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AN ACOUSTICAL AID FOR THE BLIND

ZBIGNIEW MARCIN WÓJCIK

Space Research Centre of Polish Academy of Sciences
(00-716 Warszawa, ul. Bartycka 18)

Aids for the blind, used so far, which transform images to touch stimuli, are not faultless. The low resolution of mechanical operative systems and the elasticity of skin reduce practical usefulness of these aids. The aid which equivalently transforms optical images to acoustic signals is free from the faults mentioned above.

It follows from physiological investigations of the brain that the right hemisphere of one born blind can take over a parallel analysis of optical images transferred by acoustic signals. A blind person who lost sight later in his life can recognize optical images transmitted by sound by way of an analysis mainly carried out by the left hemisphere of the brain. The left hemisphere usually performs a serial data analysis.

The present paper discusses the transformation of optical images to corresponding equivalent acoustic signals, and also presents a design for the electronic system of an acoustical aid. This system should become a valuable device in research, and it may also be applied practically in future.

1. Introduction

It is obvious that information can be transferred to a blind person by acoustic signal. In order to enable a blind person to receive optical images by his hearing organ, a physical measurable carrier of visual information must be equivalently transformed to acoustical signals. After some training, a blind person will be able to translate these signals into optical images.

Black and white optical images that are invariable in time, e.g. black and white photographs, are usually represented in the Cartesian reference system composed of the *Oxy* plane of an opto-electrical converter screen (Fig. 1), and the light energy axis parallel to it. This threedimensional diagram represents a physical form of an optical image. The analysis of images that are variable in time requires successive, time discrete analyses of the threedimensional diagram. In the paper, however, we shall concentrate on the static images only.

2. The idea of transforming an optical image to an acoustic signal

The idea of an acoustical aid as presented in this paper is that of equivalent transformation of the physical form of a visual image to an acoustic signal. Since the spectrum of an acoustic signal analyzed by man is usually represented in a coordinate system of energy-frequency-time (Fig. 2) there are several possible variants of such transformation. It follows from Figs. 1 and 2 that both diagrams have a common axis, i.e. the axis of energy (or amplitude) of a signal. Thus no special converters are necessary for coding an optical image into an acoustic signal during transformation of these axes, with a possible exception of an electronic signal amplifier. The other two axes: Ox and Oy in the diagram of a visual image (Fig. 2) can be transformed in the following way:

$$tx : Ox \to \text{time}, \tag{1a}$$

$$ty : Oy \to \text{frequency} \tag{1b}$$

or, conversely,

$$tx : Ox \to \text{frequency}, \tag{2a}$$

$$ty : Oy \to \text{time}, \tag{2b}$$

where tx, ty are symbols for these transformations.

Relation (2a) represents an exact assignment of each tone of a frequency f_X to each screen element (Fig. 1) with its coordinate X on the Ox-axis of the screen. It follows from relation (2b) that the illumination energy of any screen element (Fig. 1) with its coordinate Y on the Oy-axis of the screen reference diagram is transformed into sound only within a specific time interval $t(Y)$ which is equivalent to the coordinate Y. The reference time for each interval $t(Y)$ is defined by a certain specific sound produced in a time interval $t(0)$ before the process of transformation of an optical image begins. After generation of a reference sound at a time $t(0)$, successive lines of the screen, $Y = 1, 2, 3, \ldots, N$ are transformed to acoustic signals. Since fastest possible transformation is required we shall try to achieve as short a time interval $t(y)$ as possible. On the other hand, $t(Y)$ must not be too short on the account of masking phenomena due to the sounds received by hearing in the time intervals $t(Y-1)$ and $t(Y+1)$. The number of the tones $\{f_1, f_2, \ldots, f_X, \ldots, f_M\}$ discriminated by man is also limited, amounting to about 600 [13] for an average musical hearing. Problems in the resolution of an acoustical aid for the blind will be shown in section 5 of this paper.

It follows from (2a) and (2b) that a light object equal in size to an element (X, Y) of the screen that is against a light background is transformed to a tone f_X occurring in a time interval $t(Y)$ after generation of a reference sound at a time $t(0)$. Since hearing sensations in man are directly proportional to the logarithm of energy of sounds being heard, and also the signal amplitude at the opto-electrical converter output is directly proportional to the illumination energy of the photosensitive half-tone screen mosaic, a subjective reception of the intensity of a tone f_X is directly proportional to the logarithm of lightness of an object.

