Auditory training of speech recognition with interrupted and continuous noise maskers by children with hearing impairment

Jessica R. Sullivan^{a)}

Department of Speech and Hearing Sciences, University of Washington, Seattle, Washington 98195-4875

Linda M. Thibodeau and Peter F. Assmann

School of Brain and Behavioral Sciences, University of Texas at Dallas, Richardson, Texas 75083

(Received 15 November 2011; revised 26 September 2012; accepted 19 November 2012)

Previous studies have indicated that individuals with normal hearing (NH) experience a perceptual advantage for speech recognition in interrupted noise compared to continuous noise. In contrast, adults with hearing impairment (HI) and younger children with NH receive a minimal benefit. The objective of this investigation was to assess whether auditory training in interrupted noise would improve speech recognition in noise for children with HI and perhaps enhance their utilization of glimpsing skills. A partially-repeated measures design was used to evaluate the effectiveness of seven 1-h sessions of auditory training in interrupted and continuous noise. Speech recognition scores in interrupted and continuous noise were obtained from pre-, post-, and 3 months post-training from 24 children with moderate-to-severe hearing loss. Children who participated in auditory training in interrupted noise demonstrated a significantly greater improvement in speech recognition compared to those who trained in continuous noise. Those who trained in interrupted noise demonstrated similar improvements in both noise conditions while those who trained in continuous noise only showed modest improvements in the interrupted noise condition. This study presents direct evidence that auditory training in interrupted noise can be beneficial in improving speech recognition in noise for children with HI. © 2013 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4770247>]

PACS number(s): 43.71.Ky [PNN]

Pages: 495–501

I. INTRODUCTION

Listeners with normal hearing (NH) obtain higher-speech recognition scores when the masker is interrupted rather than continuous but presented at the same signal-to-noise ratio (SNR) (Miller and Licklider, 1950). Listeners with sensorineural hearing impairment (HI) do not exhibit this release from masking (Festen and Plomp, 1990). Several explanations have been considered for the diminished benefit experienced by hearing-impaired listeners from temporal gaps. One possibility is reduced audibility of speech located in the temporal gaps of the noise. However, amplification does not restore the masking release and several researchers have found that a reduced release from masking only partially accounts for poor speech recognition in noise for some listeners with HI (Bacon *et al.*, 1998; Jin and Nelson, 2010). Another possibility is that listeners with HI experience increased forward masking (Festen and Plomp, 1990). Together with audibility, frequency selectivity and forward masking are suggested to contribute to poor speech intelligibility in noise (Gifford *et al.*, 2007).

Recent accounts have suggested that the masking release experienced by NH listeners is not the product of a single mechanism but the result of several malleable processes. Miller and Licklider (1950) proposed that listeners apply a strategy of “auditory glimpsing” to access several brief snapshots of a stream of speech to fill in the missing parts in noisy environments. This mechanism is analogous to

the visual process of glimpsing which allows an observer to interpret a visual scene based on partial information presented sequentially. Glimpsing is a complex process involving both lower-level auditory skills required for the detection of speech fragments in the gaps in the noise combined with the higher-level integration of these fragments into meaningful sentences. It has been proposed that glimpsing can occur both in the time domain and in the frequency domain (Howard-Jones and Rosen, 1993; Peters *et al.*, 1998). The current study examines temporal glimpsing only.

Computational models of glimpsing have been developed to account for one strategy individuals may use to perceive speech in noise (Cooke, 2006). Cooke’s model incorporates a spectrotemporal representation based on a simulation of auditory peripheral analysis. Spectral and temporal modulations in the speech signal (and in the masker) give rise to local regions in time and frequency where the speech is relatively less corrupted by the noise. Glimpses are defined as time-frequency regions where the local SNR exceeds a threshold (e.g., 3 dB). Glimpses extracted from these regions provide a sparse but relatively clean estimate of the target speech signal. The model applies missing-data techniques (Barker and Cooke, 1997; de Cheveigne and Kawahara, 1999) to integrate glimpses over time in an automatic speech recognition framework based on hidden Markov models. The model provided relatively accurate predictions of consonant recognition in noise and demonstrated that intelligibility is correlated with the proportion of glimpses extracted from the time-frequency plane by the model.

