The Effect of Non-Linear Amplification and Low Compression Threshold on Receptive and Expressive Speech Ability in Children with Severe to Profound Hearing Loss

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The performance of a hearing instrument during a pediatric fitting must be guided under the provision to optimise the development of speech and language. The implementation of a low compression threshold (CT) within non-linear amplification may provide amplification for soft speech, which is otherwise not audible with linear amplification or with non-linear amplification using a high CT. To demonstrate the usefulness of audibility of soft speech, receptive and expressive speech performance was measured with a group of children with severe to profound hearing impairment. Scores were collected first using the child's prescribed linear hearing instrument and then with a low CT multi-channel non-linear digital signal processing (DSP) hearing instrument. Results indicated an increase in receptive and expressive speech indices using the low CT hearing aid. These findings suggested that children who received this type of amplification during primary intervention benefited from the increased audibility of soft speech in order to enhance speech and language ability.

Keywords: low compression threshold, acclimatization, digital signal processing, severe-to-profound hearing loss, speech reception, speech production

Abbreviations: CT=compression threshold; WDRC=wide dynamic range compression; EDRC=enhanced dynamic range compression; DSP=digital signal processing; DBT=double blinded trials; NAL-RP=National Acoustics Laboratory revised fitting formula including profound loss; VC=volume control; WLSI-C=Widex listening skills inventory for children; SPL=sound pressure level; HL=hearing level

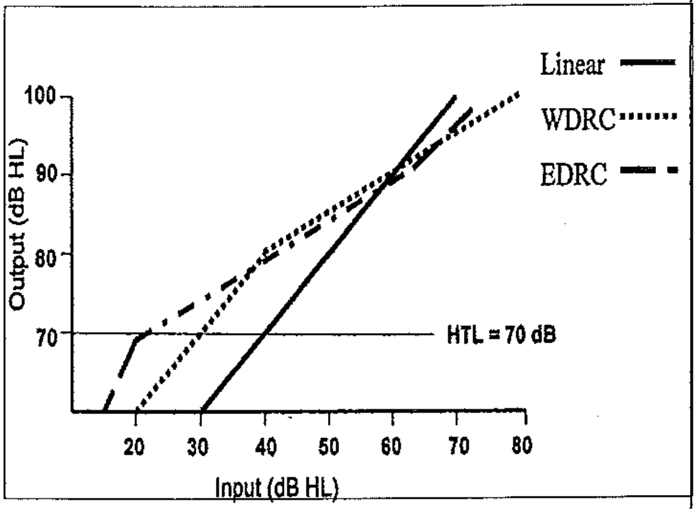
Introduction

Bilateral sensorineural hearing impairment in newborn children is a result of several etiologies and affects 1 to 6 live births per 1000 (Mauk & Behrens, 1993; Parving, 1993; Watkins, Baldwin, & McErnery, 1991). It has long been known that children with severe to profound hearing impairment typically do not develop speech and language to a level necessary to sustain an acceptable level of academic achievement (Blamey, Sarant, Paatch, Barry, Bow, Wales, Wright, Psarros, Rattigan, & Tooher, 2001; Davis, Elfenbein, Schum, & Bentler, 1986; Geers, & Moog, 1989; Moeller, Osberger, & Eccarius, 1986). Although advances in hearing aid technology and rehabilitation services have been designed to promote speech and language learning, the prognosis did not always favor a marked academic improvement (MacDougall, 1991; Rodda & Grove, 1987). It is important, however, to note that hearing-impairment was traditionally diagnosed and addressed at a few years of age, at the earliest, following parental concern. It can be hypothesised from cognitive psychology and speech perception studies that such a late onset of intervention occurs well after a period of critical auditory development (Kuhl, Williams, Lecerda, Stevens, & Lindblom, 1992). It can also be suggested that further advances in rehabilitative hearing healthcare may not realise their intended potential as long as these techniques cannot be applied during the critical period of language learning.

Studies have documented the unique speech discrimination skills that young children possess (Jusczyk, 1997; Kuhl, 1987, 1992; Miller & Jusczyk, 1989). Unlike adults, infants are able to discriminate speech contrasts that are not found within the structure of their native language (Trehub, 1976). Older children and adults, on the other hand, are limited to being effective during the recognition of speech elements that are unique to their learned languages (Logan, Lively, & Pisoni, 1991). The fact that children begin to lose the ability to achieve discrimination of non-native speech elements at approximately 6 months of age indicates that early auditory experiences are providing a directed formation and modification of neural components required for speech and language functions (Kuhl, et al., 1992; Werker & Lalonde, 1988; Werker & Tees, 1984). This finding suggests that an optimization of the auditory pathways will allocate resources to effectively process speech sounds found in the child's native language(s). A deprivation in stimulation of the auditory pathways during this critical period, such as that which is encountered with pediatric hearing-impairment, could result in an insufficient allocation of neural resources for the child to effectively process his/her auditory environment (Sininger, Doyle, & Moore, 1999). Early intervention with amplification is thus critical if a child is to avoid a permanent delay in language learning. These findings can also be verified clinically. Studies have demonstrated that hearing-impaired infants who were provided with both a diagnosis of hearing impairment and the proper intervention with hearing devices prior to 6 months of age developed speech and language at a level similar to that of normal-hearing peers (Yoshinaga-Itano, Sedey, Coulter, & Mehl, 1998). Consequently, the latter identified group demonstrated a permanent delay in speech and language performance. Although it can be concluded from these studies that the onset of intervention is of critical importance, one must also conclude that a defined intervention with hearing instruments and intensive rehabilitation is required in order to prevent such delays. The objective of the present study is to determine whether certain recent technological advancements found within hearing devices can potentially enhance and promote the development of speech and language during the rehabilitation process.

Children with severe and profound hearing loss have often been fitted with linear power hearing instruments in order to benefit from the high sound pressure level provided by these instruments, but also because these were the only powerful devices available until approximately 1995. When the volume control (VC) of these instruments is regulated to ensure comfort for most speech inputs of conversational level, they will also provide an under-amplification of low-level speech and an over-amplification of high-level speech. This imprecise allocation of hearing aid output over a wide range of input levels occurs as a result of the divergence between linear gain calculations and the non-linear loudness growth function of the hearing-impaired individual (Pascoe, 1988). A linear amplification rationale will not permit the audibility of low-level speech items when the VC is set to certain positions, and it may reduce the intelligibility of loud speech as the linear instrument produces temporal distortion (Venema, 2000). In order to reduce these drawbacks, and because the input levels in a child's environment are various, non-linear hearing instruments have been proposed (Stelmachowicz, Mace, Kopun, & Carney, 1993). The non-linear instrument may ensure the accurate representation of loudness of the sound reaching the hearing instrument microphone within the residual dynamic range of the hearing-impaired individual (Kuk & Ludvigsen, 2000; Kuk & Marcoux, 2002). Although linear amplification provides an identical amount of gain to input sounds independent of level, a non-linear wide dynamic range compression (WDRC) instrument will provide more gain for low level inputs and less gain for higher level inputs while maintaining the loudness relationship of incoming sounds within the residual dynamic range of the listener (Venema, 2000). Enhanced Dynamic Range Compression (EDRC), which is an extension of the WDRC circuit, features a non-linear amplification rationale with a low compression threshold at 20 dB HL. As illustrated in Figure 1, the benefit of the low compression threshold is the additional gain provided for low-level sounds in comparison to other non-linear WDRC instruments with higher compression thresholds (Kuk, 1999). The merit of using the EDRC circuit is illustrated by the Long Term Average Speech Spectrum measured at the child's ear level (LTASS) (Cornelisse, Gagné, & Seewald, 1991), which clearly demonstrates that the softer elements of speech correspond to intensity levels in the vicinity of 20 dB HL. It is thus important for a hearing instrument to permit the audibility of low-level speech elements and minimize the deprivation of soft speech sound to the pre-verbal hearing-impaired child.

