Alternative paths to hearing (a conjecture). Photonic and tactile hearing systems displaying the frequency spectrum of sound

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Abstract: In this article, the hearing process is considered from a system engineering perspective. For those with total hearing loss, a cochlear implant is the only direct remedy. It first acts as a spectrum analyser and then electronically stimulates the neurons in the cochlea with a number of electrodes. Each electrode carries information on the separate frequency bands (i.e., spectrum) of the original sound signal. The neurons then relay the signals in a parallel manner to the section of the brain where sound signals are processed. Photonic and tactile hearing systems displaying the spectrum of sound are proposed as alternative paths to the section of the brain that processes sound. In view of the plasticity of the brain, which can rewire itself, the following conjectures are offered. After a certain period of training, a person without the ability to hear should be able to decipher the patterns of photonic or tactile displays of the sound spectrum and learn to 'hear'. This is very similar to the case of a blind person learning to 'read' by recognizing the patterns created by the series of bumps as their fingers scan the Braille writing. The conjectures are yet to be tested. Designs of photonic and tactile systems displaying the sound spectrum are outlined.

Key words: Photonic and tactile hearing systems, brain plasticity, sound frequency spectrum, photonic display, tactile display.

INTRODUCTION

For those with total hearing loss, there are no direct remedies except for electronic (i.e., cochlear) implants (Loizou 1998). They are invasive and do not always function in a completely satisfactory manner (Summerfield and Marshall 1995). Sign language does open the window to a rich culture, but communication with the hearing world is hindered. Although lip reading can bridge this gap, communication is not without some stress. Also, the inability to detect possible life-threatening situations outside the visual field can affect the quality of life.

When the hearing process is viewed from a system engineering perspective, there is a sound source, the transmission medium of air and the ear, which is the mechanical-to-electrical signal converter. The hearing structure of the ear converts mechanical vibrations to electrical signals that are then transmitted through nerve paths to the brain. The nerve paths function in a parallel manner.

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Conversion of mechanical vibrations to electrical signals is performed inside the cochlea, which acts as a spectrum analyser (Encyclopædia Britannica 2003). The intensity of the frequency components of sound is sensed by the hair cells attached to the basilar membrane. As a result, an electrochemical substance causes neurons to fire, indicating the presence of sound. The location of the hair cells within the cochlea and their length determine the frequencies they respond to. The signals generated by the neurons are carried through parallel nerve paths to the section of the brain where the sound information is processed.

In most cases of total hearing loss, the hearing structure of the ear is non-functional. The cochlear implant bypasses this hearing structure and electronically stimulates the neurons directly. In one design, a microphone picks up the sound and its spectrum is electronically separated into four frequency bands. Amplitudes of the signals from each of the bands are then supplied to electrodes that are implanted in the cochlea (Loizou 1998, Figure 4). Today, there are versions that use more than 20 electrodes, with each one dealing with a specific frequency band. Electronic currents from these electrodes stimulate the neurons in the vicinity of the electrodes. The signals sensed by the neurons are then transmitted in parallel to the brain.

ALTERNATIVE PATHS

In order to reach the section of the brain that processes sound, instead of stimulating the auditory neurons and nerve paths directly, as in the case of the cochlear implant, the use of alternative paths, such as those relying on vision or tactile senses, can be considered.

Based on the viewpoint of system engineering, the function of the cochlea might be replaced by an electronic spectrum analyser that is similar to that used in the cochlear implant. A visual or tactile device displaying the sound spectrum can be used to provide alternative paths to the brain. Such straightforward real-time presentations of the useful part of the voice spectrum to the visual or tactile senses seems not to have been attempted before, probably because such presentations were thought to be incomprehensible to a person. However, modern understanding of the human brain in terms of plasticity or rewiring (Bonafice and Ziemann 2003) provides a motivation to examine the approach of direct real-time presentation of a voice spectrum to the visual or tactile senses.