^{a)}Author to whom correspondence should be addressed. Electronic mail: sulli10@uw.edu

Cooke's model does not address the development of glimpsing skills but there is evidence that adult listeners with NH may improve their ability to exploit silent gaps in a noise masker with extended exposure and feedback (Rhebergen *et al.*, 2008). The findings of Rhebergen *et al.* suggest that extended listening in interrupted noise can enhance NH listeners' ability to exploit masker fluctuations, which results in improved speech reception thresholds in interrupted noise over a series of trials. The focus of the current study is whether children with HI can benefit from auditory training to gain a benefit from masker fluctuations.

Children with HI appear to have a similar pattern of auditory skill development as their peers with NH in quiet listening conditions. However, in more complex listening tasks that require sophisticated auditory skills, such as speech recognition in noise, deficits emerge in children with hearing loss (Jerger, 2007). This difficulty of understanding speech in noise has a negative impact on their language development and academic progress and is well documented in the literature (Dockrell and Shield, 2004; Finitzo-Hieber and Tillman, 1978; Stelmachowicz *et al.*, 2004). Little is known about the strategies or underlying mechanisms involved in speech recognition in noise for children with HI. Studies of masking release in younger NH children suggest that similar to HI adults, they experience little or no masking release, however this ability is fully developed by children 11 yrs of age with NH (Stuart, 2008; Stuart *et al.*, 1995). Children with HI may not follow the same developmental time course for speech recognition in noise and do not benefit from the masking release as shown by peers with NH.

The purpose of the present study was to determine if the reduction in masking release experienced by children with moderate-to-severe sensorineural HI can be improved by a training procedure that focuses the listener's attention on the important properties of speech during masker interruptions. Children with HI were assigned to one of two training groups: Auditory training in interrupted noise and auditory training in continuous noise so that the immediate and long-term effects of intervention could be determined. Immediate effects were examined by comparing speech recognition in conditions of interrupted and continuous noise maskers for children with HI before and directly after seven 1 h training sessions over a 3 week period. Long-term training-related improvements were examined by comparing speech recognition in conditions of interrupted and continuous noise maskers before and 3 months after training. The auditory training paradigm was designed to adapt to the individual's performance across several levels. This type of perceptual training has been successful in examining neural and behavioral changes in animals and humans (Alain and Tremblay, 2007; Atienza *et al.*, 2002; Boothroyd, 2010; Kilgard *et al.*, 2007; Moucha and Kilgard, 2006; Tremblay *et al.*, 1997; Tremblay *et al.*, 1998). Auditory training in noise resulted in improved speech recognition in noise for adults with HI and in some instances led to a generalization of improvements to novel stimuli (Burk and Humes, 2008; Sweetow and Sabes, 2006). Currently, there is no evidence on the effectiveness of auditory training in noise for pediatric hearing aid users.

The current auditory training paradigm included three manipulations that varied the difficulty level adaptively based on word recognition performance: SNR, the number of keywords, and time delay. The stimuli used during the auditory training were simple sentences with words and themes familiar to children. Children were asked to listen to a sentence in either continuous or interrupted noise and to identify the keyword(s) via the computer. The first manipulation was the SNR to ensure training was at an audible but challenging level. The second manipulation was the number of keywords to be held in working memory and rehearsed. The third manipulation was a time delay between the offset of the auditory stimulus and the appearance of the answer grid on the computer screen. The purpose was to vary the amount of time required to hold the keyword(s) in the auditory memory loop. Two questions were examined: (1) Do children who trained in the interrupted noise demonstrate improved speech perception in noise scores when tested in interrupted or continuous noise immediately following training, and (2) are the perceptual improvements associated with training maintained three months post-treatment?

II. METHODS

A. Participants

Twenty-four children, ages 6–17 with a mean age of 11 yrs, with moderate-to-severe sensorineural hearing loss were divided equally into three training groups: Auditory training interrupted (ATI), auditory training continuous (ATC), and a control (described below). A quasi-randomization method was used to assign the children to a training group based on their age, pre-training speech recognition scores in interrupted noise, and better-ear pure tone average (PTA). While the etiology of hearing loss was unknown for the majority of the participants, six were hereditary and they were equally distributed among the groups. Summarized in Table I is the participant mean demographic information including age, gender, better ear PTA, and age of amplification. All children were bilateral, behind-the-ear hearing aid users. Hearing aid function was verified using the Fonix-FP40 hearing aid analyzer prior to testing and training. It should be noted that participants were asked not to make any changes to their hearing aid programming while participating in the study. Participants were oral communicators, educated in mainstream programs, and demonstrated age-appropriate expressive and receptive language as measured by the Oral and Written Language Scales: OWLS (Carrow-Woolfolk, 1996).

