Biol. Cybernetics 27, 89–98 (1977)

Biological Cybernetics

A Holographic Model for Associative Memory Chains

O. Wess and U. Röder

Gesellschaft für Strahlen- und Umweltforschung, Abteilung Kohärente Optik, Darmstadt, FRG

Abstract. Holographic brain models are well suited to describe specific brain functions. Central nervous systems and holographic systems both show parallel information processing and non-localized storage in common. To process information both systems use correlation functions suggesting to develop cybernetical brain models in terms of holography. Associative holographic storage is done with two simultaneously existing patterns. They may reconstruct each other mutually. Time-sequentially existing patterns are connected to associative chains, if every two succeeding patterns do exist within a common period of time in order to be stored in pairs. Read out (recall) of associative chains—reconstructing coupled patterns which didn't exist simultaneously—requires advanced holographic techniques. Three different methods are described and tested experimentally. The underlying principles are *feedback mechanisms, nonlinearities* of the storage material and tridimensional architecture of the *voluminous* recording medium. Those principles evidently occur in neural storage systems supporting analogous information processing in neural- and holographic systems.

1. Introduction

The idea to model special brain functions in terms of holography was previously used by several authors (see for example Gabor, 1968; 1969, Greguss, 1968; van Heerden, 1963; Longuet-Higgins, 1968; Westlake, 1970). There are some striking reasons, which seem to justify these investigations. Several strong analogies exist between holographic systems and the central nervous system (CNS) as there are:

1. The storage of information is not strongly localized and therefore relative insensible to distortions.

2. Holographic systems as well as CNS essentially perform parallel information processing, including pattern recognition.

3. Both systems have very high storage capacity $> 10^{10}$ bits (Flechtner, 1970; Kiemle, 1974).

Most impressive however is the fact, that a common mathematical background can be found to describe holographic system as well as essential functions of CNS. Correlation functions which serve well for holographic purposes nowadays play an important role in neurosciences (Reichardt, 1957; Borsellino et al., 1972; Hauske et al., 1976).

According to the complexity of the CNS a straightforward analysis is extremely difficult. Yet to come to deeper understanding of the subject, it may be useful to develop cybernetical models, investigate them in detail and try to answer the question, how far the model can hold for the subject itself. For the reasons mentioned above we think a holographic model is well suited to explain some features of the CNS and offers new possibilities to analyse functional brain structures. The purpose of this paper is to develop a holographic brain model for an associative memory. Holographic associative storage in the optical field is well known (Gabor, 1969). A holographic brain model however requires advanced methods as it is necessary to couple items associatively, which are not present at the same time. In particular three different methods are suggested which couple several patterns existing time-sequentially to associative chains.

The first method is based on *feedback mechanisms*, the second makes use of *nonlinear characteristics* of storage materials and the third one depends on a tridimensional structure of the storage medium performing *volume coupling*. The underlying principles of all three methods are evidently used by the CNS.

2. Principle of Holographic Associative Memory

Holography is a method to store and reconstruct complex wave patterns of arbitrary coherent wave fields. Amplitude and phase are stored simultaneously by interference techniques. Whereas in ordinary holo-

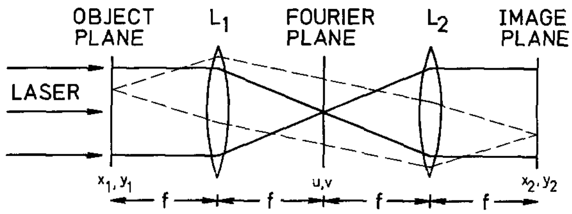


Fig. 1. 4-f-arrangement, an optical image processing set up. The lens system L_1, L_2 images the object plane onto the image plane. The image is inverted with respect to the object orientation. Parallel coherent illumination (expanded laser beam) generates the spatial frequency spectrum (Fourier transform) of the object in the back focal plane of lens L_1

graphy an object wave is stored by interference with a plane or spherical reference wave, in the case of associative storage a coherent background for one object wave is delivered by another object wave. In ordinary holography the object field is reconstructed by illuminating the hologram with a plane or spherical wave, whereas in the case of associative holographic storage a recognizable reconstruction of one object field is given only if illumination of the hologram is done with the other object field and vice versa. This property is what we call associative storage and reconstruction of two fields existing at the same time. Following the definition of Willwacher (1976) we call it *parallel association.*

2.1. Formal Description

Since the holographic experiments are made with a so called 4-f-arrangement (Fig. 1) the mathematical formalism is related to this special set up. Although many other optical experimental configurations are possible, the 4-f-arrangement has two main advantages. A practical one is, that information processing in general and associative storage in particular can be done in a translation invariant manner. The second point is a formal one because Fourier transform formalism can be applied which simplifies a theoretical treatment.

The input plane of the system is imaged onto the output plane by lens L_1 and L_2. An object transparency $a(x_1, y_1)$ in the input plane appears in the output plane with inverted spatial coordinates. Coherent parallel illumination approximately produces the Fourier transform

$$FT[a(x_1, y_1)] = \int\int_{-\infty}^{+\infty} a(x_1, y_1) \exp[-2\pi i(x_1 u + y_1 v)] dx_1 dy_1 = A(u, v)$$

in the back focal plane of L_1, the so called Fourier plane. Lens L_2 performs another Fourier transform

$$FT[A(u, v)] = \int\int_{-\infty}^{+\infty} A(u, v) \exp[-2\pi i(ux_2 + vy_2)]\, du\, dv = a(-x_2, -y_2)$$

leading to the amplitude distribution of the object being inverted as mentioned above.

Parallel associative storage is done with two object transparencies denoted by $a(x_1, y_1)$ and $b(x_1, y_1)$ placed simultaneously side by side in the input plane. A hologram is taken by exposing a photographic plate in the Fourier plane to the light intensity which is the square of the modulus of the amplitude distribution.

$$I(u, v) = |A(u, v) + B(u, v)|^2 \tag{1}$$

where $A(u, v)$ and $B(u, v)$ denote the Fourier transforms of $a(x_1, y_1)$ and $b(x_1, y_1)$ respectively. To emphasize it once more, there is no need of a further reference wave since the phase is recorded by mutual interference of $A(u, v)$ and $B(u, v)$. After linear photographic processing the amplitude transmission $T_A(u, v)$ of the hologram is proportional to the intensity ($^\times$ means conjugate complex)

$$T_A(u, v) = cI(u, v) \quad (c < 0), \tag{2}$$

$$T_A(u, v) = c|A(u, v) + B(u, v)|^2 = c[A(u, v) \cdot A^\times(u, v) + B(u, v) \cdot B^\times(u, v) + A(u, v)^\times \cdot B(u, v) + B^\times(u, v) \cdot A(u, v)]\,. \tag{3}$$

The last two terms of (3) are relevant for associative storage.

