Hearing Aid Noise Reduction Algorithms and the Acquisition of Novel Speech Contrasts by Young Children

Algorithmes de réduction du bruit dans les appareils auditifs et acquisition de contrastes nouveaux de la parole chez les jeunes enfants

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Abstract

A previous study by the authors concluded that digital noise reduction (DNR) does not have an influence on the acquisition of a second language in adults. On the basis of results from adult subjects, it was inferred that DNR is not likely to influence language acquisition in pre-verbal infants. The present study serves as an update to determine whether the tasks being modeled could be conducted with younger participants of 4- and 5-years of age, and whether similar results would be found. Two groups of normal-hearing, monolingual English-speaking children were presented with noise-embedded Hindi speech contrasts that were difficult to discriminate. One group listened to both speech items and noise processed with DNR while the other group listened to unprocessed speech in noise. To ensure task appropriateness, these results were also compared to measures from a third group composed of Hindi-speaking children of the same age. Results indicated that Hindi-speaking children performed better than English-speaking children, confirming age-appropriateness of the cross-language task, but that DNR did not enhance nor impair the acquisition of novel speech contrasts by young listeners.

Abrégé

Une étude précédente des mêmes auteurs a mené à la conclusion que la réduction du bruit numérique n'a pas d'influence sur l'acquisition d'une langue seconde chez les adultes. À partir de résultats obtenus auprès de sujets adultes, on a postulé que la réduction du bruit numérique n'était pas susceptible d'influencer l'acquisition d'une langue chez les jeunes enfants à l'étape préverbale. La présente étude se veut un suivi pour déterminer si les tâches démontrées pourraient servir avec de jeunes participants de 4 et 5 ans et si l'on arriverait à des résultats semblables. Dans le bruit, on a présenté à deux groupes d'enfants monolingues anglophones ayant une acuité auditive normale des sons opposés en hindi difficiles à distinguer. Un groupe a écouté les deux sons et le bruit transformés avec la réduction du bruit numérique, tandis que l'autre groupe a entendu les sons sans transformation. Pour assurer la pertinence de la tâche, on a aussi comparé les résultats à des mesures d'un troisième groupe d'enfants parlant le hindi et ayant le même âge. Les résultats montrent que les enfants parlant le hindi ont mieux réussi que les enfants anglophones, ce qui confirme la pertinence de la tâche inter-linguistique pour l'âge, mais la réduction du bruit numérique n'a pas amélioré ni freiné l'acquisition de contrastes de sons nouveaux chez les jeunes.

Key words: Digital Noise Reduction (DNR), language acquisition, cross language, speech recognition, discrimination, Signal-to-Noise Ratio (SNR), audibility, hearing aids

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A recently published report (Marcoux, Yathiraj, Cote, & Logan, 2006) documents that tasks focusing on language acquisition cannot be enhanced with one version of digital noise reduction (DNR), a processing algorithm commonly found in digital hearing aids and said to increase hearing comfort in situations of competing noise. As proposed by Marcoux et al. (2006), DNR attempts to provide less amplification for noise than for speech, thereby increasing the signal-to-noise ratio (SNR) of the amplified output in hopes of facilitating speech recognition. More specifically, there are four general processes involved in providing this type of output: (a) a prediction is made based on assumptions about the properties of speech and noise envelopes and whether speech and/or noise is represented at the output of each of the hearing aid's frequency-specific bands or channels, (b) a calculation that predicts the SNR based on the classification of inputs is made, (c) an attempt to improve the overall SNR by decreasing gain in channels with low SNRs while maintaining or increasing gain channels with higher SNRs is made, and (d) a calculation to maintain audibility of speech to the utmost level possible without compromising the overall SNR is made. (For a review of digital noise reduction, see Chung, 2004).

