Hearing Aids Can Reduce Listening Effort in School-Age Children Who Are Hard of Hearing

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ABSTRACT

Objectives: For children who are hard of hearing, listening to speech can be effortful, especially in noisy classroom environments. While hearing aids provide improved access to sound, it is still unclear if hearing aids also help to reduce listening-related effort. The present study tested the hypothesis that hearing aids can reduce listening effort when children who are hard of hearing listen to sentences in quiet or in noise.

Design: Thirty-three school-age children who are hard of hearing (mean age = 10.11 years, range = 8.25 to 11.92 years) who used hearing aids participated in a dual-task paradigm. In the primary task, each child listened to and repeated back sentences that were presented in speech-shaped noise or in quiet with and without their hearing aids. Concurrently, participants responded on a keyboard to a simple visual reaction time task. Dual-task cost was calculated as the percentage change in response time on the secondary task performed in isolation compared with when the secondary task was performed concurrently with the primary task. In addition, children provided subjective feedback about their effort exerted during the experiment.

Results: Dual-task costs were lower in the aided condition compared with the unaided condition when listening in noise, but did not differ when listening in quiet. In quiet, children reported lower ratings of listening effort in the aided condition compared with the unaided condition. In noise, children's subjective ratings of effort did not differ between unaided and aided conditions. Correlational analyses between behavioral and subjective measures of listening effort revealed absent to weak relationships. However, correlations between subjective effort and primary task performance were moderate in noise and in quiet when children did not use their hearing aids.

Conclusions: This is the first study to demonstrate that hearing aids reduce listening effort in noisy conditions in school-age children who are hard of hearing. Dual-task results were sensitive to changes in effort when listening in noise, but not in quiet. Subjective measures were sensitive to changes in effort in quiet, but not in noise. The present study makes a novel and important contribution to the literature on listening effort in school-age children who are hard of hearing. The results of this study support consistent hearing aid use in children who are hard of hearing, as we demonstrated that hearing aids provide benefits beyond auditory access.

Key words: Children, Dual-task, Hearing aids, Hearing loss, Listening effort, Speech recognition.

(Ear & Hearing 2026;47;1080–1092)

This article has received an OSF badge for Open Data.

INTRODUCTION

For children who are hard of hearing (CHH), understanding speech can be challenging and effortful, especially when listening in noise. CHH spend a large portion of their time learning and communicating in noisy environments, such as in the classroom (Crukley et al. 2011). Successful speech understanding in noisy environments requires children to rely on bottom-up and top-down cognitive processes that are still developing (Luna et al. 2004; McCreery et al. 2019). While hearing aids are a common and successful intervention for this population, CHH are still at risk for language delays (Tomblin et al. 2015; Wiseman et al. 2023) and for exerting extra effort during listening in comparison to children with typical hearing (CTH; Hicks & Tharpe 2002; McGarrigle et al. 2019). The need to continually exert more effort during communication puts CHH at a higher risk of listening-related fatigue (Hornsby et al. 2016, 2017; Bess et al. 2020; Davis et al. 2021; Adams et al. 2023; Klein et al. 2024), which may have a negative impact on language and academic outcomes (Werfel & Hendricks 2016; Camarata et al. 2018). Thus, the present study seeks to better understand how listening effort can be modulated by hearing aid use in CHH.

Listening Effort

Listening effort is the intentional use of extra cognitive resources to achieve a listening-related goal (Kahneman 1973; Pichora-Fuller et al. 2016). Effortful listening is modulated by cognitive demands, which are influenced by a number of factors such as signal distortion (Pals et al. 2013; Winn et al. 2015), signal to noise ratio (SNR; Wendt et al. 2016; Hsu et al. 2017), semantic context (Winn 2016; Gianakas & Winn 2025), and a listener's familiarity with the language heard (Borghini and Hazan 2018). For CHH, cognitive demands during listening are impacted by signal distortion due to hearing loss and the presence of background noise (Hicks & Tharpe 2002; Larsby et al. 2005; Lewis et al. 2016; McGarrigle et al. 2019). Thus, identifying interventions that reduce cognitive load during listening is important for improving communication outcomes for CHH.

Amplification and Listening Effort • Currently, there is a dearth of research examining the role of amplification on listening effort in children who have hearing loss. To date, McGarrigle et al. (2019) published the only study that directly compared aided and unaided listening conditions and found no effect of amplification on effort in CHH. Recent work in older adults with hearing loss demonstrated that hearing aids reduced both subjective reports of effort and oxygenation in the prefrontal cortex, indicating reduced cognitive load or effort while listening to sentences (Vaisberg et al. 2024). Previous studies on adults have demonstrated that hearing aids provide relief from effort using dual-task paradigms (Downs 1982; Hornsby 2013; Picou et al. 2013) and subjective measures (Hällgren et al. 2005; Ahlstrom et al. 2014; Vaisberg et al. 2024). Given the growing evidence on the impact of hearing aids on listening effort in adults, further investigation with children is warranted. Other studies have indirectly examined the effect of hearing aid technology on listening

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<zdoi; 10.1097/AUD.0000000000001802>

effort. For instance, studies have shown that hearing aid features such as noise reduction and microphone directionality reduce listening effort in both children and adults with typical hearing (Sarampalis et al. 2009; Desjardins & Doherty 2014; Gustafson et al. 2014; Picou, Moore, et al. 2017). Gustafson et al. (2021b) also found variation in listening effort for children using a remote microphone when listening in complex environments. The underlying source of that variance appeared to be related to the amount of benefit children received from omnidirectional hearing aid microphones. Children who already performed near ceiling with an omnidirectional microphone showed increased listening effort when using a remote microphone. This finding suggests that the effects of remote microphone technology on listening effort may be contingent on the amount of benefit a child receives from their hearing aid microphones. Therefore, understanding if a child benefits from their hearing aids—via improved speech recognition or easier listening—could influence additional accommodation recommendations. In the present study, we examine the overall effect of amplification on listening effort in CHH using both subjective and behavioral measures.

Noise and Listening Effort in Children • One potential factor contributing to effortful listening in children is the presence of background noise. Previous studies have examined the effect of background noise on listening effort in children, showing that greater levels of noise increase listening effort in general. For example, as SNR becomes more unfavorable, children take longer to verbally respond, indicating greater effort and longer processing time (Gustafson et al. 2014; Lewis et al. 2016; McGarrigle et al. 2019; Visentin et al. 2023a). Decreases in SNR have been shown to increase reaction times on secondary tasks in some studies (Howard et al. 2010; Seitz et al. 2024), but not in others (Choi et al. 2008; McFadden & Pittman 2008; McGarrigle et al. 2019). In addition, increases in noise levels result in greater pupil dilation when children listen to speech, indicating increased listening effort (McGarrigle et al. 2017; Trau-Margalit et al. 2023). These findings demonstrate the need for a listener to engage in effortful processing to overcome listening breakdowns (Rönnberg et al. 2013, 2019; Pichora-Fuller et al. 2016; Mattys et al. 2025).