The use of function (1) causes the following sensation of the position of the object:

– the location in the horizontal direction – as a time interval between the time signalled and the time of hearing a tone exceeding all other adjacent tones in energy;

– while the location in the vertical direction – as the pitch (frequency) of the tone.

The presence of several such objects in the image analyzed causes several different tones to occur at various time intervals. Differences of lightness of these objects result in sensation of equivalent intensities of these tones.

The dimensions of these objects are proportional to:

1. Using function (1):

(a) dimensions in the direction of the *Ox*-axis (horizontal) – durations of tones exceeding all other tones in energy,

(b) dimensions in the direction of the *Oy*-axis (vertical) – the number of tones heard;

2. Using function (2), conversely:

(a) horizontal dimensions – the number of tones heard,

(b) vertical dimensions – durations of these tones.

Distances from objects to a blind person are measured by the position of the depth of focus in the optical system through which the images investigated are projected onto the opto-electrical converter. The depth of focus can be manually adjusted by a blind person. If there are objects in the depth of focus as determined by a blind person (sensed through touch), their presence is signalled by corresponding tones. If there are not, white noise due to a uniform unfocussed background and the internal noise of the converter can be heard. If the objects are at the limits of focus depth, the optical image is fuzzy and the sounds received are close to white noise. Tones heard are indistinct. Even a slight change in the position of focus depth causes a considerable change in tone articulation (the articulation of a tone f_X is here the ratio of the energy of this tone to the energy of tones f_{X-1} and f_{X+1}).

The presence of sounds corresponding to optical images investigated that are close to white noise, is the acoustical criterion for focus depth adjustment. The focus depth is selected so that the energy ratios of tones $f_X, f_{X+1}, \ldots, f_{X+n}$, to tones $f_{X-m}, f_{X-m+1}, \ldots, f_{X-1}$ and also tones $f_{X+n+1}, f_{X+n+2}, \ldots, f_{X+n+k}$ is maximum or minimum.

3. The overal structure of the acoustical aid for the blind

Currently used optoelectrical converters use sequential scanning, i.e. the following elements of the screen S are analyzed successively in time:

$$\begin{array}{l} S = p(1,1), p(2,1), \ldots, p(X,1), \ldots, p(M,1), \\ \quad\; p(1,2), p(2,2), \ldots, p(X,2), \ldots, p(M,2), \\ \quad\; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \quad\; p(1,Y), p(2,Y), \ldots, p(X,Y), \ldots, p(M,Y), \\ \quad\; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \quad\; p(1,N), p(2,N), \ldots, p(X,N), \ldots, p(M,N), \end{array} \tag{3}$$

where $p(X, Y)$ are coordinates with indexes X, Y on the optoelectrical converter screen (Fig. 1).

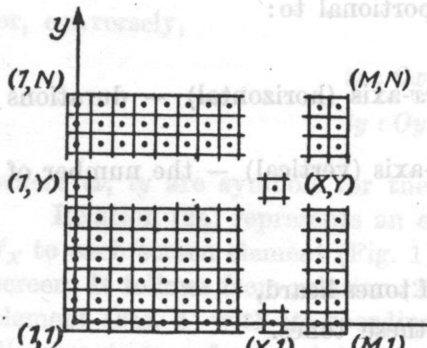

Fig. 1. Ideal half-tone screen of the opto-electrical converter (i.e. photosensitive mosaic net on to which a visual image is projected)

The equivalent transformations (1) or (2) of an optical image to acoustic signals are retained if whole screen lines are simultaneously being transformed. The time sequence of these transformations is

$$\{1, 2, \ldots, Y, \ldots, N\} = L, \tag{4}$$

i.e. from the bottom to the top of the screen (Fig. 1). The set L of the screen lines is therefore orderly. The optical image transformation from expressions (2a) and (2b) requires:

(a) memorizing of the values of elements $1, 2, \ldots, X, \ldots, M$ of the Y line of the screen, $Y \in L$;

(b) transformation of the Y line to a signal F,

$$F = \sum_{X=1}^{M} f(X, Y) = \sum_{X=1}^{M} v(X, Y) k(X), \tag{5}$$

where $k(X)$ is a constant level of the generator output signal at a frequency equivalent to the X column of the screen; $v(X, Y)$ is the value of the optoelectrical converter output signal, corresponding to a screen element with coordinates $p(X, Y)$ and modulating a signal $k(X)$ $f(X, Y)$ is the amplitude of a signal over the range of acoustic frequencies that is equivalent to the X column of screen elements, modulated by the signal $v(X, Y)$; M is the number of signals at various acoustic frequencies generated by the aid; M is at the same time the number of the optoelectrical screen elements in one line of the screen;

