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# Cochlear Implant Speech Processor Placement and Compression Effects on Sound Sensitivity and Interaural Level Difference

Todd Ricketts*
D. Wesley Grantham*
Patrick D'Haese†
Jason Edwards†
Amy Barco†

**Abstract**

The purpose of this investigation was to determine the impact of commonly recommended cochlear implant (CI) speech processor placements on microphone output both with and without single channel front-end compression. The impact of this compression use on interaural level difference (ILD) magnitude was also evaluated for the ear-level position. Finally, pilot localization data collected with and without single channel front-end compression was collected on seven bilateral cochlear implant recipients. The results revealed that differences in signal audibility due to clinical placement of CI speech processors in ear, shoulder, and collar positions can at least partially be offset through the use of front-end compression. These data also revealed that compression impacted ILD cues. Preliminary data indicated that some bilaterally implanted subjects were able to take advantage of the enhanced ILD cues when compression was turned off, while other bilaterally implanted subjects did not localize better in the compression-off condition.

**Key Words:** Cochlear implant, interaural level difference, localization, microphone location

**Abbreviations:** CI = cochlear implant; ILD = interaural level difference; MLE = microphone location effect

**Sumario**

El propósito de esta investigación fue determinar el impacto de los sitios de colocación comúnmente recomendados para el procesador de lenguaje del implante coclear (CI) sobre la salida del micrófono tanto con y sin compresión frontal de canal único. El impacto del uso de esta compresión sobre la magnitud de la diferencia interaural de nivel (ILD) también fue evaluado para la posición a la altura del oído. Finalmente, datos piloto de localización con y sin compresión frontal de canal único fueron recolectados en siete pacientes con implante coclear bilateral. Estos resultados revelaron que las diferencias en la audibilidad de la señal debido a la colocación clínica de los procesadores de lenguaje a nivel del oído, del hombro o del cuello pueden ser parcialmente compensadas por medio del uso de la compresión frontal. Estos datos también revelaron que la compresión impactaba las señales de la ILD. Los datos preliminares indicaron

*Department of Hearing and Speech Sciences, Vanderbilt Bill Wilkerson Center; †MED-EL Corporation

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Todd A. Ricketts, Ph.D., Dan Maddox Hearing Aid Research Laboratory, Vanderbilt University Medical Center, Department of Hearing and Speech Sciences, 1215 21st Ave. South, Room 8310, Medical Center East, South Tower, Nashville, TN 37232-8242; Phone: 615-936-5258; Fax: 615-936-6914; E-mail: todd.a.ricketts@vanderbilt.edu

que algunos sujetos implantados bilateralmente pudieron sacar ventajas de las señales aumentadas de la ILD cuando se apagaba la compresión, mientras que otros sujetos implantados bilateralmente no obtenían mejor localización en la condición de compresión apagada.

**Palabras Clave:** Implante coclear, diferencia interaural de nivel, localización, colocación del micrófono

**Abreviaturas:** CI = implante coclear; ILD = diferencia interaural de nivel; MLE = efecto de la colocación del micrófono

When first introduced, cochlear implants (CI) were body-worn devices that primarily provided awareness of sound and improved lipreading. Cochlear implant technology has progressed significantly, however, and open set word recognition performance of 80% or more is now common for cochlear implant recipients (e.g., Wilson, 2000).

As CI technology has improved, the placement of the externally worn speech processor has also changed. While early devices were body-worn, a variety of device placements are now employed, including ear-level placement (offered by all three current implant manufacturers). It is well known that port placement can have a significant impact on frequency response at the output of the microphone. These changes in frequency response are usually reported as microphone location effects (MLE) and are well established for all styles of hearing aids in use (e.g., Dillon, 2001). Differences in MLEs result from the reflection, baffle, and diffusion of anatomical structures of the body given a specific microphone placement. Consequently, similar MLEs are expected for cochlear implant speech processors and hearing aids given the same microphone position.