Associative reconstruction (recall) is initiated by only one input transparency, for instance $a(x_1, y_1)$. To calculate the amplitude of the reconstruction just behind the hologram the transformed input amplitude distribution $A(u, v)$ in the hologram plane is multiplied by the amplitude transmittance $T_A(u, v)$ of the storage hologram.

$$A(u, v) \cdot T_A(u, v) = A(u, v) \cdot c[\ldots A^\times(u, v) \cdot B(u, v) \ldots]\,. \tag{4}$$

In (4) only the third term on the right side of (3) is considered, as this is the important one for the reconstruction. The amplitude distribution in the output plane can be calculated by the Fourier transform of (4) using correlation and convolution theorems (see for instance Bracewell, 1965) and is given by

$$a(-x_2, -y_2) \otimes a^\times(-x_2, -y_2) \times b(-x_2, -y_2) \tag{5}$$

if constant factors are neglected and $\otimes$ and $\times$ denote correlation and convolution respectively. Now, the better the autocorrelation $a(-x_2, -y_2) \otimes a^\times(-x_2,$

$-y_2)$ approaches a δ-function, the more yields the following convolution with $b(-x_2, -y_2)$ the object $b(-x_2, -y_2)$ itself as shown in the reconstruction scheme in Figure 2.

The reconstruction of $b(-x_2, -y_2)$ (and correlation background) is due to the input $a(x_1, y_1)$ what means associative reconstruction in our terms. Using another transparency $c(x_1, y_1)$ as input generally no recognizable reconstruction will occur since the corresponding crosscorrelation function $c(-x_2, -y_2) \otimes a^{\times}(-x_2, -y_2)$ usually won't yield to a strong δ-like peak but to a smeared noisy background. However input $b(x_1, y_1)$ will reconstruct $a(-x_2, -y_2)$ as shown in the scheme of Figure 3. In this case only the fourth term on the right hand side of (3) has to be considered.

To approximate a δ-function with an autocorrelation function $a(-x_2, -y_2) \otimes a^{\times}(-x_2, -y_2)$ or $b(-x_2, -y_2) \otimes b^{\times}(-x_2, -y_2)$ the object amplitude $a(x_1, y_1)$ and $b(x_1, y_1)$ may be multiplied by a random phase distribution. It is achieved easily for instance by bringing a groundglass into contact with the rear plane of the transparency. In this way one gets good image quality in the optical analogous experiments. This principle of parallel associative coupling of two simultaneously existing object transparencies underlies all the following experiments and is basical for time sequential holographic associative coupling. According to Willwacher we denote the latter with *serial associative storage*. The principle of parallel associative coupling can be used also to recall the whole pattern by small fraction of the pattern itself. The resulting optical reconstruction is known as ghost image in optical literature (van Heerden, 1963).

2.2. Serial Associative Storage

The CNS is capable to perform associative coupling of patterns which may exist at very different time and connect them to associative chains, covering an extensive period of time. At first sight holographic methods seem to be unsuitable to give an analogous solution of the problem in a cybernetical brain model since a striking condition for holographic storage is a high degree of mutual coherence of the corresponding wave fields. Wave patterns existing at different time are incoherent by definition. However time sequential associative chains connecting the patterns *a*, *b*, *c*, *d* and so on can be generated by means of holography if at any given time two patterns are present simultaneously such as $a+b$, than $b+c$ and so on. Patterns *a* and *c* exist at different time.

The intensities of the corresponding wave patterns $I_1 = |A+B|^2$; $I_2 = |B+C|^2, \ldots$

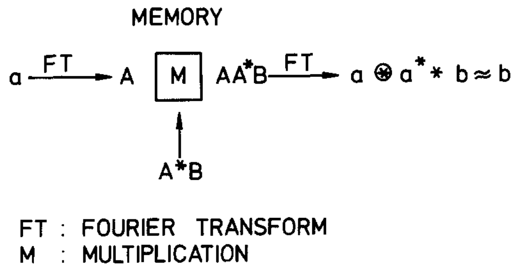


Fig. 2. Reconstruction scheme. Pattern *a* initiates the reconstruction of pattern *b*. Input pattern *a* is Fourier transformed (*A*) and multiplied by the transparency of the holographic memory. The product of the incoming pattern and the stored pattern gives $AA^{\times}B$ and after another Fourier transform the pattern *b* approximately

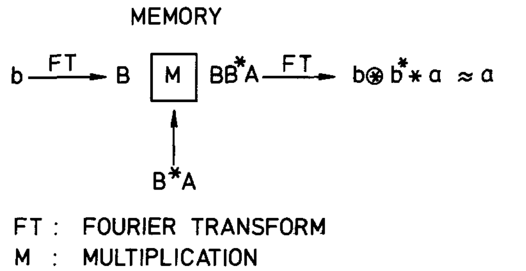


Fig. 3. Reconstruction scheme. Pattern *b* initiates the reconstruction of pattern *a*. Input pattern *b* is Fourier transformed (*B*) and multiplied by the transparency of the holographic memory. The product of the incoming pattern and the stored pattern gives $BB^{\times}A$ and after another Fourier transform the pattern *a* approximately

are recorded one after another on a holographic storage medium. Notice, that I_1 and I_2 contain pattern *B* in common which is the coupling element for *A* and *C* being not present simultaneously.

Generating associative chains is sketched in Figure 4.

The patterns may be stored one above the other in the same place of the storage medium. The number of sequentially stored holograms is limited by the properties of the storage material. Reconstruction starts with an input of an arbitrary element and yields to the retrieval of the two nearest neighbouring elements.

To compare it with associative storage in the CNS, $a, b, c \ldots$ may be the sensory input (for instance the visual input on the retina) and A, B, $C, \ldots$ the corresponding patterns in the memory system itself.

