

# EARLY VISUAL PERCEPTION<sup>1</sup>

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## 1.0 INTRODUCTION

Last year in this series, Russell & Karen De Valois (1980) undertook the difficult task of summarizing the many important findings that have accumulated in our field of specialty since the remarkable review by Sekuler (1974). Their bird's-eye view agrees to an astonishing degree with ours, and so we can afford to zoom in on a few select topics of strategic importance.

<sup>1</sup>Abbreviations used: AM, apparent movement; MTF, modulation transfer function; NP, neurophysiological atoms-perceptual molecules; PP, perceptual atoms-perceptual molecules; RDS, random-dot stereogram(s); RM, real movement; SF, spatial frequency.

These topics have one guiding principle in common: they all deal with global percepts (perceptual molecules) that can be successfully decomposed into more elementary perceptual building blocks (perceptual atoms). Such an ambitious program has been carried out only recently in some relatively early stages of visual information processing.

This guiding principle sets us apart in important ways from the above-mentioned reviewers. We are interested in psychological models whose building blocks are themselves psychological units (perceptual channels, feature analyzers, etc) and whose existence is revealed by psychological methods alone. Thus we are interested mainly in research that tries to explain a perceptual phenomenon as an interaction of even more elementary psychological percepts. We call this *type PP* research. On the other hand, we regard attempts to describe a perceptual phenomenon by neurophysiological units as interesting, but rather speculative. We call such attempts *type NP* approaches, and include them in our review rather cautiously. We believe that the perceptual atoms of the psychologists are rather complex quantities for the neurophysiologist, and we know of very few instances where even a hypercomplex neural feature analyzer in the visual cortex could be correlated with the simplest percept.

We have focused our review on the most recent years, but have not refrained from citing earlier work when we feel that the impact of ideas that originated in the past are being, or perhaps only just coming to be, felt today.

### *1.1 Toward a Perceptual Atom Theory*

That type PP problems are fundamental in perception is attested to by history, since the first model in visual perception was the three-color channel theory of Thomas Young in 1802, or of George Palmer in 1777 [whose publications are reprinted in a well-selected historical collection on color perception by MacAdam (1970)]. The opponent-color theory of Hering (1878), the first perceptual model of how the basic color channels interact, is also very old, even if only recently was the existence of these opponent-color channels hinted at by indirect neurophysiological evidence (Gouras 1970, De Valois 1973).

We believe that the benchmark of mature sciences is their ability to identify their basic elements ("atoms," "quarks," "genes," "phonemes," etc) and to explain their phenomena as the interaction of these elements. That Palmer introduced his atomistic theory of color perception years before Dalton proposed his atom theory to explain chemical reactions explains why this structuralist theory of color perception became the most scientific branch of psychology. [Interestingly, Dalton, who was the first to describe color blindness (see MacAdam 1970) believed in some aberrant

color filter over the retina, while Palmer had the correct explanation.] Similar psychological atoms (channels) were discovered in other modalities several decades ago, such as the "critical bands" in audition by Bekesy (1929), or the elementary taste analyzers by Pfaffman (1941). Nevertheless, in vision, if we discount color, it is curious that perceptual channels were not postulated by a psychologist before the dawn of the neurophysiological feature extraction era. For instance, the waterfall illusion discovered by Purkinje (1820), and particularly the spiral aftereffect discovered by Plateau (1850) (which cannot be attributed to scanning eye movements), were explained only recently by Sutherland (1961), and corroborated by Sekuler & Ganz (1963) in terms of the selective adaptation of pools of cortical movement detectors (velocity channels). This is a most curious delay since Wohl-gemuth (1911) proposed movement-channel adaptation for the movement aftereffects several generations ago, and many of the pitch aftereffects in audition had already been explained by Bekesy (1929) in terms of selective adaptation of channels. [See the review of the recent history of the emergence of the channel concept for spatial frequencies (Julesz 1980b).] Except for Wohl-gemuth's theory, which was overlooked prior to Hubel & Wiesel (1959), we are not aware of any channel-type explanations whatsoever for the many perceptual phenomena, such as optical illusions, figural, tilt, depth, motion aftereffects, etc for which channel concepts are now widely used. Just a year before the discoveries by Kuffler (1953) and Barlow (1953), the most up-to-date theory of figural aftereffects by Osgood & Heyer (1952) was very different from the idea of feature detectors, emphasizing the role of eye movements and positing unspecified neurons.

So it seems that type NP ideas—such as Sutherland's explanation of the motion aftereffect in terms of cortical velocity detectors—had a revolutionary impact on visual perception. Nevertheless, when one wants to apply type NP ideas in detail, such attempts are usually premature. For instance, it was obvious after the discovery of Kuffler (and Hubel & Wiesel) units that such single neural units cannot function as perceptual dot (bar) detectors. After all, one of these neural units alone cannot distinguish between a narrow dot (bar) with high contrast or a wider dot (bar) with a lower contrast, while we can perceive the two cases properly. Therefore, one has to assume that the perceptual system encodes the luminance distribution at a given retinal position by multiple detectors with different receptive field widths, as pointed out explicitly a long time ago (Julesz 1971, p. 12). This type NP idea surfaced again in a more elaborate form, (Marr & Hildreth 1979) explaining why at least two channels are required to separate contours in machine vision, and "justifying" why Wilson & Bergen (1979) found two channels for sustained or transient stimulation, respectively. Indeed, after the discovery of multiple psychological channels tuned to

spatial frequencies (SF) by Campbell & Robson (1968), which is a type PP finding in its own right, a type NP idea becomes unnecessary in the framework of psychology.