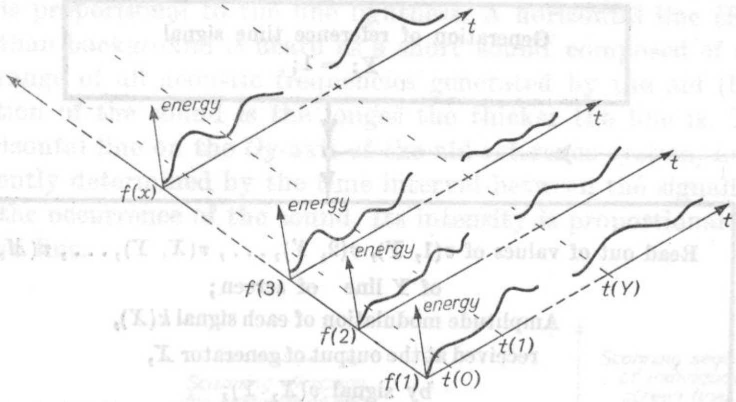

Fig. 2. Physical information carrier of sound signal; the real time spectrum of sound

(c) elimination from memory of the values of elements of the Y line of the screen and storing in memory of the values of a successive screen line, $Y+1$.

This process repeats cyclically as in point (b) until all values of the screen elements have been read. The functional diagram for the acoustical aid is shown in Fig. 3.

It should be noted that it is possible to build an aid which can successively transform individual screen elements (formula (3)) to individual tones. This aid however would be M times slower, compared to the aid whose functional diagram is shown in Fig. 3. The aid operating according to the algorithm in Fig. 3, using relation (2) to transform static optical images, will be discussed later in the paper. Transformation of selected elements of graphic images such as straight lines of different finite thicknesses, arcs and curves of these lines and so forth will be also considered.

After beginning of each cycle of transforming an arbitrary optical image to an acoustical signal, a sound signal is generated which means that the image to sound transformation is beginning. After a single transformation of all the screen lines to an acoustical signal, another reference sound signal is generated, and the aid working cycle is repeated (Fig. 3). Thus the beginning of each scanning of the whole screen is signalled. The beginnings of scanning of successive lines are not signalled.