Visual path

The visual path has already been explored by a number of methods. In one method, the sound spectrum is separated into a limited number of bands. They are used to illuminate a set of light- emitting diodes (LEDs). The LEDs are placed in front of the pupil and viewed as out-of-focus images by the retina (U.S. Patent No. 4,117,265; Gerlach 1978). This visual information is used as an aid to hearing. The useful part of the sound spectrum is not completely displayed because of the limited number of LEDs that are used in this device. Therefore, the device did not prove to be as effective as a hearing aid for those who do not have the ability to hear. Placement of the display device in front of the pupil was also a hindrance to the normal function of the eye.

An earlier version of a photonic hearing system was presented elsewhere (Hara 2002). It is discussed here again with some additional information in order to provide a complete picture of the alternative paths to hearing.

Tactile path

The tactile path has been explored by a number of products such as Tactaid (2003) and Siemen's Fonator (Szeto and Christensen 1988).

In the Tactaid unit, sound information is received through a microphone. The features of sound that aid in comprehending speech are extracted and supplied to vibrators that stimulate the skin. The vibrators are usually worn on the wrist. The device was found not to be that useful for a person with total hearing loss.

The Fonator picks up sound through a microphone and amplifies the resulting electrical signal. This is then converted into mechanical vibrations by using an electromagnetic vibrating unit that is worn on the wrist. Again, the device proved to be of limited use for those who do not have the ability to hear.

The following sections first discuss the plasticity of the brain and then outline designs of photonic and tactile hearing systems.

PLASTICITY OF THE BRAIN

A blind person can perform echolocation of objects by tapping a cane (Schenkman and Jansson 1986). It appears that the visual cortex is active when performing this task (Weeks *et al.* 2000). In other words, the brain is rewired so that the ears hear the reflection of the sound pulses and the resulting signals are routed to the vision processing part of the brain. Using this acoustic information, a rough visual image of the surroundings is formed. This points to the remarkable plasticity of the brain, that is, the ability of the brain to rewire itself.

Plasticity of the brain is also seen in patients who receive cochlear implants. If they had lost their hearing in midlife, the sounds they hear through the cochlear implant are often quite different from what they had heard before their ability to hear was lost. Over a period of training to learn how to understand the sound patterns, they eventually are able to carry on a normal conversation (Delaney 2004). This indicates that the sound and language processing sections of the brain are being rewired.

When a blind person is reading Braille, the visual cortex of the brain is active (Gizewski *et al.* 2003). Clearly, tactile signal paths have been rewired to the visual cortex, which aids in the comprehension of a language.

Braille reading might be considered as a pattern recognition function of the brain that translates tactile signals from the fingertips into a recognizable language. In a similar way, visual or tactile systems that display the frequency spectrum (i.e., bands) of sound can be considered as alternative paths to the brain for acoustic signals. The conjecture is that the brain should be able to rewire itself to perform a pattern recognition process on this visual or tactile information and translate it into a recognizable language. The designs of such visual or tactile hearing systems and their displays are described in the following sections.

PHOTONIC HEARING SYSTEM

A binaural photonic hearing system using a visual display of the sound spectrum is shown schematically in Figure 1. Two microphones are used to pick up the sound. They are placed on the outside edges of an eyeglass frame that supports the photonic displays of the sound spectrum. This placement approximates the location of human ears.

The schematic shows a block diagram of the circuitry associated with the left-side microphone. A filter to restrict the passband from 300 Hz to 3 kHz follows the pre-amplifier. An automatic gain control amplifier adjusts the signal level to prevent saturation by loud sounds. This

