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

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 et al., 2001; Geers & Moog, 1989). Although advances in hearing aid technology and rehabilitation services have been designed to promote speech and language learning, the prognosis did not always favour a marked academic improvement (Rodda & Grove, 1987).

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 power 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.

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.

Several Widex Senso instruments provide Enhanced Dynamic Range Compression (EDRC), which is an extension of the WDRC circuit and 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.

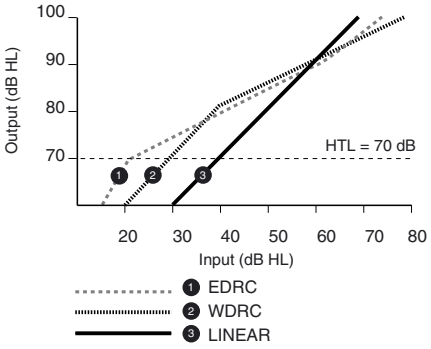

Figure 1. *Hypothetical input-output curves of a linear instrument, a WDRC instrument and the EDRC test instruments matched in output for a conversational input level received at the microphone of the instruments worn by a hearing-impaired listener with a 70 dB HL loss.*

Speech reception and production skills of severely and profoundly periverbal hearing-impaired children were monitored during a transition from a linear hearing device to a Widex Senso instrument with EDRC.

The present study will determine whether the amplification strategy provided by a low compression threshold (CT) multi-channel non-linear DSP provided by the Widex Senso 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. The 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). All were fitted with a power linear instrument shortly following diagnosis. These hearing devices were provided from a 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 unilingual Spanish speakers, attending mainstream schools. Because some children were also prone to having frequent otitis media, appropriate documentation of middle ear function was conucted 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. These values ranged between 71 and 98 dB HL. Inclusion in the study also required adequate parental support and interest.

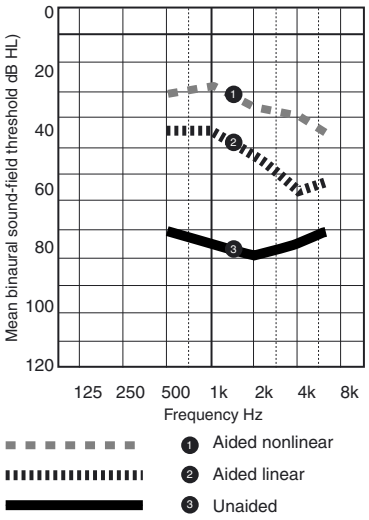

Figure 2. *Mean binaural sound-field thresholds obtained in the unaided condition (bottom), with linear instruments, where the VC was fixed in order to provide comfort for conversational-level inputs (middle), and with the test instruments fitted according to the manufacturer's recommendations (top).*

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 Senso 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 which 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. The C18+ is aesthetically smaller than the P38 and was provided 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.

Procedure

Initial session

The children's analogue instruments were evaluated using electroacoustic measurements in order to determine their suitable performance in accordance with 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 Widex Senso P38 and C18+ instruments were evaluated using electroacoustic measurements and programmed according to each child's audiometric thresholds collected during the previous session, following the manufacturer's recommended fitting protocol *(Marcoux & Hansen, 2003).*

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 Widex Senso P38 and C18+ 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 Widex Senso P38 and C18+ instruments were able to meet these criteria.

Third, fourth and fifth sessions: 1, 3 and 5 months 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 Widex Senso P38 or C18+ test 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. 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.

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 which 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 and with the Widex Senso P38 or C18+ instrument.

Speech production measurements consisted of monitoring the production of words belonging to an induced Spanish phonological registry. 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.

Results and Discussion

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. 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 Senso 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 volumecontrol.
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.
When considering that the softest speech elements within a child's normal environment correspond to approximately 20 dB HL, it would be useful to confirm that such low-level sounds are detected by the child following the provision of adequate amplification *(Kuk, 1999).*
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.
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 criteria, 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. It is however 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 will not affect the adequate provision of gain and output for high-frequency conversational input levels.

Although the improvement in aided thresholds with the Senso 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.
This was verified with scores obtained from tests of speech discrimination and identification using low-level inputs of 45 dB SPL. Figure 3 illustrates the 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 Senso instrument, which the hearing-impaired child could access in order to facilitate the discrimination and identification of speech.

