Holography, Information Theory, and the Cerebral Cortex

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ABSTRACT

When applying information theory to the study of sensory communication processes, the researcher must provide an exact definition of the physical stimulus—in terms of amplitude, frequency, and phase at the electric level—if the unit of information measurement is to be defined. Detection of the registration of correlates of these three variables in the central nervous system implies communication of *all* aspects of information available in the stimulus. When this is the case, such a structure might be considered an example of a hologram. When the unit of information measurement is sought in the visual system, however, it appears to be indefinable. The visual system's mechanisms of contrast enhancement act as detection mechanisms but do not convey the registration of quantity. In effect, they answer "yes" or "no", but do not state "how much." This gives rise to certain illusions of the Mach band kind. In the auditory system, however, the unit of information has been defined as $\Delta f \cdot \Delta t \simeq 1$. The auditory system, therefore, offers a more convenient sensory system for the researcher who wishes to describe his results in terms of information theory.

INTRODUCTION

Writers on the subject of memory, influenced by Lashley's conclusions [1] that the principles of equipotentiality and mass action describe the brain's activity as far as memory is concerned, have concluded that the brain disperses information in a way similar to a hologram [2–6]. Whereas their conclusions are based on the results of memory research, mine are based on the physics of information theory. From the consideration that *perception* requires a dimension of information conveyance not needed in *sensation*, I have postulated that the registration of this extra dimension (phase) in the central nervous system (CNS) implies the total reception of all the information available from a given source. The central nervous system thus can be said to function as a receiver of all information, or as a hologram [7–9].

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INFORMATION ANALYSIS

There is a direct equivalence between a complete description of the information content of a signal varying in amplitude, frequency, and phase and a hologram. The information content of such a signal is dependent on the resolution limits for the detection of minimum amounts of energy representing the signal. In a hologram the minimum amount of signal energy representing, say, 1 bit of information, is represented as a volume contained on three axes: signal duration $\times$ signal bandwidth $\times$ signal phase. The minimum volume (i.e., the minimum energy) detectable is dictated by quantum mechanical considerations and represents 1 bit. The total information content of the signal is the total volume divided by the minimum detectable volume.

Whereas signals of a given bandwidth and duration have *associated* energy levels, signals of a given bandwidth, duration, and phase have *relative* energy levels; that is, phase requires a referent. This relative energy is represented by the volume contained within the three above-mentioned axes. By the storage or registration of relative energy levels we may be said to possess a more complete, a more whole, conception of a complex signal. Phase is not lost; hence we have a hologram.

We have mentioned associated energy levels—when only signal duration and signal bandwidth are available. Relative energy levels are present when a set axis or a second signal provides a referent. We are concerned only with relative energy levels in this article. And what of *absolute* energy levels? This topic involves signal-to-noise ratios and is the concern of signal detection theory. We will not address this topic here.

Information theory is not readily applicable to a description of the physical stimulus for visual perception. It has been pointed out that cues signaling the third dimension of phase do occur in the sensory input of the visual system [10, 11]. However, the perception of space is learned and these cues must be discriminated from the intensity dimension, hence *this extra dimension of information is not contained in the sensory input per se*. Discrimination in the visual modality is an active process. It involves a selective treatment of the visual input, possibly by centrifugal control. The active use of a discriminated cue for inference to a third dimension is *not*, therefore, the same as the third dimension acting as a transmitter and providing a signal for the organism as a passive receiver. We, as mammals, do not *receive* a signal transmitted from the third dimension when we *perceive* the third dimension. No doubt for a machine able to detect relative wavelengths (i.e., phase) my statement would not be true. For *Limulus*, the horseshoe crab, with its compound eye, my statement may not be true. However, the mammal's retina detects wavelengths but not the phase of those wavelengths. Photochemically it is impossible. To look for phase input in the mammal's visual system is a fruitless task. Visual perception, therefore, cannot be studied the way a communications engineer would study a simple input channel. Starting with the original sensory stimulus, this input is enriched by the addition of memorial associations attached to certain aspects of the input, which are then discriminated. This addition and discrimination prevent a description of the process of visual perception in simple through-put terms. It also means that the sensory physiologist cannot define a visual perceptual stimulus exhaustively in physical terms, that is, at the electric level: amplitude, frequency, and phase—that recur at the receiving (CNS) end.