However, recent neurophysiological findings (reviewed in Section 3.1.1) suggest that Hubel & Wiesel units are SF analyzers rather than bar detectors. Therefore, there is a possibility that the perceptual atom (SF channel) is also a neurophysiological atom (simple or complex cortical neuron). Thus a perceptual molecule (e.g. detection of a bar, thought to involve the pooling of SF channels) can be explained by both type PP and type NP models.

Recently we witnessed another type PP finding being explained by a type NP finding. Blakemore & Julesz (1971) found a perceived depth shift following depth adaptation in RDS which demonstrated the existence of a global stereopsis detector, although the neural site of such a highly global unit (pooling many disparity detectors in complex ways) was unknown. However, Gian Poggio has recently informed us that several of the binocular disparity sensitive units in area 17 of the monkey that fire for elongated bars having certain disparities (Poggio & Fischer 1977) continue firing when the same elongated bars are portrayed by a dynamic RDS without monocular cues. It remains to be seen whether all kinds of RDS are processed at such an early stage, particularly in the light of the ablation studies in the medial temporal cortex of monkey by Cowey & Porter (1979). The ablation had no effect on stereoacuity with line stereograms but impaired global stereopsis of RDS. Furthermore, Poggio's cyclopean neurons are orientation sensitive, contrary to some psychological evidence that the global stereopsis detectors are not orientationally tuned (Mayhew & Frisby 1978b).

In order to fully understand the problems of trying to model a percept by current neurophysiological findings, consider a study by Julesz & Hesse (1970). They made a computer movie in which areas of rotating "needles" perceptually segregated, provided the needles in adjacent areas rotated with different speeds. However, clockwise and counterclockwise rotating needle arrays of the same velocity did not segregate. If vertical needles moved laterally left-right or right-left, respectively, the adjacent areas segregated even when the oppositely moving needles had the same velocity. No knowledge of single electrode neurophysiology would permit an armchair theory of the striking difference in the global utilization of neuron pools shown by these tasks. The example shows the role of psychology in suggesting to neurophysiology what molar functions to look for. So the question of when a neurophysiological finding can be used to model a global percept critically depends on the psychological criterion. The reader is referred to a chapter, "The psychobiological silly season—or—what happens when neurophysiological data become psychological theories" (by Uttal in Nelson et al 1971).

While we will stress those rare instances when type NP models might be

relevant, most global percepts in suprathreshold perception are still too complex for present-day single microelectrode neurophysiology. However, rapid progress in global neurophysiological techniques (e.g. radioactive glucose and similar metabolic markers) might bring neurophysiology into the realm of perception (Sokoloff et al 1977, Hubel et al 1978).

Early feature extractors must have evolved to enable the visual system to extract essential information without being swamped by the deluge of irrelevant input. In a sense, our interest in channels complements last year's review by Johansson, von Hofsten & Jansson (1980). The beautiful experiments by Johansson and his co-workers show how a minimum element set of a few dots attached to living creatures, and therefore having a complex structure, are adequate to evoke their complex spatiotemporal memory images. We are reviewing work that tries to clarify how a maximum element set of many dots (such as textures, gratings, dynamic arrays of dots, random-dot stereograms, etc) having a relatively simple structure can give rise to some unique global percepts with minimal load on memory. Particularly we are interested in those structures in usually unfamiliar stimuli that the early stages of the perceptual system are designed to extract.

Finally, early perception is rich in phenomena that permit the study of linearity/nonlinearity, probability summation/cooperativity, bottom up/top down processing, and psychoanatomy (i.e. skipping early stages operationally). We think that early perception is a model system to study these important and poorly understood phenomena, and serves as a link between spatial vision and cognition.

### *1.2 Personalialia, Books, and Major Events*

During this review period we lost Mike Fuortes, who used his immense neurophysiological knowledge to build one of the first sophisticated models of temporal mechanisms (Fuortes & Hodgkin 1964), and initiated a trend followed by Sperling & Sondhi (1968) and many others. His scholarship, advice, and warm personality will be remembered by many of us. Another tragic loss was the departure of Hans-Luke Teuber, whose work of correlating well-defined injuries of the nervous system with perceptual deficits had a unique interest for our area. A tribute to his leadership is the publication of Volume 8 of the *Handbook of Sensory Physiology* entitled "Perception" (edited by Held, Leibowitz & Teuber 1978) which he planned, solicited, and organized with great vigor. It contains important review articles by Brad-dick, Campbell & Atkinson (1978) and by Maffei (1978) on psychological and neural aspects of SF channels; by Sekuler, Pantle & Levinson (1978) on movement channels; by Stromeyer (1978) on form-color aftereffects; by Foley (1978) on distance perception; by Julesz (1978a) on global stereopsis and cooperative stereoscopic phenomena; by Ingle (1978) on shape recognition in vertebrates; by Dodwell (1978) on pattern and object perception; by

Coren & Girgus (1978) on optical illusions; by Oyama (1978) on figural aftereffects; by Yin (1978) on face perception; by Fox (1978) on visual masking; by Anstis (1978) on apparent movement; by Johansson (1978) on visual event perception; by E. J. Gibson (1978) on reading; by Dichgans & Brandt (1978) on visual-vestibular interactions; and chapters on visual deprivation (plasticity) by Blakemore (1978), Ganz (1978), and Hatwell (1978). Leaving out many other interesting chapters, we emphasize the chapter by Teuber (1978) on perceptual effects of cerebral lesions, one of his last published works.