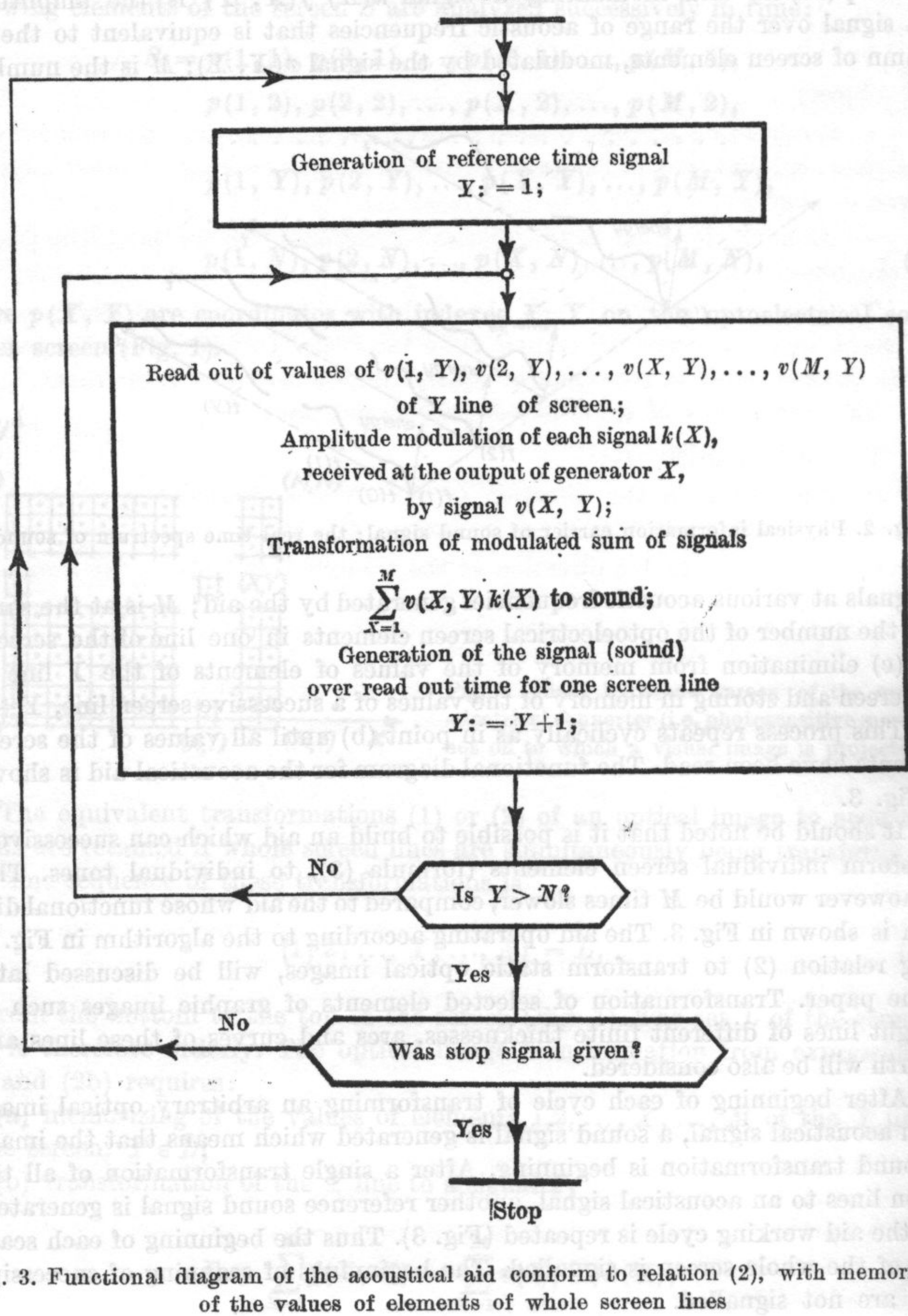

Fig. 3. Functional diagram of the acoustical aid conform to relation (2), with memorizing of the values of elements of whole screen lines

A vertical straight line (Fig. 4a) that is lighter than background is transformed by the aid to a sound composed of a certain number of tones. The thinner the line is, the fewer tones occur. The tones occur throughout the observation of the line, i.e. without changing in any of the time intervals separated by reference signals.

The frequencies of these tones equivalently determine the position of the line on the Ox-axis of the screen reference system, i.e. horizontally. The sound intensity is proportional to the line lightness. A horizontal line (Fig. 4b) that is lighter than background is heard as a short sound composed of all the tones over the range of all acoustic frequencies generated by the aid (formula (5)). The duration of the sound is the longer the thicker the line is. The position of the horizontal line on the Oy-axis of the aid reference system, i.e. vertically, is equivalently determined by the time interval between the signalled reference time and the occurrence of the sound. Its intensity is proportional to the lightness of the line.

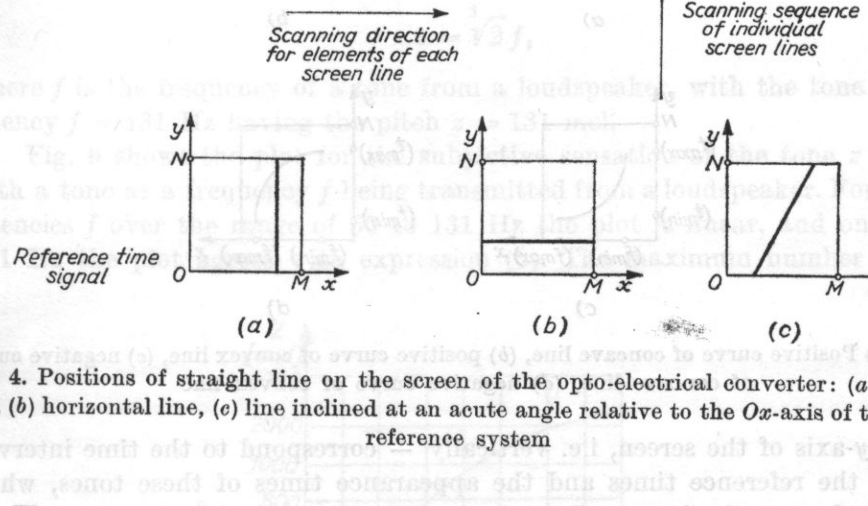

Fig. 4. Positions of straight line on the screen of the opto-electrical converter: (*a*) vertical line, (*b*) horizontal line, (*c*) line inclined at an acute angle relative to the Ox-axis of the screen reference system

The same straight line inclined at an acute angle with respect to the Ox-axis of the screen reference system (Fig. 4c) is heard as a sound composed of a number of tones. The number of these tones decreases with decreasing thickness of the line. Its loudness is proportional to the lightness of the image. The frequencies of the tones of the sound increase linearly in time. The increase rate is the greater the more inclined the line is (the more acute its angle is relative to the Ox-axis of the screen reference system — Fig. 4c). The duration of the sound perception also decreases with decreasing angle a. A line that is lighter than background, inclined at an acute angle with respect to the Ox-axis of the screen is heard in an analogous manner — however the frequencies of the audible sound tones increase in time.