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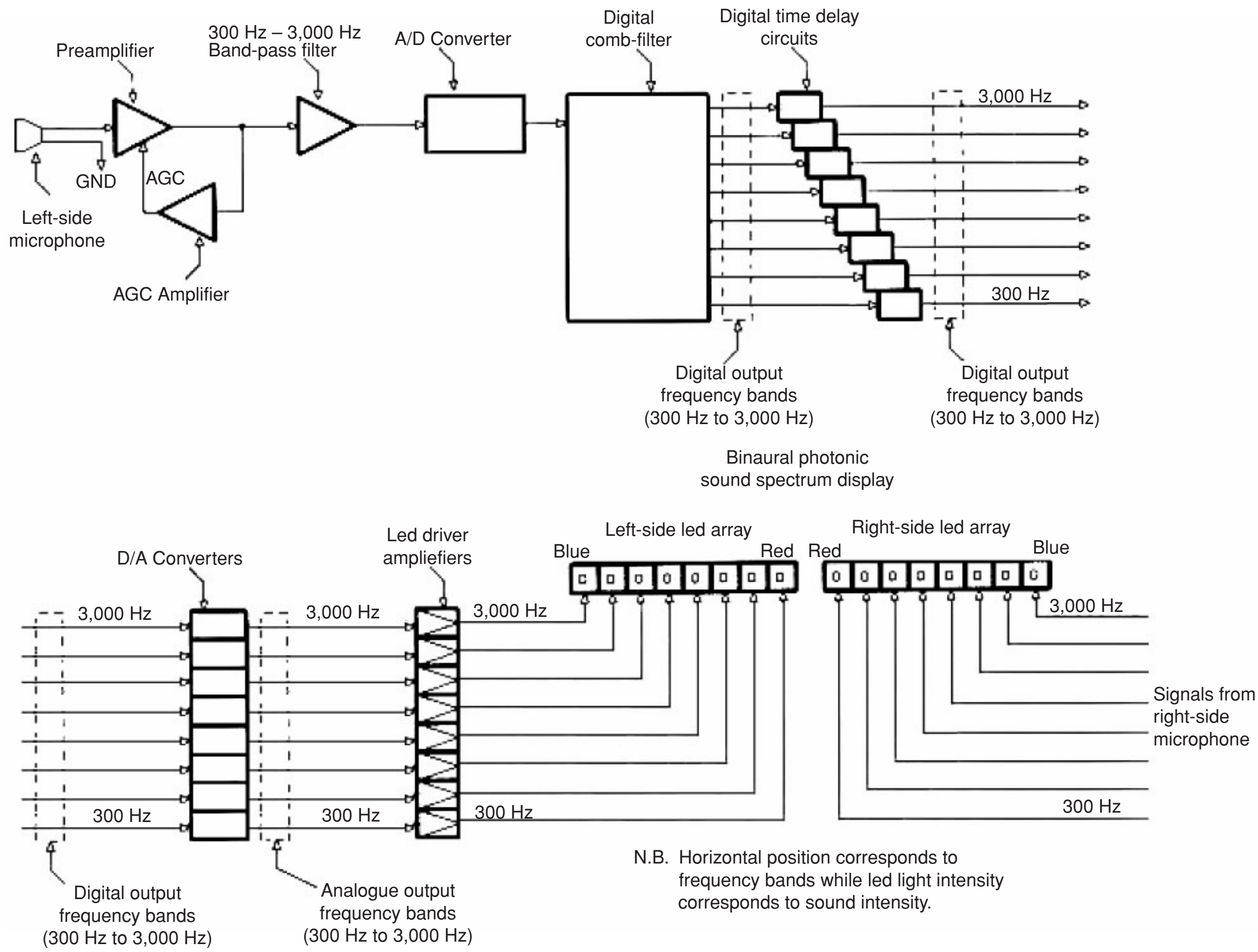

Figure 1 Photonic hearing system.

passband has been found to be adequate for comprehension of the spoken word and has been in use by the telephone industry for many years.

The analogue signal is then converted to a digital signal by an analogue-to-digital converter and digitally processed through a comb filter to separate the sound signal into frequency components (i.e., bands) of the sound spectrum. The comb filter can be a standard fast Fourier transform integrated circuit. This separation of the sound signal into frequency components corresponds in part to the function performed by the cochlea.

The digital signals representing the strength (i.e., intensity) of each frequency band are then passed through a set of digital time-delay circuits that approximate the delay experienced by the frequency components (i.e., bands) of sound waves being detected by the cochlea. The digital signal of each frequency band is then converted back to analogue signals by digital-to-analogue converters. The resulting analogue signals are used to drive LEDs, which are arranged into linear arrays that display the spectrum of sound visually.