The auditory system, however, is another story. It is a more "honest" system. The amplitude, frequency, phase, and time of arrival of the stimulus or stimuli are all contained in the sensory input. The third dimension is cued in the input as a transmitter of phase signals or time differences in arrival at the two ears that the ear is able to detect. This is because (a) auditory signals have such a low frequency compared with visual signals and (b) frequency has a place representation along the basilar membrane. The auditory system is therefore amenable to the analysis methods applied to a through channel. There are centrifugal influences that act upon the sensory input, but the third dimension's representor is physically definable and does not have to be learned from our interaction with the external world. Thus, in the auditory mode, information can be represented as in Fig. 1 in both a physical and physiological sense. In the visual mode, Fig. 1 may represent the central nervous system's final registration of a "perception" but this certainly does not represent the original physical components of the received input, as it does in audition.

It has become accepted among information theorists that the duration and bandwidth of a signal are contravariantly related for information to remain constant. As for minimum detectable information, by referring to one-dimensional wave mechanics, Gabor [12, 13] showed that

$$\Delta f \cdot \Delta t \simeq 1, \tag{1}$$

and in so doing provided a definition of the absolute unit of information to the CNS. Use of such a stimulus in the auditory mode has indicated the presence of exact tonotopic relationships upon the cortex [14].

Now, to recognize a tonal frequency from noise takes 10 msec. To recognize a minimum number of swings (4, of effective bandwidth 4.7 cycles) away from or back to a 500 Hertz tone requires 250 msec [15]. The product of these two values of Δf and Δt is 1.17. To register the beginning of a second sensation of bandwidth 50 cycles around a 500 Hertz tone requires 21 msec [16, 17]. The product of these two values

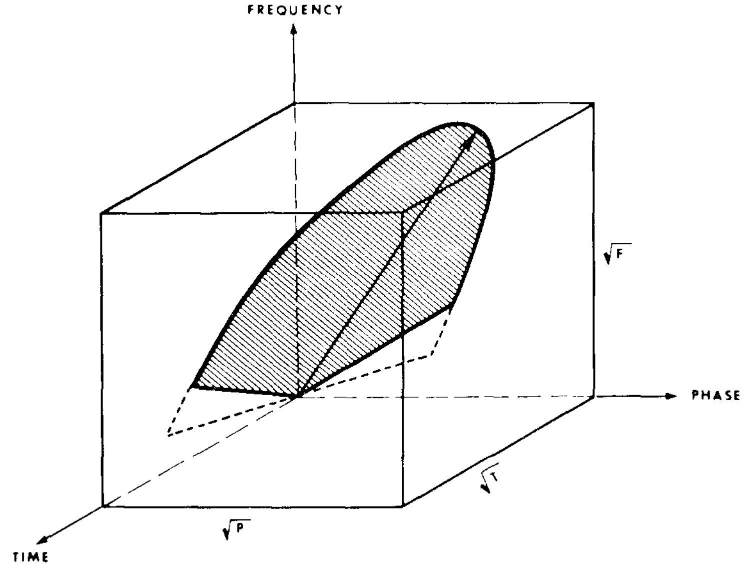

FIG. 1. Information representation of a signal in three dimensions. $S = F + T + P =$ an invariant under rotation, where the eigenvalues of the matrix representation of signal are S (= total information content of signal), F (= frequency bandwidth of signal), P (= phase with respect to an arbitrary axis), and T (= duration of signal). Square of the diagonal of the ellipsoid = sum of squares of the principal axes. For information conservation, all transformations of the signal are rotations of the ellipsoid.