Subjective Measures of Effort • Subjective measures can provide valuable insight into the experience of hearing loss and are commonly used in the clinic. For example, the Hearing Handicap Inventory for Adults (Newman et al. 1990) or the Speech, Spatial and Qualities of Hearing Scale (Gatehouse & Noble 2004) are commonly used when evaluating hearing aid benefit in the clinic. However, self-reports of listening effort in adults tend to be less reliable than secondary task performance in a dual-task paradigm (Downs & Crum 1978; Gosselin & Gagné 2010). For example, listeners tend to report on performance rather than effort (Moore & Picou 2018), and listeners tend to report more effort as the SNR decreases (Picou et al. 2017, 2019). There are a limited number of studies that have measured subjective effort in children (von Lochow et al. 2018; Visentin & Prodi 2021; Visentin et al. 2023b; Seitz et al. 2024) and even fewer in CHH (Picou et al. 2019; Oosthuizen et al. 2021; Brännström et al. 2022). Obtaining reliable subjective reports from children can be a difficult endeavor, and different approaches have been used to better understand factors that can contribute to self-perceived effort in children. For example, prior work has used a variety of subjective report prompts to achieve more reliable reporting of perceived effort or listening difficulty. Children have been asked to report their perceived sound clarity (Gustafson et al. 2014), ease of listening (Picou et al. 2019; Oosthuizen et al. 2021), perceived listening difficulty (Gustafson et al. 2021a) and perceived effort (von Lochow et al. 2018; Visentin & Prodi 2021). In general, results indicate that children report less perceived effort in more favorable listening conditions (Picou et al. 2019; Seitz et al. 2024), but these results are not always consistent across studies (Hicks & Tharpe 2002). It is possible these discrepancies in findings arise in part from different approaches to elicit subjective reports of effort.

Approaches in measuring subjective reports in children have varied across studies (Spoorthi et al. 2025). Some studies have employed numeric rating scales (von Lochow et al. 2018; Oosthuizen et al. 2021; Brännström et al. 2022), categorical scales (Visentin & Prodi 2021), visual analog scales (Nirme et al. 2019; Picou et al. 2019; Visentin et al. 2022, 2023a, 2023b) and subjective questionnaires (Seitz et al. 2024). Others have used comparative ratings to improve the reliability of children's responses. For example, instead of rating sound clarity on a numeric scale, children were shown pictures that were visually degraded and asked to pick the picture that best corresponded to their perceived sound clarity (Gustafson et al. 2014). In addition, there is a scarcity of studies that have reported whether they provided children with the opportunity to practice the self-perceived rating task before task. Picou and Moore (2018) recommended a practice protocol for effort rating to elicit more reliable responses, which is likely important for the pediatric population. The present study followed a similar approach by employing a self-perceived effort rating practice protocol that included a similar comparative rating task as the one by Gustafson et al. (2014) to promote the use of the entire rating scale by children.

Dual-Tasks and Listening Effort

Dual-task paradigms are a frequently used behavioral method of measuring cognitive demand/listening effort (Gagné et al. 2017). Dual-task designs operate under the multiple resources theory, meaning a finite number of cognitive resources can be allocated to varying degrees among multiple tasks (Wickens 2002). In other words, there is a limited amount of cognitive resources that can be used for different processes at the same time (Kahneman 1973). During a dual-task paradigm, an individual performs two tasks simultaneously. As the primary task (i.e., speech recognition) increases in difficulty or cognitive demand, decreases in performance on the secondary task (i.e., slower reaction times on a decision-making task) reflect increased effort and the reallocation of cognitive resources. Calculations of dual-task cost have been used to reflect the effect of dual-task cost for a given experimental condition as a proportional or percentage change of the outcome variable between the dual- and single-task (Gagné et al. 2017; Kuchinsky et al. 2024). In general, positive dual-task cost values indicate that there is an additional cost (represented by lower performance) to a multitasking condition as compared with a single-task or baseline condition.

Although speech recognition tests are clinically useful for evaluating auditory function, they are not sensitive to the cognitive demands of real-world listening, which requires multitasking and reliance on cognitive-linguistic skills. This is particularly true in school, where a student is expected not only to listen to a teacher's message in a degraded listening environment, but also to fully comprehend and integrate that message, while simultaneously performing other tasks (e.g., taking notes). For CHH, there is evidence that multitasking situations are taxing due to the additional listening effort needed to understand speech (Hicks & Tharpe 2002; McFadden & Pittman 2008; Grieco-Calub et al. 2017; McGarrigle et al. 2019). In comparison to standard clinical tests of speech perception, dual-task designs may be more ecologically valid, as children are often multitasking during real-world communication.

Methodological Variety Across Dual-Task Studies in Children • Results of dual-task paradigms examining the effects of noise have had inconsistent findings in children (Hicks & Tharpe 2002; Choi et al. 2008; McFadden & Pittman 2008; Pittman 2011; McGarrigle et al. 2019; Picou et al. 2019; Cruz et al. 2020; Gustafson et al. 2021b). However, these studies differed widely in their methodologies, including the SNR used, participants' age and hearing status, and task demands. For instance, SNRs used in these studies vary from more favorable (e.g., +10- and +20-dB SNR in Hicks & Tharpe 2002) to more challenging (e.g., −4 and +4 dB SNR in Howard et al. 2010), resulting in different findings. A number of studies have tested with the dual-task paradigm using fixed SNRs (Hicks & Tharpe 2002; Stelmachowicz et al. 2007; Choi et al. 2008; McFadden & Pittman 2008; Howard et al. 2010; Pittman 2011; Cruz et al. 2020), and Picou et al. (2019) is the only study that used an individualized-performance-based SNR approach. Some studies focus on CTH (Howard et al. 2010; Picou et al. 2019), whereas others include CHH (Hicks & Tharpe 2002; McGarrigle et al. 2019). In addition, secondary tasks have ranged from simple visual reaction time tasks (McGarrigle et al. 2019) to more complex tasks like a digit recall (Stelmachowicz et al. 2007; Choi et al. 2008; Howard et al. 2010), color memory (Cruz et al. 2020), or word learning tasks (Pittman 2011). The large variation in SNR levels tested across studies, accompanied by differences in populations tested and task demands, creates the need for further research to better understand listening effort in children.

The Current Study • Previous studies of listening effort in children using the dual-task paradigm have incorporated a wide range of methodologies and tested a variety of pediatric populations. The differences between these studies have likely contributed to the inconsistent findings in children. Of the studies examining listening effort in children, only Picou et al. (2019) used a performance-based approach by using individualized SNRs for each participant to achieve specific primary task performance levels. McGarrigle et al. (2019) is the only study to date that compared unaided and aided conditions among CHH; however, their study used a less individualized approach by presenting speech at three levels of fixed SNRs, designated as Easy, Moderate, or Hard SNRs. The present study followed a similar approach to that of Picou et al., using an individualized SNR for each participant to better understand the effect of amplification on listening effort in CHH. Furthermore, this study used a perceived effort rating practice protocol before testing to elicit reliable subjective reports of listening effort in children.