Figure 1. Hypothetical input-output curves of a linear instrument, a WDRC instrument and the EDRC test instruments matched in output for a conversational input level received at the microphone of the instruments worn by a hearing-impaired listener with a 70 dB HL loss.



Hearing instruments which utilise Digital Signal Processing (DSP) technology have shown greater potential than their analogue predecessors for processing a complex acoustic signal in the hearing-impaired individual's environment into an output signal which is able to meet the auditory demands of the hearing-impaired user; including comfort, audibility, fidelity and intelligibility. However, there has been some debate as to whether these more complex DSP instruments are actually able to provide additional benefits in order for the hearing-impaired user to actually signal a perceptible and significant improvement. A recent editorial from Parving (2001) has discussed certain important issues that are at the center of this debate. One of the main issues is that many studies that have attempted to draw conclusions with regard to the benefit of DSP instruments have been likely to include some bias within the description of tests of significance. This type of contamination stems from the subject or, in the case of children, the parent knowing that a more complex, more expensive DSP instrument is being fitted. There is thus a favorable bias for the DSP instrument during various exercises based on the subjective predisposition that, in general, more complex and more costly instruments should be more functional and thus offer greater benefit. In order to minimize this bias, Parving has emphasised that studies that attempt to draw conclusions as to the benefits of one type of hearing instrument over another should be the product of double-blinded trials (DBT). In such studies, neither the clinicians administering the performance tests nor the experimental subjects (or their entourage) are given any information on the characteristics of the hearing instrument being evaluated. Gatehouse (2001) has underlined, however, that, although DBT studies are ideal in order to determine the additional benefit of a hearing instrument, there are other study designs that can provide scientifically sound conclusions. These experimental designs typically include objective testing parameters, such as speech recognition, which are rather insensitive to bias. It is apparent that a significant amount of evidence must be provided by DBT studies in order to preclude a technological advantage of certain hearing instruments during the delivery of audiological services. Nevertheless, outcome measures provided by study models that promote objectivity may also provide suitable evidence with regard to the advantage of certain technological features.

Speech reception and production skills of severe-to-profound peri-verbal hearing-impaired children were monitored during a transition from a linear hearing device to an EDRC hearing instrument. Because these children were not early-identified, it was not expected that their improvements would amount to a level of language ability similar to that of normal-hearing peers. It is worthwhile, however, to determine whether the benefit provided to the child with severe to profound hearing impairment by the EDRC instrument is significantly greater than that provided by a well-fitted hearing instrument with linear amplification. Hence, the present study will determine whether the amplification strategy provided by a low compression threshold (CT) multi-channel non-linear DSP instrument might potentially enhance speech and language learning in a group of children with severe to profound hearing impairment.

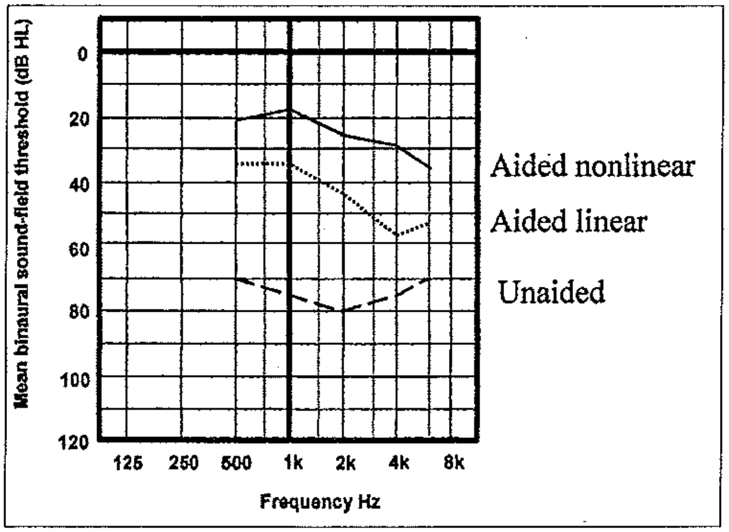
Methods

Subjects

Fourteen subjects were selected from a clinical database. All were children with bilateral, mostly symmetrical hearing loss in the severe to profound range. Children were 6.5 years to 13.2 years of age (M=8 years). Most children had been diagnosed with hearing loss at 9 months to 3 years of age (M=2 years, 7 months). Two subjects had been diagnosed at 4 years of age. All were fitted with a linear instrument shortly following diagnosis. These hearing devices were mostly power hearing instruments from a wide variety of manufacturers.

All children were pre-verbal prior to using a hearing aid and have since acquired the Spanish language to various levels of proficiency. At the time of study, all children were monolingual Spanish speakers, attending mainstream schools using an oralist teaching method. Most children received some signing training but always used verbal communication in the home setting. Because some children were also prone to having frequent otitis media, appropriate documentation of middle ear function was conducted prior to each testing session. Figure 2 describes the binaural pure-tone average thresholds (500, 1000, 2000 Hz) of the children as assessed at the time of the study. Individual puretone averages ranged between 71 and 98 dB HL. Inclusion in the study also required adequate parental support and interest. Informed consent was obtained from the children's parents and, although the participants were not remunerated, they were able to receive a discount on any hearing instrument used during the study if they chose to purchase them at upon completion of the study.

Figure-2. Mean binaural sound-field thresholds obtained in the unaided condition (bottom), with linear instruments, where the VC was fixed in order to provide comfort for conversational-level inputs (middle), and with the test instruments fitted according to the manufacturer's recommendations (top).



Hearing instruments

Analogue instruments

Analogue instruments had been worn by the children until the onset of this study. These power instruments provided linear processing with peak clipping or compression limiting as an output limiting feature. A volume control was provided as a standard feature on all instruments, permitting the regulation of output to levels not exceeding 135 dB SPL. These instruments had been used on a daily basis with minimal complaint for a period of 2.5 years on average.

Digital test instruments

The Widex P38 and C18+ instruments were used during this experiment. Both aids are DSP 3-channel instruments and include an enhanced dynamic range of compression (EDRC), a result of the low compression threshold which permits the amplification of inputs 20 dB above the threshold of normal-hearing listeners in all three channels (Ringdahl, Magnusson, Edberg, & Theilin, 2000). An expansion circuit is utilized below this low compression threshold in order to minimize the amplification of microphone and extraneous low-level noises. A reduction in gain is then applied for inputs that exceed the value of the low compression threshold up to a conversational input level, after which additional gain reduction is applied as an output limiting mechanism. Gain for conversational input levels was prescribed by the

NAL-RP fitting formula (Byrne, Parkinson, & Newall, 1990) and reconsidered in order to account for device-specific features, such as the number of compression channels and their time constants, which are not considered within the fitting formula (Kuk & Ludvigsen, 1999). These instruments are not provided with a volume regulation option but rather have fully automatic gain control. Although the P38 and C18+ apply a similar gain prescription for inputs below the CT and inputs that activate the output limiting range of the instrument, the calculation of gain for inputs in the range of compression is achieved using a slightly different method. There may therefore be slight differences in the prescription of gain between instruments for conversational inputs. However, because the C18+ is aesthetically smaller than the P38, it was necessary to offer this instrument to children who did not require the higher gain provided by the P38. The C18+ offers a maximum output of 130 dB SPL while the P38 offers a maximum output of 138 dB SPL as measured in a 2cc coupler. These instruments will from this point be referred to as the test instruments.