Colours ranging from red to blue following the order seen in a rainbow represent the sound spectrum from 300 Hz to 3 kHz. The red LEDs represent the low frequency component of 300 Hz, while the blue LEDs represent the high frequency component of 3 kHz. The brightness of each colour represents the intensity (i.e., loudness) of each frequency band.

Left-side and right-side arrays of LEDs are used to support binaural ‘hearing’. An array can be about 3 mm high and 50 mm in length and have more than 50 sets of miniature red, green and blue LEDs. For simplicity, the schematic shows only a limited number of LED sets. By adjusting the relative drive currents through each of the red, green and blue LEDs, colours from red to blue can be reproduced by each set. Such LED sets are well within the manufacturing capabilities of today’s optoelectronic component packagers.

The LED arrays are arranged left and right on the top side of an eyeglass frame, within the peripheral field of views of the eyes when the wearer is looking straight ahead. To coincide with the left–right symmetry of the human body, the arrays are arranged in such a way that the red colours representing the 300 Hz frequency bands are placed close to each other at the centre with a separation of about 10 mm and the blue colours representing the 3 kHz

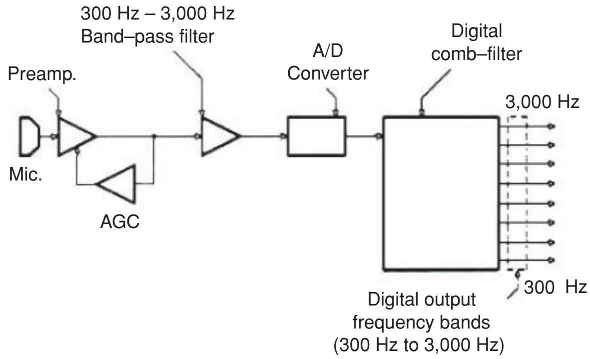

Figure 2 Sound pickup and spectrum analyser.

frequency bands are placed close to the left and right temples of the eyeglass frame.

The logarithmic response of the eye to the intensity of light serves to mimic the logarithmic response of the ear to sound.

One point to note is the comparatively long response time of the eye, which results in a frequency response below 100 Hz (Kolb *et al.* 2000). The variation in the intensities of the LEDs representing each frequency band can be expected to be of the order of 100 Hz because the sound has been separated into its frequency components.

There has been mention of an old U.S. Air Force study that tested the visual response time of pilots by flashing a photograph of an aircraft on a screen in a dark room for a time interval of $1/220$ s $= 4.55$ ms (Brand 2001). Apparently, the pilots were able to identify the aircraft type consistently. The time interval corresponds to a frequency response above 200 Hz and implies that the photonic hearing system displaying the sound spectrum may be practical provided the rewiring of the brain is realized.

Experimental confirmation will be required to ascertain that the variation of intensity of each LED is within the detectable range of the eye.

TACTILE HEARING SYSTEM

Figure 2 shows a block diagram of the sound pickup and spectrum analyser section of a tactile hearing system. A preamplifier amplifies the sound sensed by the microphone and supplies the result to a filter that restricts the passband from 300 Hz to 3 kHz. An automatic gain control amplifier prevents saturation caused by loud sounds.

The analogue-to-digital converter converts the analogue sound signal into digital form and provides it to a digital comb filter, which, in effect, is a Fourier transform circuit.

Figure 3 shows a block diagram of the arrangement for digitally detecting the amplitude (i.e., intensity) of each of the frequency components (i.e., bands). The amplitude discriminator has a logarithmic scale to mimic the actual response of the human ear. As done in the photonic hearing system, in order to mimic the function of the cochlea, digital delay circuits can be inserted in between the comb filter and the amplitude discriminators of each frequency band.