The present study examines the effect of amplification on listening effort in CHH in quiet and in noise. Using a dual-task design and subjective ratings of effort, we hypothesize the following:

1. Lower dual-task cost (lower effort) and lower subjective ratings of effort when CHH listen to speech in quiet in an aided versus unaided condition.
2. Lower dual-task cost (lower effort) and lower subjective ratings of effort when CHH listen to speech in noise in an aided versus unaided condition.

MATERIALS AND METHODS

Participants

Thirty-three CHH who use bilateral hearing aids (mean age: 10.05 years, range = 8 to 11 years) participated in the study. Four of the participants were removed from the analysis due to difficulty in perceiving speech in quiet in the unaided condition, resulting in performance levels <40% during the dual-task procedure. One additional participant was removed due to a data saving error. The number of participants was chosen based on a power analysis, which indicated that 30 participants would provide >80% power to detect an effect size of 0.5 with $\alpha = 0.05$. The power analysis was based on preliminary data for the dual-task method using an SNR-50 (SNR in which children achieve 50% accuracy in sentence recognition) when comparing aided and unaided conditions. Due to concerns with task engagement because of poor performance and overall audibility of the signal, an SNR-70 was used in the present study.

All children were monolingual speakers of North American English with no diagnoses of neurodevelopmental disorders. Each child had better-ear 4-frequency pure-tone average (500, 1000, 2000, and 4000 Hz) between 18- and 54-dB HL. Of the 28 participants whose data were included in the analysis, 27 participants wore behind-the-ear hearing aids, and one had receiver-in-canal hearing aids. All participants had bilateral hearing loss and used hearing aids in both ears. Four had frequency compression, and 24 did not have any kind of frequency-lowering algorithm. Eighty percent (20/25) of HAs were fitted to within 5 dB root-mean-square (RMS) error of DSL targets (3 participants' RMS error data were unobtainable). Table 1 summarizes participant demographics. Children and parents provided written consent to participate, and each child was compensated $15/hr for participating. All study procedures were approved by the University of Iowa's Institutional Review Board (IRB), Number 201512760.

Procedures

Each child completed an audiologic assessment, hearing aid verification, subjective rating of effort, and a dual-task experiment that contained a concurrent auditory sentence recognition task and simple visual reaction time task. Parents completed an intake questionnaire to report their child's age at hearing loss diagnosis and age of first hearing aid fitting (reported in Table 1).

Audiologic Assessment

Participants received hearing assessments conducted by ASHA-certified pediatric audiologists (CCC-A). Air-conduction thresholds were measured in each ear at 250, 500, 1000, 2000, 4000, 6000, and 8000 Hz using ER-3A insert earphones with

TABLE 1. Demographic and audiologic characteristics and test scores for children who are hard of hearing (CHH)

Test Variable	CHH (n = 28)	
	M (SD)	Range
Gender	13 Males, 15 Females	
Race	26 White, 1 Hispanic, 1 Multi-race	
Age (yrs)	10.19 (1.04)	8.25–11.92
Maternal education level (yrs)	16.40 (2.40)	12–22
BEPTA (dB HL)	40.24 (9.73)	18.75–53.75
Better-Ear Aided SII (65 dB)	85.39 (7.95)	65–98
Better-Ear Unaided SII (65 dB)	43.53(25.86)	6–99
RMSE	3.89 (1.73)*	1.22–7.68
Age at HL confirmation (mos)	20.32 (27.36)	0–86
Age at HA fit (mos)	22.05 (27.95)	1–89

BEPTA, better ear pure-tone average; HA, hearing aid; HL, hearing level; RMSE, root-mean-squared-error; SII, Speech Intelligibility Index.
**Three participants' RMSE data were unobtainable.*

foam tips. Bone-conduction thresholds were measured in each ear at 500, 1000, 2000, and 4000 Hz.

Hearing Aid Verification

Hearing aid function was evaluated by an audiologist using ANSI (2014) conformity measures of hearing aid function. The Speech Intelligibility Index (ANSI 1997; Wiseman et al. 2025) was calculated to quantify audibility for unaided and aided conditions. The SII is calculated by estimating the audibility of a speech signal for multiple frequency bands based on the listener's unaided hearing thresholds. Each frequency band is given an importance weight based on the role the band has in the average speech recognition score for a group of adults with normal hearing. This importance weight is multiplied by each band's audibility to create a weighted audibility. Each band's weighted audibility is summed together, resulting in a score between 0 and 1. This number illustrates the weighted audibility of the long-term average speech spectrum (LTASS). A score of 0 indicates that none of the LTASS is audible, and a score of 1 indicates full audibility. The audibility of the amplified LTASS signal through the HAs measured during verification is used for the aided SII calculation.

Simulated real-ear measures were used to calculate aided and unaided SII. Probe microphone measures were initially used to quantify the real-ear-to-coupler difference (Bagatto et al. 2005). Hearing aid verification was then completed in the 2-cc coupler. Audioscan Verifit software calculated unaided SII and aided SII at the participant's user settings using the standard male speech signal (carrot passage; Cox & McDaniel 1989) presented at average conversational levels (65 dB SPL) following ANSI S3.5 (1997). We computed indices of aided and unaided SII for the average level of input for all participants.

Performance-Based SNR Setting Procedure

Before the experimental dual-task procedure, each child's individual unaided SNR-70 was obtained using similar methods as Wu et al. (2016) and Perreau et al. (2017). During this preliminary measure, the participants listened to sentences presented at a 65 dB SPL, and the level of the speech-shaped noise was adjusted based on the participant's responses using the two-up, one down procedure (Levitt 1971), starting at +12 dB SNR. The initial SNR was selected based on pilot data for the study. For the first five sentences, 4 dB steps were used, and for the remaining sentences, 2 dB steps were used. If a participant responded correctly in two consecutive sentences, the noise level increased, and if they responded incorrectly, the noise level decreased. Twenty sentences were used, and the SNRs of the last 17 sentences were averaged. SNR-70 was determined by adding 2 dB to the averaged SNR. This procedure was intended to result in an SNR level at which a child's unaided speech recognition scores were approximately 70%. SNR-70 was selected to minimize the likelihood that children would disengage from the task due to poor performance (Wu et al. 2016). The individualized SNR obtained from this procedure was then used during the dual-task paradigm described later.

Primary Task • Each child participated in a sentence recognition task while simultaneously performing a secondary visual monitoring task (described later). Sentences were from the Hearing in Noise Tests (HINT; Nilsson et al. 1994; Soli & Wong 2008) and were presented in speech-shaped noise or in quiet. Speech-shaped noise rather than a multitalker masker was used to avoid the additional top-down processing required in the presence of informational masking (Wightman & Kistler 2005; Mattys et al. 2012). There was a total of 24 lists containing 10 sentences each. Two lists were presented (20 sentences) per condition. The combination of lists and the order of lists were randomized for each participant. Participants were asked to repeat as much of the sentence as they could understand and were encouraged to guess if they were unsure. For quiet testing, each child was tested at a fixed level of 65 dB SPL. For noise testing, each child was tested at their individualized unaided SNR-70 from the preliminary adaptive procedure (described earlier).