Procedure

Initial session

The children's analogue instruments were evaluated using electroacoustic measurements in order to determine their suitable performance in accordance to the manufacturer's specifications. Otoscopy and tympanometry were performed in order to ensure the absence of outer and middle ear pathology. New earmold impressions were taken and earmolds were ordered for children in order to ensure the optimal use of their hearing instruments. Unaided air and bone conduction pure-tone thresholds were measured using TDH headphones and a bone conductor respectively, with sinusoidal tones of 250, 500, 1000, 2000, 4000 and 6000 Hz presented in a calibrated double-walled sound-treated booth. Binaural unaided thresholds were also obtained in free-field using warbled tones at the same audiometric frequencies presented with a loudspeaker positioned at a 0° azimuth. Children were seated 1.5 meters from the loudspeaker.

Second session: Fitting of test instrument

The test instruments were evaluated using electroacoustic measurements and programmed according to each child's audiometric thresholds collected during the previous session.

With the new earmolds, binaural aided thresholds were obtained using warbled sinusoids of 250, 500, 1000, 2000, 4000 and 6000 Hz in free-field with the child's linear hearing aids. The VC of the linear instrument was fixed in order to maximize comfort and audibility of the tester's voice with a normal vocal effort (this volume setting was documented for future testing sessions).

The non-linear test instruments were then fastened to the child's earmolds and a feedback test was performed in order to ensure that recommended gain did not exceed the limit of stability. During the feedback test, the instrument's gain in each channel was automatically set to a level 6 dB below the gain causing instability. The resulting gain represented the amount of gain available for the amplification of low-level inputs at the CT (i.e. 20 dB HL). Because one objective of this study was to demonstrate the importance of the amplification of low-level inputs, it was important to ensure that the available gain was not below the recommended value. Nevertheless, because the appropriate amplification of low-level inputs required a significantly greater amount of gain than that of conversational-level inputs, it was often difficult to provide the recommended amount of gain without the occurrence of acoustic feedback. A criterion was thus established in order to determine the minimal amount of available gain required in each frequency channel to promote an acceptable amplification of low-level inputs and consequently soft speech. It was concluded that the available gain should not be lower than the manufacturer's recommended gain in the two lower frequency channels. Because acoustic feedback occurs more frequently in the higher frequency range, it was concluded that the amount of available gain should be no lower than 10 dB below the manufacturer's recommended value. All children's instruments included in this study were able to meet these criteria. Although the maximal audibility could not always be provided for low-level inputs because of the occurrence of acoustic feedback, the audibility of these sounds was subsequently evaluated. With programming complete, the clinician recorded the child's initial reactions to the overall performance of the non-linear test instruments. It was suspected that the non-linear instruments would be rejected by the children on the basis that they would provide a different loudness and quality of sound in comparison to the linear instruments. This can be observed in Figure 1, which represents the provided output at various input levels for a hypothetical flat 70 dB HL hearing loss. It was hypothesised that children would notice a decrease in output for high-level inputs. However, outcome measures were required in order to confirm the child's increased perception and benefit from the amplification of low-level inputs. Rather than jeopardize the child's participation in the study, the non-linear instruments were adjusted in order to alleviate the child's initial concerns, while attempting to reason with the child as to the advantages of the perceived differences in order to remain as close to the initial recommendations as possible. Comments and adjustments were recorded. Fine-tuning guidelines were also established in order to minimize unnecessary adjustments. If conversational speech was too loud, the gain setting was lowered in 2.5 dB steps in all three channels. If conversational speech was too soft, the gain setting was raised in 2.5 dB steps in all channels. If conversational speech was clear and comfortable, but the overall loudness was different, the gain settings were not changed. A maximum of 2 fine-tuning steps was permitted. The children and parents were instructed to substitute the use of the linear instruments with the exclusive use of the test instruments .

Third session: 1 month post-fitting

This session occurred 1 month following the second session. A discussion was initiated with the child and parent. The child was asked about the perceived performance of the non-linear instrument. Both the child and parent were asked about the frequency with which the test instruments were used. The test instruments were then programmed to the initial recommended gain and output targets. In any case wherein the child did not accept this change in setting, the test instrument was given settings as close to the initial recommendation as possible while respecting the preferred sound quality of the child. The mismatch between the recommended gain settings and the actual gain settings did not exceed one fine-tuning step. Otoscopy and tympanometry were repeated in order to ensure the absence of outer and middle ear pathology. Binaural thresholds were obtained using warbled sinusoids of 250, 500, 1000, 2000, 4000 and 6000 Hz in free-field with the child's test instruments.

Discrimination of phonological oppositions (Bosch, 1984; Bruno & Brusi, 1990) and identification of Spanish monosyllables and bisyllables (Huarte, Molina, Manrique, Olleta, & Garcia-Tapia, 1996) were measured using live voice at two presentation levels: 40 and 65 dB SPL, corresponding to a soft speech level and a conversational speech level respectively. A sound level meter placed at ear level next to the child consistently monitored these presentation levels. The presentation of speech items was done in a manner that eliminated associated visual cues. The repetition of the speech item was only permitted when the child had been distracted during the presentation of the original item. During tasks of discrimination of phonological oppositions, picture identification lists consisted of four different illustrations containing the correct word and three incorrect illustrations corresponding to words that differ from the correct item with a minimal consonant opposition. During tasks of identification of Spanish monosyllables and bisyllables, picture identification lists consisted of four different illustrations containing the correct alphabetical character and three incorrect illustrations corresponding to neighbouring speech tokens. Both tasks were done with both the linear instrument set to the original fixed volume control position, deemed to ensure comfort for conversational speech, and with the non-linear instrument.

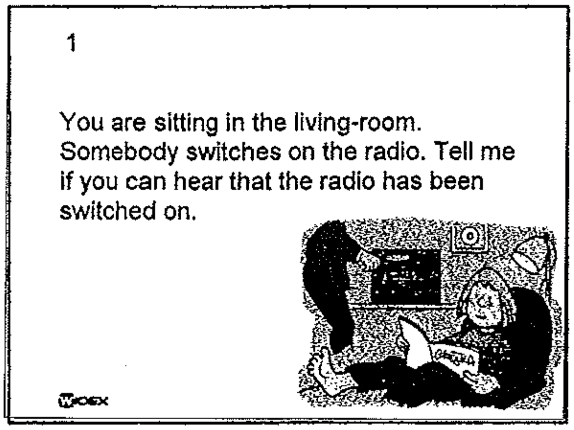
The production of the vowel /a/ was recorded and digitized. Speech quality was measured with the Multi-Speech program (Kay Elemetrics) and included the measurement of the fundamental frequency, shimmer, and jitter. The fundamental frequency of the vowel /a/ should be between 210 and 315 Hz for a group of children between the ages of 5 to 12 years, while vocal jitter, the fluctuation in amplitude of the speech envelope, should be less than 1% during the speech production. Vocal shimmer, the fluctuation in frequency, should be maintained below 0.6% in order for a vocal effort to be of appreciable quality (Baken & Orlikoff, 2000; Gurlekian, 2001). Furthermore, productions from children were compared to local norms of speech quality. These norms specified speech quality parameters of normal-hearing monolingual Spanish speaking children of different gender and age (Valero & Casanova, 2001). Other speech production measurements consisted of monitoring the production of words belonging to an induced Spanish phonological registry (Montfort & Juarez, 1989). A series of 57 picture cards were presented to the child and the induced productions from the child were recorded in digital form. The production was phonologically transcribed and evaluated. Errors in overall production and place-specific errors (i.e. initial, medial, final) were then calculated. Speech production measures were obtained with the linear instrument set to the original fixed volume control position and with the test instrument.