B. Stimuli

Two types of speech materials were used in auditory training and assessments, each accompanied by noise maskers.

1. Auditory training target sentences

A corpus of 3000 sentences used for auditory training was recorded by young-adult male and female talkers. The sentences were recorded in a double-walled Wenger sound-treated booth using a desktop microphone (Condenser Shure model SM94). The speech materials were declarative

TABLE I. Mean demographic information.

Training groups	Gender, <i>N</i>	Age at testing (Years/SD)	Better ear PTA (dB HL/SD)	Age at first hearing aids (Months/SD)	Pre-training SRT interrupted (dB A/SD)
ATI	<i>M</i> ,2; <i>F</i> ,6	12/3.55	51.87/17.59	52.45/56.60	9.46/2.96
ATC	<i>M</i> ,4; <i>F</i> ,4	11/3.55	54.0/18.91	25.50/21.99	10.44/2.63
Control	<i>M</i> ,4; <i>F</i> ,4	11/2.78	49.87/16.48	32.87/30.87	7.33/5.26

Note: ATI = auditory training interrupted; ATC = auditory training continuous; *N* = number of participants; *M* = male; *F* = female; Ages are given in years (age at testing) and months (age at first hearing aid); PTA = pure tone average; SRT = speech recognition threshold; SD = standard deviation.

sentences ending with a noun phrase composed of adjective, adjective, and noun; or possessive noun, adjective, and noun. For example, *we ate three green grapes*. The sentences were based on 6 themed categories (Food 1, Food 2, Animals, Clothing, Transportation, and Toys) with 216 sentences each and 1 category (House) with 125 sentences. The final three keywords were monosyllabic consonant-vowel-consonant words to increase homogeneity of the stimuli within the category. The sentences were recorded at a sampling rate of 48 828 Hz using recording hardware for the Tucker Davis System 3. The sentences were recorded at a relatively slow, clear speaking rate of approximately 4 s in duration. The total recording time was approximately 5 h per talker. All of the sentences were manually edited for errors and extraneous noise using WaveSurfer © (Sjölander and Beskow, 2000) and then scaled to an equal root-mean-square level.

2. Auditory training maskers

Two types of speech-shaped noise were used. Continuous noise was generated from random samples of digital speech (male and female) and shaped based on the long-term average speech spectrum of the female-talker stimuli. Interrupted noise was generated from the speech-shaped noise by adding random interruptions of 5 to 95 ms at a duty cycle of 0.50 to mimic the acoustic properties of speech (Stuart, 2005; Stuart and Phillips, 1996).

a. Auditory training paradigm. An adaptive auditory training paradigm was designed to change the difficulty level by manipulating SNR, number of keywords, and time delay. The initial starting level was a +6 dB SNR, ¹ 2 keywords, and a 2 s time delay. A block is three sets of ten sentences within each set the target keywords varied based on their position in the sentence. If the average performance for any particular block was less than 80% the task changed to an easier SNR, fewer keywords or shorter time delay condition, in that order, until an 80% correct performance level was achieved. If an average of 80% or greater was achieved on a given block, the difficulty level was increased in the same order. Only one change occurred in each block of trials.

3. Speech recognition in noise assessments

The automated Hearing in Noise Test (HINT), version 6.3 (Nilsson *et al.*, 1994) was administered at three intervals: Pre-training, post-training, and 3-months post-training. The masking noise from the HINT calibration track was modified following the same procedure as previously described to generate interrupted and continuous noise conditions.

C. Procedure

All auditory training and speech recognition testing was conducted in a double-walled sound booth with speech from the front loudspeaker at (0° azimuth) and noise from the rear (180° azimuth). Auditory training target sentences were presented using the computer sound card via a custom MATLAB © script and a Crown amplifier. Auditory training noise maskers were routed from a compact disc player. The speech stimuli were presented at a fixed level of 55 dB A and the noise level varied adaptively based on the required SNR for the training level. The speech recognition in noise assessments consisted of HINT sentences that were generated by the hearing threshold device (Nilsson *et al.*, 1994). Participants completed speech recognition testing in interrupted noise and continuous noise in counterbalanced order. The noise was generated and routed in the same manner as in the auditory training. During the auditory training and assessment, noise was present throughout the entire session.