Recently we lost J. J. Gibson, whose influence on perception, particularly his pioneering work on the importance of textures and adaptational aftereffects, set the tone for much research reviewed here. In his third book (1979), published just before his death, he elaborated on his theory of direct (immediate) perception. For a lucid discussion and critique of Gibson's ideas the interested reader should turn to Ullman's recent paper (1980). According to Ullman, describing the stimuli-percepts relation as "immediate" would be justified only if the relation had no meaningful decompositions into more elementary constituents. If we accept this summary of Gibson's basic concept, then our review of channels (elementary constituents) is contrary to the spirit of immediate perception. At the same time, Gibson's ideas of gradients and movement invariants of textures greatly influenced research in perception. This shows how rich and multifaceted a creative person's scientific heritage really is.

Another event was the long awaited publication of *Visual Coding and Adaptability*, edited by Harris (1980), that contains very relevant articles on developmental problems by Mitchell and Hein; on perceptual plasticity by Held and Harris; on physiological mechanisms by Robson and Teller; and on SF tuned channels by Graham, Julesz, Weisstein and Harris, and Weisstein. As a result of the careful work of Harris, the articles are self-supporting and complement each other, and serve as a lucid introduction to perceptual channels and plasticity.

An interesting symposium was organized by Kubovy & Pomerantz (1980) on "Perceptual Organization" where the contributors, leading researchers in acoustical and visual perception, were asked to go beyond their findings and give their opinion on the status and future of their fields. Among the contributors to this symposium were: Biderman, Graham, Hochberg, Julesz, Kahneman & Henik, Pomerantz, Pomerantz & Kubovy, Shaw & Turvey, and Shepard (see reference list).

Finally, the "Festschrift" commemorating the retirement of Lorrin Riggs, entitled *Visual Psychophysics and Physiology* (edited by Armington, Krauskopf & Wooten 1978), containing articles by many of his former students and coworkers, demonstrates the impact of Riggs, not only as a scientist but also as an educator.

## 2.0 THRESHOLD PERCEPTION

### 2.1 Spatial Frequency (SF) Channels

Within the scope of this chapter, the study of channels in spatial pattern vision has enjoyed the most vigorous attention in recent years. A diverse assortment of tasks have now shown that overall visual sensitivity to targets of different sizes or spatial frequencies is the envelope of the sensitivities of a number of mechanisms, each having narrower sensitivity than the observer as a whole. Important early developments in this area were reviewed with great clarity and insight by Sekuler (1974), and more recent and also excellent reviews may be found in Braddick et al (1978) and De Valois & De Valois (1980), who summarize many of the most recent results and trends.

In the earliest experiments on multiple channels, it was adequate just to show their existence convincingly (Pantle & Sekuler 1968, Blakemore & Campbell 1969, Graham & Nachmias 1971, Stromeyer & Julesz 1972). Recently, however, considerable effort has been devoted to solving the more exacting problems of how SF channels interact with each other at and above threshold, of describing the spatial structure of individual channels, and finally of showing how channels behave above threshold.

Sachs et al (1971) first pointed out that if each spatial frequency channel has its own independent source of noise and its own detector or threshold element, then when two or more mechanisms are activated by a stimulus, detection could be based on the response of either mechanism, and so psychometric functions should follow a form based on the probabilistic combination of the component psychometric functions. This combination, termed "probability summation," occurs because, like simultaneously flipping several coins and asking for at least one head, there are several independent chances to detect a single stimulus. The motive for studying probability summation has been to distinguish such purely statistical pooling effects from other, physiological pooling properties.

The study of probability summation has been made considerably easier by the introduction of an analytically convenient form for the psychometric function, or probability-of-seeing curve, by Brindley (1960), and first applied to grating detection by Quick (1974). Since the form appears to be replacing the traditional cumulative Gaussian curve as the standard psychometric function, we devote some space here to its character and to useful references. The expression for the probability of mechanism  $i$  detecting a stimulus is  $P_i = 1 - 2^{-|R_i|^k}$ , where  $R$  is a response measure proportional to stimulus intensity, energy, or contrast, and  $k$  controls the steepness of the function. The convenience of this expression derives from the fact that the product of a number of independent probabilities of failing to see a stimulus

yields a sum in the lower exponent, and thus the overall probability of detecting a stimulus by at least one of  $j$  channels is  $P_c = 1 - 2^{-\sum I R_{ik}}$ .

