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COMPUTER BASED SYSTEMS TO ENABLE PEOPLE WITH SEVERE HEARING LOSS TO PERCEIVE MUSIC MORE CLEARLY

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INTRODUCTION

Clear perception of music requires different types of sound processing from that given by hearing aids for speech. For many types of hearing impairment, much superior results can be obtained by avoiding the use of hearing aids and instead using quite standard commercial analogue audio equipment, suitably set up and interconnected [1].

The two main types of deafness are conductive and sensory-neural. While the above analogue processing is nearly always very successful for conductive deafness, for certain types of sensory-neural loss such processing is inadequate on its own. Additional possibilities exist if the music is generated by, or under the control, of a computer system rather than processing existing sounds, and many of these are discussed in [2].

The main purpose of this paper is to review the usefulness of these possibilities, in the light of results from further work.

CONDUCTIVE HEARING LOSS

As the name implies this results in an attenuation of the signal, due perhaps to perforation of the ear drum, or to some problem in the transfer of vibration of the ear drum to the oval window via the chain of ossicles. Such attenuation is frequency dependent, but in a smoothly varying way, and a graphic equaliser with 10 bands is more than adequate to achieve the necessary equalisation.

It might be stressed yet again that the usual pure tone audiogram produced in routine ear tests by hospital ENT departments is not a very useful guide to setting up the equalisation, and sometimes tend to mislead. Such audiograms are a measure of the threshold of detectibility of tones at different frequencies, not a measure of whether musical sounds can be discriminated, far less meaningfully interpreted.

When music covers a large dynamic range, some amplitude compression is appropriate. This statement may give some surprise for purely conductive loss, but suppose the sound level from a symphony orchestra varies from 45 up to 110dBA in brief loud passages. If the conductive loss is around 40dB this would imply that additional amplification would be required to bring the sound levels up to a range of something like 85 to 150dBA! Even if such levels could be realistically attained one might doubt that the conductive loss remained as a constant loss of 40dB up to these very high sound levels.

COMPUTER BASED SYSTEMS TO ENABLE PEOPLE WITH SEVERE HEARING LOSS TO PERCEIVE MUSIC MORE CLEARLY

In any event, sound levels around the 120dBA level can generally be clearly felt as a vibro-tactile effect, quite apart from hearing. For any individual, the maximum level at which some undesired effect sets in varies, and compression should be such as to keep below this limit. A useful starting point in establishing this level would be something like 110dBA. An additional reason for introducing some compression is to improve the signal noise ratio for the listener in very quiet passages in the music. Raising the signal level in these by a few dB would be suggested.

SENSORY-NEURAL HEARING LOSS

Here the threshold audiogram is of even less value on its own: what is needed to give a useful guide is the addition of a measure of the loudness discomfort levels (LDL) at various frequencies. Such audiograms are often produced by private hearing aid dispensers, so it is worth enquiring if one is available. The gap between the threshold and the LDL shows how much dynamic range compression will be required, and whether it is worth trying compression which varies with frequency as discussed in [1].

HEADPHONES

When headphones are used, the left and right channels of a graphic equaliser, intended for domestic stereo use, may be used to adjust for the ears individually. However, experience has shown something which was not initially apparent: that it is better to start by making a choice from three types of headphones, rather than adjusting the equaliser with the same headphones each time. Having established the most suitable headphones the setting of the equaliser follows. The headphones used are : (a) Tandy model 16, which has a good bass and lower mid-range response but poor response at high frequencies, and which has moderately high sound pressure level (SPL) capability; (b) JVC model HA-D515, which might be described as moderately good and not too expensive hi-fi headphones; and (c) special headphones produced by St John's School for the Deaf, Boston Spa. The latter, when used with a normal hi-fi amplifier rather than the special driver used at that school, give a substantially rising response from the bass to the mid frequency range and are capable of high SPL and much better than usual isolation from other sounds in the room. Trials have shown that for people with sensory-neural hearing loss, the clarity of perception can sometimes be significantly increased in this way, relative to that obtained with equally careful setting of the equaliser using one of the other headphones. This is true in spite of the fact that the same overall equalisation can be achieved over the range of frequencies one might consider important. (Trials have not been done to see if this is also true for conductive losses.) One might expect that by choosing the headphones first, the system would be more energy efficient, but this is not a consideration here, and this result illustrates how unwise it is to make assumptions in this field of work, where subtle audio effects are combined with a poor knowledge of the details of the damaged hearing.