1. Auditory training in interrupted and continuous noise

Training sessions for each participant were conducted in seven 1 h sessions over a 3 week time period. Prior to the beginning of each session, the examiner selected the gender of the talker (alternating male and female) and one of six themes (chosen at random). Before training, the children completed a practice run of ten sentences in quiet to familiarize them with the training procedure. The children were instructed to listen to the sentence and then select a response button that displayed an image and a superimposed printed keyword. The answer grid and target keyword(s) changed every ten trials as described above. The answer grid displayed response buttons that were arranged in three columns each with six rows showing the available choices. On any given block of 30 trials, 1, 2, or 3 columns were activated based on the number of keywords, and the non-target column(s) were grayed out. Depending on the theme, column 1 contained either names or numbers, column 2 contained colors or numbers, and column 3 contained objects or animals, as shown in Fig. 1. The active columns corresponded to the position of the keyword in the sentence and semantic category based on the theme. For example, if the sentence was *Grandmother gave Bob red beans*, the word *Bob* would appear in column 1, *red* in column 2, and *beans* in column 3. When two target keywords were required then the block progression was as follows: Columns 2 and 3 (10 trials), followed by columns 1 and 2 (10 trials), and then columns

FIG. 1. Example of answer grid requiring a three keywords response.

1 and 3 (10 trials). With one target keyword the block progression was as follows: Column 3, column 2, and column 1. To maintain consistent motivation and provide positive feedback, 1 of 50 familiar cartoon characters was randomly presented after each correct response. Following an incorrect response, a yellow square, neutral feedback, was presented.

The training activities were scored online, and changes in the difficulty level were automated within MATLAB for the time delay and number of keywords while the SNR was changed manually via the crown amplifier. All of the responses were recorded for each block in a separate file. The number of blocks completed ranged from 4 to 12 blocks per session. Typically, the older children were able to complete more blocks within a 1-h session.

2. Control group

Children in the control group were asked to complete visual training games in quiet on the same time course as the experimental groups. A variety of commercially-available analytic games and puzzles were selected because they lacked linguistic or auditory content. Prior to the beginning of a session, the game was selected by the examiner for the 1-h session. Because a variety of commercially-available analytic puzzles were used, quantifying performance across games was not possible. The control group was reinstructed at the beginning of each session because the games varied from session to session. For this reason performance was closely monitored by the examiner.

D. Speech recognition in noise assessment

The automated-HINT (version 6.3) was administered in two conditions, interrupted and continuous noise, over three time periods: Pre-training, post-training, and 3-months post training. The noise conditions were counterbalanced for each

participant. Auditory responses digitally recorded by a second scorer who was blind to the training were used to verify the reliability of scores offline for 25% of all sentences.

III. RESULTS

A. Auditory training

During the auditory training conditions, children were asked to identify keywords from simple sentences in the presence of interrupted or continuous noise. Mean daily performance was slightly higher in the ATI group compared to ATC. However, the mean daily performance in both groups consistently ranged between 80% and 95%. Children in the ATI group demonstrated a consistent performance between 75% and 100% across the seven training sessions. All children in the ATC group except for one demonstrated consistent performance greater than 80% across all training sessions.

B. Speech recognition in noise assessments

To examine the relative speech recognition in noise abilities across the three training groups prior to training, the pre-training speech recognition thresholds (SRTs) were compared.

Figure 2 illustrates the average change in group SRTs over time in each noise condition. The ATI group demonstrated improved SRTs over time in both noise conditions, however, this pattern of improvement was not demonstrated by the ATC or control group. A simple effects planned comparison was performed on the pre-, post-, and late post (3 month) SRT to determine if there were significant changes in SRTs across groups and noise conditions. There was a significant improvement in pre- to post-training SRT scores for the ATI group in interrupted noise $F_{1,21} = 37.17$, $p < 0.0001$ and continuous noise, $F_{1,21} = 31.83$, $p < 0.0001$, respectively. The ATC group demonstrated a significant

FIG. 2. Average SRT change measured in interrupted and continuous noise over time training by the training group. Note: Error bars indicate $\pm$ standard errors of the mean. ATI=auditory training in interrupted noise, ATC=auditory training in continuous noise.

improvement pre- to post-training in the interrupted noise condition, $F_{1,21} = 4.43$, $p < 0.04$. There was no significant difference in pre- and post-training SRT scores in the continuous noise condition for ATC, $F_{1,21} = 0.20$. The control group did not demonstrate a significant improvement in pre- to post-training in interrupted noise $F_{1,21} = 1.94$. The control group demonstrated a significant improvement in pre- to post-training in the continuous noise $F_{1,21} = 7.92$, $p < 0.01$.