This simple expression yields a convenient prediction of the behavior of many independent channels acting at once. Also the function preserves its shape over changes in the number involved, consonant with the behavior of empirical psychometric functions, as noted by Green & Luce (1975). Useful examples of the application and interpretation of this function can be found in Quick (1974), Stromeyer & Klein (1975), Graham & Rogowitz (1976), Quick et al (1976), Graham (1977), Graham et al (1978), Watson (1979), Watson et al (1980) and Graham (1980b).

The identification of probability summation effects has clarified and unified a number of earlier results. When two widely separated frequencies are combined, threshold contrast for the compound is found to be somewhat less than that for the most detectable component; this has been explained by probability summation over independent mechanisms (Graham et al 1978). Similarly, Graham (1977, 1980b) has argued that the evidence of Kulikowski & King-Smith (1973) and of Shapley & Tolhurst (1973) for a large family of quite broadly tuned channels selective for lines, edges, etc, is invalid because apparent broad bandwidth could be due to probability summation among many narrower channels activated by broadband stimuli.

A more interesting application of probability summation involves decomposing a single SF channel into a number of independent spatial subunits. King-Smith & Kulikowski (1975) showed that the visibility of spatially extended stimuli could be understood as the probabilistic summation of independently activated local units, but they studied only extended stimuli that were composed of local elements widely spaced on the retina. With the idea of local spatial subunits in mind, Stromeyer & Klein (1975) suggested that the very narrow channel tunings of Sachs et al (1971) could be due to a subtle methodological artifact of the subthreshold summation experimental procedure. Frequencies close together, when added, produce spatial "beats" at the difference frequency when a system deviates from linearity. Indeed, if detection of a spatially extended pattern involves probability summation over spatial subunits, "beats," or regions of low contrast, will reduce the number of available subunits, causing an apparent reduction in sensitivity. How this artifact would lead to excessively narrow channel tuning estimates is discussed by Graham & Rogowitz (1976), Graham (1980b), Quick et al (1978), and Bergen et al (1979).

Such probability summation "over space" has been further suggested as the reason why adaptation to a spatial impulse fails to elevate threshold for gratings (Legge 1976). If detection of extended gratings is based on re-



sponses of many subunits, then only a few such subunits might be adapted by a spatially local bar stimulus. However, Weisstein et al (1977) have questioned whether a thin line is local or not, showing reductions in the perceived contrast of a grating when "masked" at  $4^\circ$  separations by a thin line, a somewhat strange result. Probability summation over space has also been suggested (Robson & Graham 1978, Bergen et al 1979) as the reason why a single grating becomes more detectable as the number of cycles presented is increased (Hoekstra et al 1974, Savoy & McCann 1975, Estevez & Cavanaugh 1976, Legge 1978).

Another important refinement to the channel model was first explicitly suggested by van Doorn et al (1972) and was incorporated into a detailed model of threshold vision by Limb & Rubinstein (1977). Since visual sensitivity is well known to vary across the retina (Hines 1976, Virsu & Rovamo 1979), each component of a spatially extended stimulus composed of different spatial frequencies might be detected at different retinal locations. Thus, there might be only one channel at any one retinal location, and evidence for independent detection of the components of a compound stimulus (Graham & Nachmias 1971) would then be explained just by a space-variant single channel model. Graham et al (1978) showed this objection to be wrong by using a new technique of multiplying a spatial sine wave by a spatial Gaussian. This results in a stimulus which is narrow in its SF content but also well localized in space. Graham et al were able to conclude that at each retinal location there must be more than one channel.

Wilson & Bergen (1979, Bergen et al 1979) have combined many of the above-mentioned refinements into a well-specified model of threshold vision. Their model postulates four mechanisms, though this number only reflects parsimony, being the least which gives a good fit to their data, and should not be taken as a rigorous claim in itself. Each mechanism varies in size and in sensitivity with changes in eccentricity, and probability summation over both mechanisms and space is incorporated. The model performs quite well in predicting the visibility of a variety of periodic and aperiodic simple and compound stimuli, though with 21 parameters (each well motivated) it would be surprising if good fits were impossible to achieve. Interestingly, the fairly broad channels Wilson & Bergen stipulate, almost 2 octaves wide, are too broad to explain the lack of subthreshold summation of two gratings even when inhomogeneity and probability summation are taken into account (Watson 1980, Watson & Nachmias 1980).

There is also evidence for the inhibition of inhibition (disinhibition), another type of nonlinearity, which, if valid, could make matters even more complex. Wilson, Phillips, Rentschler & Hilz (1979) had observers detect a test line in the presence of two slightly subthreshold flanking lines, and they report clear evidence of facilitation of detection at test-flank separa-

tions larger than those at which inhibition of performance occurs. The authors of this paper have contrasting views in explaining this finding. Wilson and Phillips believe that only probability summation operates, while Rentschler and Hiltz assume disinhibition. It is intriguing that the same experimental data can be explained by two different nonlinear mechanisms, and it remains to be seen whether an experimental paradigm can be invented that distinguishes between them. Disinhibition has been shown to be important in suprathreshold vision, particularly in the tilt aftereffect (Carpenter & Blakemore 1973, Magnussen & Kurtenbach 1980). Perhaps even in threshold vision such a highly nonlinear effect is at work.