A higher than usual SPL at the headphones may be needed and a simple way of providing this with appropriate headphones, is to drive them from the speaker output of an amplifier, via a small resistor. It is useful to make up a switch box so that either or both earphones can be driven in this way or from the normal headphone output. With care, and appropriate equalisation, not too many headphones will be burnt out with this arrangement! Amplification and equalisation is never a problem, and hearing through a so called "worse", ie less sensitive ear, may give superior sound clarity for music at appropriate sound levels.

Many people, both normal hearing and hearing impaired, find listening to music using headphones gives only impoverished enjoyment. Two well known disadvantages of headphone listening to normal recordings are that the sound image moves as the head is turned, which is most unnatural, and that the recording is made to give a sound field for listening through loudspeakers rather than for headphone listening (eg by using microphones on a dummy head). But quite apart from these disadvantages, it is believed that some people, consciously or unconsciously, sense sounds impinging on parts of the body other than the ears, and that this is missing in headphone listening. This has been the case for nearly all the subjects tested who would commonly be described as "deaf". Hence it is useful to be able to have an additional loudspeaker output, where the volume and equalisation can be adjusted independently of the headphones.

OPPORTUNITIES THROUGH COMPUTER GENERATED MUSIC

We now consider the strategies for improved perception through music generated by, or under the control of, a computer system as outlined in [2]. Where hearing deficiencies necessitate such use, some sacrifices have to be made, eg changes of tempo, timbres and articulation, in order to obtain clear perception of the most important features of the music.

It may be argued that these effects can be produced as well, or better, by having musicians perform the music in a special way with different choices of instruments, but this would of course mean the individual having a private group of musicians to perform the music in a special way.

Pitch Shifting

Looking at audiograms where one sees a smaller hearing loss at certain frequencies, most commonly the low frequencies, one might imagine that there was substantial scope for benefits through pitch shifting. Certainly lowering the pitch is the first thing many people think of and so the following observations may be useful. For the common cases with relatively little hearing loss at low frequencies, pitch shifts of more than an octave

COMPUTER BASED SYSTEMS TO ENABLE PEOPLE WITH SEVERE HEARING LOSS TO PERCEIVE MUSIC MORE CLEARLY

have not been found useful. But a drop in pitch of up to a fifth, and more rarely up to an octave, can be useful for some individuals. Why should there be this limitation in the usefulness of larger pitch shifts? It is believed it is because we have been misled into thinking that shifts of an octave or more will help because of the tendency to forget that the audiogram, even with the LDL as well as thresholds, provides measures of the sensitivity of the ear at various frequencies, not clarity of perception. Amplification and equalisation to counteract sensitivity differences are no problem: our goal is to obtain clarity. Even to persons with good hearing, when music is transposed an octave or more down the sound is often described as being "muddy". In addition there is the physical effect that difference frequencies in the bass can be small enough for beating to be evident when is was not at the original pitch.

However in order to separate more clearly the parts in music, particularly where much of the interest in the music is in contrapuntal effects, it can be useful to transpose some of the parts by an octave (usually downwards) especially where this results in a removal of overlapping in pitch.

Choice and contrasts of Timbre

Where recognition of separate parts in the music is important, giving each part a clearly different timbre has been found to be useful in nearly all cases. For example, perception of the "Italian Concerto" by J S Bach, which is usually played on the harpsichord, benefits by having the parts allocated to contrasting instrumental sounds such as flute, oboe and guitar. The ability to set the volume for each part is useful.

Arrangement of the music

Where hearing loss severely restricts perception of music, it is recommended that an arrangement of the music should be made. Making a "reduction", ie maintaining the essence of the piece while reducing the number of simultaneous notes or parts, is generally useful. Just as a conventional piano reduction can be made of an orchestra piece, music such as the "Italian Concerto" can be reduced to 3 parts, and only 2 parts in certain passages. The computer system greatly facilitates this process and allows easy experimentation.

Slowing of tempo

Very often this is valuable when the music has a fast tempo, that is sequences of notes each lasting a short time, which tend to blur into one another for many people with sensory neural hearing loss. The tempo should be chosen by the listener, irrespective of whether it sounds too slow to someone else.

COMPUTER BASED SYSTEMS TO ENABLE PEOPLE WITH SEVERE HEARING LOSS TO PERCEIVE MUSIC MORE CLEARLY

Localisation and directionality of sound

For many listeners 2 channel sound has been found to be a great improvement on mono, and some people tested who would commonly be described as "deaf" can perceive true stereo and they report that it is of considerable benefit to them in picking out instruments and parts.