Secondary Task • The secondary task was a simple visual reaction time task using stimuli adapted from Wu et al. (2016) and Perreau et al. (2017). Participants first saw a computer monitor with four boxes with color names (red, blue, green, yellow) inside each box and an asterisk in the middle of the screen. During the secondary task, a target word would appear in the place of the asterisk (Fig. 1). Participants were instructed to press the space bar on the wireless keyboard as quickly as possible after seeing the target word (either "red," "blue," "yellow," or "green") appear on the computer screen, regardless of which color word appeared.* This task was completed simultaneously with the repetition of the HINT sentences, in which one target word was visually presented during the presentation of one HINT sentence per trial. The target word was visually presented at random intervals between the midpoint and the end of each sentence. The target word disappeared, and the screen returned to its original format with the asterisk once the space bar was pushed. The experiment did not proceed until the child provided a response, meaning the visually presented word remained on screen until a response was provided. Response times to the secondary task were logged via the E-Prime Studio 2.0 software.

*The stimuli were designed to be used as either a simple visual reaction-time task or in a Stroop test paradigm, which increased the difficulty level and processing load of the secondary task. Only the simple visual reaction-time stimuli were used in the present study.

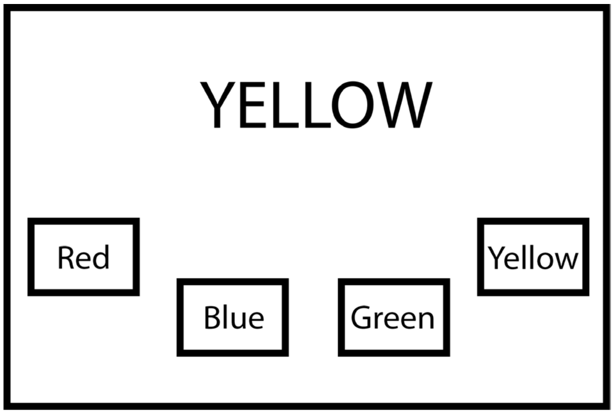

Fig. 1. Example of the simple visual reaction time task shown on the computer screen.

All participants practiced the secondary task on its own before the experiment and then 20 trials of secondary task baseline measurement were logged following practice. Consistent with Wu et al. and Perreau et al., baseline reaction time was measured without the presence of sound.

Subjective Effort Rating • After each test block, which consisted of two HINT lists (20 sentences total), participants reported their subjective listening effort by pointing to a laminated paper with a scale from 0 (no effort) to 10 (the most effort one could possibly put into something). Children were instructed to select only whole numbers on the effort rating scale, which is displayed in Figure 2. To familiarize the participants with the effort scale, they completed a subjective rating training protocol as recommended by Moore and Picou (2018). The purpose of the training was to provide practice with the subjective rating scale of effort required to do the task because previous studies have indicated that children may not be reliable reporters of effort (see Visentin & Prodi 2021 for further discussion on self-perceived effort in children). First, each participant was asked to define what effort was. Regardless of the participant's definition, the examiner then provided their own definition of effort (i.e., how hard you must try to do a task, or how much work you put into completing a task). Participants then practiced rating the amount of effort they would put into completing various tasks like lifting an object, solving a math problem, and reading a book. Each practice item (lifting an object, solving a math problem, reading a book) had three levels of difficulty (easy, medium, hard) to encourage the participants to use the whole scale when rating effort. Regardless of how participants responded on the training task, they continued to the test procedure after completing the practice items to ensure that all children received the same amount of feedback and practice.

Experimental Procedure • Participants were tested in a sound-treated booth or a mobile testing van. They sat at a desk facing the loudspeaker that was three feet away at zero degrees azimuth. Speech stimuli and noise (when presented) were co-located at 0° azimuth. In the noise condition, the noise onset occurred 1 second before the speech stimuli onset, and the noise offset occurred 1 second after the speech stimuli offset. A computer monitor was located directly to the right of the loudspeaker, and a keyboard was placed on the desk in front of the participant. The participants were asked to sit in a comfortable position and try not to move their heads significantly from that location throughout testing. The examiners also encouraged the participants to take as many breaks as needed between conditions. Prior to the experiment, the participants practiced the dual-task paradigm to ensure familiarity with the procedure using ten sentences from HINT List 25.

The dual-task experiment consisted of four conditions: (1) unaided/quiet, (2) aided/quiet, (3) unaided/noise, (4) aided/noise. Participants wore their personal hearing aids using their everyday settings for all aided conditions, and each participant's unaided SNR-70 was used in the noise conditions. The

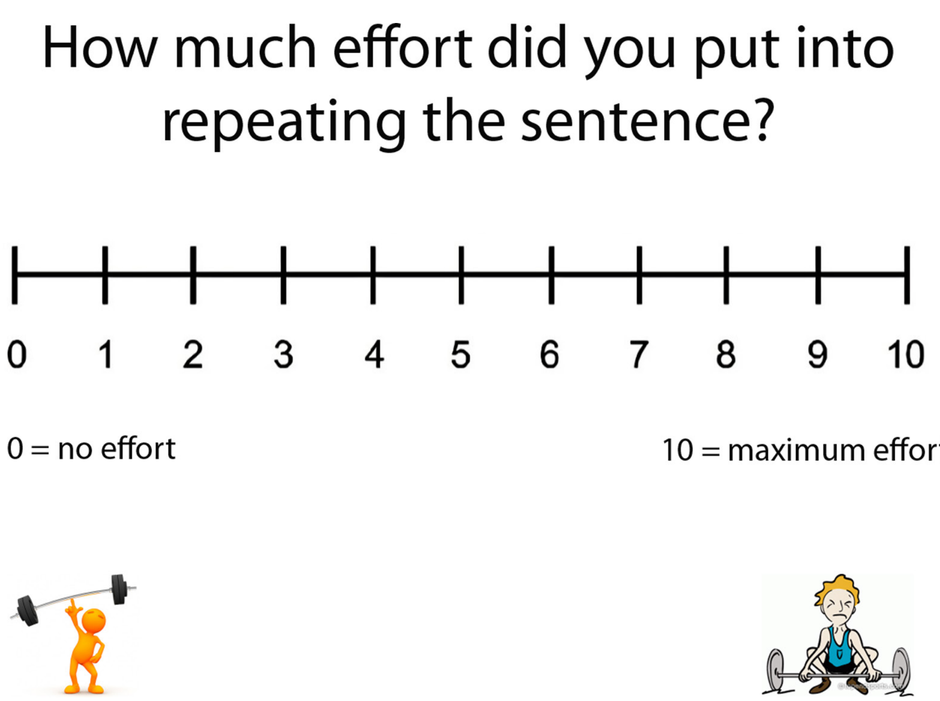

Fig. 2. Subjective rating scale used for rating effort.

condition order was randomized for each participant. HINT sentences were scored by the number of target words repeated correctly. Per each condition, participants repeated 20 HINT sentences while simultaneously completing the visual reaction time task, as performed in the dual-task practice. After each condition (test block), the participant was asked to rate the amount of effort put into the primary task (procedure described earlier). Figure 3 displays an example of a single experiment trial.