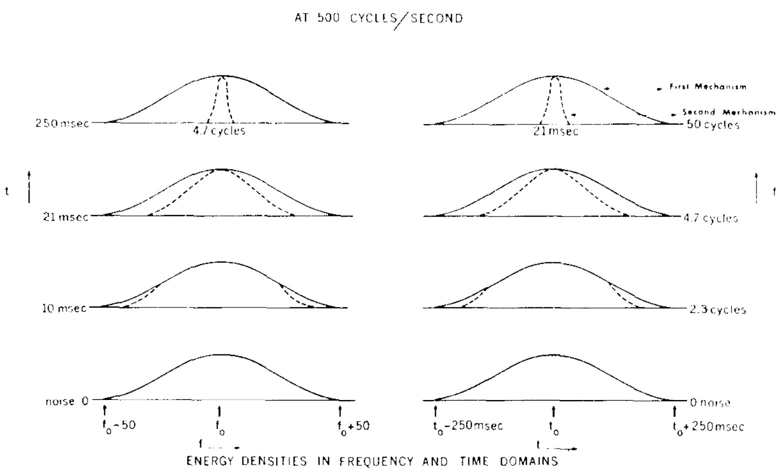

FIG. 2. The two mechanisms of hearing. Solid curve in left column refers to the dashed curve in the right column, and vice versa. Data in left column are from Gabor [13].

of Δf and Δt is 1.05. Gabor's hypothesis is thus supported by psychological evidence.

It is apparent, also, that the ear is able to operate with both a wide and narrow band of frequency pass at the same time (cf. Fig. 2). Thus after 250 msec another bandwidth discrimination is able to take place. Temporal discrimination can be renewed after 21 msec, however. The discrimination is noticeably of a set amount. It is not a mere "detection." Conceivably lateral inhibition, the "unifying principle of sensory physiology" [18] is operative here. Two mechanisms, detection and discrimination, are required.

The elementary signal showing contravariance between signal duration and bandwidth is represented by the following relationships.

$$S(t) = \exp[-\alpha^2(t - t_0)^2] \cdot \exp[i(2\pi f_0 t)], \tag{2}$$

$$S(f) = \exp\left[-\left(\frac{\pi}{\alpha}\right)^2 (f - f_0)^2\right] \cdot \exp[i(2\pi t_0 f)], \tag{3}$$

where α is a real constant. This is an exponential function modified by a probability pulse. Figure 2 represents the symmetry of these arrangements.

Agreed that an information theory analysis has applications to auditory research and has been applied successfully in physiological studies of the auditory system [19], what then can be said of the visual system? Quantum theory has demonstrated the existence of an elementary signal for light waves. Thus, the unit of information measurement can be defined for light. Gabor [20] has shown that monochromatic illumination can be represented by an *illumination ellipsoid* in N-dimensional (complex) information space. An elliptical volume defined on three axes (amplitude, frequency, and phase) would retain its volume (i.e., information would be conserved) if an operation on one of these dimensions could be compensated for by corresponding and complementary operations on the remaining dimensions. But, and this is the catch, the eye takes no notice of light frequency (except in the case of color vision). Thus the input is not truly three-dimensional. Whereas with the ear the two mechanisms involved in auditory perception are symmetrical, in the eye these two mechanisms are not mutually linked, as will be shown. This leads us to the conclusion that for the visual system the absolute unit of information is indefinable.

Now, Wolter [21] has made the analogy between the field of optics and communication networks. The rule according to which a group dipole antenna can concentrate radiation in an angular half width (cf. Fig. 3), where Δx is the breadth of the group, is

$$\Delta x \cdot \Delta(\sin \alpha) \geqslant \lambda, \tag{4}$$

which is analogous to the diffraction relation in optics:

$$\Delta x \cdot \Delta(\sin \alpha)\frac{h}{\lambda} \geqslant h \tag{5}$$

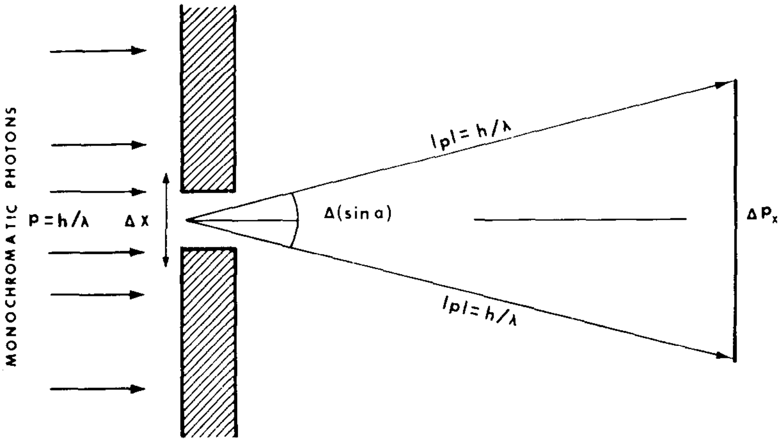

FIG. 3. On Heisenberg's uncertainty condition (after Wolter [21].