There is also evidence for inhibition between channels, which also would complicate the interpretation of studies of channel properties. Thomas et al (1979) showed that the discrimination of two gratings  $f_1$  and  $f_2$  requires lower contrast than the detection of a compound grating  $f_1+f_2$ . This could be due to inhibition between the channels detecting the two components, which would increase performance on the discrimination task and decrease performance on the detection of the compound. Evidence for interchannel inhibition, based on adaptation studies, has previously been presented by Tolhurst (1972) and De Valois (1977b). An alternative considered by Thomas et al to explain their results is that the noise within channels is correlated; this would have the same effect as interchannel inhibition. Again, it should be interesting to see if these interpretations can be distinguished experimentally. An incautious comparison of Thomas et al's result with Graham et al's (1978) finding, that a compound of two widely separated components can be detected at lower contrasts than can either of these components, leads to the seeming paradox that discrimination of  $f$  from  $3f$  is easier than detection of  $f$  or  $3f$  alone. This paradox might be due to the different psychophysical procedures and experimental settings used in these studies.

Many researchers interested in visual thresholds study a rather simple task: When does a Ganzfeld change into something else? The detection of deviation from a Ganzfeld might seem to require the lowest threshold, and one could assume that the identification of the SF of a grating, or discrimination between two gratings, would require larger contrasts. Therefore, the finding by Nachmias & Weber (1975) that two gratings in a 3:1 frequency ratio are discriminated as soon as they are detected, is a most interesting result. This suggests not only that each grating is detected by a separate channel, but also that the channels are "labeled," so that the patches that make up a grating are not just barely detected as being different from the surround, but the extent of a patch seems to selectively stimulate the proper SF channel.

## 2.2 Spatiotemporal Channels

While much of this research belongs to suprathreshold movement perception, recent advances permit us to review some spatiotemporal studies at threshold. Last year the spatiotemporal contrast detection threshold surface was measured in two independent laboratories. Koenderink & van Doorn (1979) found this surface to be bimodal with a peak at low SF and high temporal frequency, and another at high SF and low temporal frequency. They called their peaks "flicker" maximum and "pattern" maximum, respectively. Kelly (1979), who measured this surface under retinal stabilization, found only a unimodal shape and claimed that the "pattern" maximum is created by natural eye movements and disappears under stabilization. Earlier studies had already shown that the spatiotemporal threshold surface is not separable, thus  $f(x,t) \neq f_1(x)f_2(t)$  (Robson 1966, Kelly 1966). This meant that such a surface could not be constructed by multiplying together a standard MTF curve with a standard flicker threshold (deLange) curve. Kelly's threshold surface is not cylindrical in shape (as a function of space and time) and therefore also is not separable.

These spatiotemporal MTF surfaces are only an envelope of many spatiotemporal frequency tuned channels. These were studied by Wilson & Bergen (1979), who found two kinds of channels for transient stimulation of grating patches and two kinds for sustained presentation. The channels sensitive to transient (higher temporal frequency) stimulation were sensitive to low SF, while those sensitive to sustained (low temporal frequency) stimulation were sensitive to high SF. Psychophysical evidence for such spatiotemporal interactions had earlier been provided by Robson (1966), van Nes et al (1967), Keesey (1972), Breitmeyer (1973), and Kulikowski & Tolhurst (1973). Breitmeyer & Julesz (1975) measured detection thresholds for gratings with rapid or gradual temporal onsets and decays. They found that for low SF gratings the rapid onset yielded lower detection thresholds than the gradual onset. However, no difference was found between rapid and gradual offsets. This asymmetry between onset and offset argues for spatiotemporal nonlinearity.

## 3.0 SUPRATHRESHOLD PERCEPTION

### 3.1 Contrast and Pattern Perception

Masking experiments with filtered noise or compound gratings use somewhat more sophisticated criteria than detecting departure from a Ganzfeld (i.e. the detection of something in nothing). They use a kind of dual criterion: When does the noise (spanning all possible signals) become a grating?

Therefore, it is interesting that Stromeyer & Julesz (1972), using one-dimensional filtered noise, corroborated the Blakemore & Campbell (1969) finding of critical bands obtained by adaptation. Neither study showed interactions between channels when their SF spectra differed by about two octaves. On the other hand, Henning et al (1975) used as a masker a compound grating composed of only three sinusoidal components instead of many, as in noise. They found that such a mask of high SF interfered with the detection of a sinusoidal grating two octaves lower in SF. Their finding is thus inconsistent with the hypothesis that the visual system spatially analyzes patterns in independent critical bands. They suggest the possibility that their data could be explained by a model that performs a squaring nonlinear distortion of high SF but not of low SF signals, but they regard such a model as being unlikely.

Rogowitz & Nachmias (1979) were able to reject this model since they found a failure of additivity of the effects of the putative distortion product and of a real grating at the distortion SF. Further, the masking effect differs depending on whether the components of the mask are added in sine phase or in cosine phase, though the distortion product is identical in both cases.

As was discussed in Section 2.1, even at absolute threshold for the detection of gratings there is evidence for nonlinear behavior. Obviously, suprathreshold vision must be even more nonlinear. Therefore, it is most surprising that for several suprathreshold phenomena quasilinear effects have been observed. Such linearity has been revealed either through the absence of SF cross-products (that is, through the independence of channels) or through linear input-output relations.