Analysis

Speech Recognition (Primary Task) • Primary task performance (speech recognition) was measured as the percentage of words repeated correctly. Speech recognition data were analyzed using a linear mixed-effects regression model using the lmerTest package (Kuznetsova et al. 2017) in the R statistical analysis environment (R Core Team 2023). The model tested the effect of device condition (unaided or aided) and age on speech recognition. Stepwise regression was completed using forward selection, starting with the intercept-only model. A single predictor was added to each subsequent model and compared using the likelihood ratio test (the "anova" function in R) to determine the importance of each predictor to the model and which model had the most support given the data. Each model included a random effect of participant intercepts to account for repeated measures. There were two separate stepwise regressions performed in this manner, one model that included data collected in the quiet condition and another model that included data from the noise condition. The noise and quiet data were examined separately for all analyses because of the difference in methodology used between the two listening conditions (i.e., fixed presentation level for quiet condition and performance-based SNR for noise condition).

Dual-Task Cost (Secondary Task) • Secondary task performance was measured using reaction times, which included both correct and incorrect responses, as previous work has reported no difference in secondary task performance between all responses and only correct responses (Hicks & Tharpe 2002; Lewis et al. 2016; Hsu et al. 2017; McGarrigle et al. 2019; Huang et al. 2023). Consistent with Hicks & Tharpe (2002), we filtered the data for reaction times that exceeded the limits of 1.5 times the interquartile range to reduce the influence of potential outlier data (e.g., a child had their attention on something else during the task and responded atypically). Across all conditions, an average of 8.78% of the data points were removed from the analysis as outliers (10.5% for the unaided dual-task in quiet, 8.7% for the aided dual-task in quiet, 7.5% for the unaided dual-task in noise, 8.9% for the aided dual-task in noise, and 8.3% for the baseline condition).

Dual-task costs were calculated as the percentage change in response time on the simple visual reaction time task when performed alone without the presentation of sound (baseline) versus when the task was performed concurrently with the speech recognition task (dual-task condition) in quiet (presented at 65 dB SPL) or in noise (SNR-70). The percentage change dual-task cost formula was used because it mitigates potential influences of differences in primary task performance on listening effort (Gagné et al. 2017; Grieco-Calub et al. 2017; Ward et al. 2017). The formula used in the present study is as follows:

$$\text{Dual Task Cost} = ([\text{Baseline} - \text{Dual Task}]/\text{Baseline}) \times 100$$

Dual-task costs were then subtracted from zero to essentially flip the sign for ease of interpretation (lower values mean less dual-task cost; Grieco-Calub et al. 2017; Picou et al. 2019).

Following the calculation of dual-task cost, the data were analyzed using a linear mixed-effects regression model using the lmerTest package (Kuznetsova et al. 2017) and followed the same stepwise regression procedure as the analysis for the speech recognition data. The model tested the effect of device condition (unaided or aided) on dual-task cost. Participant age was also included as a predictor variable in the model to determine whether dual-task cost significantly varied across the participant age range.

Subjective Rating Analysis • Subjective ratings of effort ranged from 0, indicating no effort, to 10, indicating maximal effort. The effect of the Device condition and Noise Condition on subjective ratings was analyzed using a linear mixed-effects regression model. Similar to the primary and secondary task analysis, we included participant age and device condition as fixed effects and included a random effect of participant intercepts. The model selection process also used forward selection, starting from the intercept-only model with each model including a random effect of participant intercept. There were two separate stepwise regressions performed in this manner, one using ratings collected during the quiet condition and one using ratings from the noise condition.

RESULTS

SNR-70 Procedural Results

During the performance-based SNR setting procedure (described earlier), unaided speech recognition performance was measured at adaptive SNRs with the goal of determining the SNR at which participants would achieve 70% sentence recognition accuracy. Results from the unaided adaptive speech

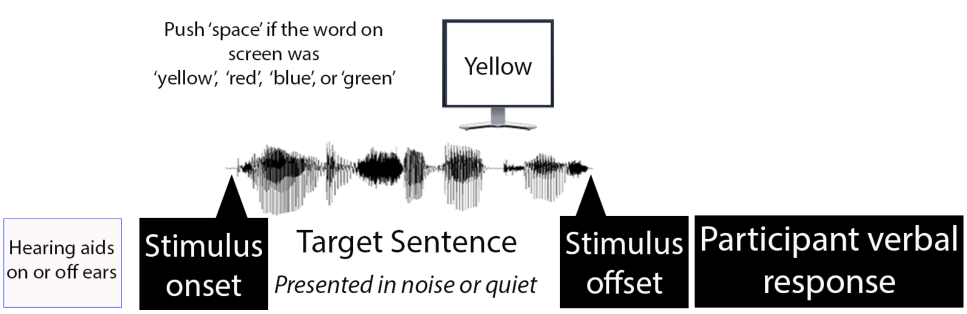

Fig. 3. Timeline of a single trial, depicting the presentation of the sentence and secondary task followed by the verbal response and subjective rating.

recognition task were better than expected, with a mean of 82.82% and an SD of 14.01. The range of SNRs to achieve the individualized unaided SNR performance level was −2 to 20 dB with a mean SNR of 9.71 dB (SD = 7.56).

Sentence Recognition Results

Primary Task: Listening in Quiet • Primary task performance was high in the quiet condition. In the aided condition, mean sentence recognition was 98.12% (SD = 2.15). In the unaided condition, mean sentence recognition was 91.11% (SD = 11.56). The effects of device condition and chronological age on primary task performance in quiet were modeled using a forward selection process (described earlier). Compared to the intercept-only model, device condition ($\chi^2 = 354.14$, $p < 0.001$) provided significant explanatory power to the model; however, age did not improve the model's explanatory power ($\chi^2 = 1.57$, $p = 0.21$) and was removed from the model. When listening in quiet, there was a significant effect of hearing aids on primary task performance ($\beta = 6.69$, $p < 0.001$).

Primary Task: Listening in Noise • The mean primary task performance in noise was 87.12% in the aided condition (SD = 15.16) and 84.18% in the unaided condition (SD = 11.81). Consistent with the analysis of primary task performance in quiet, the effects of device condition and age on primary task performance in noise were subjected to a forward selection process. Device condition did provide significant explanatory power to the model ($\chi^2 = 32.08$, $p < 0.001$). Age was not a significant predictor in the model ($\chi^2 = 0.0007$, $p = 0.98$) and was therefore removed from the model. When listening in noise, there was an effect of hearing aids on primary task performance ($\beta = 3.33$, $p < 0.001$).