The hypothesis of the model is the simultaneous existence of two neural activation patterns *a* and *b* for instance in short term memory to be stored in a way which can be described mathematically by $|A+B|^2$. *A* and *B* may be the somehow transformed patterns of *a* and *b* respectively. $|B+C|^2$—also existing at the same time—is stored in a following step and so on. If the neural activation pattern *B* is activated again by the corresponding input pattern *b*, the interaction

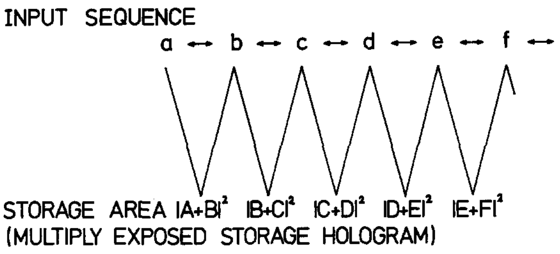


Fig. 4. Associative chain. The input patterns are time-sequentially presented in pairs. Each pair is stored holographically, forming the holograms $H_1 = |A+B|^2$, $H_2 = |B+C|^2$ and so on. Holograms $H_1 \dots H_N$ are superposed one above the other, yielding a multiply exposed hologram

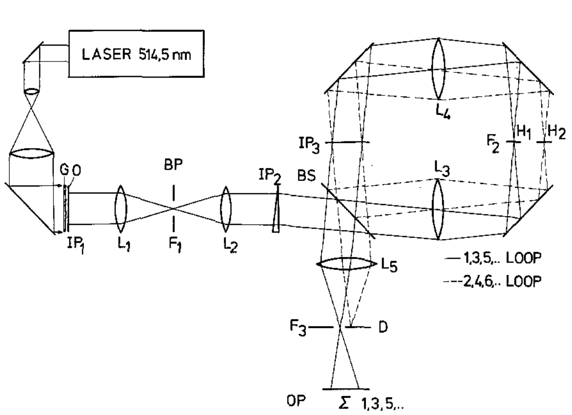


Fig. 5. Feedback arrangement. An expanded laser beam illuminates the input plane IP_1 of the pre-processing 4-f-arrangement L_1, L_2 with input pattern O and groundglass G in contact. A diaphragm BP in the spatial frequency plane F_1 limits the spatial frequency spectrum of inserted objects. Plane IP_2 is the image plane of the pre-processing system and the input plane of the feedback loop L_3, L_4. IP_3 is the image plane of the feedback loop and equivalent to IP_2 with respect to the beamsplitter BS. The prism in IP_2 changes the direction of illumination shifting the centre of the spatial frequency spectrum out of the center beam alternating to positions H_1 and H_2 in the frequency plane F_2, depending on the number of cycles around the feedback loop. The collected patterns of IP_3 are imaged by lens L_5 through the beam splitter into the final output plane OP. The diaphragm D in plan F_3 selects only the patterns originating from odd numbers of cycles

with the stored pattern $|A+B|^2$ and $|B+C|^2$ will retrieve neural patterns A and C respectively by correlation. The sensation of the recalled pattern will be nearly the same as those of the original input patterns a and c. The associated recall of A and C will be the better the more similar is the activated pattern B compared to the stored one.

To reconstruct sequentially more than the nearest neighbours in both directions — those patterns didn't exist simultaneously with the recalling pattern— three different advanced techniques are applied in the holographical model and described in detail in the following chapter.

3. Serial Reconstruction

The first method (3.1) is an optical feedback technique. The simple idea is to use an arrangement with equivalent input—and output planes. The just reconstructed pattern in the output plane serves as input pattern to reconstruct the following one and so on.

The second method (3.2) is independent of an feedback system and performs sequential reconstruction by coupling, originating from nonlinear expansion terms of the complex transmittance curve of the storage material.

The third method (3.3) is based on a tridimensional storage medium. Recall is started by an input wave pattern which reconstructs sequentially one after another wave pattern while propagating through the volume.

3.1. Storage and Reconstruction by Coherent Optical Feedback

A 4-f-arrangement of Figure 1 is modified and folded that the output plane is imaged back onto the input plane (Fig. 5). Plane IP_2 and IP_3 are equivalent with respect to the beamsplitter and are the actual input- and output-planes of the intrinsic feedback loop.

Another pre-processing 4-f-arrangement is placed in front of the feedback loop to limit the spatial frequency spectrum of the input pattern by low pass spatial filtering. The input pattern is illuminated by an expanded parallel beam of an argon ion laser. The input pattern of plane IP_1 appears pre-processed in plane IP_2. The prism in plane IP_2 is not of basical importance but of technical one. It shifts the spatial frequency spectrum out of the centre beam of the feedback loop without changing the position of the patterns in planes IP_2 and IP_3. For an odd number of cycles the centre of the spectrum is at position H_1 in plane F_2 and for an even number of cycles at position H_2. In this way a simple diaphragm inserted in plane F_3 selects the output of odd cycles to be imaged to the final output plane of the entire system and the directly reflected light from the beamsplitter is eliminated. For recording, two transparencies a and b in the input plane IP_1 are pre-processed and imaged onto IP_2. By means of a beamsplitter the patterns are fed into the feedback loop.

The storage hologram $|A+B|^2$ is taken at position H_1 in the Fourier plane F_2. Pattern a in plane IP_1 is removed, pattern c is inserted in Plane IP_1. Hologram H_1 is also removed. Hologram $|B+C|^2$ is taken at position H_2 in the second cycle. Succeeding input patterns are recorded in couples alternating at positions H_1 and H_2 superposing them incoherently on the photographic plates.