Equation (5) is related to Heisenberg's uncertainty relation

$$\Delta p_x = p \cdot \Delta(\sin \alpha) = \Delta(\sin \alpha)\frac{h}{\lambda}. \tag{6}$$

It was considered that with

$$\Delta x \cdot \Delta(\sin \alpha) \geqslant \lambda \tag{7}$$

the limit of information had been obtained. However, it is possible to make measurements of greater accuracy by using the absence or presence of a detection as information, rather than the discrimination of an object (cf. Fig. 4). If the two halves of the group dipole antenna are connected with opposite phase, this is accomplished. In this case, the absolute unit of information is indefinable. Instead of a *maximum* and finite reading (for a discrimination), we look for a *minimum* qualitative reading (for a detection). Research on Mach band phenomena has shown that the eye detects inhomogeneities in the visual field but does not discriminate a finite unit (cf. Fig. 5). In the case of Fig. 5, detection of a change was not accompanied by a discrimination of the extent of the change. The eye, then, operates according to a "minimum" principle—either something is there or it is not—and if it is, then this does not inform how much is there. O'Brien [22] has even reported the case where there is an inverse relation between the perception of brightness and the actual intensity of the stimulus. The perception of brightness and the intensity increment threshold are also related in no simple way [23]. The visual system, therefore, affords

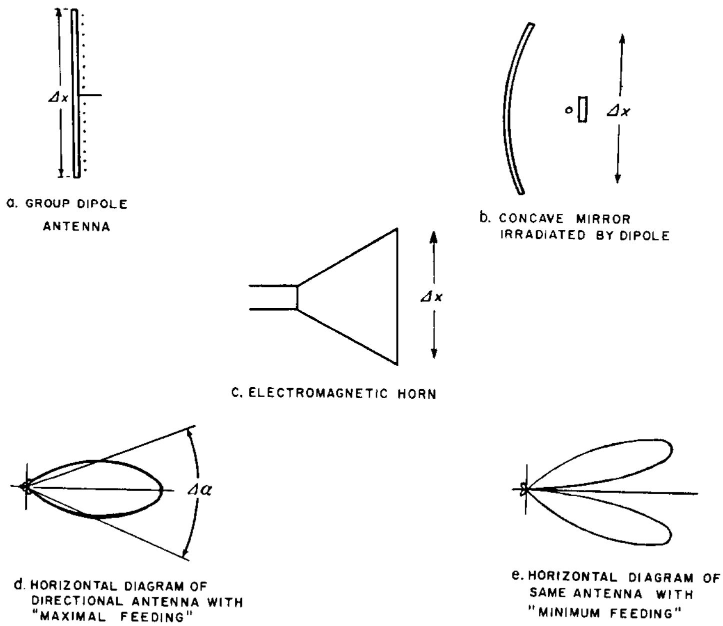

FIG. 4. After Wolter [21].

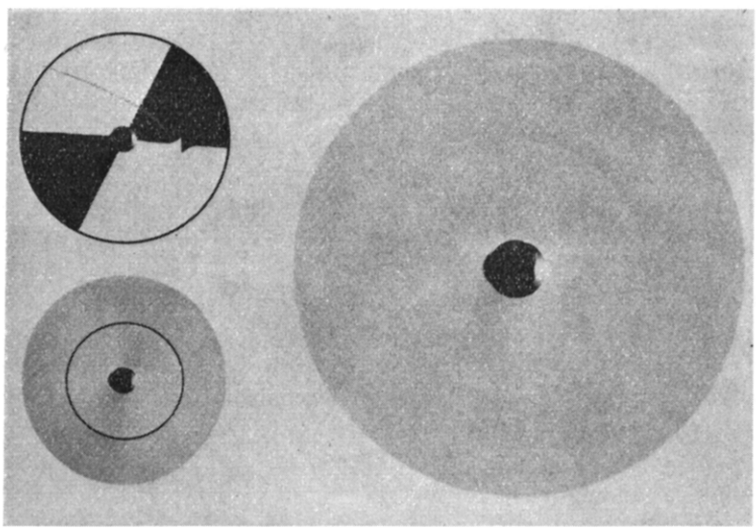

FIG. 5. From [34, page 75], after T. N. Cornsweet. Difference in brightness of two zones of equal luminance due to the nature of the transition zone. Lower left disc is rotated and appears as at the top. When the transition is masked with a heavy line, the inner and outer zones appear equally bright.

