response times (ms)	Rating of task difficulty	Rating of recognition performance	Rating of hard to think
Participants with NH					
Age (years)	.27 (.273)	−.25 (.323)	−.04 (.866)	.23 (.355)	−.08 (.751)
Triplet recognition (rau)		−.15 (.555)	.13 (.614)	−.23 (.354)	.05 (.844)
Response times (ms)			.04 (.877)	−.52* (.028)	−.13 (.604)
Rating of task difficulty				.18 (.487)	.64** (< .0001)
Rating of recognition performance					.27 (.272)
Participants with LUHU					
Age (years)	.03 (.907)	.01 (.960)	.68** (< .0001)	.52* (.026)	.78** (< .0001)
Triplet recognition (rau)		−.63* (.005)	−.06 (.827)	−.32 (.198)	−.27 (.286)
Response times (ms)			.13 (.595)	.17 (.490)	.25 (.324)
Rating of task difficulty				.81** (< .0001)	.91** (< .0001)
Rating of recognition performance					.76** (< .0001)

Note. Significant correlations are in boldface type and are indicated by asterisks: *p< .05 and **p< .001. NH = normal hearing; rau =rationalized arcsine units; LUHU = limited useable hearing unilaterally

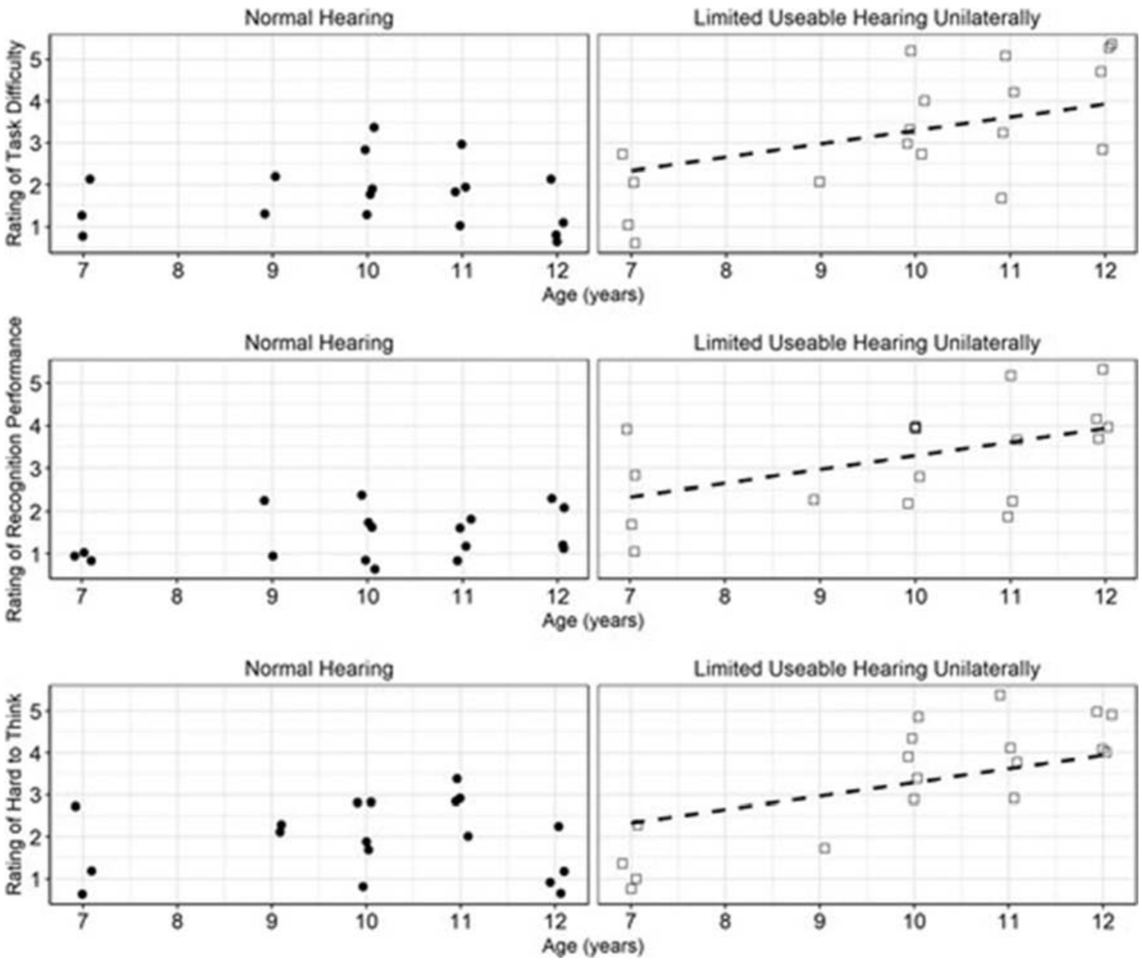

Figure 3. Relationship between age and subjective measures for both participant groups in the indirect condition with noise. Solid circles indicate participants with normal hearing. Dashed lines and squares indicate participants with limited useable hearing unilaterally.

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.

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.

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 average 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.

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 indicate that children with LUHU demonstrate 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.

Study Limitations and Future Directions

Generalizability of the findings 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) and relatively directional noise sources. Typical contemporary classrooms have primarily diffuse noise that is present at least 70% of the time (Crukley et al., 2011; Ricketts et al., 2017). In addition, 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). Therefore, future studies can consider the use of more diffuse background noise and/or different types of masker noise (e.g., speech-like background noise) in evaluating listening effort in school-aged children with LUHU in order to better resemble a realistic classroom situation. Furthermore, in the midline loudspeaker condition as correlated noise was presented from the side loudspeakers, 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. Future studies can 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). This study 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.

Finally, no intervention options were evaluated. Non-surgical intervention options for children with LUHU include a remote microphone system (RMS) or contralateral routing of signal (CROS) system. Results from previous studies revealed RMS benefits for improved speech recognition in noise in midline and indirect loudspeaker conditions, and CROS benefits in the indirect condition (Kenworthy et al., 1990; Picou et al., 2020a; Updike, 1994). However, the effect that these intervention options for children with LUHU might have on reducing the listening effort experienced in noisy listening scenarios have not been evaluated yet. Research investigating the effect of intervention options on listening effort in the children with hearing loss is scarce and it is not clear that improving audibility will also reduce listening effort (e.g., McGarrigle et al., 2019). For example, McGarrigle et al. (2019) reported personal amplification, which improves audibility, did not affect behavioral listening effort for school-aged children with mild-moderate bilateral sensorineural hearing loss. The authors suggested that future research should determine if intervention options that can improve SNR (e.g. directional microphones, remote microphone systems) could reduce listening effort for children with hearing loss. Therefore, future studies should determine the effect of intervention options on listening effort in children with LUHU in order to support the type of intervention options recommended for school-aged children with LUHU.

CONCLUSIONS

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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APPENDIX

Description of the Procedure Followed for RT Calculation

To ensure the RTs 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 child's response. The following steps were followed to determine the RT 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 RT was compared to that produced by the MATLAB program.