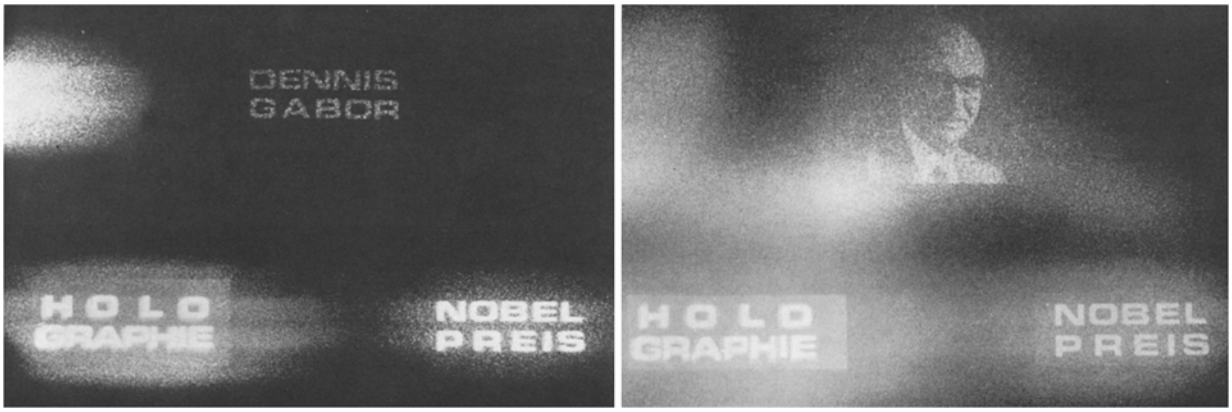


Fig. 6a. An example for an associative chain of the three elements "HOLOGRAPHIE—NOBELPREIS—DENNIS GABOR". The pattern "HOLOGRAPHIE" recalls the second pattern "NOBELPREIS" which in turn recalls the next pattern "DENNIS GABOR". The first pattern thus gives rise to reconstruct all the following patterns although only each two sequential patterns were stored simultaneously. **b** The third pattern is replaced by a grey-tone object, the portrait of the Nobel Prize winner

After photographic processing reconstruction is initiated by a single pattern, for instance a in the input plane IP_1. The first cycle will reconstruct the coupled pattern b which reconstructs the next pattern c in the second cycle and so on. The collected output of plane IP_3 is imaged by lens L_5 through the beamsplitter into the final output plane OP.

Using a shifted low pass filter in the back focal plane F_3 of lens L_5 only those patterns are admitted to appear in the final output plane which originate from odd cycles and are not inverted. An experimental example is shown in Figure 6.

Beside the input and the associatively recalled output patterns, correlation noise appears since the autocorrelation of (5) yields not exactly a δ-function and cross-correlation terms actually are not completely neglectable.

3.2. Nonlinear Coupling

The second method depends strongly on the complex transmittance characteristics of the recording material but only a simple optical set up, for instance an ordinary 4-f-arrangement (Fig. 1) is required. Figure 7 shows a typical amplitude transmittance characteristic for Agfa Scientia 10 E 75 holographic plates (after Goldman, 1976). Taylor's expansion at the working point with the coordinates $\bar{E}$ and $\bar{T}(\bar{E})$ gives

$$T(E)=\bar{T}+\frac{dT}{dE}\cdot(E-\bar{E})+\frac{d^2T}{dE^2}\cdot\frac{(E-\bar{E})^2}{2}+\ldots$$

or

$$T(I)=t[C_0I^0+C_1I^1+C_2I^2\ldots] \tag{6}$$

with $E=I\cdot t$ and exposure time t taken to be constant. $C_n(n=0,1,2\ldots)$ are the expansion coefficients.

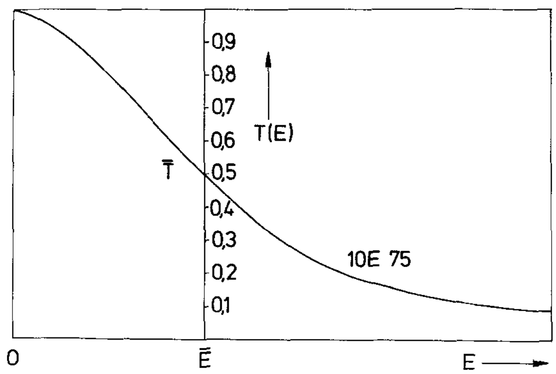


Fig. 7. Amplitude transmission of Agfa Scientia 10 E 75 plates (after Goldman, 1976), E exposure, $T(E)$ amplitude transmission

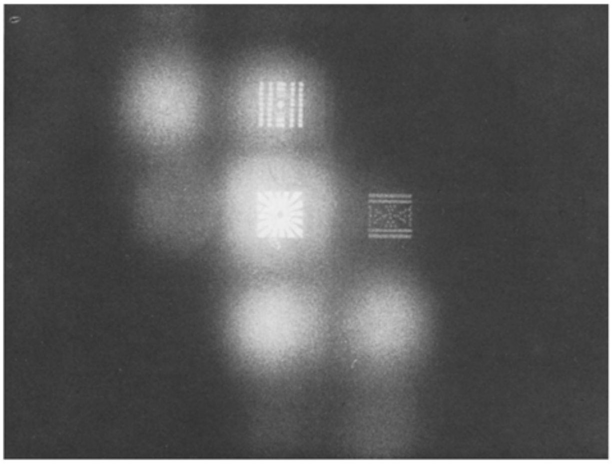
The term tC_0I^0 of (6) will attenuate the incoming intensity homogeneously. tC_1I^1 gives rise to an associative reconstruction of the next neighbours as shown in Chapter 2.

The higher order terms—if existing at all—will reconstruct the following neighbours by higher order correlation. This is shown examplary for a chain of three patterns a, b, and c.

One hologram is taken with the intensity $I_1=|A+B|^2$ another with $I_2=|B+C|^2$, both with the same exposure time. Since the holograms are recorded at different time, the intensities are added to the total intensity.

$$I_{tot}=I_1+I_2=AA^\times+BB^\times+A^\times B+B^\times A+BB^\times+CC^\times+B^\times C+C^\times B\,. \tag{7}$$

According to (6) the holographic record contains terms proportional to powers of I. There are O-order terms, first-, and second order terms if the expansion