In the Marcoux et al. (2006) study, adult listeners were used despite the fact that the possible influence of DNR on speech and language development is more pertinent in the pediatric population. As seen in the pediatric amplification protocol of the American Academy of Audiology (2003), there is much hesitancy to provide DNR to infants amidst audibility-driven approaches (Seewald, Moodie, Scollie, & Bagatto, 2005; Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004). Nonetheless, the authors were able to state a case for studying language development in adult listeners as proxy to preverbal children. First, certain aspects of second language learning in adults can be inferred to primary language learning in children (for a review on cross language speech research, see Strange, 1995). For example, the Hindi retroflex contrasts, ɖ (voiced) and ʈ (unvoiced), are not represented in the English or French languages in Canada and as such would need to be identified and learned in a manner similar to that seen during infant language acquisition prior to being discriminated from the native voiced dental counterparts, d̪ (voiced) and t̪ (unvoiced). Secondly, data can be collected in an adult population at a more rapid rate and with fewer retention pressures to the research schedule.

Results obtained from Marcoux et al. (2006) concurred with observations from several other studies which saw that DNR will not improve the SNR and the resulting speech intelligibility in situations where noise is found overlapping with most of the frequency spectrum of speech (Alcantara, Moore, Künnel, & Launer, 2003; Boymans & Dreschler, 2000; Ricketts & Hornsby, 2005). Furthermore, because of the cross language test paradigm used in Marcoux et al. (2006), the authors were able to provide evidence that DNR did not influence the discrimination of novel (i.e., Hindi) phonemes in an adult population. The authors inferred that DNR would not influence, either positively or negatively, overall phoneme discrimination and language development in children or listening in noise and that the provision of DNR for pediatric hearing aid fittings would not have a significant influence on language outcome.

The purpose of the present study was to determine whether the task could be applied to younger individuals who do not possess the same cognitive biases as the adult groups from Marcoux et al. (2006) and who are more active in their language development. It has been shown in several reports that infants below the age of 1 year are an ecologically valid population for studying phonemic specialization where, as a result of increasing language experience, infants' discrimination is optimized for phonemes specific to the native language and reduced for contrasts that are not. As such, developmental changes occurring during the first year of life result in increased discrimination skills and subsequent language specificity (Werker & Tees, 1984). However, it has also been shown that children of 4 years of age may still be active in learning some of the late-acquired phonemes of their native language (Sundara, Polka, & Genesee, 2006). Hence these children may still be actively honing their discrimination of phonetic information contained in their native language. More practically, it is commonly accepted that children of this age can participate in discrimination tasks of low-context speech items without controlled reinforcement protocols. As such, it can be expected that the groups of children participating in this study could closely represent the function of preverbal children discriminating speech items from their native language without the methodological difficulties associated with testing infants. An inference from these results could inform the effect of DNR during the language development phase of preverbal children. The purpose of the study was (a) to determine whether the cross language task used in Marcoux et al. (2006) could be useful in younger listeners and (b) to assess whether DNR influences language acquisition of a second language independently of the age of the verbal listener.

A subset of the stimuli used in the Marcoux et al. (2006) study were selected for this experiment and were played to normal-hearing children. As with the previous study, the authors acknowledge that a common pitfall of several DNR studies is the recruitment of patients with hearing loss who have a history of hearing aid use. While participants with hearing loss constitute an ecologically valid population, it is difficult to control for the varying degree of hearing loss and hearing aid history (type of previous hearing aids, hearing aid features and settings, and duration of use). This may influence speech intelligibility scores, thereby confounding estimates of DNR-related effects. As well, the cochlea of a normal-hearing individual does not put into play the distortions caused by recruitment and the resulting poor frequency selectivity (Moore, 1996). It is difficult to quantify these distortions to enable the formation of a homogenous group of individuals with hearing loss without processes such as frequency selectivity and auditory sensitivity being measured and paired. To avoid the logistical complexities of forming such a group of children, the use of a normal-hearing population is a good first step towards understanding the effects of algorithms, such as DNR, on speech and language development.

Methods

Subjects

Nineteen monolingual English-speaking, normal-hearing children between 4.1 and 5.2 years of age, as well as 10 native Hindi normal-hearing children between 4 and 7 years of age, were selected to participate in this experiment. The English-speaking children were randomly assigned to two groups with a similar number of females and males to each group. The control group (N = 10; 6 females and 4 males, M = 4.6 years) listened to Hindi speech contrasts in noise that had not been processed through DNR. The experimental group (N = 9; 5 females and 4 males, M = 4.7 years) listened to Hindi speech contrasts in noise that had been processed by DNR. Inclusion factors were the following: (a) little proficiency in the spoken form of a language other than English; (b) no history of speech, language, or hearing disorders; and (c) normal distortion product otoacoustic emissions following a stimulation intensity of 65 dB SPL for frequencies from 1000 Hz to 4000 Hz or audiometric thresholds of less than 20 dB HL for 250 Hz up to 4000 Hz.