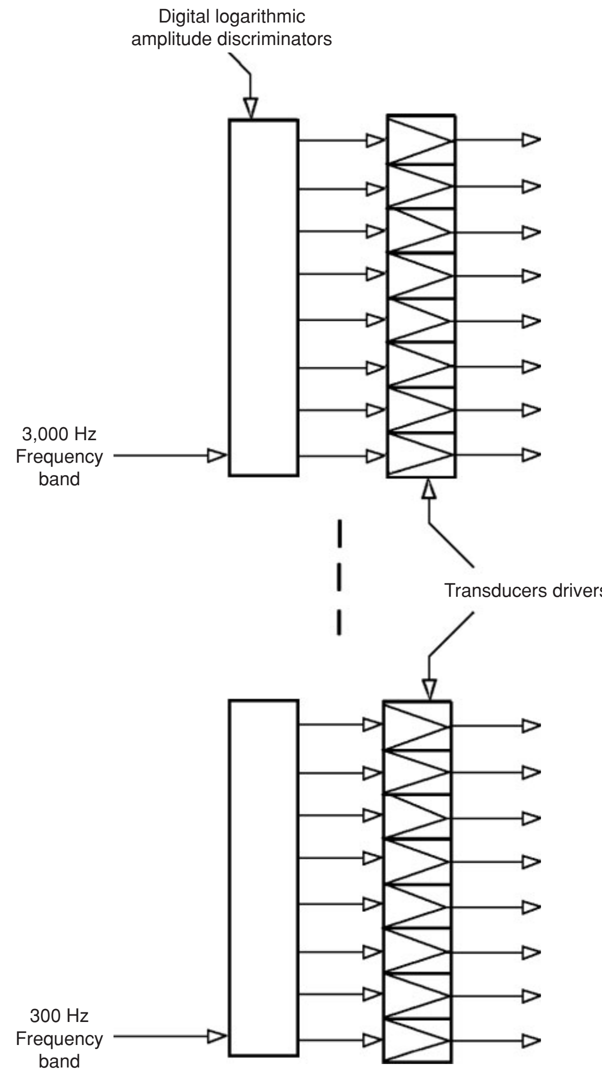

Figure 3 Tactile driver circuits.

The outputs from the amplitude discriminators are provided to tactile display drivers that activate the tactile display elements. Figure 4 schematically shows the basic element of the tactile display. Current from the transducer driver energizes the electromagnetic coil, and the flange and needle made of soft steel are activated downwards against the spring. The rounded needle tip comes into contact with the skin surface with just enough force to exert pressure but not injure the skin.

The size of the basic element is about 5 mm^3. A large number of them are mounted on a flexible printed circuit board and arranged into a matrix array as shown in Figure 5. The drive circuitry is designed in such a way that the horizontal axis represents frequency bands while the vertical axis represents the maximum amplitude (i.e., intensity) of a given frequency band. Of course, this sound spectrum display operates in real time.

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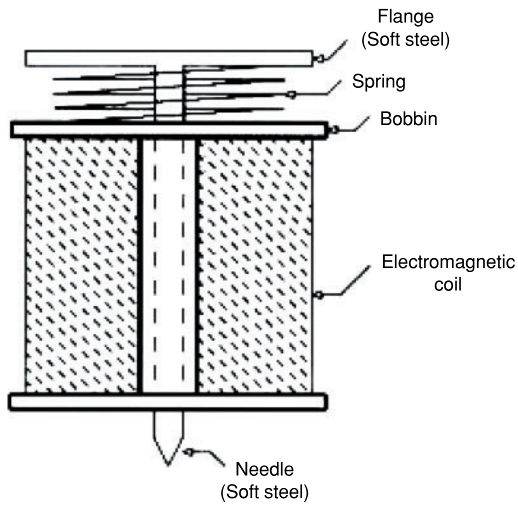

Figure 4 Tactile display basic element.