The children and their parents were then asked to complete the Widex Listening Skills Inventory for Children (WLSI-C) questionnaires. The WLSI-C is constructed of two questionnaires: a parent/teacher questionnaire and a child questionnaire. This test is geared towards a population of children, their parents, and educators. Infants and very young children will not be able to participate in the validation exercise because the cognitive abilities required to complete the test will typically develop around 3 years of age. The parent/teacher questionnaire can be administered to the parent(s) or educator(s) during the child's early years as a useful validation measure.

The WLSI-C questionnaires were conceived to 1) initiate a productive communication between the audiologist or hearing healthcare provider and the parent and educators of the hearing-impaired child. The objectives of this communication are to determine areas of strength and weakness within the realm of listening skills of the child, 2) provide strategies for the modification and fine tuning of hearing aid function, 3) provide strategies for the improvement of the child's listening environment, and 4) provide a longitudinal report of the child's progress for counseling purposes.

The child questionnaire consisted of 12 stimulus illustrations and one illustrated 3-point rating scale. Each of the stimulus illustrations contained a drawing of a child in a different everyday listening environment. These listening environments were selected to depict listening and understanding situations that are typically enhanced with the use of power nonlinear DSP instruments with EDRC. An example of a WLSI-C stimulus slide is illustrated in Figure 3a.

Figure 3a. Example of the WLSI-C stimulus slide.



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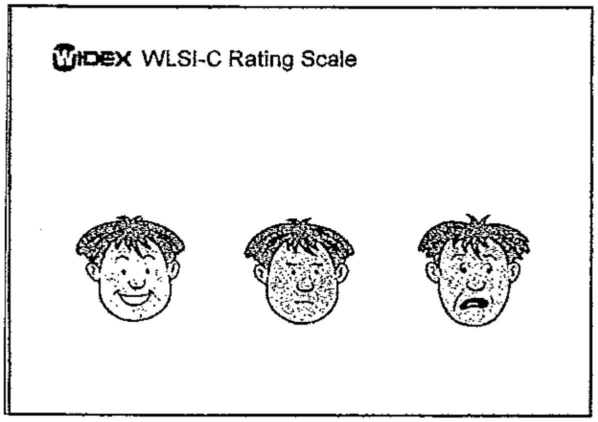
You are sitting in the living-room.
Somebody switches on the radio. Tell me
if you can hear that the radio has been
switched on.

The researcher showed the rating scale to the child and asked the child to point to the "easy face", the "difficult face" or the "OK face". Make sure the child is comfortable with this rating scale before starting the questionnaire. The stimulus slides were then presented to the child along with a verbal description of the stimulus slide. Then child was then asked to rate the difficulty associated with the situation depicted in the stimulus slide. The rating scale is illustrated in Figure 3b. Additional information was provided to the child when comprehension was not achieved at the onset. The child's answer was then recorded on the questionnaire along with any relevant descriptive comment provided by the child.

Figure 3b. Example of the WLSI-C rating scale.



The parent/teacher questionnaire required the parent or teacher to rate the performance of the hearing-impaired child with regard to specific areas of listening, understanding, and speech production. Instructions were written on the questionnaire itself.

Fourth and fifth sessions: 3 and 5 months post-fitting
An identical procedure to that underlined for the 1-month post-fitting session with the test instrument was followed for these two subsequent testing sessions.

Statistical analyses

Two-way repeated measures ANOVA were conducted in order to determine the effect of technology (i.e. linear vs. non-linear) and level of presentation (i.e. 40dB SPL vs. 65 dBSPL) on the performance of children during discrimination and identification tasks. Follow-up analyses consisted of paired comparisons at each level of the independent variables. One-way repeated measures ANOVA were conducted in order to observe the effect of time of non-linear instrument use on the discrimination and identification processes. Similar analyses were performed in order to assess the effects of non-linear instrument usage on speech quality and speech production errors. Degrees of freedom of the repeated measures analyses were adjusted for sphericity violations using the Huynh-Feldt epsilon adjustment. Significance was confirmed at the 0.05 level for all analyses.

Results

A proper earmold fit was obtained prior to recording outcome measures. An adequate fit was confirmed with respect to the criteria of available gain provided by the test instruments during the feedback test. The mean binaural aided sound-field thresholds with the linear and test instruments are illustrated in Figure 2. A significant difference is observed between the binaural aided thresholds with linear and non-linear amplification in the sound field at all audiometric frequencies. Aided thresholds obtained with the test instruments were 15-25 dB better than those obtained with the linear instruments at all audiometric frequencies. Aided thresholds obtained with the test instruments at the 3- and 5-month post-fitting test sessions were not significantly different from those obtained from the onset with the test instruments. Significance was confirmed at the 0.05 level during individual two-tailed t-tests at each audiometric frequency.

Tests of discrimination of Spanish phonological oppositions revealed significantly different performance by the children from the time they used their linear instrument (mean=37,36, s.d.=34.24) to when they used the test instrument (mean=76.04, s.d.=22.39), (F=60.39, $p<0.0001$). Results also indicated that children were able to discriminate significantly more phonological oppositions with a higher level of presentation (mean=73.50, s.d.=23.66) as opposed to a lower level of presentation (mean=39.89, s.d.=36.10), (F=214.80, $p<0.0001$). Analyses also revealed a significant interaction effect, which indicates that differences in performance between the test and linear instruments were greater when a lower level of presentation was used as opposed to when a higher presentation level was used, (F=9.40, $p<0.01$). Follow-up analyses revealed an improvement in discrimination with the test instrument (mean=83.71, s.d.=16.05) over that obtained with the linear instrument (mean=63.29, s.d.=26.09) when using a conversational presentation level (t=-3.48, $p<0.01$). A larger improvement is observed, however, with the test instrument (mean=66.54, s.d.=25.71) over that obtained with the linear instrument (mean=11.42, s.d.=17.49) when using a low presentation level (t=-8.02, $p<0.001$). Figure 4 illustrates the discrimination of phonological oppositions with the linear and test instruments at a low-level and conversational-level input. It was also determined that the children discriminated significantly better over a 5 month period (F=5.72, $p<0.01$), as illustrated in Figure 5, where discrimination was significantly better after using the test instrument for 5 months. While there was no improvement between the 1 month (mean=83.71, s.d.= 16.05) and a 3 month period (mean=85.57, s.d.=16.59), (t=-0.,91, ns), there was a significan improvement between the 3 month and 5 month period (mean=93.57, s.d.=0.95), (t=-2.29,$p<0.05$).

Figure 4. Mean scores for discrimination of phonological oppositions obtained with the linear and test instruments at two presentation levels.

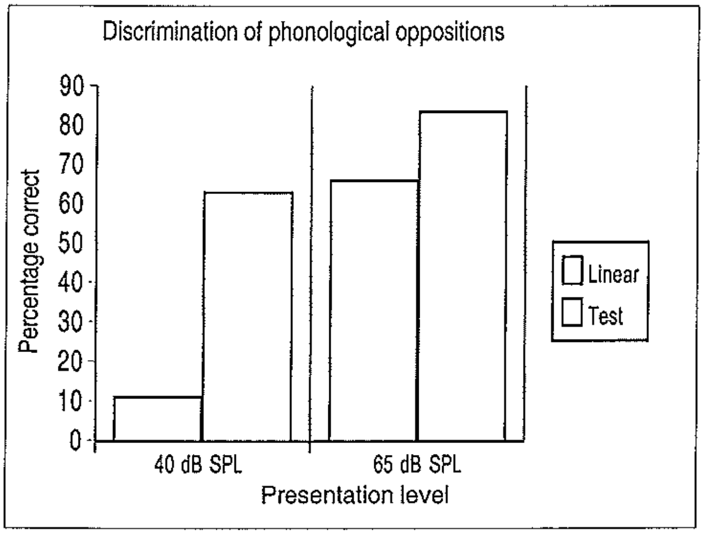


Figure 5. Mean scores for discrimination of phonological oppositions and identification of monosyllables and bisyllables obtained at the 1-month, 3-month and 5-month testing period following the fitting of the test instruments.