The group of Hindi speakers (M = 5 years) was selected to ensure that the stimuli were intelligible to native Hindi listeners. Inclusion criteria were identical to those stated above, except that these individuals were monolingual Hindi speakers. As such, these listeners would also provide a gauge as to whether the task was feasible for the groups of Anglophone children and whether DNR influenced speech perception in noise for native listeners. Informed consent was obtained from the parents of all participants and verbal assent was obtained from the children themselves. There were no dropouts resulting from children who were unable to complete the required task.

Stimuli

All stimuli in this experiment were chosen from the existing collection of 90 minimal pair stimuli used in the Marcoux et al. (2006) study. To create this initial set of 90 minimal pairs, a female native Hindi speaker spoke 60 natural speech items containing dental or retroflex stop consonants which differed in voicing: retroflex, ɖ (voiced) and ʈ (unvoiced), and dental, d̪ (voiced) and t̪ (unvoiced). These stop consonants were utilized to create vowel–consonant (VC) and vowel–consonant–vowel (VCV) syllables. All syllables were recorded in digital format with the Creative Wave Studio software (Stirling, Cavill, & Wilkinson, 2000) using 16-bit resolution and a 16 kHz sampling rate and then normalized to equal loudness by means of equating the root mean square of these items.

The intelligibility of all items was assessed in Marcoux et al. (2006). They were played back and assessed by 10 native Hindi adult speakers to assess their intelligibility. An identification task was used in which listeners typed what they heard using word processing software. The criteria for including a word in the experiment was that it had no more than a 10% error rate across subjects and that no errors were due to the phonemes constituting the minimal pair (i.e., dental or retroflex stops).

For the present experiment, nine pairs of stimuli containing Hindi voiced retroflex or dental consonants (/ɖ/ and /d̪/, respectively) were chosen from the original 90 pairs selected for the Marcoux et al. (2006) study; these were chosen for different reasons. The stimuli used had phonemic structures corresponding to VCV syllables only and were chosen based on the fact that stop consonants were embedded in VCV combinations, which generally offer transition cues from the neighbouring vowels and render them easier to discriminate. This was supported by the fact that these VCV minimal pairs were some of the most discriminable items from Marcoux et al. (2006). Therefore, these items were selected with the realization that frequency discrimination in children is not as well-defined as in adults (Maxon & Hochberg, 1982). As such, the list for the present study consisted of three pairs of identical voiced dental stops (əd̪ə–əd̪ə, ed̪e–ed̪e, id̪i–id̪i), three pairs of identical voiced retroflex stops (əɖə – əɖə, eɖe–eɖe, iɖi–iɖi), and two pairs of dental–retroflex stop contrasts (əd̪ə – əɖə, ed̪e–eɖe).

An unmodulated International Collegium of Rehabilitative Audiology (ICRA) noise (Dreschler, Verschuure, Ludvigsen, & Westerman, 2001) was integrated into the speech pairs to create an SNR of 0 dB and was gated from 500 ms preceding to 500 ms following the speech pair presentation. The pairs were separated by a 500 ms pause prior to ICRA noise insertion so that subjects could hear noise before, during, and after stimulus presentation. Noise was mixed to produce an SNR of 0 and +5 for all stimulus pairs to create the unprocessed version of the stimulus pairs that were to be played to the control group.