There was a significant improvement in pre- to late-post-training SRT scores for the ATI group in interrupted noise $F_{1,21} = 83.30$, $p < 0.0001$ and continuous noise, $F_{1,21} = 94.30$, $p < 0.0001$, respectively. The ATC group demonstrated a significant improvement in pre- to late-post-training in the interrupted noise condition, $F_{1,21} = 18.64$, $p < 0.04$. There was no significant difference in pre- and post-training SRT scores in the continuous noise condition for ATC, $F_{1,21} = 0.20$. There was no significant difference for the control pre- and post-training SRT scores in the interrupted $F_{1,21} = 0.05$ continuous noise conditions, $F_{1,21} = 0.74$.

No significant difference emerged between post- and late-post-training SRT scores in the interrupted noise condition for ATI, $F_{1,21} = 2.30$. In the continuous noise condition there was a significant improvement from post- to late-post-training SRT scores for the ATI group, $F_{1,21} = 5.29$, $p < 0.03$. The ATC group did not demonstrate a significant difference in post- to late-post SRT scores in the interrupted or continuous noise conditions. There was no significant difference for the control pre- and post-training SRT scores in the interrupted or continuous noise conditions.

To assess whether there were any differences among the group prior to training, an analysis of covariance (ANCOVA) was performed on pre-training SRT in each interrupted and continuous noise condition, $F(1,48) = 0.00$, $p = 0.99$. It is important to determine if other factors contribute to observed differences, therefore better-ear PTA and age were held constant. The ANCOVA revealed no significant differences among ATI, ATC, and control pre-training SRT in both noise conditions.

In order to determine whether the speech recognition in noise abilities has improved following auditory training, the

changes from pre-training SRT to post- and late-post (3-months) training were calculated and reported as difference scores. Difference scores were calculated by subtracting the post-SRT and late-post score from the pre-SRT score to determine changes in performance over time in the respective noise conditions. Nominally positive difference scores were observed which indicated an improvement in speech recognition. Across time and noise conditions, positive difference scores were observed for 6 out of 8 (ATI), 2 out of 8 (ATC), and 3 out of 8 (control). Figures 3 and 4 display the mean pre vs post and pre vs 3 months post difference scores for the ATI, ATC, and control conditions, respectively. The ATI group showed similar speech recognition improvements in both noise conditions at each time interval and the highest average improvement of all training groups.

An ANCOVA was conducted to establish whether SRTs improved following training, with group as a between-subject factor, and time and noise as within-subject factors, and better-ear PTA and age as covariates. The dependent variable was difference scores. There was a significant main effect of group, $F(2,96) = 8.75$, $p < 0.0003$, $R^2 = 0.14$. There was no significant main effect of time ($p = 0.27$) or noise ($p = 0.83$). There was a significant effect of age, $F(1,96) = 7.12$, $p < 0.01$, $R^2 = 0.06$ and better-ear PTA, $F(1,96) = 4.12$, $p < 0.04$, $R^2 = 0.03$. Further *post hoc* analysis (Tukey Kramer HSD criteria) revealed that with age and better-ear PTA held constant, the ATI group was significantly different from the ATC and control groups. In other words, children who participated in auditory training in interrupted noise demonstrated greater improvement in speech recognition in noise than those in the auditory training in continuous noise and visual training groups. Despite the fact that age and better-ear PTA were significant covariates, their contribution to the total amount of the variance was relatively small, $R^2 = 0.06$ and $R^2 = 0.03$, respectively.

Figure 4 illustrates that the improvements in speech recognition in interrupted and continuous noises were

FIG. 3. Mean pre vs post difference scores on the HINT measured in interrupted and continuous noise across training groups. Note: Error bars indicate standard errors of the mean. ATI=auditory training in interrupted noise, ATC=auditory training in continuous noise.