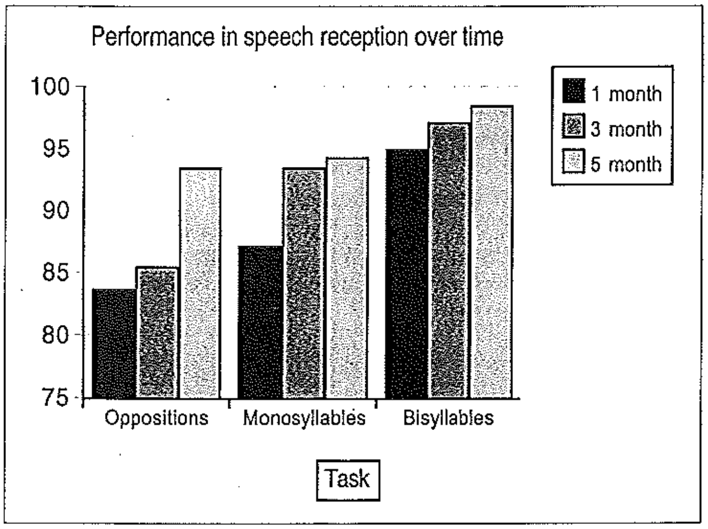
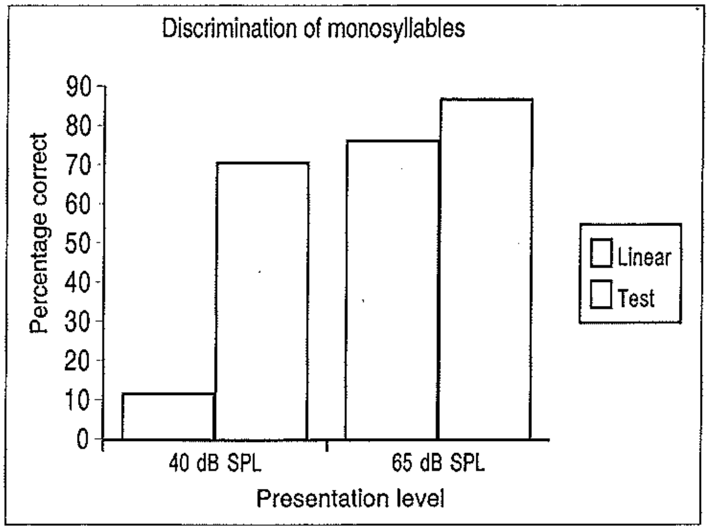


Figure 6. Mean scores for identification of monosyllables obtained with the linear and test instruments at two presentation levels.

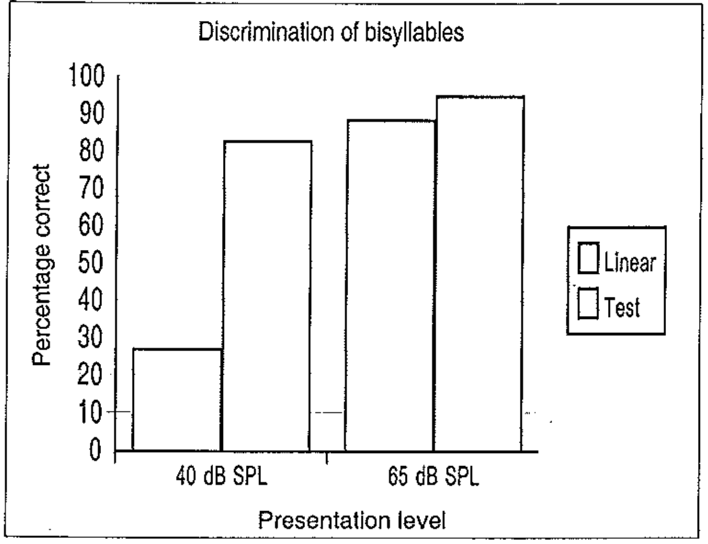


Tests of identification of Spanish words revealed a similar effect. The identification of monosyllabic words significantly improved from using linear instruments (mean=44.18, s.d.=37.01) to using the test instruments (mean=79.00, s.d.=22.27), (F=107.60, p<0.0001). Results also indicated that children were able to identify significantly more monosyllabic words with a higher level of presentation (mean=81.68, s.d.=18.75) as opposed to with a lower level of presentation (mean=41.50, s.d.=36.22), (F=84.69, p<0.0001). Analyses also revealed a significant interaction, which indicates that differences in performance between the test and linear instruments were greater when a lower level of 40 dB SPL was used as opposed to when a higher level of 65 dB SPL was used (F=41.51, p<0.0001). Follow-up analyses revealed that there was no improvement in identification between the test instrument (mean=87.14, s.d.=14.37) and linear instruments (mean=76.21, s.d.=21.43) when using a conversational presentation level (t=-1.96, ns). A significant improvement is observed, however, with the test instrument (mean=70.86, s.d.=26.10) over that obtained with the linear instrument (mean=12.14, s.d.=13.69) when using a low presentation level (t=-11.70, p<0.001). Figure 6 illustrates the identification of monosyllabic words with the linear and test instruments at both a low-level and conversational-level input. It was also determined that the children discriminated significantly better over a 5 month period (F=5.69, p<0.05), as illustrated in Figure 5, where discrimination improved significantly up to 3 months of using the test instrument (mean=93.57, s.d.=11.51) or 1 month of use (mean=87.14, s.d.=14.37), (t=-2.39, p<0.05). There was no additional improvement in discrimination following the 3-month testing period (t=-0.249, ns).

Tests of identification of Spanish bisyllabic words revealed a similar effect. The indentification of bisyllabic words significantly improved from using linear instruments (mean=57.93, s.d.=35.34) to using the test instruments (mean=88.89, s.d.=20.25), (f=48.46, p<0.0001). Results also indicate that children were able to identify significantly more bisyllabic words with a higher level of presentation (mean=91.79, s.d.=12.49) as opposed to with a lower level of presentation (mean=55.04, s.d.=36.05), (F=124.70, p<0.0001). Analyses also revealed a significant interaction, which indicates that differences in performance between the test and linear instruments were greater when a lower level of presentation was used as opposed to when a higher level was used (F=61.06, p<0.0001). Follow-up analyses revealed that there is no improvement in identification between the test instrument (mean=95.00, s.d.=8.55) and the linear instrument (mean=88.57, s.d.=15.12) when using a conversational presentation level (t=-1.88, ns). A significant improvement is, however, observed with the test instrument (mean=82.79, s.d.=26.42) over that obtained with the linear instrument (mean=27.29, s.d.=18.52) when using a low presentation level

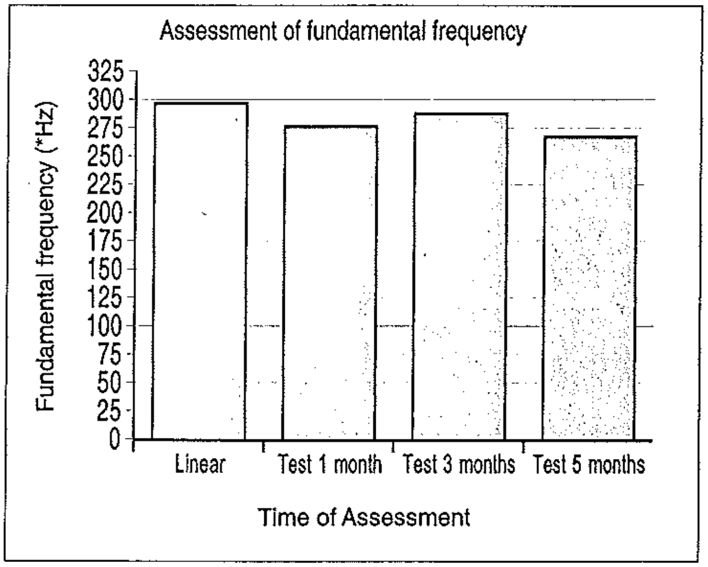
($t=-11.46$, $p<0.0001$). Figure 7 illustrates children's identification of bisyllabic words with the linear and test instruments at both a low-level and conversational-level input. It was also determined, as illustrated in Figure 5, that children's ability to identify bisyllabic words did not significantly improve over time when wearing the test instrument ($F=1.83$, ns).