Despite this expected agreement, further investigation of the impact of microphone position specific to CI applications is of interest. This interest stems in part from the fact that even though ear-level CI speech processors were designed for over the ear use, clinical and practical factors sometimes dictate that they be worn in other positions. Clinical reports and manufacturer recommendations suggest these devices are sometimes worn on the collar, on the shoulder, and on the back, as well as other positions. These different positions might be expected to dramatically impact sound sensitivity and input to the processor. If changes to the frequency response are large enough, audibility of speech could be negatively impacted.

In practice, the impact of speech processor placement is expected to be lessened by the use of input compression. Specifically, all CIs compress the microphone output prior to delivery of the signal to the processor. This is commonly referred to as “front-end” compression since it occurs prior to the additional signal processing provided by the speech processor that occurs before delivery of the electric signal to the cochlea. This additional signal processing is necessary, among other reasons, for ensuring that desired input levels generally fall within an individual listener’s dynamic range for electric stimulation. It is important to note that the specific implementation of front-end compression varies across manufacturers and that some compression parameters can be controlled by the clinician, and in some cases, the end user.

Regardless of the specific implementation, the use of input compression will result in a reduction of the level differences that are present in input signals for sound levels above the input compression threshold. For example, consider the case of two talkers, one speaking at 62 dB SPL and one speaking at 72 dB SPL as measured at the input of the microphone. Also assume that the speech processor implements input compression with a compression threshold of 55 dB SPL and a compression ratio of 2:1. In this example, the input to the processor after front-end compression will differ by 5 dB, rather than the 10 dB difference that would be present without compression. Similarly, given a discrete source location, the level differences present at the output of the microphone that result from changes in speech processor placement will also be reduced by compression.

The potential interaction between front-end compression and bilateral CI fittings is also of interest. While relatively new, a number of studies now suggest there may be significant benefits to bilateral cochlear implantation in terms of improvement in sound location and speech intelligibility in noise (Au et al, 2001; Muller et al, 2002; Tyler et al, 2003; van Hoesel and Tyler, 2003, Nopp et al, 2004; Grantham et al, 2005). It has been generally agreed that localization ability in bilateral recipients is enhanced because these individuals can make use of the interaural level difference (ILD) cues present between the two implants (e.g., van Hoesel and Tyler, 2003; Grantham et al., 2005). Since the front-end compression used in CIs yields a relative increase in gain with decreasing input, the magnitude of the ILDs resulting primarily from head shadow effects will also be reduced by compression. That is, the level differences between the ears will be reduced. It is of interest to examine the relative impact of compression on measured ILDs, since it is expected that distortion of the ILD cue may result in reduced localization performance under specific listening conditions. Data to date support a strong, perhaps even monotonic, relationship between the perceived lateral position of a sound source and the ILD in bilateral cochlear implant recipients (Long et al, 2003; Laback et al, 2004). These data, however, were collected without an active front-end compression system.

The purpose of this investigation was to determine the impact of common cochlear implant speech processor placements on microphone output both with and without single-channel front-end compression. In addition, the effect of placing the primary source at azimuthal angles surrounding the listener was also evaluated for the ear-level position. These data were used to determine the impact of the front-end compression processing commonly used in CIs on the magnitude of the ILD across frequency.

## METHODS

A standard clinical TEMPO+ speech processor (Helms et al, 2001), used as part of the MED-EL C40+ cochlear implant system, was evaluated. The microphone/processor unit was coupled to a custom output unit that allowed for the measurement of microphone output after front-end compression but prior to further sound processing. This custom device, provided by the manufacturer, takes the analog voltage from the output of the compressor and allows for it to be fed directly to "line level" inputs of measurement and recording systems. Sensitivity was adjusted to "maximum" or "off" prior to testing. The sensitivity setting in the MED-EL device affects the compression threshold applied to the signal input. A setting of "off" deactivates the single-channel compression system while a setting of "maximum" results in a compression threshold of approximately 45 dB SPL (Stobich et al, 1999). The input compression ratio in the TEMPO+ unit is fixed at 3:1. The volume control was set to maximum for all testing.