Dual-Task Cost Results

Secondary Task: Listening in Quiet • Dual-task cost results for the quiet condition are displayed in Figure 4A. To assess the effects of the predictors, device condition (aided or unaided) and chronological age on dual-task cost, a forward selection process was used (described earlier). As compared with the intercept-only model, device condition ($\chi^2 = 2.79$, $p = 0.094$) did not

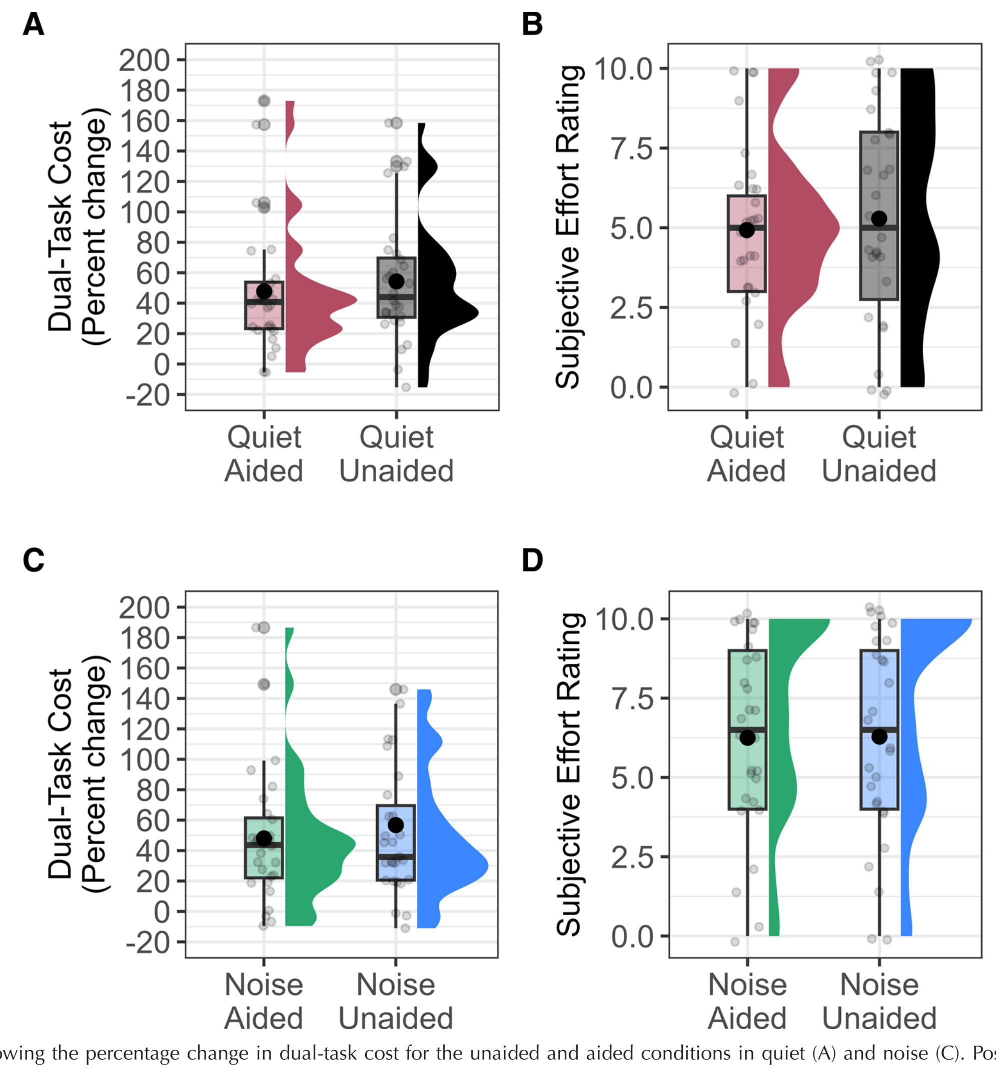

Fig. 4. Boxplots showing the percentage change in dual-task cost for the unaided and aided conditions in quiet (A) and noise (C). Positive values indicate greater dual-task cost. Boxplots showing the subjective rating of listening effort for quiet (B) and noise (D) when children had aided and unaided hearing. Zero indicates no effort, and 10 indicates maximal effort. In all plots, the group average data for each condition is represented by the large black dot, with smaller points representing average data for each participant. Density distributions for each condition are shown to the right of the boxplot. The width of the density distribution corresponds to the number of data points for a given dual-task cost or rating.

provide explanatory power to the model; however, this predictor remained in the model given the goal of the study. The addition of age did not improve the explanatory power of the model (χ^2 = 0.18, p = 0.67). When listening in quiet, there was no effect of hearing aids on dual-task cost (β = −6.56, p = 0.09).

Secondary Task: Listening in Noise • Dual-task cost results for the noise condition are displayed in Figure 4C. To assess the effects of the predictors, device condition (aided or unaided) and chronological age, on dual-task cost, a forward selection process was used (described earlier). As compared with the intercept-only model, device condition added significant explanatory power to the model (χ^2 = 3.92, p = 0.047), according to the likelihood ratio test. The addition of age did not significantly contribute to the model (χ^2 =0.008, p = 0.93); thus, age was removed from the fixed terms. Dual-task costs were significantly lower in the aided condition (β = −8.38, p = 0.047) compared with the unaided condition.

Subjective Ratings Results

Listening in Quiet • Subjective ratings of effort in quiet results are displayed in Figure 4B. The analysis of the subjective data followed a similar approach to the dual-task analysis by using forward selection. Compared to the intercept-only model, device condition provided significant explanatory power (χ^2 = 30.08, p < 0.001). Age did not contribute to the model (χ^2 = 0.23, p = 0.63) and was dropped from the fixed terms. Subjective ratings of effort in quiet were significantly lower in the aided condition compared with the unaided condition (β = −0.38, p < 0.001).

Listening in Noise • Subjective ratings of effort in noise results are displayed in Figure 4D. The analysis of the subjective data followed the same forward selection process described earlier. Compared to the intercept-only model, device condition did not provide significant explanatory power (χ^2 = 1.93, p = 0.16), but this predictor remained in the model because the goal of this study was to examine the effects of hearing aids on effort. Age did not contribute to the model (χ^2 = 0.003, p = 0.96) and was dropped from the fixed terms. There were no differences in subjective-effort ratings in noise between the unaided and aided conditions (β = −0.12, p = 0.17).

Correlations Between Behavioral and Subjective Measures of Listening Effort • A Spearman correlation analysis was conducted between the primary task performance (sentence recognition), secondary task performance (dual-task cost), and the subjective ratings to determine whether behavioral and subjective measures of listening effort were associated with one another. These analyses were completed separately for the unaided and aided conditions when listening to speech in quiet and noise. All p-values were corrected to account for multiple comparisons using the Bonferroni method.

Listening in Quiet • In the quiet condition, there was no correlation between dual-task cost and subjective measures of effort (r = 0.05, p = 0.77) when unaided, but there was a weak correlation when aided (r = 0.23, p < 0.001). There was a weak, but significant correlation between dual-task cost and primary task performance when unaided (r = −0.16, p < 0.001), but not when aided (r = 0.05, p = 0.78). In addition, there was a moderate correlation between primary task performance and subjective effort rating when unaided (r = −0.44, p < 0.001) and a weak correlation when aided (r = −0.23, p < 0.001).

Listening in Noise • In noise, there was no correlation between dual-task cost and subjective effort when unaided (r = −0.03, p = 1) or aided (r = 0.05, p = 0.79). There was no correlation between dual-task cost and primary task performance when unaided (r = 0.09, p = 0.97). There was a weak but significant correlation between dual-task cost and primary task performance in the aided condition (r = −0.2, p < 0.001). In addition, there was a moderate correlation between primary task performance and subjective effort rating when unaided (r = −0.44, p < 0.001), but no correlation when aided (r = −0.06, p = 0.63).

