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The Psychoacoustics of Profound Hearing Impairment

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A group of profoundly hearing-impaired adults is being studied in order to determine their residual auditory capabilities. Most tests use acoustic contrasts that have relevance for the perception of speech, so that the results obtained may be used to guide the development of appropriate hearing aids. All the listeners are postlingually deafened, with losses >95 dB HL at and above 500 Hz, and least loss at low frequencies. Trends in detection thresholds, discomfort levels, dynamic ranges, intensity discrimination (both static and dynamic), frequency selectivity, spectral shape discrimination, gap detection, tone/noise discrimination, frequency discrimination and phase sensitivity are reported and discussed. Generally speaking, temporal resolving power seems to be more resistant to degradation than mechanisms of frequency selectivity. Furthermore, at least some of the differences in performance between normal and profoundly-impaired listeners may be attributable to the loss of frequency selectivity. Implications are drawn for hearing aid fitting and design, and comparisons made to the electro-auditory abilities of users of single-channel cochlear implants. *Key words: detection threshold, dynamic range, frequency selectivity, intensity discrimination, frequency discrimination, spectral shape discrimination, phase effects, cochlear implants.*

INTRODUCTION

A significant number of hearing-impaired people have losses so profound that they receive little or no benefit from available hearing aids. Yet most of them retain a degree of residual auditory ability that is theoretically exploitable by an appropriate aid. Such people are of particular interest to those designing signal processing hearing aids, not least because they are more likely to be willing to wear (as are users of cochlear implants) the large and clumsy boxes needed to house sophisticated electronics!

Our aim in the work described here was to determine the residual auditory capabilities of such listeners, with particular reference to acoustic contrasts that have relevance for the perception of speech. In this way we hope to establish guidelines for the development of appropriate aids, and to suggest efficient ways to encode speech information (1–3).

MATERIALS AND METHODS

Subjects

Twelve adults with postlingually acquired deafness of profound degree have been tested. Their four-frequency mean losses are 105 dB HL or more (averaged at 0.5, 1, 2 and 4 kHz). A wide variety of aetiologies occur (e.g., head injury, mumps, progressive and sudden hearing loss) but no listener shows evidence of a conductive loss. Their residual hearing is best at low frequencies, so they are often said to have ‘left-hand corner’ audiograms (Fig. 1).

General techniques

In order to allow for accurate headphone calibration, and correction of headphone amplitude and phase responses, sound pressure levels were monitored on listeners’ heads with a small microphone mounted on the headphone grid (4). In adaptive testing, we

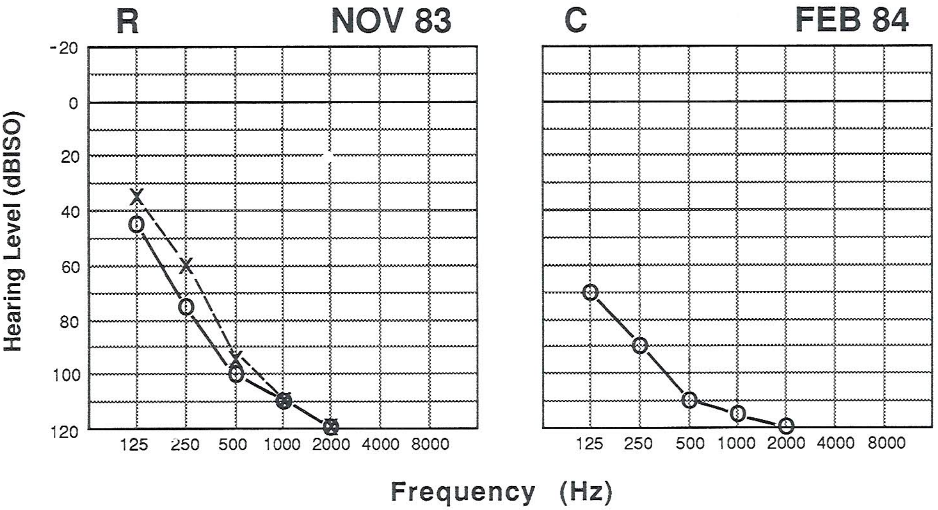

Fig. 1. Two examples of audiograms from profoundly hearing-impaired listeners. O——O, right ear; x–––x, left ear. "C" had no measurable hearing in his left ear.

have typically used a staircase method that tracks 79% correct (3-down, 1-up) instead of the more common 71%. This gives the listeners more confidence and should give more stable performance. When there is some difficulty or uncertainty in attaching a label to a perceptual attribute in a discrimination task (e.g., phase discrimination), three-interval oddity tasks have been used. Otherwise, we have employed two-interval tasks. In order to ensure reliable results, much time before tests begin is spent explaining the task to the listener, and in experimenter-controlled practice.