When there are 3 or 4 distinct parts in the music, then by using a sound generator such as the Roland D110 MIDI expander module, one can obtain a separate audio output for each part and feed each to an individual loudspeaker mounted well apart from the others. It was hoped that by this means, the listener, with free movements of the head, would be aided in perceiving the separate parts clearly. This arrangement has been tried in comparison with two channel sound produced via a mixer. So far, additional benefits have been found infrequently, but further testing is needed before drawing conclusions.

Equalisation and compression

The greatest hearing losses are not necessarily the most difficult for which to obtain clear perception. In [1] the hypothesis was advanced that for some severe, rather than profound, hearing losses, this was due to the partly damaged hair cells producing inappropriate signals for the spatial mechanism of pitch determination whereas in the case of profound loss the person was relying purely on a temporal mechanism which was still functioning well, and the spatial mechanism no longer operating.

With certain types of sensory neural loss, the equalisation required does not change smoothly with frequency, but can vary considerably from note to note. In other words if a scale is played the listener can hear some notes as significantly louder and/or more distorted. To have some understanding of what is happening in the damaged ear, the reader is referred to [3]. A conventional graphic equaliser cannot deal with this, but in a computer system we can equalise separately for each note.

When the gap between threshold and the LDL is small, and it can be as small as 10dB or less compared with something like 110dB for normal hearing, extreme compression is required. What we require is a just sufficient sound level at the frequency of each note to adequately stimulate the hair cells in the cochlea at the place corresponding to that frequency. These hair cells are responding to a much broader range of frequencies than usual and with just sufficient stimulation for the perception of each musical note, we stimulate as few hair cells as possible which would not normally correspond to that note. Again the reader is referred to [3]. For many individuals there will still be scope for some small dynamic range in the music, at least in some pitch regions. In a computer system, compression varying with frequency can be readily obtained, and a software package is being developed which allows individual compression ratios for each musical note as well as equalisation. The software is designed to allow this to be done for

COMPUTER BASED SYSTEMS TO ENABLE PEOPLE WITH SEVERE HEARING LOSS TO PERCEIVE MUSIC MORE CLEARLY

individual MIDI channels, enabling separate settings for each ear when used with a MIDI expander module or keyboard which has at least 2 audio outputs which can be allocated to MIDI channels. Although this was not the original intention, it has the important benefit of saving the cost of both a separate graphic equaliser and a dynamic range compressor.

This type of frequency selective compression is much superior to the analogue type described in [1] which has turned out to have relatively little to recommend it for many listeners, because the timbre, and the apparent position of sounds in the stereo image, shift to a disturbing extent with sound level.

Where it is necessary to go to the lengths of individual note equalisation and compression, one might expect that it would be important to use sounds approximating to sine waves, so that strong harmonics would then not affect hair cells at other positions on the cochlea. In some cases this has been found to be clearly beneficial.

However, amongst people exhibiting sensory neural hearing loss generally and significant recruitment of volume, it has only occasionally been found beneficial to use sine waves. The hypothesis is advanced that this is because the temporal mechanism for pitch perception is predominant over the spatial mechanism in the majority of these cases and that this mechanism might be expected to operate better with sharply changing waveforms. In the less common cases where sine waves are beneficial and individual note equalisation required, then the spatial mechanism is predominant.

This matter may be important and the author would be grateful to anyone can shed any light on it.

<u>Envelope shaping</u>

This is an area where considerable scope has been found for enhanced perception. When a note is maintained at a constant level it is easier to perceive the pitch than if the amplitude is falling sharply (as in the sound of a harpsichord). But this has to be balanced against the need to cue the damaged hearing to the new note starting, and the best compromise has been found to be envelope shaping as described in [2].

Although one might expect, from elementary physics theory, that temporal resolution would be enhanced when the sharpness of the filtering in the cochlea becomes degraded, the opposite is found to be the case. Introducing detachment gaps, as described in [2], has been found to be generally beneficial, very much so in many cases. For detachment gaps to be effective the release rate of the sound has to be chosen to be sufficiently fast. In the case of fast tempos, a reduction in tempo is generally beneficial, as already mentioned, but doubly so in the case where detachment gaps are being used. The detachment gap needs to be long enough as an absolute time

COMPUTER BASED SYSTEMS TO ENABLE PEOPLE WITH SEVERE HEARING LOSS TO PERCEIVE MUSIC MORE CLEARLY

interval, not just as a percentage of the time allocated to a note, and this can necessitate a reduction in tempo.