little help to the researcher in the field of holographic information storage *if he wishes to define the physical stimulus for perception exhaustively.*

Granted the visual system of the mammal has no physically definable bit of information as the auditory system has, nevertheless, after the patterning of light intensities has reached the ganglion cells of the retina, the patterning could be considered that of a spatial representation of "pseudofrequencies." But even this gives no help in defining the physical stimulus. Binocular disparity provides an intensity difference cue [24] for interocular (not intraocular) "pseudofrequency" differences. Phase, however, is not represented. The interocular differences are contemporaneous and do not represent a temporal difference signal but an *intensity difference cue.* Let us now consider the physics of a hologram.

If we were to present a stimulus of an elementary kind defined in terms of amplitude, frequency, and phase to a sensory system, then the registration within the system of these three dimensions would warrant calling that structure a *hologram.* As such, it would obey the following two laws.

1. *Huygens' principle:* Every point of a wave front may be considered as the center of a secondary disturbance that gives rise to spherical wavelets, and the wave front at any later instant may be regarded as the envelope of these wavelets [25].

2. *The Bragg relation:* Interference patterns considered must satisfy the condition that amplitudes of waves diffracted from differential parallel planes add up in phase.

It has been stated that to obtain a hologram, phase must be registered, and for this to occur, the two foregoing principles must apply. We are stating here that if phase is represented in a structure, then the structure is a hologram, and *therefore* the two principles above must apply to that structure.

Now, the registration of phase relations is not possible without a *coherent source.* Within the CNS the thalamus appears to provide a trigger pacing the cortex to produce this coherent source [26, 27]. It has been shown that the absolute unit of information is at least two-dimensional ($\Delta f \cdot \Delta t \simeq 1$). We require a coherent source not only so that phase might be represented, but in order that *both signal bandwidth and signal duration have one resolution mechanism.* Is there a mechanism available already that performs these two functions? The answer is the well-known frequency converter.

The physical analogy is as follows (cf. Fig. 6). Let f_0 = frequency of film, v = speed of film, $u = (1 - k) \cdot v$ = velocity of slits where k is the frequency conversion ratio, $f_1 = [(v - u)/v]f_0$ = converted frequency, s = slit spacing, $\tau = [s/(1 - k)] \cdot v$ = correlate of slit spacing.

The spectrum of the frequency input consists of sharp lines that differ from one another by multiples of $1/\tau$; that is, the spectrum consists of all combination notes of the original frequency f_0 with the repetition frequency $1/\tau$. Let N be the slit number, that is, the number of slits in the length over which the transmission falls from unity to $1/e$. Then the total length of the window in which the transmission exceeds 1 % is $4.3Ns$. Thus the total

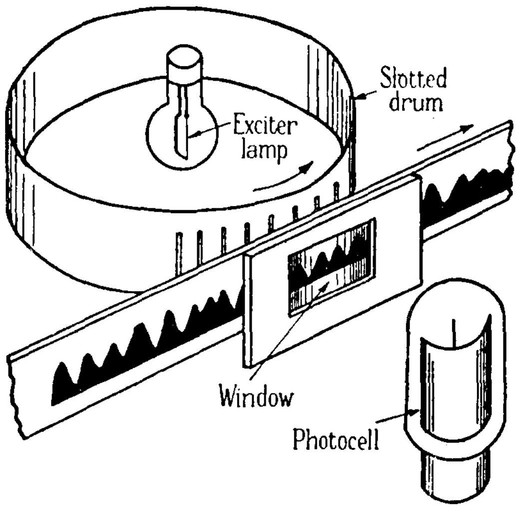

FIG. 6. Frequency converter with sound film. After Gabor [12, page 446].