RESULTS

Detection thresholds and dynamic ranges

Extensive measurements of thresholds, most comfortable levels, and levels of discomfort have been made, mostly experimenter-controlled using modifications of standard audiometric techniques with better resolution of level (typically 1–2 dB). Detection thresholds were rarely obtainable above 2 kHz, and never obtainable above 4 kHz. Dynamic ranges are typically largest near 125 Hz, and decrease monotonically with increasing frequency (1–3). For many of these listeners, somewhere in the frequency region 0.5 to 2 kHz, it becomes impossible to present a sound that is perceived as even moderately loud without a non-auditory sensation of discomfort (Fig. 2). Uncomfortable loudness levels are often limited by feelings of vibration at low frequencies (≤125 Hz), and by tactile sensations of a different quality at higher ones (often described as 'sharp' or 'piercing').

Intensity discrimination

Intensity discrimination at a listener-determined most-comfortable level seems to be (at 1–2 dB) nearly normal with little or no dependence on frequency. However, because the dynamic ranges are narrow, the number of discriminable steps in loudness at any particular frequency is much smaller than that found in normal listeners.

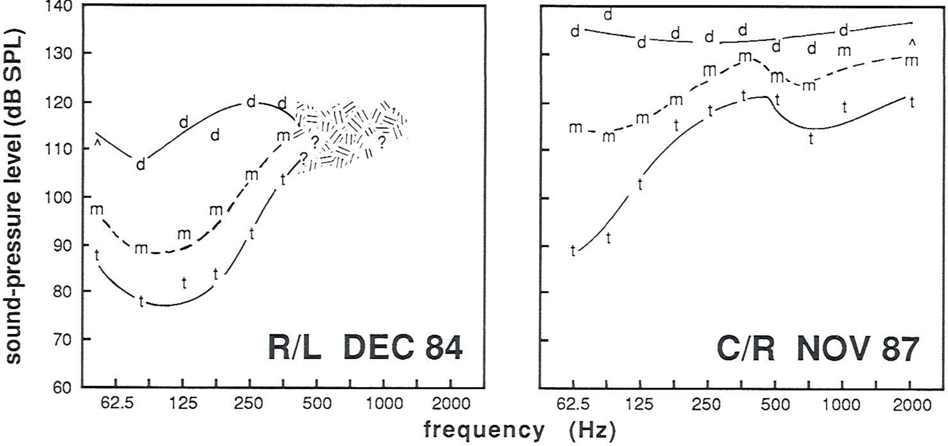

Fig. 2. Two examples of auditory areas from the same 2 listeners as in Fig. 1. Absolute thresholds are marked with *t*, most-comfortable levels with *m* and discomfort thresholds with *d*. Upward arrows indicate the places where the maximum sound-pressure level of the equipment had been reached. For listener "R", the hatched area indicates a region where the percepts were "more of a sensation than a note" or "horrid squeaks".

Frequency selectivity

Due to the high intensity levels involved, it is difficult to apply some of the standard techniques for measuring frequency selectivity (e.g., using notched noise). We have found a version of the psychophysical tuning curve (PTC) technique that works reasonably well. The probe tone is a sinusoid presented at 10 dB SL, while the masker is an 80-Hz-wide band of noise. Fig. 3 shows PTCs obtained from 2 subjects. "L" is one of the subjects who showed the highest degree of selectivity. Even so, her selectivity is greatly impaired relative to what would be found with a normal listener. Two of 7 subjects tested have