Figure 7. Mean scores for identification of bisyllables obtained with the linear and test instruments at two presentation levels.



The effect of type of amplification was also observed on the mean fundamental frequency of children's speech production of the vowel /a/. A significant difference was not observed between the fundamental frequency of productions obtained when the linear instrument (mean=297.69, s.d.=56.07) was used in comparison to after the test instrument was used for a period of one month (mean=276.62, s.d.=40.97), ($t=2.14$, $p=0.52$). It is, however, important to note that the decrease in fundamental frequency from the linear condition to the test condition reaches significance at a level of probability slightly higher than the 0.05 criterion. Figure 8 illustrates the fundamental frequency of the vowel /a/ produced with the linear and test instruments at various testing periods. There is, furthermore, no significant change in fundamental frequency over time with additional use of the test instrument ($F=0.91$, ns). An analysis of vocal jitter did not reveal a significant change between vocal productions obtained using the linear instrument and the test instrument after one month of use ($t=1.55$, ns). There was also no significant change in vocal jitter as a function of the time during which the test instrument was used ($F=1.73$, ns). The analysis of vocal shimmer is quite similar, where no significant improvement was noted between productions obtained with the linear instrument and one month later with the test instrument ($t=-0.23$, ns). A significant change did not occur over time ($F=0.55$, ns). Figure 9 illustrates vocal jitter and shimmer during productions of the vowel /a/ with the linear and test instruments. This figure also illustrates the change in vocal jitter and shimmer over time with use of the test instrument.

Figure 8. Mean fundamental frequency measurements during the production of the vowel/a/ obtained with linear instrument prior to the fitting of the test instruments and at three testing periods following the fitting of the test instruments.



The mean number of incorrect speech productions during the production of the induced Spanish phonological registry was significantly different between the linear (mean=19.21, s.d.=12.96) and test condition (mean=14.64, s.d.=11.37), ($t=5.90$, $p<0.001$). Figure 10 illustrates the reduction in production errors in an induced registry from using the linear instrument to using the test instrument at various testing periods. Furthermore, there was a signifi-

Figure 9. Mean vocal jitter and shimmer measurements during the production of the vowel /a/ obtained with the linear instrument prior to the fitting of the test instruments and at three testing periods following the fitting of the test instruments.

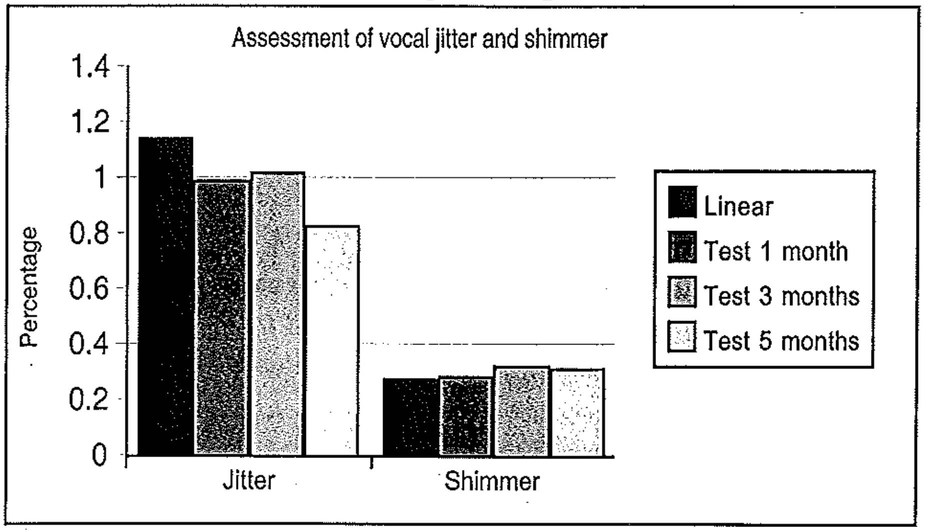
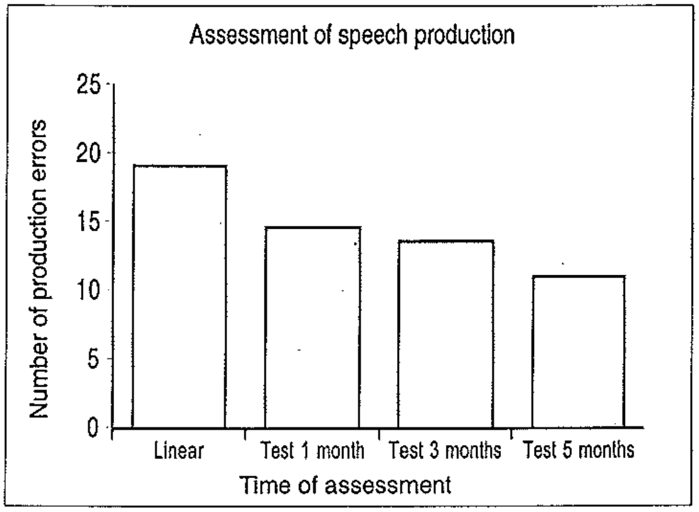


Figure 10. Mean number of production errors from an induced registry with the linear instrument prior to the fitting of the test instruments and at three testing periods following the fitting of the test instruments



cant change over a 5-month period using the test instrument (F=8.05, p<0.05) where the number of errors was significantly reduced after 5 months of using the non-linear instrument (mean=11.00, s.d.=9.50) from 3 months of use (mean=13.57, s.d.=11.02), (t=2.69, p<0.05), or from 1 month (mean=14.64, s.d.=11.37), (t=1.97, p<0.05).

The validation of preference for the Senso was measured using the WLSI-C questionnaire. The child's questionnaire revealed highly qualitative ratings, thus often giving the responsibility to the experimenter to decide on the rating category to choose on the WLSI-C. Because observations were not independent, tests of significance were not performed on this set of data. The parent questionnaire of the WLSI-C, however, indicated significant effects. Parents demonstrated a significant preference for the test instrument, underlining a significant improvement using the new instrument in all 12 subcategories of the questionnaire (p < .05).

Discussion

The present study was designed to determine whether multichannel non-linear processing with low compression threshold could enhance the performance of hearing-impaired children during speech reception tasks, such as speech discrimination and identification, and speech production tasks. An underlying premise of this study was that if this type of amplification strategy enhanced auditory performance, it could also offer an important contribution during the development of speech and language. The results of this study may provide guidelines for the fitting of hearing instruments to pre- and peri-verbal children. Clear guidelines have yet to be determined regarding the optimal type of amplification for this population. Although certain studies have determined that young children should be fitted with non-linear DSP instruments (Stelmachowicz, et al., 1993), the exact number and types of features available from DSP technology have not been examined and refined for the hearing-impaired pediatric population. Although this study is not an exhaustive examination of the effects of DSP features on speech and language ability, it does offer some insight on the role of a low compression threshold in combination with multi-channel DSP processing.