DISCUSSION

The purpose of this study was to examine the effect of hearing aids on listening effort in school-age CHH in quiet and in noise. In the present study, listening effort was measured using a dual-task paradigm and subjective ratings of effort. Dual-task costs were found to be lower in the aided versus the unaided condition when listening in noise, but not when listening in quiet. CHH subjectively reported lower listening effort in the aided condition compared with the unaided condition when listening in quiet, but not when listening in noise.

The Effect of Amplification on Listening Effort

An important and novel contribution of the present work is that this is the first empirical study to show that hearing aids reduce listening effort in CHH. The main finding of our study was that dual-task costs were lower when CHH wore their hearing aids in comparison to listening without their devices in noise, indicating lower effort with the use of amplification in more challenging listening environments. Prior studies have shown that hearing aids reduce listening fatigue (Jorgensen et al. 2025), facilitate growth in speech, language, and listening skills (Tomblin et al. 2015; Walker, Redfern, et al. 2019; Walker, Sapp, et al. 2019; Farquharson et al. 2022), and improve academic, social-cognitive, and executive function outcomes (Walker et al. 2017; Tomblin et al. 2020; McCreery & Walker 2022). Our findings indicate that reduced listening effort is an additional potential benefit of amplification for CHH, and that hearing aids may help CHH with managing listening demands in complex listening environments (Eisenberg et al. 2007). Taken together, these data provide support for consistent device use and optimizing acoustic access in noisy settings.

Variations in Methodologies Across Studies • Our results align with the findings of Sarampalis et al. (2009) and Gustafson et al. (2014) showing reduced listening effort when adults and CTH use hearing aid features (e.g., noise reduction or directional microphones) when listening in noise. It is important to note that the CHH in the present study did not have comparable auditory access as compared with the CTH in the study by Gustafson et al. The reduced access to speech information experienced by CHH, along with the masking of acoustic details (from noise), leads to higher reliance on top-down processes required to understand speech (Rönnberg et al. 2013). These factors ultimately influence how children allocate their effort. However, findings from the present study suggest that the use of amplification alleviates this additional effort in CHH to a degree.

Our results are inconsistent with McGarrigle et al. (2019), who showed no effect of amplification using a dual-task paradigm. It is important to note that their results trended toward traditional measures of significance, and in contrast to the present study, their sample was not based on a power analysis. In addition, the methods and population tested were different between the study by McGarrigle et al. and the present study. For example, the present study used sentence stimuli, providing more top-down linguistic information, instead of the single words used in McGarrigle et al. McGarrigle et al. tested children with a wider age range (6 to 13 years compared with 8 to 11 years), which could have contributed to differences between studies because older children tend to perform better in dual-task paradigms than younger children (Spandita & Jain 2025). Moreover, age not only influences dual-task performance but can also influence speech recognition in noise performance in general. McGarrigle used multitalker babble that ranged from −4 to +12 dB SNR rather than speech-shaped noise at a performance-based level as a masker in the present study. Prior studies show that children are more challenged by multitalker masking than speech-shaped noise over a longer developmental period (Leibold & Buss 2013; Corbin et al. 2016; Leibold et al. 2016). Differences in the susceptibility of multitalker and speech-shaped maskers in children may explain the inconsistencies between the present study and McGarrigle et al. (2019), which used multitalker maskers in a pediatric group with a wider age range. Furthermore, speech recognition in speech-shaped noise develops during childhood, maturing around 10 years old (Corbin et al. 2016). Some children in this study may have mature perception under these conditions, while others may still be developing this skill, which could impact results. However, it is unlikely that differences in population would impact the effect of hearing aids on this task.

Differences in secondary task procedures between studies could also play a role in the conflicting findings. McGarrigle et al. (2019) obtained secondary task baseline reaction times in the presence of auditory stimuli, which likely resulted in slower baselines in comparison to the present study. Thus, our approach may have resulted in higher dual-task costs because of the quicker baseline reaction times. In contrast to McGarrigle, our secondary-task probe occurred on all trials, meaning participants were not required to inhibit irrelevant visual stimuli. Given that these methodological differences could result in either increasing or decreasing dual-task costs, it is difficult, if not impossible, to speculate on how variations in the secondary task across studies affect the present results in relation to previous work. The discrepancies in methods and results described here (and in the introduction) highlight the need for more consistent methodological designs across studies examining listening effort in children.

Subjective Reports of Effort

In addition to the dual-task paradigm, CHH participated in subjective ratings of effort. In quiet, CHH reported lower effort in the aided condition versus the unaided condition, confirming our hypothesis that amplification reduces subjective reports of listening effort. However, there was no significant subjective benefit of hearing aids for effort when listening in background noise. The discrepancy between the dual-task and subjective results suggests that processing effort and subjective effort may reflect different aspects of the listening experience (McGarrigle et al. 2014; Francis & Love 2020). Moreover, the relationship between the behavioral and subjective measures of effort was absent or weak in both quiet and noise when aided and unaided. Our findings are in line with previous results demonstrating that behavioral and subjective measures of listening effort tend to have weak to fair relationships (Shields et al. 2023). However, significant relationships were found between primary task performance (i.e., speech understanding) and subjective effort ratings when children did not wear their devices in both noise and quiet. This finding suggests that children may base their effort judgments on their speech understanding performance rather than effort, which is consistent with studies in adults (Moore & Picou 2018). Together, the results of the present study are consistent with prior work suggesting that listening effort is multidimensional, and various approaches to measuring effort may assess different aspects of listening effort (Strand et al. 2018; Alhanbali et al. 2019; Francis & Love 2020; Shields et al. 2023).

Current Models of Listening Effort

The present study's results are in support of both the Ease of Language Understanding model (ELU; Rönnberg et al. 2013, 2019) and the Framework for Understanding Effortful Listening (FUEL; Pichora-Fuller et al. 2016). Within the ELU model, factors that degrade auditory signal transmission would increase listening effort due to the increased need to resolve ambiguities between the speech signal and an individual's long-term representation. In the present study, the finding that hearing aids reduce listening effort aligns with the ELU model, as this reduction in effort may be due to an increase in sensation level, potentially reducing the need to rely on higher-level top-down processing abilities to understand speech. Going further, FUEL incorporates the Capacity Theory of Attention (Broadbent 1958; Kahneman 1973), which proposes that the brain has a fixed capacity for attention. If a listener directs more attention towards the primary auditory task when the signal is degraded, more resources are directed towards attending to the acoustic-phonetic input. Thus, there is a reduction in resources for cognitive-linguistic processes, and performance on the secondary task declines. The FUEL expands this seminal theory by incorporating a motivation component to its framework and defining listening effort as the intentional allocation of mental resources to overcome obstacles in goal pursuit during listening tasks (Pichora-Fuller et al. 2016). The behavioral results from this study correspond with the FUEL as the lower demands on cognitive resources in the aided condition enabled children to allocate such resources toward the secondary task, leading to faster response times and ultimately lower dual-task cost.