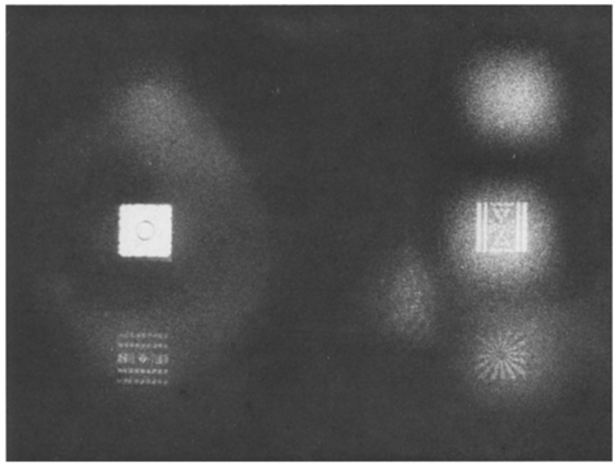


Fig. 8. Nonlinear coupling. The star-like pattern (centre) is linearily coupled to the pattern of rectangular dots (top) and by quadratic nonlinearities to the striped and dotted pattern (right). The star-like pattern reconstructs both patterns although the striped and dotted pattern (right) didn't exist simultaneously with respect to the centre pattern. The bright stains are disturbing cross-correlation terms

Fig. 9. Third order coupling in thermoplastic recording material. The circular pattern (top left) recalls the striped and dotted pattern (top right) by linear coupling, the dotted pattern (bottom left) by quadratic coupling and the star-like pattern (bottom right) by third order coupling. Only the pattern top right existed simultaneously together with the recalling pattern (top left) during the storage period. When copying the original negative film to get an photographic positive print, the exposure of the two top patterns was five times that of the bottom patterns

is cut after the second order which is sufficient to couple next but one neighbours.

Beside zero order terms and linear terms of (7) in particular 64 nonlinear terms occur by taking (7) into the second power. Neglecting constant factors, the following terms are relevant.

1. linear terms $A^{\times}B$ (and $B^{\times}A$);
2. nonlinear terms $A^{\times}BB^{\times}C$ (and $C^{\times}BB^{\times}A$).

If the first element a is taken for reconstruction the corresponding pattern A is multiplied in the Fourier plane by the transparency distribution of the hologram. The relevant products are

1. linear $A(A^{\times}B)$;
2. nonlinear $A(A^{\times}BB^{\times}C)$.

After another Fourier transform the following amplitude distribution is given in the output plane.

1. Linear: $a \otimes a^{\times} \times b \otimes b^{\times}$ +noise,

this was treated above and

2. nonlinear: $a \otimes a^{\times} \times b \otimes b^{\times} \times c \approx c$ + noise,

which is a second order correlation.

Presupposing again that the autocorrelation functions $a \otimes a^{\times}$ and $b \otimes b^{\times}$ approach a δ-function with sufficient accuracy, the correlation of two autocorrelation functions correlated with c will give c itself approximately. Pattern a reconstructs pattern c although again a and c were stored mutually incoherent. In the output plane several patterns appear. First the pattern a itself in an attenuated manner, than pattern b by linear coupling and pattern c by nonlinear coupling. Finally the influence of some 60 nonrelevant terms give rise to crosscorrelations generating additional bright stains in the output plane as shown in Figure 8.

In the reversed case reconstruction is started with pattern c and the coupled reconstructions are generated in an analogous manner out of the terms $C^{\times}B$ and $C^{\times}BB^{\times}A$.

To couple more than the next but one neighbours nonlinearities of higher order must be considered. The recording materials we used were Agfa Scientia 10 E 75 plates developed 5 min in Agfa Gevaert G3P developer showing only strong enough second order nonlinearities. Thermoplastic phase material however showed significant third order expansion coefficients so that "third order coupling" could be performed as shown in Figure 9.

Thus depending on the expansion coefficients of the complex transmittance function of the particular recording material more or less elements of an associative chain can be coupled incoherently one after another and reconstructed.

3.3. Volume Coupling

This chapter is divided into two parts dealing with different coupling characteristics of tridimensional storage material. In Part 3.3.1 volume self-coupling of a hologram during read out, so called selfenhancement is described for a simple two plane wave hologram and in Part 3.3.2 serial associative coupling and reconstruction of different holograms—the essential idea of this chapter—is treated.

3.3.1. Selfenhancement. The selfenhancement effect strongly depends on the characteristics of the storage material. Actually it is only possible in tridimensional materials which need no development. In our experiments we used Fe-doped $LiNbO_3$ crystals the properties of which have been extensively studied (see for example von der Linde et al., 1975).

For our purpose it is important, that nearly pure phase holograms are recorded with little absorption and high diffraction efficiency. Furthermore the hologram stored as an interference pattern in the volume will only be erased slowly during read out that means a strong asymmetric write-read characteristic originating from a strong doping concentration of Fe.

A typical behaviour of the material is shown in Figure 10. Two plane waves A and B with equal intensities interfere within the crystal with a mean intensity of about $100\,\mathrm{mW/cm^2}$. Throughout all volume coupling experiments an argon ion laser with $\lambda = 488$ nm was used. The intensities of the waves behind the crystal are measured by photocells and plotted versus a time scale. During recording the interference pattern interacts with the crystal generating a spatial refractive index pattern. The nascent index pattern again interacts with the generating interference pattern. The diverging curves in the storage period Figure 10 characterize this interaction since energy is shifted from one wave to the other.

The direction of energy shift depends on the orientation of the crystal. The immediate following read out starts with a diffraction efficiency of considerable 10% and increases by a factor 3 approximately. The diffraction efficiency η is defined by

$$\eta = \frac{I_{+1}}{I_0},$$

where I_{+1} and I_0 denote the intensities of the reconstructed and the reconstructing wave respectively. This strong selfenhancement during read out is due to the fact that the reconstructing wave A and the just reconstructed wave B generates a secondary interference pattern within the crystal which is written in while travelling through the crystal. Selfenhancement by factors around 10 were observed for shorter storage times.

Maximum diffraction efficiency is about 30%. This is far less than theoretical value of 100% (Kogelnik, 1969) for pure phase material. The crystals we used showed some absorption, limiting diffraction efficiency considerably. After some time both curves in Figure 10 decrease due to scattering of the crystal.

3.3.2. Serial Associative Volume Coupling. A quantitative description of this third method demands some theoretical expenditure which is not appropriate to this paper. A theoretical treatment concerning associative coupling in $LiNbO_3$ crystals is given by Wess (1976). It is based on a paper by Case (1975) who again extrapolate coupled wave theory of Kogelnik (1969) to an incoherent superposition of two spatial gratings with a common bragg angle of diffraction. To get a rough idea of the coupling mechanism the situation is sketched in Figure 11.