Perceptual performance effects at low levels

This study was able to provide evidence that overall receptive auditory performance at low-level input levels could be enhanced. The aided sound-field thresholds with non-linear processing and low CT were significantly reduced. Because aided thresholds were obtained with the presentation of pure-tones, they did not provide an indication of how the hearing-impaired child would perceive low-level speech or low-level environmental sounds. Despite its limitations in clinical application, aided thresholds do provide an indication of the softest detectable levels of sound. In the present study, aided threshold measurements demonstrated a significant improvement of 15-25 dB in the detection of low level pure-tones with the test instruments over that provided by the linear instruments. This improvement is, of course, directly dependant on the amount of gain permitted with the linear instrument based on the position of its volume control. For example, the improvement in aided threshold observed in this study with the test instrument could be reduced if a child were permitted to change the volume control of the linear instrument during the aided threshold measurement and thus increase the amount of provided gain. Although the detection of low-level inputs could be enhanced with a higher volume control setting, this greater provision of gain could also cause discomfort to the child when listening to more conversational or loud-level inputs, such as what is normally present in the child's everyday environment. Thus, in order to ensure comfort in most listening situations, the volume setting would typically be lower than the setting used to maximize the perception of low level inputs during the aided threshold task. Although an adult or older child may be able to maximize perception of various situations by monitoring the particular situation and adjusting the volume setting, an infant or young child is unable to achieve this task. In sum, the perception of low-level inputs in a young child's normal environment is greater with the non-linear instrument with a low compression threshold in comparison to conventional linear amplification.

When considering that the softest speech elements within a child's normal environment correspond to 20 dB HL, it would be useful to confirm that such low-level sounds are detected by the child once adequate amplification is provided. This low-level speech could consist of speech produced with a normal vocal effort but at a distance, or low-level speech of specific frequency found within conversational speech produced with a normal speech effort at a normal distance of .75 to 1 meter from the child. The results from this study confirmed that these lower level elements of speech would likely be perceived in the low frequency regions. The aided thresholds with the non-linear instrument at 2000, 4000 and 6000 Hz were slightly higher than the 20 dB HL criterion: 25, 32 and 35 dB HL respectively. Although these values do not respect the 20 dB HL criterions, they were nevertheless acceptable in light of the poor unaided thresholds measured with these children and the common occurrence of acoustic feedback from hearing instruments in these high frequency regions of amplification. Because the occurrence of acoustic feedback increased with an increase in hearing aid gain, feedback occurred more frequently when maximum gain was provided by the hearing instrument, which in this case occurred for high frequency low-level inputs. The lower amount of gain required for the adequate provision of gain for conversational inputs would reduce the occurrence of acoustic feedback from the non-linear instrument. It is thus important to note that although the provision of gain for low-level high-frequency inputs may be insufficient to provide the hearing-impaired child with perception at 20 dB HL without the occurrence of acoustic feedback, this may not affect the adequate provision of gain and output for high-frequency conversational input levels.

Although the improvement in aided thresholds with the low CT non-linear instrument provided a clear indication of the increase in audibility of low-level inputs from the child's normal listening environment, it was important to demonstrate the usefulness of this additional audibility during speech reception and production tasks. It could be hypothesised that an overall increase in audibility of low-level inputs would lead to an improvement in the detection of low-level speech and subsequently improve the child's performance during speech reception tasks. This was verified with scores obtained from tests of speech discrimination and identification using low-level inputs of 45 dB SPL. There was a significant improvement during the discrimination of Spanish phonological oppositions and the identification of monosyllabic and bisyllabic Spanish words when using the test instruments in comparison to the linear instruments. This result was likely due to the additional audibility provided from the low CT non-linear instrument, which the hearing-impaired child could access in order to facilitate the discrimination and identification of speech.

Perceptual performance effects at conversational levels

Performance at conversational input levels could be described upon observation of the analyses' interaction between technology type and the presentation level of the test stimuli. Because the volume control of the linear instrument was set in order to promote comfort and audibility for conversational speech levels, it was assumed that children would be able to perform rather well using their linear aids during speech tests at conversational presentation levels. It could also be assumed that because the test instrument was able to provide audibility independently of the presentation level of speech items, children would also perform well during speech tests using a conversational presentation level. The current study showed that there was no statistical advantage of using either non-linear or linear processing during performance of identification tasks of conversational level speech items. However, children performed better during discrimination tasks of phonological oppositions at the conversational level using the non-linear instruments. Furthermore, it is noteworthy to mention that there appeared to be a clear trend that the test instrument provided a slight improvement in performance during identification tasks. The absence of significance during identification tasks may have also been due to ceiling effects that were reached during these tasks and may have prevented the maximal separation of scores between the linear and test conditions. Nevertheless, the improvement in discrimination tasks may be explained in light of the high-level compression (HLC) used in the test instruments. This gain reduction limited gain for inputs above a conversational level in order to minimize temporal distortion otherwise caused by an excessive provision of gain. Van Tassell and colleagues (1987) have documented the importance of temporal cues during speech recognition. It was thus possible that although less output was allocated by the test instruments for inputs exceeding conversational levels, the test instrument also provided an output with fewer temporal distortions than the linear instruments, leading to greater discrimination and identification scores. Furthermore, an excessive provision of gain for conversational and loud level inputs, such as what may have resulted from linear amplification, may have actually hindered the hearing-impaired children's performance during speech recognition tasks (Ching, Dillon & Byrne, 1998). The following results suggested that children might have also benefited from low CT non-linear multi-channel amplification during the discrimination and identification of speech at conversational levels. It could be suggested that the low-level elements of conversational speech access additional gain from the non-linear amplification. Although the compression characteristics of the non-linear test instruments used in this study did not permit the compression of individual phonemes within longer phonemic structures, the multi-channel processing of these instruments permitted a frequency-specific amplification of the low-level high frequency elements of speech. The level-dependant processing combined with the low CT in the high-frequency range permitted additional audibility for low-level high-frequency speech elements. This additional high-frequency audibility appeared to enhance the performance of hearing-impaired children during speech reception tasks.

Acclimatization effects

The hearing-impaired may slowly acclimatize to new hearing conditions provided by different hearing instrument characteristics and show increasingly better auditory performance over the course the first few months of wearing a new instrument (Gatehouse, 1993). In order to consider the role of acclimatization on children's performance during speech discrimination and identification tasks, outcome measures were obtained over the course of 5 months. Our results showed a significant acclimatization effect measured using discrimination of phonological oppositions and identification of monosyllabic words. The acclimatization effect was not revealed during tasks of identification of bisyllabic words. This absence of significance, however, could be attributed to ceiling effects, where measurements with the linear and non-linear instruments often reached a perfect score. Because bisyllabic words are given more contextual support than monosyllables based on the possible lexical combinations of syllables, children achieved greater performance during this type of task. The resulting ceiling effect did not permit the maximal separation of results over time. From these results, it was suggested that most children benefited from low CT non-linear multi-channel processing and this benefit could increase over time. These children were expanding their scope of speech reception skills. Although it could be argued that this acclimatization is simply due to maturation, this improvement, measured within a 5-month time period, should have surfaced much earlier during development, considering the age of our group of children and their successful use of linear hearing instruments. It was thus hypothesised that the improvement in receptive auditory performance did not coincide with normal speech and language development but rather with the onset on the low CT non-linear amplification.