When the curve of the concave line being transformed by the aid, which is lighter than background, is positive (due to the sign of the first derivative — Fig. 5a), the frequencies of sound tones heard increase in time less and less than linearly. When the curve of the convex line being analyzed by the aid, which is lighter than background, is positive (Fig. 5b), the frequencies of sound tones heard by a blind person increase faster and faster (faster than linearly). The loudness of these tones is proportional to the lightness of images. The number of these tones is proportional to the thickness of images in the directions of the Ox-axis of the screen. The positions of successively analyzed in time fragments of light images in the observation field of the aid — in the directions

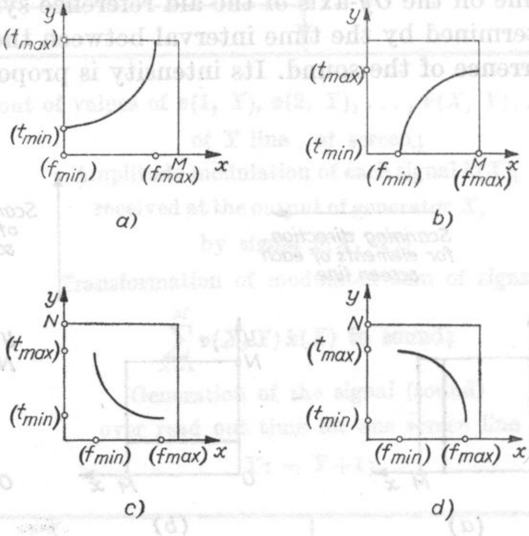

Fig. 5. (*a*) Positive curve of concave line, (*b*) positive curve of convex line, (*c*) negative curve of concave line, (*d*) negative curve of convex line

of the Oy-axis of the screen, i.e. vertically — correspond to the time intervals between the reference times and the appearance times of these tones, which are equivalent to the images. Durations of these tones are proportional to the widths of objects in the direction of the Oy-axis of the screen. The minimum ($t_{\min}$) and the maximum ($t_{\max}$) time intervals between the reference and appearance times correspond to the extreme positions of the images analyzed by the aid, in the direction of the Oy-axis of the screen (Fig. 5). Current frequencies of the tones heard equivalently define the positions of light images being analyzed by the aid in the directions of Ox-axis of the screen. The widths of images in the horizontal direction, i.e. in the direction of the Ox-axis of the screen, correspond to the number of the sound tones. The lowest ($f_{\min}$) and the highest ($f_{\max}$) frequencies of these tones equivalently define the extreme positions of these sound tones of the investigated light object in the direction of the Ox-

axis of the screen. The loudness of these tones equivalently corresponds to the lightness of individual fragments of images. If the curve of the concave lighter-than-background line analyzed by the aid is negative (due to the sign of the first derivative of the line — Fig. 5 c), the sound can be heard that is composed of tones whose frequencies decrease more and more slowly (more slowly than linearly). Analogously, the negative curve of the convex lighter-than-background line results in tones whose frequencies decrease faster than linearly i.e. faster and faster (Fig. 5d).

It is now hard to predict how useful the aid will be for recognition of complex geometrical figures such as letters. It is certain however to be useful in recognizing large, simple objects such as greens, streets and pavements, walls of houses, light windows, and strong lamps.

4. Possibilities of perceiving optical images by hearing

The subjective sensation of the pitch z of a tone by hearing, for acoustic frequencies $f > 131$ Hz is [13] the function

$$z = \sqrt[3]{2} f, \tag{6}$$

where f is the frequency of a tone from a loudspeaker, with the tone at a frequency $f = 131$ Hz having the pitch $z = 131$ mel.