To create the stimulus pairs in the processed condition, which were to be played to the experimental group, stimulus pairs were electrically input into the master program of the Widex Senso Diva hearing aid with active DNR along with 30 seconds of pre-noise (also ICRA) in order to activate the DNR to the maximum effect. The electrical input had an identical RMS value to the level generated by a 65 dB SPL sound through a microphone. The master program was programmed to provide a transparent input/output function and set to omnidirectional mode to ensure that processing functions, other than the DNR algorithm, were inactive. The Senso Diva's DNR analyzes spectral–intensity–temporal patterns of the incoming signal across 15 independent processing channels (Kuk, Ludvigsen, & Paludan-Müller, 2002). Adaptive frequency-weighting in the DNR is based on the Speech Interference Index (American National Standards Institute, 1997), which averages speech-to-noise ratios in a set of frequency bands that approximate the critical bands of hearing. Each channel's SNR and the overall incoming SNR, in conjunction with the adaptive frequency-weighting function, dictates the amount of gain reduction. The Widex Senso Diva starts gain reduction in a frequency channel only when input levels exceed 50 to 60 dB SPL. This allows for preservation of the signal audibility at low levels and reduces upward spread of masking and distortion at high output levels. When the threshold input for DNR activation has been reached, channels with poor SNR will generally have more gain reduction than channels with high SNR.

Once the processed stimuli were created, the 30 seconds of pre-noise was removed and replaced with 500 ms of noise preceding and following the stimulus pairs so that noise was heard before, during, and after presentation of each pair, to match the duration of the unprocessed versions.

As noted in Marcoux et al. (2006), an electroacoustic analysis of processed speech stimuli revealed that the level of speech was, on average, 5.5 dB lower than that measured for identical items in unprocessed versions. Furthermore, the level of the ICRA noise occurring along with processed speech items was, on average, 6.5 dB lower than that measured for identical occurrences in unprocessed versions. From this simplistic calculation, it was concluded that the DNR used for this study improved the SNR by 1 dB on average.

Procedure

The experiment consisted of training listeners to discriminate the dental from the retroflex voiced Hindi consonants in competing noise. A training session was administered immediately before each of the testing sessions to ensure that the children understood the task. All children recruited for the experiment were able to understand the training task and perform adequately. The procedure of the training session mimicked the formal testing sessions with the exception of the VCV syllables. Those used during training consisted of six different pairs of speech stimuli: four pairs of identical stimuli and two pairs of differing stimuli. The training session was also used to familiarize the children with the response modalities and expected response time so that the formal testing sessions, described below, could be kept to a maximum of 20 minutes, after which children of the selected age range can become distracted and uninterested. Seldom did children become distracted or unfocussed during the testing session. Only in a few instances did the experimenter need to pause the procedure. In such cases, the children were permitted to take a short break and could easily be brought back to the task when reassured that the session would soon be completed. Responses were not recorded during the training session.

Subjects were seated in a quiet room and were positioned in front of a laptop computer during the listening session. Microsoft Visual Studio 2003 was used to present stimuli as well as record subjects' responses. A response box specifically designed for this experiment was constructed and equipped with two arcade-style buttons of differing colours. This box was connected to the laptop and was utilized by the subjects during the discrimination task. Stimuli were presented at 65 dB SPL output through Sony MDR-V600 headphones. Measurement of output was performed using a Brüel and Kjaer 2235 sound level meter coupled to a Brüel and Kjaer 4132 microphone and a Brüel and Kjaer 4153 artificial ear.

Subjects' performance was tested on a two-alternative identification task. The software setup was such that a picture of a human ear was presented when the stimuli were playing. Subjects were instructed to select the button on the response box which corresponded to "same" or "different" if both speech syllables were perceived as identical or if the pair was not perceived to be exactly the same. No time limit was enforced for a response after the presentation of the stimuli, which created a variable inter-trial interval. When the subject answered correctly, a short video (3–8 seconds in length) was displayed on the screen. This served as visual and auditory reinforcement for a correct response. When the subject's answer was incorrect, the participant was audibly instructed to try again and a blank screen appeared on the laptop. This was done in order to limit reinforcement and encourage future correct selections.

Following the participant's response, it was necessary for the examiner to press a "next" button in order for the next stimulus pair to be presented. This allowed for potential commentary from the subjects who were enthusiastic young children. No feedback was given by the examiner post-response. Prior to the next stimulus presentation, the child was asked "Are you ready?" in order to refocus the child to the task.

Once the data collection was ready to begin, stimuli sets were randomly presented, first at 0 dB SNR and then a second time at +5 dB SNR. Signal-to-noise ratios were presented in ascending order in order to determine the onset of speech discrimination within the competing noise floor. The formal testing session lasted approximately 20 minutes.