One suprathreshold phenomenon where the independence hypothesis seems to hold is the unmasking (recognition) of Harmon's famous block Lincoln picture when the "quantization noise" spectrum is filtered to be two octaves away from the image spectrum (Harmon & Julesz 1973). Julesz & Chang (1979) corroborated this finding. They combined a low-pass random-dot array with onefold symmetry and a high-pass array (two octaves apart in spectrum) with onefold symmetry but along an axis orthogonal to the first. Previously it had been shown that the sum of a horizontal and a vertical symmetric pattern (with overlapping spectra) appeared random (Julesz 1971). As expected from a multiple-channel theory, the sum of orthogonally symmetric filtered patterns in the Julesz & Chang study did not have a random appearance, but both the horizontal and vertical symmetry could be perceived simultaneously, provided the high-pass pattern was weighted in contrast about twice the low-pass pattern.

Other evidence for independent SF channels at suprathreshold levels was found in an apparent contrast matching task by Arend & Lange (1980), who repeated some suprathreshold contrast matching experiments of Hamerly

et al (1977). Both groups found similar phase-insensitive mechanisms for contrast matching at 30x threshold, and Arend & Lange (1980) further found that the same gratings that fail to summate with one another in the determination of threshold also fail to summate above threshold in the determination of perceived contrast. It would be interesting to know the effect on contrast perception of the spatial "beats" which are present, since such "beats" in compounds made of nearby SF gratings appear to be important at threshold (as discussed in Section 2.1).

While this result is evidence of independence, it also appears to show a peculiar "peak response only" kind of nonlinearity, since compound gratings of widely separated components have the same apparent contrast as the larger component presented alone. It seems that contrast matching judgments utilize only the strongest response given by any active mechanism. Results of Ginsburg et al (1980), using contrast matching and magnitude estimation tasks, support this interpretation since they observed that the apparent contrast of a square wave grating is  $4/\pi=1.27$  times that of a sine wave at the same SF and physical contrast at contrasts ranging from 10% to 50%. Thus, the fundamental component of the square wave determines apparent contrast even though many higher harmonics are well above threshold. If one overlooks this perceptual disregard for higher SF components, other evidence for linearity in contrast perception was found by Ginsburg et al (1980). Perceived contrast was observed to be a linear function of physical contrast.

Using magnitude estimation, Cannon (1979) also showed that the perceived contrast of SF gratings is a linear function of physical contrast at large contrasts. However, he also replicated a finding of Georgeson & Sullivan (1975), who studied contrast matching, that the constant perceived contrast contour (across SF) flattens out above contrasts around 10–20%. This means that at low contrasts (less than 5%) contrast sensation is nonlinearly related to physical contrast, and the nonlinearity varies for different SF.

After reviewing evidence on suprathreshold linearity (or quasi-linearity) and independent SF channels, we mention several findings that show the contrary. Quick et al (1976), using a suprathreshold contrast matching task, found that the apparent contrast of a complex rating usually can be predicted from the apparent contrast of its components viewed alone, if contrast of these components is summed in a Pythagorean fashion:  $C_{\text{complex}} = \sqrt{\sum C_i^2}$ . Mayhew & Frisby (1978a) extended the validity of this power law to monocular random-dot arrays with different spectra. They point out that a single-channel model is adequate to account for this power law of contrast summation for suprathreshold random textures. They kept the granularity (shape of the ellipsoid Fourier spectra) identical and changed only the

orientation of the ellipsoid spectra, which permitted an easy matching between adjacent texture pairs for identical contrast; this is a rather difficult task for textures having widely differing spatial frequencies.

These studies might be reconciled with the previously cited results if the nonlinearities of contrast perception were confined to lower contrasts, as suggested by Cannon (1979). In this regard, it is interesting that the translation of stimulus contrast into channel response—the transducer function of SF channels—seems to be markedly nonlinear just above threshold (Nachmias & Sansbury 1974, Foley & Legge 1979). The contrast required to detect a grating is three to four times larger than the contrast difference required to discriminate two slightly above-threshold gratings. This can be explained if the transducer function is positively accelerated at low contrasts so that the discrimination task reflects performance on a steeper part of the transducer function (Stromeyer & Klein 1974, Van Meeteren 1978). Possibly a “linearization” of contrast sensation occurs only at medium to high contrasts.

### *3.1.1 Bars versus Gratings and Shifts in Attention*

Recently considerable attention has been directed to the problem of whether bars or gratings are the elementary trigger features in visual perception. Since De Valois & De Valois (1980) devoted considerable space to this problem, we add only a few comments. Ever since Hubel & Wiesel (1959, 1962, 1968) discovered that cortical cells in the cat and monkey optimally respond to bars and edges, these neural units have often been regarded as bar or edge detectors. Campbell & Robson (1968) suggested a quasi-linear theory based on SF-tuned filters selective to sinusoidal gratings instead of seminaturalistic objects such as bars and edges. Neurophysiologists (Campbell et al 1969, Maffei & Fiorentini 1973; Movshon et al 1978) showed that the Hubel & Wiesel type bar and edge sensitive units were also sensitive to sinusoidal gratings. Indeed, Movshon et al found that the response of simple cells to narrow slits of light could be predicted quite well from their response to gratings. Nevertheless, in a psychological experiment, Sullivan et al (1972) reported that while adaptation to a grating selectively elevated thresholds for only nearby SF, adaptation to a bar adapted all bar widths nonselectively. They thus concluded that SF, and not bar width, is the “atom” of visual pattern mechanisms. Similar conclusions were presented in a neurophysiological study by Albrecht et al (1980), who reported that although visual cells in the macaque monkey's striate cortex are sensitive to bars, edges, and gratings, they are nevertheless far more selective for gratings of a given SF than for bars of a particular width.