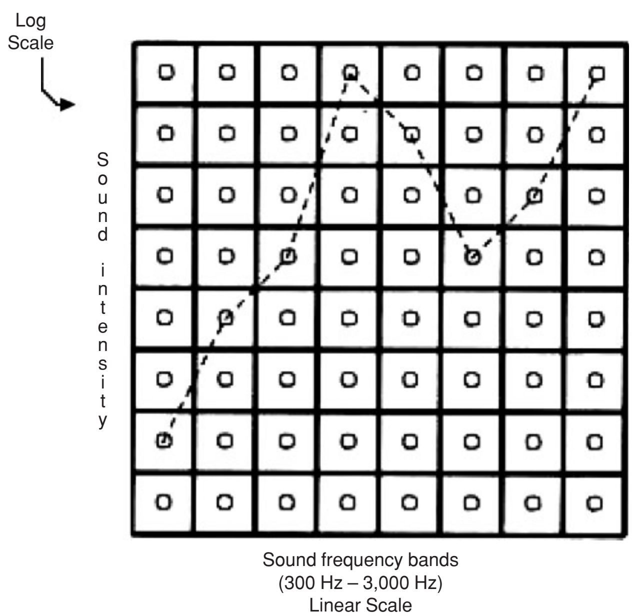

Figure 5 Tactile sound spectrum display matrix.

The sound spectrum can be displayed as a bar graph or a line graph. In order to minimize electrical power consumption, a line graph would be more efficient. For illustrative purposes, a line graph is shown in Figure 5 as a dotted line. The basic elements on the dotted line are activated in this example. Of course, the actual matrix can have a large number of elements such as 20 × 20 to form a display 60 mm × 60 mm in size. In order to provide a spectrum of sufficient resolution, the largest practical number of elements should be used.

Surveying the miniature inductive coils manufactured for radio frequency applications, a basic element of 3 mm^3 appears to be realistic. Therefore, a 20 × 20 matrix might be fitted on to a flexible printed circuit board about 60 mm × 60 mm in size.

The tactile senses of the forearm appear to be capable of reliably resolving stimulation sites that are 50 mm apart (Sherrick and Cholewiak 1986). The layout of Braille characters has a six-dot cell consisting of 2 three-dot columns. The dot height is about 0.5 mm, and the horizontal and vertical spacing between dots within a cell is approximately 2.5 mm. Horizontal separation between cells is about 3.8 mm while vertical separation is approximately 5 mm.

Therefore, a tactile display for the sound spectrum with 3 mm separation between needles might be practical because with usage, the stimulation should cause nerve endings to become more sensitive as is the case when a person is learning to read Braille. Also, new neural paths might be developed because of the stimulation.

Experiments will need to be carried out to determine the most effective design for a tactile display matrix for the sound spectrum.

Two such displays can be placed on a suitable part of the human body, such as the upper left and right sides of the chest, or wrapped around the left and right arms. Using two displays will support stereophonic reception of sound and allow detection of location of the sound source.

One point to note is that a real-time display of a sound spectrum component fluctuates comparatively slower than the frequency component that it represents. This means that the spectrum component for 3 kHz should be changing at a lower frequency that can be well within the response range of the tactile senses, which can respond to frequencies slightly below 1 kHz (Verrillo 1993).

It can also be noted that, for exactly the same reason, the comparatively slow responding neurons and nerves associated with the cochlea are able to detect sound frequencies well above 10 kHz that are sensed by the cochlea, which acts as a spectrum analyser as mentioned earlier.

DISCUSSION

The photonic and tactile hearing systems may be designed to have a coarse spacing for low frequency components and fine spacing for high frequency components. This is based on the notion that high frequencies contribute more to the comprehension of the spoken word.

The conjecture offered here is that by providing a photonic or tactile display that mimics the function of the cochlea, a person without hearing can over time learn to recognize the patterns of the sound spectrum specific to the spoken word, just as in the case where a person learns to read Braille and understand the written word. This conjecture is yet to be tested.

A person in his or her teens who had lost his or her hearing just before becoming a teenager may be the best subject to test this conjecture because teenagers can learn languages more readily than adults, an indication that their brains are still very plastic. Once a toehold is gained in the pattern recognition of words represented by the photonic or tactile hearing system, the subject person can modify the electronic circuits to optimize the ability to 'hear'.

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Of course, rewiring of the brain is expected to take some time but this can be shortened by dedicated practice on the part of the subject. If they prove to be practical, photonic and tactile hearing systems might eventually become the preferred choice because they are not invasive like the cochlear implant.

Patents have been granted for the concept and designs discussed in this paper (Hara and McRae 2001 and 2002).

For photonic and tactile hearing systems to be perfect, the information carried by the phase of sound waves may still need to be captured and displayed. Work on this aspect is being considered.

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