FIG. 4. Mean pre vs 3-months post difference scores on the HINT measured in interrupted and continuous noise across training groups. *Note:* Error bars indicate standard errors of the mean. ATI = auditory training in interrupted noise, ATC = auditory training in continuous noise.

maintained 3-month post-training for the experimental groups. The ATI group maintained the largest improvements of speech recognition abilities in interrupted [$M = 7.46$ dB, standard deviation (SD) = 7.21] and continuous noise ($M = 7.13$ dB, SD = 5.14) 3-months following auditory training. The range of improvements 3-months post-training for the ATI group was 4.50 to 23.10 dB in the interrupted noise condition and 1.40 to 16.9 dB in the continuous condition.

Similarly, the ATC group demonstrated a sustained benefit in the interrupted noise ($M = 3.51$ dB, SD = 4.19) and the continuous condition ($M = 1.06$ dB, SD = 3.13) 3-months following training. Furthermore, the control group demonstrated minimal sustained improvement in speech recognition in interrupted ($M = 0.19$ dB, SD = 4.64) and continuous noise ($M = 0.89$ dB, SD = 4.46) as expected.

IV. DISCUSSION

The purpose of this study was to compare the immediate and long-term effects of auditory training in interrupted and continuous noise for children with moderate-to-severe hearing loss. It was hypothesized that children who participated in 7 h of auditory training in interrupted noise delivered over a 3-week period would demonstrate greater immediate benefits in speech recognition in noise compared to those who trained in continuous noise. A significant main effect of the training group was observed and a *post hoc* analysis revealed that the group that trained in interrupted noise had significantly greater improvements in speech recognition in noise than the visual training group. In addition, it was revealed that ATI was significantly better than ATC and control in both interrupted and continuous noise conditions.

The auditory training was designed to provide several changes in SNR, number of keywords, and time delay to vary the difficulty level of training. However, the ATI and ATC groups worked consistently above 80% on the daily training task, indicating that the parameters were not chal-

lenging enough despite being in noise. Therefore, the degree of improvement may have been reduced due to less challenging tasks. Perhaps a greater achievement could have been achieved in the interrupted noise condition with a more challenging training task by providing more severe SNR, a larger SNR step-size, or an increase in the number of keywords to recall. Previous researchers have reported the greatest benefit from a perceptual-learning task occurs when training is at a challenging level (Atienza *et al.*, 2002; Kilgard *et al.*, 2007; Moucha and Kilgard, 2006; Tremblay, 2007). Burk and Humes (2008) provided evidence that using lexically-hard words in auditory training in noise was beneficial for improving speech recognition in noise for adults with HI.

Despite comparable-duration of training in the similar word-identification tasks there was a significant difference in the benefits seen in the ATI and ATC groups in speech recognition performance in the presence of both interrupted and continuous noise maskers. The ATI group demonstrated at least 4 and 5 dB greater improvement in difference scores in interrupted and continuous noise conditions, respectively, compared to ATC and control groups. This finding suggests that participating in auditory training in interrupted noise may provide a greater perceptual advantage for individuals with HI than training in continuous noise.

The ATI and ATC groups were similar in age, pre-training SRT, and performance on the word-identification task during training. A plausible interpretation of the large differences in pre vs post difference scores in interrupted and continuous noise could reflect a further development of glimpsing skills by the ATI group. The children who trained in interrupted noise demonstrated a generalization of improvements to continuous noise. Thus, it could be concluded that glimpsing occurs in a variety of complex listening environments but that the interrupted noise provided more opportunities to “glimpse” auditory cues that improved speech understanding in noise. The improvements observed following auditory training in interrupted noise demonstrate a more efficient and sophisticated development of glimpsing skills than those in the ATC group.

In conclusion, this investigation provides direct evidence that auditory training in interrupted noise is beneficial in improving speech recognition in noise for children with HI. This is the first step in developing computer-based auditory training programs that could lead to better management of children with HI. It is important to provide materials designed to improve speech recognition in noise for children with HI. Furthermore, improving the speech recognition in noise for children with HI may result in increased access to socialization with peers, extracurricular activities, and academic instruction. The findings from this investigation have clinical and theoretical implications for further development of aural habilitation interventions. Remarkably, the average improvement 3-months post-training was approximately 7.46 dB in interrupted noise and 7.13 dB in continuous noise for children who trained in interrupted noise for 7 h. A 1-dB improvement on the HINT is equivalent to an 8.9% improvement in speech intelligibility (Nilsson *et al.*, 1994). Therefore, based on the HINT speech recognition prediction, the ATI group demonstrated approximately 51% and 47%

improvement of speech intelligibility in interrupted and continuous noise, respectively. This corresponds to an approximate 63% improvement in word recognition based on the predicted 8.9% enhancement in speech intelligibility for every 1-dB change on the HINT. Perhaps short-term auditory training in interrupted noise could have a considerable impact on the academic and social achievement for children with HI who are educated in mainstream settings.