The tridimensional holographic recording material is exposed corresponding to Figure 4 to the total intensity $I_{tot} = |A+B|^2 + |B+C|^2 + \dots$. The total volume can be considered as cut into as many layers as the number of superposed holograms. Each layer contains all information of all the single elements since it is a multiply exposed hologram.

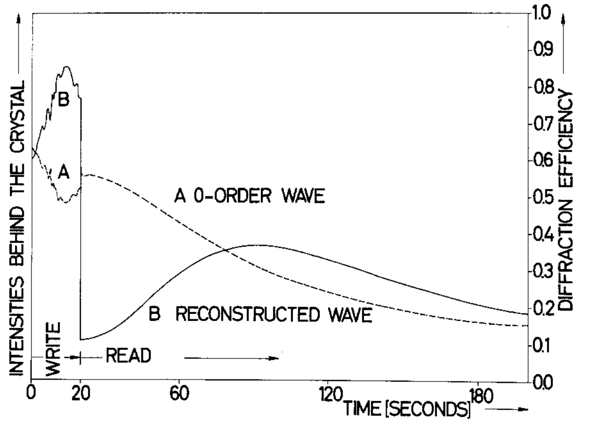


Fig. 10. Associative storage and reconstruction of two plane waves. The storage period is 20 s, showing an interaction of the nascent diffraction index pattern and the generating interference pattern (wave B gains energy of wave A). After 20 s wave B is blocked and reconstruction takes place with the energy of wave A. Wave B shows selfenhancement due to energy loss of the recalling wave A. After some time both waves decay because of an increasing scattering of the crystal

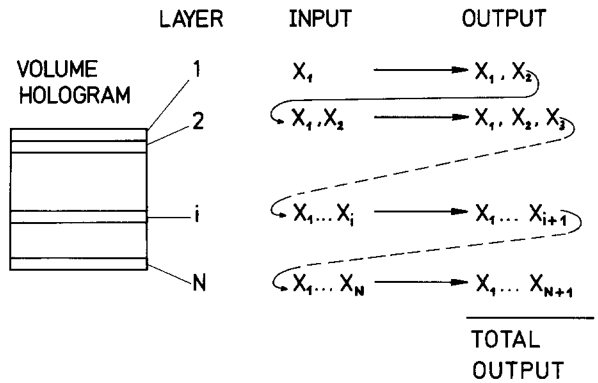


Fig. 11. Schematic volume coupling. All holograms $H_1 = |X_1 + X_2|^2 \dots H_N = |X_N + X_{N+1}|^2$ are incoherently superposed on the tridimensional storage material. Each layer is a complete multiply exposed hologram. Any arbitrary input element recalls its next neighbour out of any arbitrary layer. The just recalled elements will recall the following neighbours out of the following layers, thus reconstructing the complete associative chain step by step

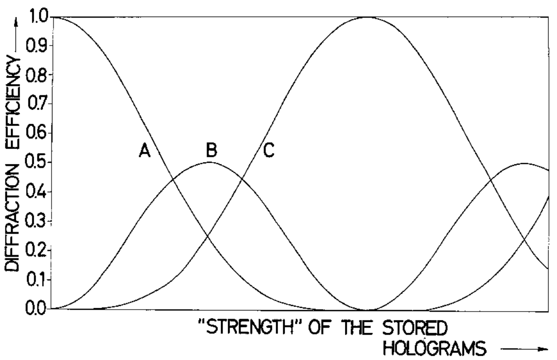


Fig. 12. Theoretical diffraction efficiency of two incoherently superposed plane wave holograms $H_1 = |A+B|^2$ and $H_2 = |B+C|^2$. The "strength" of the hologram is related to the corresponding diffraction effciency of a single exposure hologram [for details see Wess (1976) or Case (1975)]. Both holograms are of equal strength. *O*-order wave *A* reconstructs waves *B* and *C* with different rates. Directly coupled wave *B* can reach up to 50% diffraction efficiency where as cross-coupled wave *C* may come up to 100%

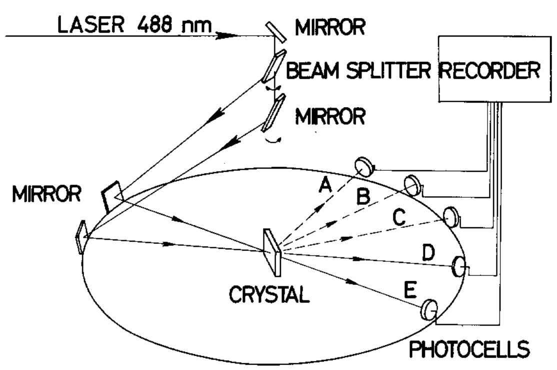


Fig. 13. Experimental set up (schematic) for associative volume coupling. Rotatable beam splitter and mirrors generate two coherent laser beams interfering with arbitrary angles at the place of the central crystal. Writing starts with wave *A* and *B*, then the orientation of wave *A* is changed in order to generate wave *C*. The second hologram is taken with waves *B* and *C*. Then wave *B* is rotated to become wave *D* and the waves *C* and *D* form another hologram etc.

If reconstruction starts with the first element *a* of the chain the Fourier transformed pattern *A* will reconstruct the pattern *B* in the first layer of the volume. This again will reconstruct *C* in the second layer and so on, although *a* and *c* were stored at different times.

In the case of associative storage of three plane waves the theoretical considerations will offer an interesting property. Depending on the modulation depth of the storage material—or somewhat that can be described as the "strength" (Case, 1975) of the stored hologram—the diffraction efficiency varies over a wide range and the next but one element of the chain may come out stronger than the next neighbours. For instance if both holograms $|A+B|^2$ and $|B+C|^2$ are stored with the same strength and *A*, *B*, and *C* are of equal amplitudes when stored, pure non absorbing phase material will shift the incoming intensity of the reconstructing wave *A* with different rates to simultaneously reconstructed waves *B* and *C* as shown in Figure 12. Only 50% of the incoming energy can be shifted to the next neighbour however all energy can flow over to the incoherently stored next but one neighbour (Fig. 12).

3.3.3. Experiments. The experimental set up is shown in Figure 13.

The laser beam is split into two by a rotatable beam splitter. The reflected beam as well as the transmitted one is guided by a system of rotatable mirrors to be superposed within the crystal. The common axis of rotation is centered in the place of the crystals. Thus the incident angles are easily changed and interference of the two waves within the crystal is guaranteed. The two beams are adjusted sequentially to the positions *A*, *B*, then *B*, *C*, then *C*, *D* and so on.