Fig. 6 shows the plot for the subjective sensation of the tone z by man, with a tone at a frequency f being transmitted from a loudspeaker. For the frequencies f over the range of 50 to 131 Hz the plot is linear, and only above 131 Hz the plot agrees with expression (6). The maximum number of tones

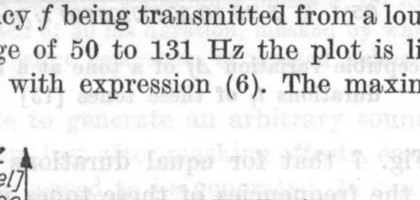

Fig. 6. The plot for subjective sensation of the pith z of a tone by hearing in relation with the frequency f of the tone [13]

heard, neglecting the masking effects, does not exceed $z = 2400$ mel. An average man perceives more than 600 different tones [13]. In building an acoustical aid 600 generators can be used, each generating a tone with the pitch z, according to the diagram in Fig. 6. An arbitrary, successive pitch z must be higher than the preceding by at least $\sqrt[3]{2}$, beginning with $f = 131$ Hz.

For the acoustic frequencies $f < 131$ Hz, however,

$$z = f. \tag{7}$$

Due to the system assumed for the transformation of optical images, the pitch z must have a discrete behaviour:

$$f_X := z. \tag{8}$$

Fig. 7 shows three plots for the maximum frequency variation Δf perceived by man for tones at frequencies $f = 0.25$ kHz, 1 kHz, 4 kHz as a function of duration t_i of these tones. The tones were produced by sine pulses. Each of the three plots was made for the tones f separately.

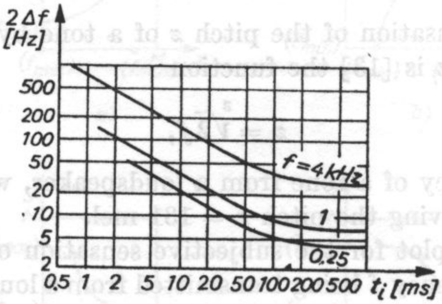

Fig. 7. The minimum perceptible variation Δf of a tone at a frequency f in relation with durations t_i of these tones [13]

It follows from Fig. 7 that for equal durations of arbitrary tones, the variation perceived in the frequencies of these tones increases with increasing frequencies of these tones. The increase in the magnitude of variation in frequencies perceived follows the Meli scale Fig. 6. For durations t_i of sound pulses longer than 200 ms, the perceived interval Δf from a frequency f does not change. $2\Delta f = 7$ Hz for $f = 1$ kHz; $2\Delta f$ decreases with deacreasing f.

It follows from the plot in Fig. 7 that in building the aid for the blind, a duration t_i of an arbitrary sound pulse of 20 ms can be assumed.

Fig. 8b shows three plots for the audibility threshold L(dB) of Gaussian sound pulses, masked by rectangular pulses of white noise, in relation to the interval Δt between the white noise and Gaussian pulses. These pulses are schematically shown in Fig. 8a; S is the intensity of white noise rectangular pulses, L is the intensity of Gaussian pulses. At an intensity L of Gaussian pulses, after a time Δt from the end of the rectangular masking white noise pulses at an intensity S, the Gaussian pulses begin to be perceived by human hearing. From the plot, the sound which corresponds to any Y line on the opto-electrical converter screen is masked by the sound corresponding to the preceding line, $Y-1$, of the screen. Assuming in building the aid a mean level of the sound generated by the acoustical device, equal to 80 dB $= S = L$ (Fig. 8), we obtain the interval between two arbitrary sound pulses equal at least to 20 ms. This interval is necessary to minimize the effect of masking on the hearing of an arbitary, successive sound pulse. Masking effects analogous to those in Fig. 8b occur when white noise is transmitted from a loudspeaker in pulses after the generation of Gaussian sound pulses (conversely to Fig. 8a).

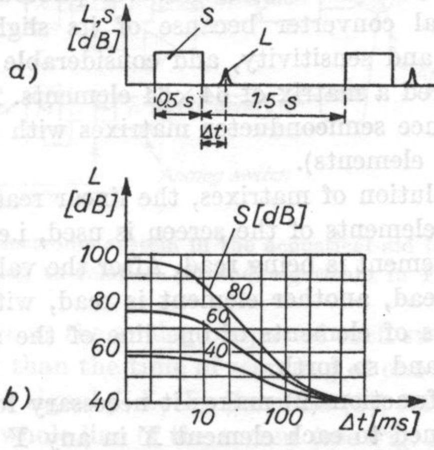

Fig. 8. (*a*) Graphic interpretation of Gaussian sound pulses L from a loudspeaker after a time Δt from the generation of rectangular white noise pulses S, (*b*) Audibility threshold L (dB) of Gaussian sound pulses, each of 30 ms duration, masked by white noise with an intensity S(dB) before generation of masked pulses [13]