Speech production effects

It was also hypothesised that the additional audibility of low-level speech could result in an improvement in speech production abilities from our hearing-impaired children. Because these children could now discriminate and identify low-level elements of speech with the test instruments, they should also be able to more frequently produce these low-level speech elements more frequently during discourse. The present data suggested that children with severe to profound hearing impairment are capable after a 5 month period of providing a significantly better speech production than prior to the study. A reduction in production errors was attributed to the increase in audibility of low-level speech elements with the low CT multi-channel non-linear instrument and to the resulting enhanced monitoring of the child's own voice. A child's speech production will be perceived much louder by the child than by others, on the order of 15-20 dB, especially in the low and mid-frequency range (Cornelisse et al., 1991). This increase in intensity is caused by the proximity of the vocal tract to the hearing instrument and the radiation characteristics of low and mid frequencies. With single-channel WDRC instruments, the gain of the instrument is dictated by the loudest inputs reaching the instrument's microphone, which in the case of speech production from the hearing-impaired instrument user correspond to these lower-frequency elements. The decrease in gain corresponding to this increase in low frequencies by the instrument user's own voice will, however, provide insufficient gain to higher frequency elements of these same speech productions, often causing them to be inaudible (Kuk & Marcoux, 2002). An accurate monitoring of one's own voice and resulting speech production may be difficult under such circumstances, as the audibility of high-frequency speech elements is important in ensuring the overall intelligibility of speech (Studebaker, Pavlovic, & Sherbecoe, 1987). The multi-channel non-linear instrument possesses an independent gain-frequency response for the softer high-frequency elements of speech. In this study, the multi-channel processing of the non-linear instrument appeared to have provided a frequency-specific gain to high-frequency speech elements in such a manner to ensure sufficient audibility of high-frequency elements from children's productions. Results also suggested acclimatization to the test instruments, which was apparent up to the 5-month testing period. Thus, children progressively provided fewer inaccurate speech productions over time. Although this improvement could also be attributed to the maturation of the child, as with improvements in speech reception, the improvement did not coincide with a maturational milestone of speech and language development but rather with the onset of low CT non-linear amplification.

Data obtained with both the linear and non-linear instruments illustrate fundamental frequencies of the vowel /a/ to be within norms with the exception of a few outliers (Valero & Casanova, 2001). Furthermore, a significant decrease in fundamental frequency is initially observed with the low CT multi-channel non-linear instrument, where this decrease provided average group data closer to the normative average. Our data did not demonstrate a significant improvement in speech quality when assessing jitter and shimmer of productions of the vowel /a/ . There was no additional change in voice quality assessed in subsequent testing sessions. It is important to note that voice quality measurements may vary with respect to the measurement conditions encountered during the testing session (e.g. status of larynx, pharynx, respiratory system, mood, etc.). The plasticity of voice quality has also been documented (Djonckere & Lebaq, 2001; Gurlekian, 2001) and this plasticity may be to some extent dependent on speech reception and production ability. Thus, although an acceptable level of voice quality is desirable for hearing-impaired children, it may be suggested that an improvement in speech reception and production is primarily important. Inspections should be achieved in a more detailed and stringent study if a parallel is to be suggested with regard to established voice quality and type of amplification.

Validation measure findings

In order to maintain the level of objectivity attributed to the following study, as outlined in the introduction, it is sufficient to report that results from the validation questionnaires were interpreted with caution. Because bias is inevitable during the administration of validation questionnaires during comparative studies, results from the WLSI-C questionnaire were mainly used for counselling purposes and to address concerns, which may have resulted during the initial transition from the linear instrument to the test non-linear instrument. The answers received on the questionnaires did not influence the outcome of the study, nor were participants rewarded for answering in a particular manner. In general, parents and children signalled a marked improvement with the non-linear instrument with regard to a heightened awareness of sound, eagerness to participate in auditory tasks and communication and an overall ease of listening to soft and distant sources of sound and speech.

Clinical implications

There are several clinical implications that could be derived from the present study. First, children who have been provided with linear amplification and have become experienced users may not initially appreciate non-linear processing. A typical concern may be that the test instrument is not able to provide enough loudness for conversational and louder inputs. Although an experienced user may have appreciated the loudness provided by a linear instrument, it was important to counsel the hearing-impaired child to persist using the test instrument despite its reduction in loudness for higher-level inputs. The objective of this line of counselling was to permit the child to acclimatize to the test instrument while demonstrating an improvement in speech reception and production skills. As this study clearly demonstrated, the improvement in speech recognition and production performance with the test instrument permitted greater speech reception for low-level and conversational-level speech and a more accurate speech production. Counselling was thus a necessary component in order to help the child accept that although the test instrument may not be appreciated at first, a certain amount of perseverance would lead to later acceptance and overall benefit.

Secondly, it is important to note that an improvement of the aided threshold appeared to be a predictor for the improvement of speech reception performance in the pediatric population. The additional audibility of low level elements of speech reflected by the aided threshold appeared useful during the speech reception of both low level and conversational level speech. With linear amplification, an improvement in aided threshold could be obtained by simply increasing the gain or volume provided by the instrument. Thus the aided threshold with linear amplification could not be obtained unless the position of the volume was fixed and kept constant with that which is optimal in a normal everyday environment. Because gain for low-level inputs was automatically fixed during non-linear processing, the aided threshold revealed the softest level of sound that the child is able to hear.

Thirdly, it appears that the benefit from a new instrument such as the test instrument used in this study may be fully realized after several months of use. Results from the present study indicate that outcome measures, which are collected prior to at least 5 months of using a new instrument, may provide misleading conclusions. The acclimatization to the new instrument did not appear to plateau for all measures prior to the termination of the study. Although an improvement in the identification of words did not continue past the 3-month period, measures of speech discrimination of phonological oppositions and measures of speech production continued to improve well after the 3-month period.

Lastly, low compression threshold multi-channel non-linear DSP instruments may enhance the development of speech and language. Our results indicated the importance of audibility of low-level speech inputs during the speech reception tasks. The observations that the hearing-impaired child acclimatized to having additional audibility to low-level speech inputs and quickly demonstrated a more efficient speech reception and production suggested that the audibility of low-level speech inputs promoted the overall development of speech. Studies would also be required in order to explore the effect of this type of amplification strategy on the development of language. Furthermore, it would be important to study the effects of this type of amplification more closely in more defined age groups within the pediatric hearing-impaired population, with groups of children who have been either early-diagnosed or later-diagnosed and who have the same amount and type of experience with hearing instruments. Although the age of onset of intervention is documented as being the strongest predictor of speech and language performance following the rehabilitation process, it could also be hypothesised that hearing instruments such as the test instruments utilized in the present study may further promote the development of speech and language and have a positive effect on the outcome of the intervention and rehabilitation processes. Following the positive improvements in speech reception and production observed in the present study with later-identified hearing-impaired children, it would be interesting to determine whether the benefits of the test instruments extend to speech and language learning with a group of early-identified children with severe to profound hearing impairment. In combination with early-identification of hearing loss, several amplification strategies may prove beneficial in order to further prevent the effects of sensory deprivation and thus minimize speech and language delays. Although many hearing health-care professionals currently recommend linear instruments for children with severe to profound hearing loss (Tharpe, Fino-Szumski, & Bess, 2001), documentation underlining the benefits of modern DSP instruments, such as that provided in the present study, will permit the provision of an optimal fitting solution for the pediatric hearing-impaired population.

Conclusions

The results from the present study showed that low compression threshold, multi-channel DSP instruments permitted a significant increase in discrimination and identification of both low-level and conversational-level speech items, in comparison to that measured with linear instruments, in a group of severe-to-profound hearing-impaired children. It was also noted that these children provided fewer speech productions with the test instruments in comparison to the number provided previously, when wearing linear instruments. It was concluded that the additional audibility provided by the low compression threshold in independent frequency regions facilitated speech reception and production processes. This facilitation was further increased over time, following an acclimatization period of 5 months to the new instrument. Voice quality improvements with the test instruments were not conclusive. These results suggest that an instrument with a low compression threshold combined with multi-channel non-linear processing may promote the development of speech abilities in the hearing-impaired population and that such an instrument should be considered during the rehabilitation process of the child with severe to profound hearing impairment.

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