The corresponding intensities are controlled and recorded by photocells during the storage- and read out process. A chain of three elements for instance is recorded with wave *A* and *B* to perform the first hologram, then beam *A* is rotated to the position *C* and the second hologram is taken with waves *B* and *C*. All holograms are taken with the same exposure. The readout process is initiated by O-order wave *C* solely. The neighboured wave *B* and the cross-coupled next but one neighboured wave *A* which was stored incoherently with respect to wave *C* are reconstructed. The intensities changing with the time of reconstruction are shown in Figure 14. They show some selfenhancement even for the incoherently coupled wave *A*. The energy transfer from O-order wave *C* to the reconstructed waves *A* and *B* is to be seen from the dashed curve of wave *C* changing in a contrary sense compared to waves *A* and *B*, according to the law of conservation of energy. The decreasing intensities observed after about 5 min of reconstruction are due to some increasing scattering of the crystal.

An associative chain of 4 elements is shown in Figure 15. O-order wave *D* initiates reconstruction of the following elements of the chain, wave *C*, *B*, and *A*. Note, that during the first two minutes of reconstruction cross-coupled wave *A* is reconstructed with more intensity than the closer coupled wave *B*. In principle this was predicted by the theoretical consideration of Chapter 3.3.2. Again all reconstructed waves show selfenhancement.

An example for a chain of 5 elements is shown in Figure 16. Only the intensities of the reconstructed waves are presented. Selfenhancement occurs and wave *B*, which is twofold cross-coupled by wave *C* and *D* to the reconstructing wave *E* has a more intensive reconstruction after about 7 min than the closer coupled wave *C*. Even the last element *A* shows a diffraction efficiency around 1%.

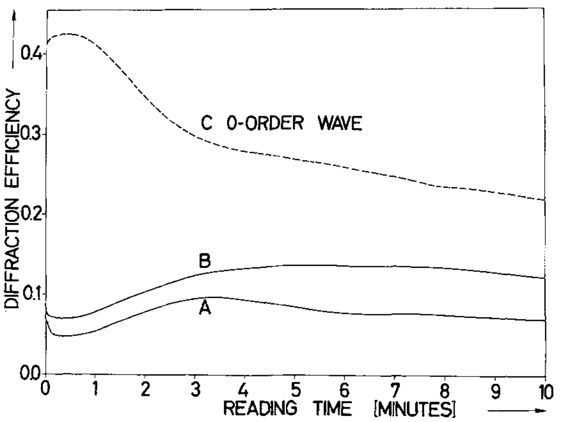


Fig. 14. Associative chain of three elements. *O*-order wave *C* reconstructs the neighboured wave *B* and the cross-coupled wave *A*. Both recalled waves *B* and *A* show selfenhancement

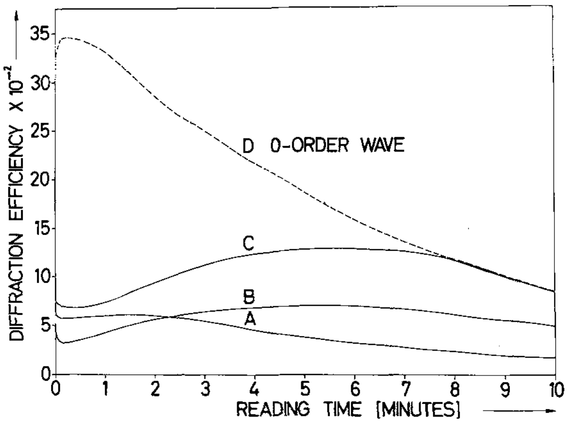


Fig. 15. Associative chain of four elements, *O*-order wave *D* reconstructs the waves *C*, *B*, and *A* with changing diffraction efficiency. Note that the two-fold cross-coupled wave *A* comes out more strongly than the previous wave *B* within the first two min of reconstruction

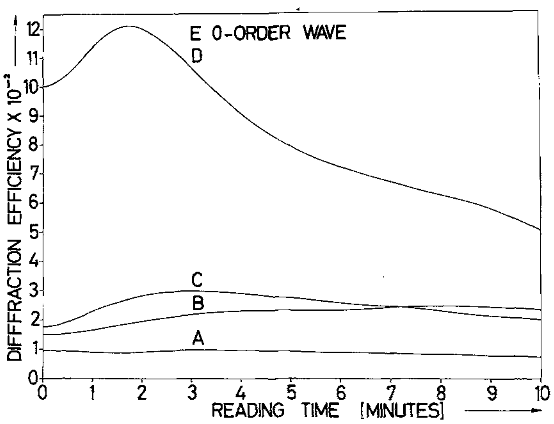


Fig. 16. Associative chain of five elements *O*-order wave *E* (not shown) reconstructs waves *D*, *C*, *B*, and *A*. After about 7 min of reconstruction the two-fold cross-coupled wave *B* comes out more strongly than the previous wave *C*

4. Discussion

Transfer of the characteristics of this model to the CNS depends on the realisation of the necessary basic principles in the CNS. Detailed experimental results authorizing or refuging our model hypothesis are not available for all we know. The principles however seem to be well established.

Feedback mechanisms are essential in biology and neuroscience (see for example Drischel, 1972). Neural information processing in connection with feedback loops has a big advantage compared with optical holographic information processing. Neurons are active elements able to generate and regenerate sequences of action potentials thus avoiding strong attenuation of the signals as in the optical case. A neural feedback mechanism may form more extended associative chains than the holographic model described above. Furthermore a noise suppressing characteristic of neurons is based upon threshold behaviour of a single neuron. Part of disturbing correlation noise as to be seen in Figure 6 for example, may be eliminated by adjusting the threshold level in a neural system.

Nonlinear coupling may be realized in the CNS since neurons show an extrem nonlinear characteristic. The input-output characteristic is typically given by a threshold below which an input signal is not answered by generation of an action potential whereas inputs above the threshold always generate action potentials of nearly the same size and hight. From Taylor's expansion one can figure out the magnitude of expansion coefficients of higher orders which may give rise to nonlinear coupling and associative reconstruction of long associative chains by multiple correlation and convolution.