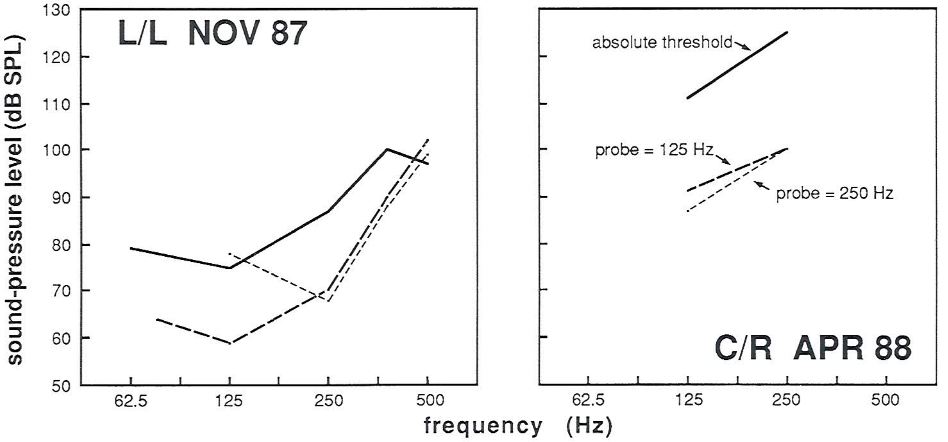

Fig. 3. Psychophysical tuning curves from two profoundly hearing-impaired listeners. ——, Absolute threshold (in dB SPL) for pulsed tones; All dashed lines indicate the level of 80-Hz-wide noise maskers (in dB SPL/Hz) that just masked the probe at 10 dB SL, as a function of masker frequency. Two probe frequencies (125 and 250 Hz) were used. ———, Masker levels needed for the 125 Hz probe; - - -, the probe at 250 Hz.

PTCs that are parallel to one another, as for "C" shown here, indicating complete lack of selectivity (2, 3).

Spectral shape discrimination

In many so-called 'place' theories, the discrimination of spectral shape depends mostly on frequency selectivity. We would therefore expect the discrimination of spectral shape to be always impaired to some degree, or even to be non-existent. Four listeners have been tested for their ability to distinguish among the three vowels "ee", "ah" and "oo" with identical duration, fundamental frequency contour and loudness (1). One listener was able to do surprisingly well in this task (scoring nearly perfectly) while one was barely above chance performance. For 3 of these listeners, we have also measured PTCs (as described above). "C", with no measurable selectivity, scored 41% correct in the vowel identification task, whereas the 2 other patients, who show clear evidence of selectivity, scored 62% and 87%. Tests involving simpler changes in spectral shape are currently underway.

Temporal resolution

Temporal resolution can be measured in many ways, as any auditory attribute can be varied in time. Dynamic variations in spectral shape and fundamental frequency are crucial cues in the perception of speech, so it is important for information about such abilities to be available (see below). However, most measures of temporal resolution involve variations of *amplitude* with time, and we too have concentrated on this aspect.

One of the most popular ways to measure temporal resolution is gap detection. We created gaps by gating white noise off and on with 1-ms fall-and-rise times, and then passing it through a band-pass filter (about 50 Hz–1 kHz) with shallow slopes. The step response of this filter is of a form that has little effect on the gap. Normal listeners can detect gaps in this signal of about 5 ms, while the profoundly-impaired listeners need some 10–40 ms.

Unfortunately, it is difficult to know to what extent the profoundly-impaired listeners' performances are limited by their poor dynamic range, rather than by their inherent temporal resolving power (5). Therefore, we have also measured temporal resolution in the form of an amplitude modulation discrimination task in which the changes in modulation are brought about by changes in the phase spectrum of the stimuli. This has the advantage that the amplitude spectra of the stimuli are invariant with changes in amplitude envelope (unlike ordinary amplitude-modulated signals). Furthermore, it is not necessary to introduce noise bands to mask off-signal splatter; with poor frequency selectivity, the masking noise could also mask the signal itself. Using such a task, it appears that for stimuli centred in the low-frequency range (below 250 Hz), most profoundly-impaired listeners are as sensitive to relatively slow dynamic intensity changes (1–30 Hz) as are normal listeners (6).

Finally, one other task has been used (7) that may reflect, in some listeners, an aspect of temporal resolution. This involves determining the minimum duration at which a listener can distinguish a periodic sound (usually a sinusoid) from an aperiodic one (usually a band of noise). Such signals can of course be discriminated from one another on the basis of either their spectral or temporal properties. In the absence of frequency selectivity, however, performance must be based purely on temporal factors. Most listeners need about 20–50 ms to discriminate a sinusoid at 141 or 200 Hz from a 100–400-Hz band of noise (1, 3). Although this is an important residual ability, discriminability is rather worse than that found for normal listeners, in whom it is typically impossible to make the sounds short enough to be indiscriminable.

Frequency discrimination

Profoundly-impaired listeners are able to discriminate frequency changes in sinusoids, especially at low frequencies. Acuity can be only slightly poorer than normal at 125 Hz, with jnds about twice normal. That low-frequency sinusoidal frequency discrimination can be nearly normal in the presence of severely impaired selectivity and normal intensity discrimination is clear evidence for temporally-based models of frequency discrimination, and thus may be seen as another reflection of good residual temporal abilities in the low-frequency range.