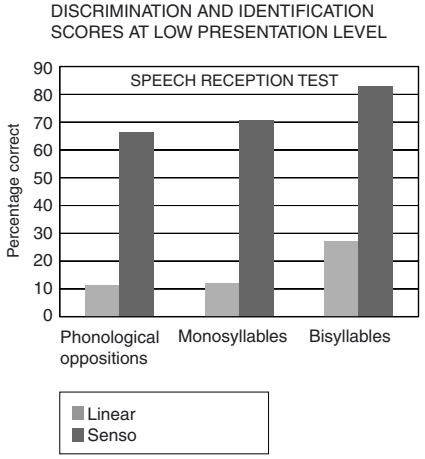

Figure 3. *Mean scores for discrimination of phonological oppositions, identification of monosyllables and identification of bisyllables obtained with the linear and Senso instruments at a low presentation level.*

Perceptual performance effects at conversational levels

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 the 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, the children would also perform well during speech tests using a conversational presentation level.
Figure 4 illustrates 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

Senso instruments. Furthermore, it is noteworthy to mention that there appeared to be a clear trend that the Senso instrument provided a slight improvement in performance during identification tasks.

The absence of significance during identification tasks may also have been due to ceiling effects which were reached during these tasks and may have prevented the maximal separation of scores between the linear and Senso conditions. Nevertheless, the improvement in discrimination tasks may be explained in light of the high-level compression (HLC) used in the Senso 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 Senso instruments for inputs exceeding conversational levels, they also provided an output with fewer temporal distortions than the linear instruments, leading to greater discrimination and identification scores.

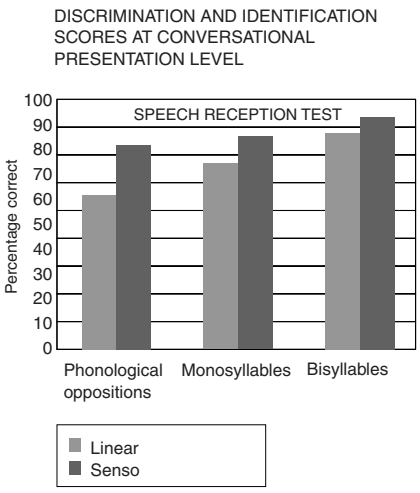

Figure 4. *Mean scores for discrimination of phonological oppositions, identification of monosyllables and identification of bisyllables obtained with the linear and Senso instruments at a conversational presentation level.*

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 of 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. From these results, it was suggested that most children benefited from Senso's low CT non-linear multi-channel processing and this benefit could increase over time.

Speech production effects

Because these children could now discriminate and identify low-level elements of speech with the Senso instruments, they should also be able to more frequently produce these low-level speech elements 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 Senso 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, in 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 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.

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 EDRC Senso instrument possesses an independent gain-frequency response for the softer high-frequency elements of speech. Figure 5 illustrates how the multi-channel processing of the Senso appears to have provided a frequency-specific gain to high-frequency speech elements in such a manner as to ensure sufficient audibility of high-frequency elements from children's productions.

Results also suggested an 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 the Senso fitting.

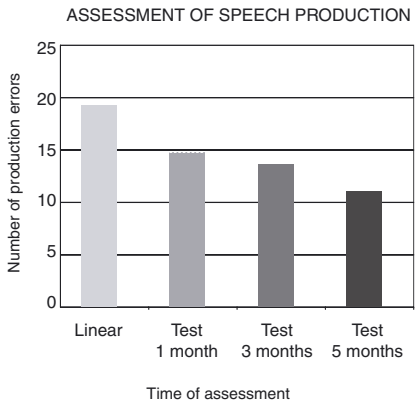

Figure 5. *Mean number of production errors from an induced registry with the linear instrument prior to the fitting of the Senso instruments and at three testing periods following the fitting of the Senso instruments.*

Conclusions

The results from the present study showed that low compression threshold, multi-channel EDRC instruments, such as the Widex Senso P38 and C18+ 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 production errors with the Senso 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.

These results suggest that the Senso instrument 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 hearing impairment.

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