All testing was completed using a Knowles Electronics Manikin for Acoustic Research (KEMAR) placed in the center of an anechoic chamber measuring 3 meters (wide) X 3 meters (long) X 3 meters (high). A men's long-sleeve buttoned shirt was placed on the KEMAR, and the CI was attached to the shirt for the placements other than ear level (postauricular). All measurements were made in response to a 70 dB SPL Gaussian noise signal output from a single loudspeaker (Tannoy system 600™) placed 1.5 meters from the KEMAR. Relative microphone output was measured by feeding the electronic output from the custom interface directly to a two-channel spectrum analyzer (Tektronix 2630).

The microphone output was measured in the free field and for ear-level, shoulder, and back-of-the-collar positions. Specifically, the speech processor was placed on the left ear, was pinned to the top of the left shoulder, and was pinned to the collar in the center of the back of the neck (pointed straight up). Output measures for the ear level placement were also taken for both compression (maximum sensitivity) and linear (sensitivity off) settings for loudspeaker angles surrounding the KEMAR in 10° increments. The KEMAR was rotated to obtain the angular output measurements using a commercial turntable (Outline Industries ET1.1™). The center of the head was used as the reference for distance across all measures. Consequently, distance varied across measures depending on position and angle. That is, the distance between the loudspeaker and the device placed on the left ear was several inches less (corresponding to the width of the head) for the 270° degree measurement angle than the 90° degree angle. One measure was taken for each condition.

## RESULTS AND DISCUSSION

The relative output for ear-level, shoulder, and back positions in linear and compression modes was calculated by subtracting the free-field microphone response from each of the three KEMAR microphone positions in linear and compression modes. The data for the 0° azimuth presentation angle are shown in Figures 1 and 2. As expected, Figure 1 revealed that microphone position greatly impacted the output in linear mode. This difference was most evident in the high frequencies and when significant body baffle and sound shadow effects were present. For example, approximately 5 to 23 dB less output was measured for the "back" position than the ear level position for frequencies above 1300 Hz. The impact of the shoulder position was smaller; however, approximately 3 to 10 dB *more* output for frequencies between 800 and 1300 Hz and between 6 and 15 dB *less* output for frequencies above 5000 Hz was measured in comparison to the ear-level position.

In comparison to the linear data presented in Figure 1, it is clear from Figure 2 that compression reduced the differences in output resulting from changes in source position. Specifically, for the majority of frequencies, the difference in output between the ear-level and the other two positions was generally less than 10 dB. The effects of using single-channel compression can also be seen in these data. The impact of single-channel compression is most evident when comparing the back position to the other two positions. Body shadow for the back position reduces the high-frequency input (as well as overall input) to the microphone. Application of compression provides increased gain to partially offset this difference. Consistent with single-channel compression, however, these data revealed that the same gain increase was applied to all frequencies. Consequently, for the back

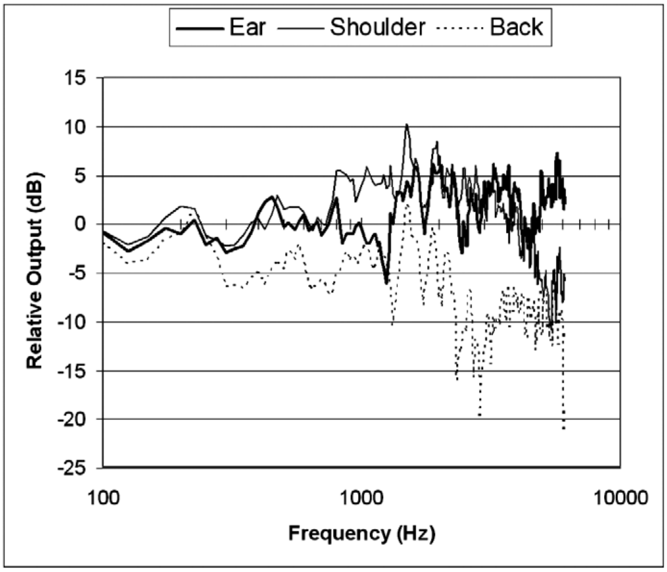


**Figure 1.** The relative output from the cochlear implant speech processor after front-end compression but prior to further sound processing for ear, shoulder, and back positions with the front-end compression system deactivated.