Results

Percentage correct and incorrect scores were calculated for each testing session. Just as with the Marcoux et al. (2006) study, the nonparametric A' statistic was used to control for the influence of response bias during the calculation of signal detection indices, such as the more commonly known d', which compares the proportion of hits to the proportion of false alarms relative to correct rejection non-similar items (Grier, 1971). A' ranges from 0.5, which indicates that signals (i.e. speech items within item pairs) cannot be distinguished from each other and performance is at chance, to 1, which indicates perfect performance. Values less than 0.5 may arise from task confusion, systematic errors, or sampling errors (Pollack & Norman, 1964).

Analyses for Hindi and English-speaking participants were done separately as Hindi participants rated both processed and unprocessed stimuli whereas Anglophone participants rated either processed or unprocessed stimuli depending on whether they were assigned to the experimental or control group, respectively. For the Hindi group, a two-way repeated measures ANOVA was conducted to determine the effect of processing (unprocessed vs. DNR-processed) and SNR on the A' measures. For the English-speaking groups, a two-way repeated measures mixed ANOVA was conducted to determine how A' measures were influenced by processing (unprocessed vs. DNR-processed) and SNR. Lastly, two separate two-tailed *t*-tests were conducted to determine whether the native language (Hindi vs. English) had an influence on the A' measures for both the processed and unprocessed conditions. Degrees of freedom of the repeated measured analysis were adjusted for sphericity violations using the Huynh-Feldt epsilon adjustment. Degrees of freedom were also adjusted using the Levene's test for equality of variances for *t*-tests. Significance was confirmed at the 0.05 level for all analyses.

A' scores from Hindi participants were not influenced by processing [$F(1, 9) = 0.47$, ns], nor were they influenced by SNR [$F(1, 9) = 1.67$, ns]. Similarly, processing did not have a significant influence on A' scores [$F(1, 17) = 0.05$, ns] for English-speaking participants. Furthermore, the SNR did not influence measures [$F(1, 17) = 3.97$, ns]. Performance across various conditions is illustrated in Figure 1.

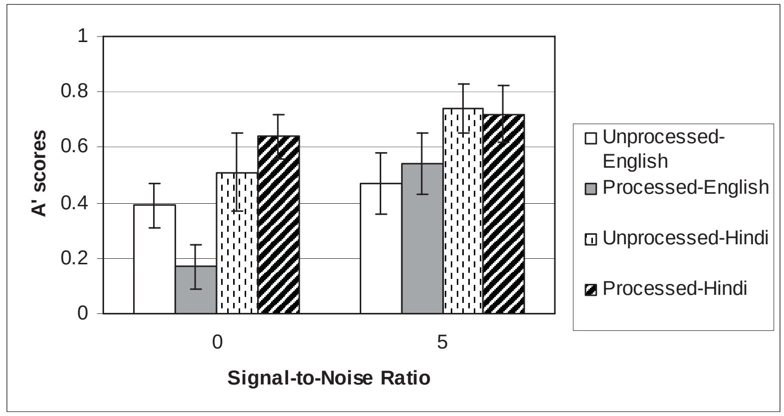

Figure 1. A-prime scores for unprocessed and processed items from English-speaking and Hindi groups for Signal-to-Noise Ratios of 0 and +5.

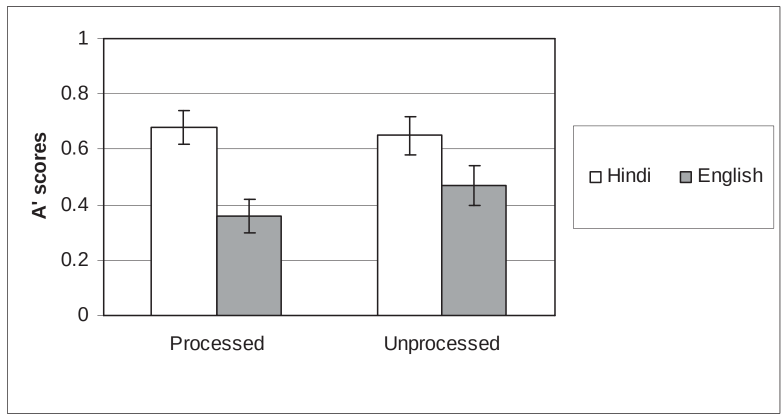

Figure 2. A-prime scores of Hindi-speaking and English-speaking groups for DNR-processed and unprocessed stimuli.