number of slits simultaneously before the window is $4.3N$. The length of the window is defined as the length of time T in which a point of the film passes through the part of the window in which the transmission exceeds 1 %. If the time T is too long, the time resolution in the reproduction will be too poor. Determining the best balance between the resolution and frequency reproduction is a matter of compromise. Suppose the information on film is speech representation. *For speech the optimum value for T is* 100 *msec* [28]. The alpha rhythm is 10 cycles/sec. In photic stimulation, the perceptual illusion of a double flash [29, page 471] also involves a 100-msec duration.

VISION AND AUDITION COMPARED AND CONTRASTED

In the auditory mode (at 500 Hertz) it takes some time (250 msec for a minimum number of swings (4) of effective bandwidth 4.7 cycles to be noticed and Δf and Δt are in a relation of mutual compensation. In the visual mode, is it the case that a change of intensity is compensated by an inversely varying spatial unit to give a constant relation?

Ricco's law states that for a light stimulus, the product of area and intensity is a constant; that is, a constant light flux is required for a threshold response. But this law does not hold for the human fovea [30] The Bunson–Roscoe law states that the product of intensity and time is a constant. But this relation does not hold for all times and intensities [31]. Even if Ricco's law or the Bunson–Roscoe law were to hold true for visual perception, intensity is one of the two variables involved in both laws. Hence spectral energy could not be invariant, as Gabor suggests it is in the auditory mode; and if it is not spectral energy that is the physical basis of the constancy relation, it can be nothing else. In the auditory mode we are considering effective frequency widths and effective durations about a mean frequency and a mean epoch, energy remaining constant. The mutual relationship of two qualities with a constant third would not appear to exist in the visual sense.

Two mechanisms, detection and discrimination, are postulated to account for auditory perception [13]. The first would appear to function similarly to the mechanisms of lateral inhibition shown in the eye of *Limulus* [32]. There are indications that lateral inhibition exists in the mammalian eye also [33] and the analogy has been drawn between the human phenomenology of Mach bands and the physiology of *Limulus* [34], although it has been pointed out that a decoding process at the central level could conceivably undo any encoding process (of lateral inhibition) at the peripheral [35, pages 598–599]. Mach bands have been shown in the auditory mode [36]. However, we must conclude that whereas in the auditory sense the operation of the two postulated mechanisms is linked, in the visual sense these neural mechanisms are quite separate. Gabor [13, page 593] has proposed that, for audition, filters are set at both a wide pass and narrow pass *simultaneously*.

Although the researcher of sensory systems, if he wishes to define the physical stimulus without remainder in information theory terms, is precluded from studying the visual system from the holographic point of view, we could say that the third dimension (phase) is added within the central nervous system. This is a problem of memory and of cross modality interaction—another field, and touched on briefly elsewhere [7]. In the localization of a sound source, the auditory system is presented with all the necessary information in the physical stimulus itself (the environment is a *complete* transmitter), but the visual perceptual system, on the other hand, is not as well endowed in the richness of dimensions of information contained in the sensation (the environment is an *incomplete* transmitter). For the auditory system the third dimension of space has its physical representative in the stimulus (phase or time of arrival of the binaural stimuli); for the visual system the third dimension of space has no such physical dimension of information to represent it, only a physical cue in a dimension of information used for other matters besides cueing depth. Memory (of action) provides the addition to the cue. This difference between the two systems might be regarded by some as no real difference. However, to those interested in defining the physical stimulus for central nervous system processes *without remainder*, it makes all the difference.

CONCLUSION

For the visual system, the physical unit of information measurement can be said to be indefinable. For the auditory system, it can be defined exactly and the definition requires two mechanisms for hearing processes: detection and discrimination. Considering a sensory system as a channel of communication, registration of three *related* modes of information in a central nervous system structure implies that the structure is a hologram. In both the visual and the auditory systems, the *registration* of information could be said to be holographic, although only in the case of auditory perception is this the result of simple through-channel input. Thus, in the case of the auditory modality the environment is a complete transmitter. In the case of the visual modality, as far as perception is concerned the environment is an incomplete transmitter.

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