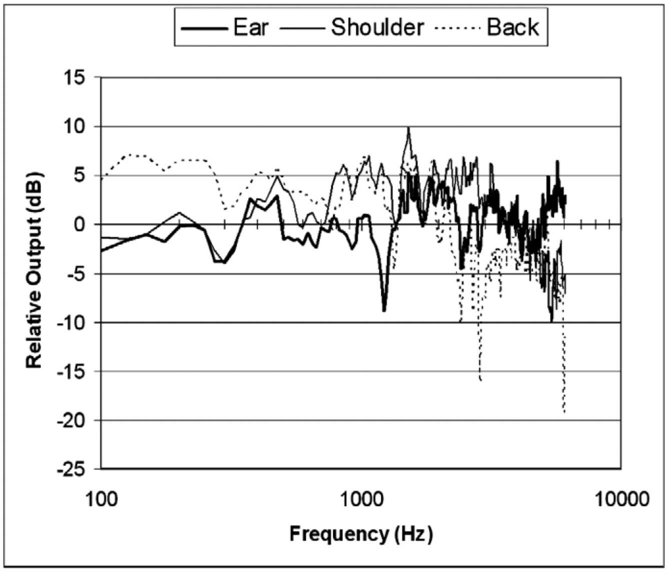


**Figure 2.** The relative output from the cochlear implant speech processor after front-end compression but prior to further sound processing for ear, shoulder, and back positions with the front-end compression activated.

position, more output was measured in the low frequencies, and less output was measured in the high frequencies relative to the ear and shoulder microphone positions. That is, single-channel compression did not affect the differences in spectral tilt introduced by microphone location effects. Rather, only the differences in overall output were offset by compression. Multichannel compression may be necessary if it is deemed desirable to offset both differences in overall level and spectral tilt due to changing microphone location. The interaction between spectral tilt, level, and the number of compression channels is discussed in detail elsewhere, and the interested reader is referred to the works of Souza (2002) and Dillon (2001).

A secondary goal of this experiment was to examine how compression interacted with microphone output as a function of source angle. These data were used to examine the impact of compression on ILDs for bilateral ear-level fittings. In order to examine ILDs, the spectral microphone output data measured in 10° increments of source angle were first used to calculate 1/3 octave levels for the octave frequencies of 500 through 4000 Hz and the midoctave 6000 Hz. The 1/3 octave levels measured on the left ear were then reassigned to opposite angles to simulate outputs from a right-ear position assuming perfect head and body symmetry. That is, the value for 10° was assigned to 350°, the value for 20° was assigned to 340°, and so on. The differences between the measured left-ear values and the simulated right-ear values were then calculated for all measured angles in order to estimate frequency-specific ILDs. The estimated ILDs for the linear (sensitivity off) and compression (sensitivity maximum) settings are shown in Figures 3 and 4, respectively.

In good agreement with a plethora of past data, the data in Figure 3 show the largest ILDs (approaching 20–25 dB) at the highest measured frequencies and for angles near 90° and 270°, with little or no level difference cues available in the lower frequencies (e.g., 500 Hz). As expected, the data in Figure 4 revealed that the use of compression resulted in a decrease in the magnitude of the ILD in the high frequencies. This decrease was consistent with the 3:1 compression ratio used in the test instrument.