Since SNR did not have a significant effect on A' scores, the means for each processing condition were computed with collapsed scores for both the 0 and 5 dB SNR conditions. Between-group analyses for the processed condition indicated a significant difference [$t(17) = 3.59, p < .05$] between Hindi and English speakers where Hindi children obtained higher values ($M = .68$, $SE = 0.06$) than English-speaking children ($M = .36$, $SE = 0.07$) when discriminating processed stimuli. Furthermore, a significant group difference was noted for the unprocessed condition [$t(18) = 2.24$, $p < .05$], where Hindi children again obtained higher values ($M = .65$, $SE = 0.07$) than English-speaking children ($M = .43$, $SE = 0.07$). The group means are shown in Figure 2.

Discussion

The results obtained in the present study are in agreement with those obtained from research focusing on the influence of DNR on speech intelligibility in the adult population (Alcantara et al., 2003; Boymans, Dreschler, Schoneveld, & Verschuure, 1999; Boymans & Dreschler, 2000; Marcoux et al., 2006). As such, both young Hindi and English-speaking children did not benefit from DNR to improve discrimination of Hindi speech contrasts in noise. This result is evident in light of the inherent difficulties of modulation-based DNR algorithms in separating speech and noise inputs of similar frequency spectra (Alcantara et al., 2003; Boymans et al., 1999; Boymans & Dreschler, 2000).

While previous studies on DNR have focused on the inability of DNR to enhance speech discrimination in noise, results from the present study highlight the inability of DNR to also diminish the negative impact on speech discrimination and processes associated with language acquisition. The results from these proxy studies suggest that DNR would not have a significant influence on the acquisition of the maternal/native language of pre-verbal children who are fitted with such technology for hearing impairment.

While this type of study should be adapted to pre-verbal children in future research, it is appropriate to suggest that the DNR algorithm used in this study would not influence language acquisition processes in noisy situations in this population. If findings such as these were also noted with other DNR systems, it may be worthwhile to revisit the strict recommendations from current pediatric hearing aid fitting protocols which do not recommend the use of DNR in light of a lack of evidence (American Academy of Audiology, 2003). Findings have yet to be provided to demonstrate that DNR negatively impacts language acquisition overall. However, considering the various types of DNR available on the market, results from the present study should not be generalized beyond the experimental conditions documented herein. Further cross language paradigms should be explored with DNR modalities found in other instruments (Bentler & Chiou, 2006). Ultimately, this type of study should be conducted in hearing-impaired children with consideration of variables such as DNR type and SNR, to provide sufficient evidence that an intermittent and dosed feature, such as DNR, could not impact processes as complex as those involved in language acquisition. While the use of a hearing-impaired population will add confounds of aetiology, level, and configuration of loss to the study design, it should also provide a more ecologically founded observation on the benefits, or lack thereof, from DNR.

The authors were able to demonstrate that the use of cross-language paradigms is useful in demonstrating acquisition aspects of a second language in participants of early school age (i.e., ages 4 to 6 years). By using an appropriate conditioned response technique, significant differences in performance between Hindi and English-speaking participants were found. It was demonstrated that Hindi children were able to discriminate between speech contrasts of their native language despite the attention necessary to participate in the visual reinforcement task. The relative difficulty of English-speaking children to discriminate these speech contrasts is unlikely to be related to the level of difficulty of the task, but to be related to a difficulty in discriminating non-native contrasts. It can be seen that cross-language research may be useful to observe the influence of several speech processing parameters, such as DNR, in participants of a wide range of ages.

Conclusions and Summary

The present study offers an update to the novel approach of studying the influence of DNR on aspects of language acquisition described in a previous publication by the authors. In this study using a group of young children, it was demonstrated that one type of DNR does not provide improvements in speech intelligibility in noisy environments, regardless of the age of the individual who has already acquired language abilities. Furthermore, it was shown that the novel cross-language paradigm used to determine these findings could be effectively applied to a younger population.

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