Volume coupling finally may be performed by the CNS since a tridimensional architecture of the CNS is self-evident and furthermore a layer by a layer configuration is observed supporting the idea of volume storage and associative reconstruction coupling from layer to layer. That means, that information storage may take place somewhere between sensor input and motor output (Creutzfeldt, 1973). If in optical analogous experiments the photographic plate is replaced by a tridimensional storage material which does not require photographic processing—for instance $LiNbO_3$ crystals—the model gets one more degree of freedom. A dynamic behaviour during writing and read out occurs, which means mixing of read—write processes resulting in selfenhancement for instance. Selfenhancement during memorizing seems to take place in CNS. A memorized pattern usually appears more and more enhanced and more details are distinguishable during the retrieval process itself.

Another result of dynamic reconstruction shows some interesting analogy to the CNS. Change of the weighting factors of reconstructed elements during read out can favour a particular element which then is reconstructed more strongly than other preceding elements. It may be an explanation for a subconscious associative chain in which one element suddenly comes to consciousness seeming to be independent of the particular input. Although foregoing elements remain unconscious an associative connection is responsible for the reconstruction.

Each of the described methods is capable to perform serial associative coupling. The result of the reconstruction occurs simultaneously. The original time intervalls between the patterns are lost. Time sequential reconstruction is done in the feedback system and in the volume storage system with propagation velocity of light. Photographic recording of the reconstructed sequence prevents the time dependence to be retained. The nonlinear coupling system is capable only to store associative chains time sequentially but to reconstruct simultaneously.

5. Conclusions

The basic formalism of our holographic brain model are correlation and convolution functions which are as well used by the CNS. This is taken as conceptual basis for analogous experiments. The incoherent chain coupling mechanisms, feedback coupling, nonlinear coupling and volume coupling may be performed by the CNS in analogy since these principles are realized by neural systems. What kind of neural mechanism actually gives rise to associative coupling in living beings is not known at all, nevertheless a bioholographic information processing is thinkable without contradiction to physiological findings. A neural interference pattern may be generated for instance by time dependent superposition of neural signals in connection with a threshold. Differences in propagation time of the signals depending on path length distribution of neural interconnections may effect constructive interference enabeling the signals to pass the threshold whereas in other places signals don't arrive within small time interval and the threshold cannot be passed. The "transmittance" of frequently used particular path ways may be changed by adjusting the threshold. According to the generated spatial neural interference pattern a spatial neural "transmittance distribution" may be formed acting as neural hologram. Analogous to optical holographic reconstruction, a spatial neural activation input pattern may be multiplied by the neural transmittance pattern to reconstruct associatively stored information. In this holographic brain model there is no need of an continuously oscillating reference source as the interference pattern is generated by mutual interference of complex object patterns.

Anyway by which neural mechanism correlation of incoming and stored patterns may be performed, correlation and convolution functions seem to be as important for neural—as for holographic systems. Moreover neural systems are much more flexible to perform various tasks because they are based on active elements instead of passiv optical arrangements we used in our model.

Acknowledgements. The authors want to thank Prof. W. Waidelich for his continuous interest and encouragement. Thanks also to Dr. H. J. Mager for initiating this work and giving technical assistance.

References

Borsellino, A., Poggio, T.: Holographic aspects of temporal memory and optomotor responses. Kybernetic **10**, 58–60 (1972)

Bracewell, R.: The Fourier transform and its application. New York-San Francisco-Toronto-London-Sydney: Mc Graw-Hill 1965

Case, S. K.: Coupled wave theory for multiply exposed thick holographic gratings. J. Opt. Soc. Amer. **65**, 724–729 (1975)

Creutzfeldt, O. D.: Some neurophysiological considerations concerning "memory". Memory and transfer of information. New York: Plenum Press 1973

Drischel, H.: Einführung in die Biokybernetik. Berlin: Akademie Verl. 1972

Flechtner, H.-J.: Grundbegriffe der Kybernetik, 5. Aufl. Stuttgart: Wissenschaftliche Verlagsgesellschaft 1970

Gabor, D.: Holographic model of temporal recall. Nature **217**, 584 (1968)

Gabor, D.: Associative holographic memories. IBM J. Res. Dev. **13**, 2–5 (1969)

Goldmann, G.: Effects of film nonlinearities on the signal-to-ghost ratio of storage holograms. Opt. Quant. Electr. **8**, 355–365 (1976)

Greguss, P.: Bioholography — a new model of information processing. Nature **219**, 482 (1968)

Hauske, G., Wolf, W., Lupp, U.: Matched filters in human vision. Biol. Cybernetics **22**, 181–188 (1976)

Van Heerden, P. J.: A new method of storing and retrieving information. Appl. Optics **2**, 387–392 (1963)

Van Heerden, P. J.: Theory of optical information storage in solids. Appl. Optics **2**, 393–400 (1963)

Kiemle, H.: Holographie und ihre technischen Anwendungsmöglichkeiten zur Informationsspeicherung. Vorlesung an der TH Darmstadt SS 1974

Kogelnik, H.: Coupled wave theory for thick hologram gratings. Bell Syst. Techn. J. **48**, 2909–2947 (1969)

von der Linde, D., Glass, A. M.: Photorefractive effects for reversible holographic storage of information. Appl. Phys. **8**, 85–100 (1975)

Longuet-Higgins, H. C.: Holographic model of temporal recall. Nature **217**, 104 (1968)

Reichardt, W.: Autokorrelations-Auswertung als Funktionsprinzip des Zentralnervensystems. Z. Naturforsch. **12b**, 448–457 (1957)

Willwacher, G.: Fähigkeiten eines assoziativen Speichersystems im Vergleich zu Gehirnfunktionen. Biol. Cybernetics **24**, 181–198 (1976)

Wess, O.: Ein holographisches Gedächtnismodell für die assoziative Speicherung. Dissertation TH Darmstadt

Westlake, P. R.: The possibilities of neural holographic processes within the brain. Kybernetik **7**, 129–153 (1970)

Received: March 1, 1977

Dr. O. Wess
Ges. für Strahlen- und Umweltforschung
Abteilung Kohärente Optik
Ingolstädter Landstraße 1
D-8042 Neuherberg/München
Federal Republic of Germany