Since single-channel compression impacts the gain of all frequencies equally, the difference between the output levels on the two sides was decreased by approximately the same level across all frequencies when compression was applied. Specifically, activation of the single-channel compression parameters used in this experiment altered the magnitude of the ILD for all frequencies

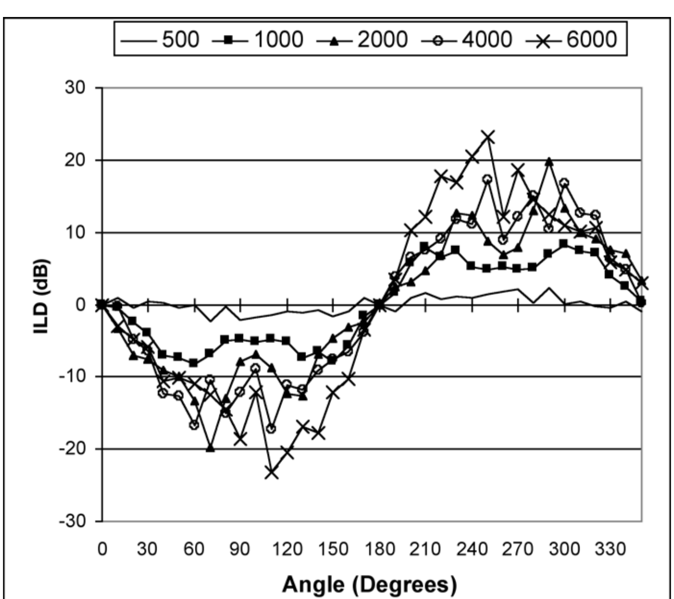


**Figure 3.** One-third octave estimated ILD values measured with front-end compression deactivated and an ear-level microphone location.

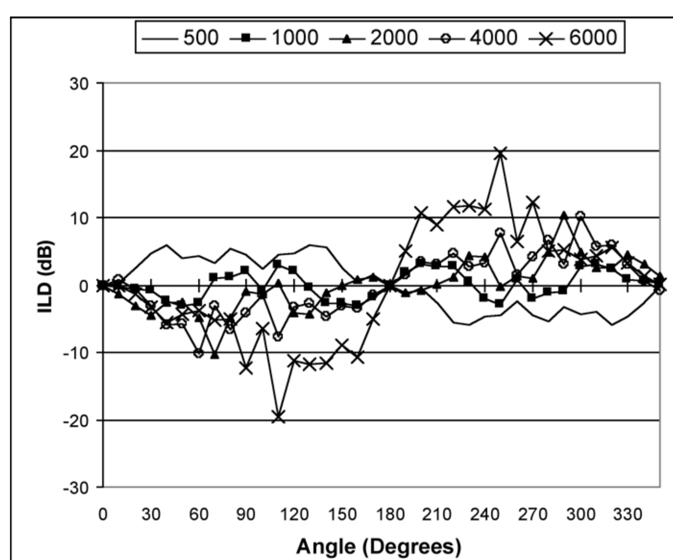


**Figure 4.** One-third octave estimated ILD values measured with the front-end compression system set to maximum and an ear-level microphone location.

of the broadband signal by approximately 7–8 dB for angles around 90°. This effect is clearly seen when the difference between ILDs calculated for the linear and compression conditions are plotted as a function of frequency as shown in Figure 5. Reducing the magnitude of the ILD by 7–8 dB for the frequencies of 1000 Hz and above has the obvious effect of reducing the magnitude of ILD cues as shown in Figure 4. For the low-frequency signals in which no ILD is present with linear processing (e.g., 500 Hz), the compression introduces an ILD cue that is in opposition to the usual cues. That is, for the 1/3 octave band around 500 Hz, the output from the microphone is actually greater for signals generated on the opposite side of the head than for the same signals generated on the same side of the head as the CI (see Figure 4). Again, this difference occurs because the compression system increases gain to all frequencies (thus not impacting spectral tilt) to offset the reduction of overall level. The reduction of overall level in this case, however, is due to head shadow and is driven by a loss of energy only in the high frequencies. Since low-frequency, band-limited signals will arrive at the two ears with approximately the same level regardless of angle, compression is not expected to impact the ILD for these signals. That is, the ILDs of low-frequency band-limited signals will remain negligible for both linear and compression processing. In contrast, the ILDs for high-frequency band-limited signals will be reduced by the use of compression in a manner similar to broadband signals.