We mentioned earlier that a Kuffler unit or Hubel & Wiesel unit alone cannot uniquely encode both contrast and stimulus width. So it is not

surprising that if contrast and stimulus width are constrained (when only sinusoidal gratings are used), the trigger features become more precisely given. That does not mean, however, that in visual perception the "atom" is not a bar (edge) built up from several neurophysiological units. Indeed, Thomas (1970) and Macleod & Rosenfeld (1974) proposed psychophysical models based on size-specific rather than SF-specific mechanisms. Under the size-specific model the visual field is covered by small, overlapping regions (perceptual receptive fields), each sensitive to objects of a particular size (width).

In order to test which of the two perceptual models better describes suprathreshold phenomena, Frome et al (1979) undertook a modified version of the Blakemore & Sutton (1969) SF-shift experiment. Blakemore & Sutton had observers adapt to a sinusoidal grating before examining a grating of varying SF. They found that gratings higher in SF than the adapting grating appeared higher still, while gratings of lower SF appeared lower still (similar to the adaptation findings in the auditory domain of Bekesy 1929). Frome et al used a sinusoidal grating for adaptation but tested with a single bar. They found a perceived widening of the bar whether individual stripes in the grating were narrower than, equal to, or somewhat wider than the test bar, although they found perceived narrowing if the adapting grating's stripes were more than twice the width of the test bar. This finding argues against a size-specific model, according to which perceived widening should be experienced for a test stimulus wider than the adapting stimulus and perceived narrowing for a narrower test stimulus. Particularly, no size change should be experienced when the test and adaptation width agree, contrary to the observed finding. A SF model is consistent with the findings, since a bar has a broad spectrum, and adaptation to a grating reduces sensitivity to SF near the adapting frequency. Perceived widening of the bar should occur when there is relatively less response from the higher SF channels.

In another variant of this experiment Levinson & Frome (1979) used a square-wave grating as the test stimulus and found a Blakemore-Sutton kind of frequency shift of increased frequency while the individual bars of the grating (or a test square) always looked wider, a paradoxical result. This perceptual paradox is particularly strong in light of the finding of Frome et al that both gratings and bars are processed by SF channels. According to the authors, the only way to resolve this paradox is to evoke a selective attention mechanism. When observers attend to a single bar (or square) they can perceptually discount the rest of the visual field. Thus the spectrum of such a "perceptual window" convolutes with the spectrum of the bar, while for global grating perception no window is used.

A problem with many of the studies comparing bars with gratings is that

a particular conception of "bar" is implicit, namely one having sharp edges. For example, Albrecht et al undoubtedly would have found greater selectivity for bar width if their "bars" had blurry edges, and it seems as reasonable for blurry bars to be considered as an alternative to gratings, in the search for the "atoms" of pattern vision, as for sharp bars.

In suprathreshold vision one-dimensional gratings and bars are very unnatural stimuli. One can expect many novel findings for two-dimensional stimuli both in the space and Fourier domains where gratings with different orientations can coexist. For instance, Heeley (1979) observed a SF-shift at orientations orthogonal to the adapting grating.

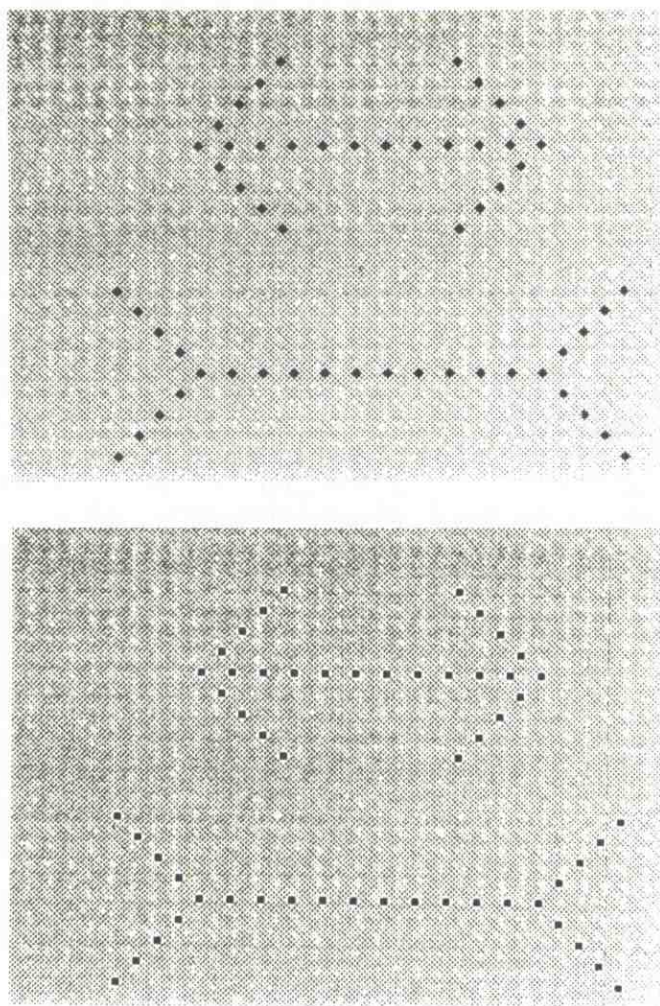
### *3.1.2 Globality versus Low SF Channels*