ACKNOWLEDGMENTS

The authors would like to thank Dr. James Jerger and Dr. Michael Kilgard for their feedback and encouragement throughout this research. Support for this research was provided by the National Institute of Deafness and other Communication Disorders F31 DC9537. We thank our participants and their families for their cooperation and support.

¹Prior to the implementation of the auditory training paradigm, a performance intensity (PI) function was obtained based on the simple sentences used during training for 10 children, ages 6 to 16 with moderate-to-severe hearing loss in interrupted and continuous noise. Percent correct scores for word recognition in interrupted and continuous noise were plotted as a function of SNR at -18, -12, -6, 0, 6, and 12 dB. Third-order polynomial regression lines were fit to determine the 80% word recognition performance level in interrupted ($R^2=0.993$) and continuous noise ($R^2=0.998$). The PI functions for interrupted and continuous noise had similar slopes and overlapped as the SNR increased. The purpose of the PI function was to determine the 80% word-recognition performance level to begin auditory training. The 80% performance level for the interrupted noise was 6.73 dB SNR and the continuous noise was 6.41 dB SNR. Because the levels were similar, the initial training level was set to 6 dB SNR in both noise conditions. To determine the step-size for the changes in SNR from the initial level of 6 dB, a confidence interval (CI) was calculated for the interrupted and continuous noise. The 95% CI for the word recognition performance at the 6 dB SNR in interrupted noise and continuous noise were ± 4.90 and ± 8.52 , respectively. In the case of continuous noise the 95% CI was so wide that increasing the difficulty level to -2.52 dB SNR could have resulted in a frustrating training experience for children [-2.52 = 6 dB (starting SNR) - 8.52 (Continuous Noise CI)]. For simplicity, a step-size was chosen that was close to the average of the CI for the interrupted and continuous noise condition. A 6-dB step-size was used so that the training SNR values would be 0, 6, and 12 dB.

- Alain, C., and Tremblay, K. (2007). "The role of event-related brain potentials in assessing central auditory processing," *J. Am. Acad. Audiol* **18**(7), 573–589.
- Atienza, M., Cantero, J. L., and Dominguez-Marin, E. (2002). "The time course of neural changes underlying auditory perceptual learning," *Learn Memory* **9**(3), 138–150.
- Bacon, S. P., Opie, J. M., and Montoya, D. Y. (1998). "The effects of hearing loss and noise masking on the masking release for speech in temporally complex backgrounds," *J. Speech Lang. Hear. Res.* **41**(3), 549–563.
- Barker, J., and Cooke, M. (1997). "Modelling the recognition of spectrally reduced speech," in *Proceedings of EUROSPEECH-97*.
- Boothroyd, A. (2010). "Adapting to changed hearing: The potential role of formal training," *J. Am. Acad. Audiol* **21**(9), 601–611.
- Burk, M. H., and Humes, L. E. (2008). "Effects of long-term training on aided speech-recognition performance in noise in older adults," *J. Speech Lang. Hear. Res.* **51**(3), 759–771.
- Carrow-Woolfolk, E. (1996). Oral and written language scales: OWLS, Circle Pines, MN, American Guidance Service.
- Cooke, M. (2006). "A glimpsing model of speech perception in noise," *J. Acoust. Soc. Am.* **119**(3), 1562–1573.