In practice, it is possible to generate an arbitrary sound pulse, corresponding to any Y line of the screen, just after masking effects, corresponding to the $Y-1$ line of the screen have ceased to be generated. It can thus be assumed that the frequency f_w of scanning of successive lines of the optoelectrical converter screen is

$$f_w = \frac{1}{(20+20)\ \mathrm{ms}} = \frac{1}{40\ \mathrm{ms}}.$$

It seems better to assume in practice that

$$f_w = \frac{1}{50\ \mathrm{ms}} = 20\ \mathrm{Hz}.$$

It is thus possible to convey to the blind about 20 lines of the screen within one second by sound pulses. It seems also difficult to increase the dimensions of the screen in the direction of the Oy-axis, i.e. vertically, since the optical image conveyed as a series of sound pulses in real time would be fuzzy; the movements of a blind person cause the image observed to move on the screen of the converter. It is however possible to read the image quickly, e.g. within 1/50th of a second, transfer it to the memory of the aid and equivalently transform the memorised image into a series of sound pulses, according to the algorithm shown in Fig. 3.

5. Construction of the electronic system of the acoustical aid

The self-contained matrix of semiconductor photodetectors is the most suitable opto-electronical converter because of its slight dimensions, small weight, high reliability and sensitivity, and considerable resolution. E.g. IPL has for some years offered a matrix of 64 ×64 elements. American companies, e.g. RCA, already produce semiconductor matrixes with a resolution of a TV camera (over 500 ×500 elements).

Due to a large resolution of matrixes, the linear readout of the values of signals from individual elements of the screen is used, i.e. at each moment at most the value of one element is being read. After the value of the signal from one element has been read, another element is read, with the readout being orderly: since the values of elements of one line of the screen are read, first then those of the next and so forth.

The application of function (2) makes it necessary for each tone $f(X, Y)$ to be equivalently assigned to each element X in any Y line, to each column X of the screen elements (see formula (5)). The intensity of this tone is proportional to the value $v(X, Y)$ of the signal received at the output of the element $p(X, Y)$,

$$\forall\big(p(X, Y) \in S\big)\big(f(X, Y) = k(X)\cdot v(X, Y)\big), \tag{9}$$

where $k(X)$ is the amplitude of a signal at a frequency corresponding to the X column of the screen, $\forall$ is a general quantifier ($\forall(p(X, Y) \in S)$ means: for each element $p(X, Y)$ in the set S (see formula (3))).

As follows from the above, a hearing aid consists of an M set of generators (M is the number of elements in one screen line — Fig. 1), with every X-generator giving an output signal $f(X, Y)$ (formula (5)), proportional to the value of lightness of the X, Y element of the screen, i.e. to $v(X, Y)$. Since the matrix is scanned linearly, a distributor must be built permitting the introduction of the value $v(X, Y)$ to a relevant generator X. The distributor can be made of a looped, series-parallel shift register with M bits, M outputs and 1 input, coupled with the time base of the readout of the photodetector matrix [8] where at the beginning of the read out of the whole matrix only one 1 is introduced. Fig. 9 shows a block diagram of the aid. The start of the matrix readout determines the signalled reference time for the perception of the position of objects vertically. As follows from Fig. 9, this moment is defined by the tone f_X. One-channel analog switches, e.g. C-MOS type [5] are designated

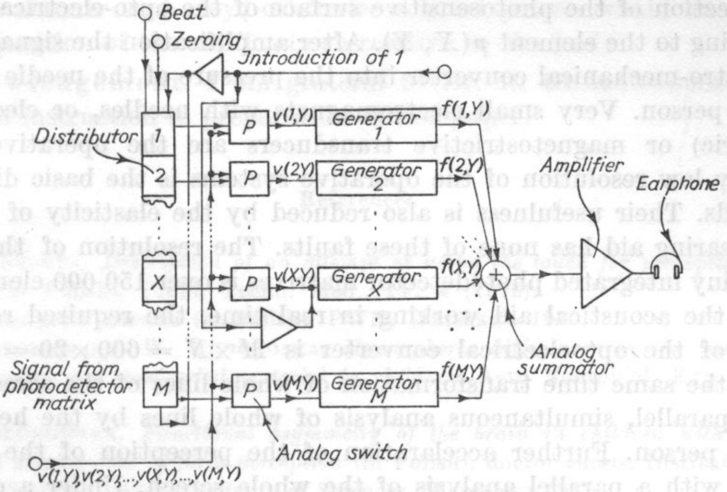

Fig. 9. A design of the electronic system in the acoustical aid for the blind, working according to relation (2) and algorithm in Fig. 3