The matter of envelope shaping, detachment and tempo can be looked at as illustrated in Fig. 1. The original sound envelope is shown in (a). If one could plug earphones into someone's head and hear what they are hearing, the whole task would be so much simpler: as it is, one has to do one's best by sensitive questioning and inference. Such an estimate is shown in (b).

Fig. 1 (c) shows the envelope shaping with detachment gap "D", including a time "T" which results in a reduced tempo. Note also that the attack rate is increased and that the release rate is higher than in (a). Such an input envelope shape is intended to give partial compensation for the "smudging" of sound of (a) to (b), ideally so that the sound of (c) should be perceived as the original sound (a) apart from the tempo reduction.

A detachment set as above is used for legato passages and staccato effects are produced by increasing the detachment for individual notes.

A reduction in tempo in addition to that necessitated by sufficient detachment gaps is often beneficial. One would expect pitch perception to be improved if the constant amplitude portion of the envelope in Fig. 1 (c) were sufficiently long. Hence any additional tempo reduction should be introduced within the region labelled "F" in Fig. 1 (c). When there is such additional tempo reduction the detachment of individual notes must be suitably adjusted for staccato/legato effects to be musically appropriate. The software carries this out when the tempo is changed as well as providing overall control of detachment gaps.

In a computer based system, the envelope shape could be obtained in two ways: by setting up a synthesiser or by combining two sounds which approximate to known musical instruments. The latter method, where two sounds are combined has been preferred by each of three musically gifted subjects tested, and that method is also technically more convenient because the relative proportions of each can be easily adjusted. In this work, no more than 4 parts in the music have been used, and to attain contrasts of timbre for the parts, one combines sounds such as a harpsichord with a clarinet, a harp with an oboe, a guitar with an organ and a piano with a flute. It is convenient to set up a number of patches on a Roland D100 with different proportions of each and switch between them in the course of trials.

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COMPUTER BASED SYSTEMS TO ENABLE PEOPLE WITH SEVERE HEARING LOSS TO PERCEIVE MUSIC MORE CLEARLY

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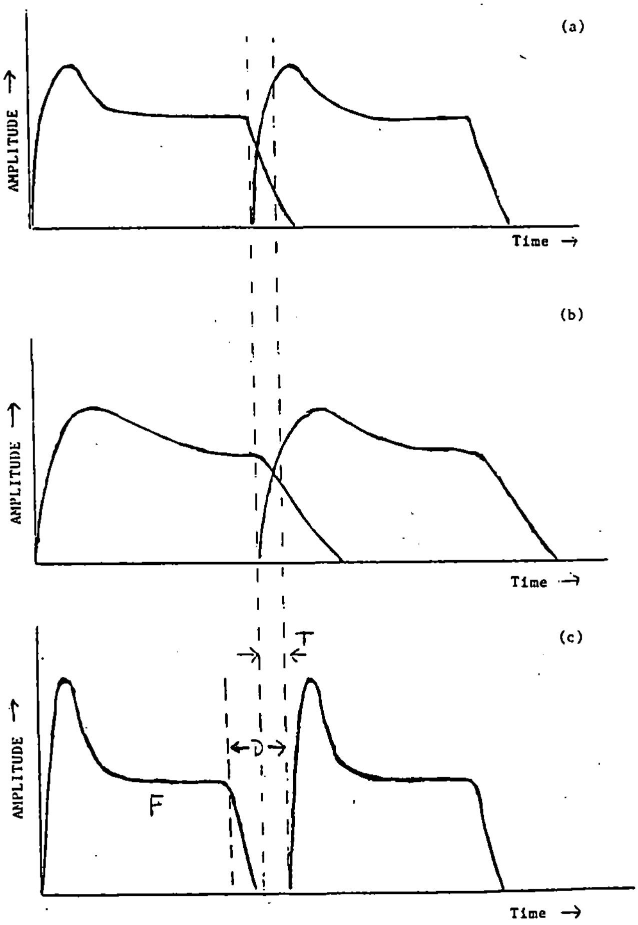
COMPUTER BASED SYSTEMS TO ENABLE PEOPLE WITH SEVERE HEARING LOSS TO PERCEIVE MUSIC MORE CLEARLY



(a) Original envelope shape.
(b) As (a) might be perceived with the sensory-neural loss described.
(c) Envelope shape to give partial compensation for the above loss.
D Detachment.
T Time contributing to tempo reduction.
F Region where further tempo reduction should be introduced.

FIGURE 1