Considerations for Future Research on Listening Effort • This study, and most prior studies on listening effort, have used materials and procedures that do not mimic real-world experiences that could ultimately shape how a child allocates their effort. The Model of Listening Engagement (Herrmann & Johnsrude 2020a) has connected the concepts of experience, motivation, and engagement during listening. Tasks examining listening absorption have recently been used to better understand the relationship between engagement, motivation, and experiences during listening. For example, listeners who knew about and liked a certain topic of a narrative they heard reported less effort when listening, greater enjoyment, and better comprehension (Herrmann & Johnsrude 2020b). Future work using such tasks may better reflect real-world allocation of effort than tasks like the one used in the present study. Moreover, children often listen to stories in the classroom and at home; thus, incorporating narratives into studies of effort and fatigue could potentially shed light on the factors that ultimately influence successful listening and overall communication. Beyond linguistic manipulations, conducting experiments in more ecologically valid settings would aid in improving the understanding of listening effort in children. For example, the present study was completed in a controlled laboratory setting; however, difficult listening environments like the classroom include a number of factors beyond noise that could influence how and when a child allocates effort, such as distractors.

Clinical Implications

Our results have relevance to both clinicians and researchers. Clinically, audiologists working with CHH should emphasize the importance of consistent hearing aid device use given that the present study's findings show reductions in listening effort with amplification. Such benefits add to the existing evidence in support of use of amplification to promote improved access to sound and spoken language development in CHH (Walker et al. 2015; Tomblin et al. 2020; Wiseman et al. 2023). Moreover, the use of hearing aids in the classroom may promote better multitasking performance (e.g., listening to the teacher while taking notes) as demonstrated by the improvement of dual-task performance in the present study. While children did not demonstrate a change in subjective effort in noise with their hearing aids, the reduction in dual-task cost suggests that they receive benefit from hearing aids via reduced effort. In other words, children were better able to allocate their effort with hearing aids in noise even when they did not notice a subjective change in effort. This finding highlights the importance of an audiologist's role in counseling, especially when a child may not subjectively perceive benefits from their hearing aids.

Limitations and Future Directions

One limitation of the present study is that it was intended for performance in the unaided condition in noise to reflect each child's specific SNR-70. Despite presenting the stimuli at the unaided SNR-70 measured before dual-task testing, children tended to score higher than 70% in both the unaided and aided condition. Practice effects may have played a role in performance being better than originally expected. However, it is more likely that our protocol of obtaining individual SNR-70 was not reliable. As demonstrated by Wu et al. (2016) and Perreau et al. (2017), this type of procedure reliably estimates adult SNRs for a given intelligibility score, but the variability in performance levels obtained in the present study suggests that this approach may not be appropriate for children. Despite this limitation, children still demonstrated an improvement in dual-task cost (i.e., reduced listening effort) with the use of personal amplification in individualized SNRs.

In the present study, the age range of participants was between 8 and 11 years. Because maturation of speech recognition in speech-shaped noise occurs at approximately 10 years old, younger children in this study may have had more challenges with the speech recognition task compared with older children. A multitalker masker would have been more ecologically valid and reflected a more real-world communication environment. Furthermore, future work in children could expand the scope of the present study to younger and older children to better our understanding of the effect of amplification on listening effort in CHH. As children develop, cognitive-linguistic skills and knowledge grow, which can influence speech recognition performance (Stelmachowicz et al. 2000; McCreery et al. 2015; Klein et al. 2017). Thus, changes in primary task performance (speech recognition) due to improvements in cognitive-linguistic skills may influence secondary task performance (listening effort). For example, if a child is more familiar with the vocabulary used in the speech stimuli, they may not exert as much effort as compared with hearing stimuli with less familiar vocabulary. Investigating how cognition and language influence listening effort would be important for addressing the underlying mechanisms related to extra effort exertion in CTH and in CHH across a wide age range.

The participants in this study varied in their aided and unaided audibility levels. In the present study, the speech signal was presented at 65 dB SPL, meaning that some children may not have had adequate access to the signal with and without their devices. Moreover, less audibility in the unaided condition could have rendered the task as more difficult, ultimately influencing effort. Due to power limitations, we were unable to examine whether aided audibility levels or RMS error (a metric of quality of hearing aid fittings) functioned as moderators in the relationships between aided versus unaided hearing and listening in quiet versus noise on listening effort. However, the average RMS error (Table 1) was less than 4 dB, suggesting that the children had well-fitted hearing devices. A future direction of this work is to explore the impact of individual differences in audibility, as well as cognitive-linguistic factors, on listening effort in CHH.

During the dual-task procedure in noise, the presentation of noise began 1 second before and ended 1 second after the presentation of speech stimuli, which provided moments of silence between trials. This methodological decision may have influenced results in two ways. First, some children's hearing aids may have used digital noise reduction (DNR), which could improve the SNR during steady state noise. However, such improvements on SNR have been shown to be relatively small (Miller et al. 2017). Previous work has shown that DNR features may not provide consistent improvements in speech perception in noise (Bentler et al. 2008; Brons et al. 2014; Wong et al. 2018), but can improve self-perceived ease of listening (Bentler et al. 2008; Gustafson et al. 2014). Second, because the noise turned on and off between trials, the repeated activation and deactivation of DNR could have altered auditory signal quality. However, DNR onset and offset times can vary across hearing aid manufacturers with onset times typically taking several seconds to activate (Bentler & Chiou 2006; Wong et al. 2018). It is possible that a single trial in the present study was not long enough in duration to activate DNR. In either case, the present study is unable to determine whether CHH experienced relief from effort because of DNR as we did not document whether the children's hearing aids had these features.

CONCLUSION

This is the first study to show that hearing aids reduce listening effort in CHH. Dual-task cost was lower when listening in noise in the aided condition versus the unaided condition, indicating that hearing aids improve ease of listening in CHH. Subjectively, children reported relief from effort when wearing their hearing aids when listening in quiet. These results highlight a benefit of using hearing aids that is not directly addressed during standard audiologic care. This study further demonstrates the importance of CHH consistently using their hearing aid devices to reduce effortful listening during everyday communication. Our findings can be used by audiologists to counsel patients and their parents about hearing device use, benefits, and to advocate for supporting hearing aid use in educational environments.

ACKNOWLEDGMENTS

We thank our participants and their parents for participating in this study.

This study was supported by the National Institutes of Health National Institute on Deafness and Other Communication Disorders (R21 DC015832 & R01 DC019081; PI: Elizabeth A Walker), the University of Iowa, and Boys Town National Research Hospital.

S.P.G. analyzed the data and wrote the manuscript. K.B.W. contributed to the analysis and writing, and E.A.W. designed and performed the experiments and contributed to the writing.

All study procedures were approved by the University of Iowa's Institutional Review Board (IRB), Number 201512760, PI: Elizabeth A. Walker.

The authors have no conflicts of interest to disclose.

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Received October 24, 2024; accepted January 16, 2026; published online ahead of print March 5, 2026

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