as P in Figure 9. Since at the analog output of each switch, the switching pulse lasts M times shorter than the time of scanning of one screen line, each generator X should generate signal $f(X, Y)$ (formula (5)) for a time τ_M equal to the readout time for one whole line of the screen (see Fig. 3). The time τ_M cannot be shorter than 40 ms (see point 4). Thus the time of storing the output signal of any analog switch can be close to the scanning time τ_M for one screen line.

Each generator X consists of a unit generating a signal $k(X)$ with a constant amplitude, which is modulated by a signal $v(X, Y)$ received at the output of the photodetector column X.

The values of constant signals $k(1), k(2), \ldots, k(X), \ldots, k(M)$, affecting the values of modulated signals $f(1, Y), f(2, Y), \ldots, f(X, Y), \ldots, f(M, Y)$ (formulae (5) and (9)), can have a distribution over the range of acoustic frequencies close to the speech spectrum.

6. Conclusions

Blind people still have no suitable device which would enable them to receive visual sensations in a satisfactory manner. The designers of visual aids are at present working towards enabling the blind to receive visual stimuli by touch receptors in the skin. The designs of suitable miniature opto-mechanical converters are becoming better due to the development of technology. These converters operate in the following way [7]: the optical image is projected on to the screen of the opto-electrical converter which is a table of $M \times N$ elements. The electrical signal received at the output of an arbitrary element $p(X, Y)$ of the screen is proportional to the illumination (or to its logarithm) of a tiny section of the photosensitive surface of the opto-electrical converter, corresponding to the element $p(X, Y)$. After amplification the signal is changed by the electro-mechanical converter into the pressure of the needle on the skin of a blind person. Very small electromagnets with needles, or electrostrictive (piezoelectric) or magnetostrictive transducers are the operative elements. A relatively low resolution of the operative systems is the basic disadvantage of these aids. Their usefulness is also reduced by the elasticity of the skin.

The hearing aid has none of these faults. The resolution of the currently produced tiny integrated photodetector matrixes is over 150 000 elements of the screen. In the acoustical aid working in real time, the required resolution of the screen of the optoelectrical converter is $M \times N = 600 \times 20 = 12\,000$ elements. At the same time transformation of whole lines of the screen to sound permits a parallel, simultaneous analysis of whole lines by the hearing organ of a blind person. Further accelaration of the perception of the aid sounds is possible with a parallel analysis of the whole screen. Under a considerable simplification it can be assumed that a parallel analysis of information is usually performed by the right hemisphere [4], with the left hemisphere of the brain usually carrying out a serial data analysis. Thus the sound from the aid should be usually directed to the right hemisphere of a blind person's brain so as to permit the fastest perception of images, e.g. through placing the earphone at the left ear. It seems that a person who was born blind has the greatest possibility to learn to recognize quickly the optical images transformed into sound signals, up to the age of five. His right hemisphere of the brain – provided it is healthy – is fully capable of a parallel analysis of both sounds and images. The right hemisphere of a blind person who, however, lost sight later in his life, is specialized in understanding, particularly, of optical images [3, 4]. The sounds from the aid can be, however, analyzed through understanding, mainly through a serial analysis performed by the left hemisphere of the brain, already accustomed to the analysis of sounds [4, 3]. The understanding can be based on the equivalent transformation of an optical image to a spectral sound image, as presented in this paper. Some characteristics of optical images and most frequent scenes can in time be used as standards for a parallel analysis of sounds from the aid [6].

A blind person can in time become accustomed to some technical shortcomings of the aid [6], e.g. different sensitivities of individual photodetectors on the screen surface, optical distortions, and those due to the electronic elements of the aid.

Recognition of coloured images and increased contrast in images can be archived by the application of suitable optical filters. An increase in contrast in black and white images (and also coloured) can be attained electronically by the application of a method of the side effect of the vision [2].

The positions of objects are correctly determined relative to the body of a blind person if the opto-electrical converter is stiffly attached to the body in the some manner each day; otherwise a blind person would have to "calibrate" the position of the artificial eye relative to the body.

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