- de Cheveigne, A., and Kawahara, H. (1999). "Missing-data model of vowel identification," *J. Acoust. Soc. Am.* **105**(6), 3497–3508.
- Dockrell, J. E., and Shield, B. (2004). "Children's perceptions of their acoustic environment at school and at home," *J. Acoust. Soc. Am.* **115**(6), 2964–2973.
- Festen, J. M., and Plomp, R. (1990). "Effects of fluctuating noise and interfering speech on the speech-reception threshold for impaired and normal hearing," *J. Acoust. Soc. Am.* **88**(4), 1725–1736.
- Finitzo-Hieber, T., and Tillman, T. (1978). "Room acoustics effects on monosyllabic word discrimination ability for normal and hearing impaired children," *J. Speech Lang. Hear. Res.* **21**, 440–458.
- Gifford, R. H., Bacon, S. P., and Williams, E. J. (2007). "An examination of speech recognition in a modulated background and of forward masking in younger and older listeners," *J. Speech Lang. Hear. Res.* **50**(4), 857–864.
- Howard-Jones, P. A., and Rosen, S. (1993). "Unmodulated glimpsing in 'checkerboard' noise," *J. Acoust. Soc. Am.* **93**(5), 2915–2922.
- Jerger, S. (2007). "Current state of knowledge: Perceptual processing by children with hearing impairment," *Ear Hear.* **28**(6), 754–765.
- Jin, S. H., and Nelson, P. B. (2010). "Interrupted speech perception: The effects of hearing sensitivity and frequency resolution," *J. Acoust. Soc. Am.* **128**(2), 881–889.
- Kilgard, M. P., Vazquez, J. L., Engineer, N. D., and Pandya, P. K. (2007). "Experience dependent plasticity alters cortical synchronization," *Hear. Res.* **229**, 171–179.
- Miller, G. A., and Licklider, J. (1950). "The intelligibility of interrupted speech," *J. Acoust. Soc. Am.* **22**, 167–173.
- Moucha, R., and Kilgard, M. P. (2006). "Cortical plasticity and rehabilitation," *Prog. Brain Res.* **157**, 111–122.
- Nilsson, M., Soli, S. D., and Sullivan, J. A. (1994). "Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise," *J. Acoust. Soc. Am.* **95**(2), 1085–1099.
- Peters, R. W., Moore, B. C., and Baer, T. (1998). "Speech reception thresholds in noise with and without spectral and temporal dips for hearing-impaired and normally hearing people," *J. Acoust. Soc. Am.* **103**(1), 577–587.
- Rhebergen, K. S., Versfeld, N. J., and Dreschler, W. A. (2008). "Learning effect observed for the speech reception threshold in interrupted noise with normal hearing listeners," *Int. J. Audiol.* **47**(4), 185–188.
- Sjölander, K., and Beskow, J. (2000). "WaveSurfer" (Version 4:464-467), in *Proceedings of ICLSP*.
- Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., Lewis, D. E., and Moeller, M. P. (2004). "The importance of high-frequency audibility in the speech and language development of children with hearing loss," *Arch. Otolaryngol. Head Neck Surg.* **130**(5), 556–562.
- Stuart, A. (2005). "Development of auditory temporal resolution in school-age children revealed by word recognition in continuous and interrupted noise," *Ear Hear.* **26**(1), 78–88.
- Stuart, A. (2008). "Reception thresholds for sentences in quiet, continuous noise, and interrupted noise in school-age children," *J. Am. Acad. Audiol* **19**(2), 135–146.
- Stuart, A., and Phillips, D. P. (1996). "Word recognition in continuous and interrupted broadband noise by young normal-hearing, older normal-hearing, and presbycusis listeners," *Ear Hear.* **17**(6), 478–489.
- Stuart, A., Phillips, D. P., and Green, W. B. (1995). "Word recognition performance in continuous and interrupted broad-band noise by normal-hearing and simulated hearing-impaired listeners," *Am. J. Otol.* **16**(5), 658–663.
- Sweetow, R. W., and Sabes, J. H. (2006). "The need for and development of an adaptive Listening and Communication Enhancement (LACE) Program," *J. Am. Acad. Audiol* **17**(8), 538–558.
- Tremblay, K. L. (2007). "Training-related changes in the brain: Evidence from human auditory-evoked potentials," *Semin. Hear.* **28**(2), 120–137.
- Tremblay, K. L., Kraus, N., Carrell, T. D., and McGee, T. (1997). "Central auditory system plasticity: Generalization to novel stimuli following listening training," *J. Acoust. Soc. Am.* **102**(6), 3762–3773.
- Tremblay, K. L., Kraus, N., and McGee, T. (1998). "The time course of auditory perceptual learning: Neurophysiological changes during speech-sound training," *NeuroReport* **9**(16), 3557–3560.