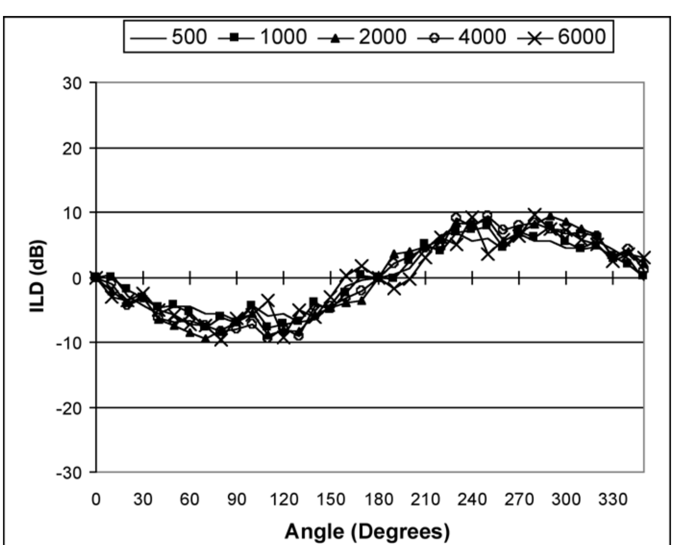


**Figure 5.** The difference in the estimated one-third octave ILD values between linear and compression conditions.

While the impact on localization of these measured changes in ILD cues is unknown, the complexity of interactions that are possible suggests careful consideration may be necessary when evaluating the impact of single-channel compression on the localization of broadband and narrow-band signals in listeners using bilateral cochlear implants.

## *FOLLOW-UP EXPERIMENT: THE EFFECTS OF COMPRESSION SETTING ON HORIZONTAL-PLANE LOCALIZATION PERFORMANCE*

### METHODS

In order to determine the effects of CI front-end compression on horizontal-plane localization, a pilot experiment was conducted with a group of seven adults, all bilaterally implanted with the MED-EL C40+ device. The seven subjects consisted of one male (age 33) and six females (ages 31–56), all of whom were postlingually deafened, and all of whom had received their two implants in a single surgical procedure 14–19 months prior to testing. Each subject wore his or her two speech processors at the standard ear-level positions. For the localization test, the subject was seated in the center of an anechoic chamber facing a semicircular array of 43 loudspeakers, 1.5 m distant, spanning azimuths from -90° (opposite the left ear) to +90° (opposite the right ear). Unbeknownst to the subject, only nine of the 43 loudspeakers were employed in the experiment; these nine loudspeakers spanned azimuths from -80° to +80° with a mean separation of 20°. The remaining loudspeakers served as "dummy" speakers.

The stimulus employed was a wideband (100–4000 Hz) Gaussian noise burst, 200 msec in duration, presented at an average level of 70 dB SPL (but with a ±5 dB random rove applied to each presentation). On each trial, the subject was instructed to face the center of the array and to push a button on a lap-held response box when ready. When the subject pushed the button, the stimulus was presented from one of the nine "active" loudspeakers, and the subject was instructed to call out the number of the loudspeaker (they were labeled 1 to 43) she or he believed produced the sound, turning to look around, if necessary. No feedback was provided. Trials were presented in blocks of 54 trials (each of the nine sources presented six times in random order), and short rest intervals were provided between blocks.

Subjects were tested in two conditions: (1) front-end compression activated (achieved by turning the sensitivity knob on the device to the maximum right position); and (2) front-end compression deactivated (achieved by turning the sensitivity knob fully to the left). Each subject ran two blocks in each condition (with testing carried out over two days), so that there were a total of 12 responses for each source position in each condition. On each day of testing, the subject was given a warm-up block of trials before any data were collected. In addition, prior to each full block of trials, the subject was given an abbreviated practice block (two trials per source position) for the particular condition to be tested next. The order of the conditions was counterbalanced across subjects. (A complete description of the experimental setup can be found in Grantham et al, 2005.)