For normal listeners, the Weber fraction for frequency decreases over the range from 125 to 500 Hz, whereas for the impaired listeners, the Weber fraction always *increases* (1–3, 8). In consequence, jnds for the impaired listeners at 250 or 500 Hz can easily be 10 times or more their normal size. If temporal mechanisms are primarily responsible for sinusoidal frequency discrimination, it appears that the inherent temporal resolving abilities of profoundly-impaired listeners are extremely degraded at these slightly higher frequencies, even though they may be nearly normal at 125 Hz. From a physiological point of view, it may be that phase-locking at the lowest frequencies is relatively intact, but that the upper limit of synchrony has been drastically lowered.

Another important difference from the patterns of performance found in normal listeners is found in comparing jnds for fundamental frequency in sinusoids and multi-harmonic complexes like pulse trains. For fundamentals in the range 125–500 Hz, normal listeners show smaller jnds for complex tones. For the profoundly-impaired listeners, frequency discrimination of complex tones is never better, and sometimes worse than that with sinusoids (1, 8). This property may arise from the lack of frequency selectivity allowing harmonic components to interact to a much greater extent than is the case for normal listeners.

These two important differences from the performance of normal listeners (worsening Weber fractions with increasing frequency, and no discrimination advantage for complex tones) have also been found in a task involving the identification of dynamically varying fundamental frequency contours (1).

Phase effects

As phase sensitivity is generally understood to arise from a lack of frequency selectivity, we might expect profoundly-impaired listeners to be more affected by changes in relative phase among stimulus components. This has been shown in a number of studies (1, 4, 6) both for harmonic complexes with fundamental frequencies appropriate for speech (125–250 Hz) and for complexes in which the inter-component spacing is quite small (8–32 Hz). Phase can affect the perception of fundamental frequency, as well as the perceived timbre of the sound.

DISCUSSION

These results have many implications for the design and fitting of both conventional and signal-processing hearing aids for the profoundly-deafened listener. Firstly, it appears that important abilities in the temporal domain usually remain, even in the complete absence of frequency selectivity. Therefore, emphasis should be placed on the temporal features of speech. Phase manipulations may provide a way to signal aspects of timbre. For many listeners, there is no point in presenting high-frequency information, due to the severely reduced dynamic range there and often complete inability to detect sounds without

Table I. *A comparison of the typical psychophysical abilities of listeners with profound hearing impairments and of users of single-channel implants*

Question marks indicate some degree of uncertainty, or where appropriate tests have not been performed

	Profoundly hearing-impaired	Single-channel electrical
Detection	Similar in form over frequency (best at low frequencies)	
		Better than acoustic at high frequencies
Dynamic range	As for detection thresholds	
Intensity jnds	Similar in being roughly normal in dB, but are high proportions of dynamic range	
Frequency selectivity	None to some (never normal)	None
Spectral shape discrimination	None to some (?)	None to some (based purely in time)
Gap detection	Not too bad, but always impaired (?)	Better than normal to very impaired
Dynamic intensity jnds	About normal	?
Periodic/aperiodic discrimination	Similar, in that some important abilities typically remain	
Frequency jnds	Similar in always being impaired, especially at frequencies >200 Hz No advantage for complex tones (frequently a disadvantage)	
Phase effects	Similar in exhibiting greater sensitivity than normal; greater influence on other perceptual attributes	

discomfort. Thus methods of fitting hearing aids which attempt to mirror the audiogram are inappropriate. Narrow dynamic ranges necessitate some type of amplitude compression, but done in a way so as to preserve the information-bearing dynamic amplitude changes. One approach to a non-conventional aid for this group of listeners is described in (1–3).

Many of the features of the residual auditory abilities of these profoundly-impaired listeners are similar to those found in users of single-channel cochlear implants (with important differences, Table I). It may therefore be that prosthetic design principles appropriate for profoundly-impaired listeners will also be suitable for implant users, and vice-versa.

For users of multi-channel implants, the essential feature is that many, if not most of them, can reliably distinguish among the sensations induced by stimulation of different electrodes. This simulates a degree of frequency selectivity (and thus allows the signalling of distinctions in timbre by variations in spectral shape) much superior to that evidenced by users of single-channel implants, and possibly even by many of the acoustically-stimulated profoundly-impaired listeners.

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