## RESULTS AND DISCUSSION

Unfortunately, the small number of subjects included in this pilot does not allow for statistical treatment of the data. Consequently, only descriptive and individual data are presented in the following. Overall rms error for the seven subjects is displayed in Figure 6 for both compression activated and compression deactivated. With compression activated (black bars), average rms error score was 29.2° (ranging from 16° to 52°), which is considerably better than chance performance (72°). This replicates previously reported data showing that bilaterally implanted subjects do quite well in a horizontal-plane localization task (e.g., van Hoesel and Tyler, 2003; Nopp et al, 2004), though performance does not reach the level attained by normal-hearing persons (~8°).

With compression deactivated (gray bars), average rms error score was 24.8° (ranging from 16° to 38°). As can be seen from the figure, three of the seven subjects (M, K, and Y) showed some improvement in performance when compression was turned off (a reduction in error score by 8–15°), while the other four showed little or no difference across the two compression conditions. Of course, there is a confound in this particular experiment, since none of the subjects was accustomed to wearing his or her device in the *compression-off* condition. To the extent that long-term experience with the device settings is important for realistic spatial perception, one might expect performance to be superior in the compression-on condition. Indeed, most of the subjects complained about having to do this localization task with compression turned off due to the soft and muffled quality of the sounds in that condition. Nevertheless, it is interesting that despite this difference in experience between the two settings, three of the subjects were able to take advantage of the better ILD information in the compression-off condition in order to localize sounds more accurately. It should be noted that these preliminary findings are further limited in that only Gaussian test signals were used. Unpublished data from our laboratory have shown that the short speech segment "hey" is localized with better precision than noise. However, it is yet unknown whether the compression effects observed with noise would be different for the two types of signals. Further, published data to date indicate that differences in localization accuracy between these two types of signals

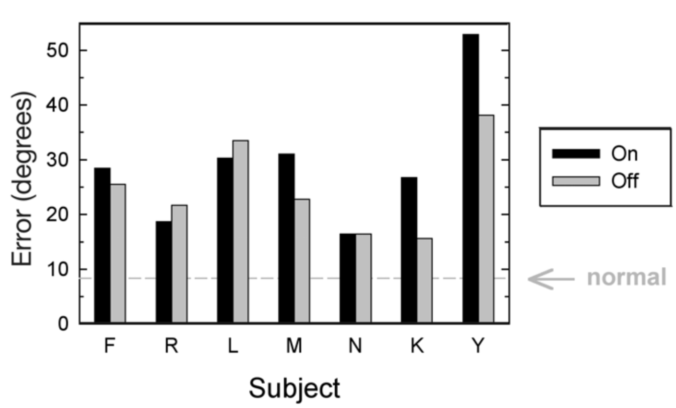


**Figure 6.** Overall (rms) error in horizontal-plane localization task, measured for seven subjects with front-end compression activated (black bars) or deactivated (gray bars). The horizontal dashed line (Error = 8.3°) shows performance from a typical normal-hearing subject (Vause and Grantham, 1999). Chance performance would be 72°.

appear to be quite small (Grantham et al, 2005).

## GENERAL SUMMARY

These data suggest that the use of input compression can be generally useful to offset some of the impact that changing CI speech processor position has on microphone output (the MLE). These data support the notion that differences in signal audibility due to clinical placement of CI speech processors in a variety of positions can at least partially be offset through the use of front-end compression. These data also revealed that compression can impact the magnitude, and in some cases the direction, of ILD cues. The specific impact of single-channel compression on the ILD depends on the signal frequency and bandwidth. Preliminary data indicated that some bilaterally implanted subjects can take advantage of the enhanced ILD cues when compression is turned off, resulting in more accurate localization of broadband sounds in the horizontal plane in this condition. Other bilaterally implanted subjects did not localize better in the compression-off condition, possibly due to their lack of experience in everyday life with this setting.

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