The idea of the Gestaltists, that the holistic character of the stimulus influences its perception, is most provocative and hindered the structuralistic approach for a long time. Therefore, the proposal by Ginsburg (1975) to regard the low-SF channels as the "Gestalt analyzers" appears at first an interesting insight. Indeed, his low-pass filtering of optical illusions and Kanizsa figures seems to produce these global interactions and at the same time justify the existence of SF channels in vision.

In spite of the great heuristic appeal of this model, at its inception it had to face some contrary facts. For instance, most optical illusions are perceived even when portrayed by RDS, in spite of the fact that the binocular information can only exist at a much later stage than the site of filtering that Ginsburg proposes (Julesz 1971). Also, the illusory (virtual) contours in Kanizsa figures seem to disappear when binocular disparity is introduced (Gregory & Harris 1974). So the postulated low-SF channel must occur after the nonlinear operation of stereopsis. However, if stereopsis occurs as early as area 17 of the cortex, one could still assume that stereopsis may be processed at the same stage as SF filtering.

Therefore, the recent demonstration by Carlson et al (1980) is most illuminating. They portrayed illusory figures by small white dots having narrow black surrounding annuli (simulating a center-surround antagonistic Kuffler unit profile) in a gray background as shown in Figure 1. These Kuffler-dotted illusory figures give rise to strong illusory percepts in spite of the fact that they lack low-pass spectra. Indeed, the slightest blur makes these figures disappear completely. Thus the low-SF channels cannot respond to these Kuffler-dotted patterns, and therefore the globality of the Gestalt-like phenomena cannot be directly accounted for by low-pass filtering. Obviously, there must be some nonlinear operation that connects nearby space tokens (defined by high-SF channels) into elongated lines as proposed by Marr (1976) in his "primal sketch" model, or as proposed in the texton model of Julesz (1980a). After such a nonlinear operation—a still





*Figure 1* Müller-Lyer illusion: (A) with low SF spectrum; (B) with missing low SF spectrum (i.e. viewing from a distance makes the figures disappear). After Carlson et al (1980).

enigmatic process—one could postulate some linear low-pass filtering. Thus, globality without essential nonlinearities cannot explain perceptual phenomena.

### *3.1.3 The Problem of Phase*

Suprathreshold vision is critically sensitive to phase (position) information. The slightest scrambling of the Fourier phase spectrum renders an image

unrecognizable. Even in suprathreshold audition, where phase plays only a minor role, one can easily discriminate between a sharp click and white noise in spite of their identical power spectra.

The discovery of phase insensitivity in threshold vision (Graham & Nachmias 1971) was a powerful motivation for models of multiple SF channels. The question naturally arises as to how these models should be extended to explain suprathreshold phase sensitivity. One possible answer is that each channel is labeled by a specific retinal locale. Another possible answer might be that within a critical band there is phase sensitivity even in threshold vision. Since the critical bands overlap, phase sensitivity might be exhibited through overlapping neighborhoods (i.e. with respect to phase sensitivity the visual system behaves like a manifold).

Notwithstanding the importance of phase in vision, we were able to find very little on this problem in the literature. Nachmias & Weber (1975), using a discrimination task, confirmed that the phase of an  $f + 3f$  compound grating cannot be distinguished until somewhat above detection level contrast. Ross & Johnstone (1980), who used compound gratings with differences between the phase of the first and fifth harmonics, recently replicated this finding but only if the fundamental had a SF of 1 cycle/deg or higher. With a fundamental SF of 0.5 cycle/deg or less, phase sensitivity was found even at detection threshold. This might indicate that just one channel exists at very low SF.

Perhaps some of the phase insensitivity found with sinusoidal gratings is due to the artificiality of restricting stimuli to variations in one dimension only. Burr (1980) has found the relative phase threshold between an  $f$  and  $3f$  grating to be as large as  $30^\circ$  (but constant for all SF for which both components can be seen). However, in two dimensions, sensitivity to vernier offsets is quite fine (e.g. 37 sec arc) for low SF (1 c/deg) cosine bars, as Krauskopf & Campbell have found (personal communication).

Very little is known about how a phase-insensitive system at threshold could become phase sensitive above threshold. One possibility is that above threshold there exist broad channels which are responsive to widely separated components. This was suggested by Nachmias & Weber (1975) to explain why the presence of a high contrast grating facilitates the detection of a grating at three times the inducing SF. Arend & Lange (1979) similarly showed phase sensitivity for the detection of an  $f + 3f$  compound in the presence of a fixed  $2f$  "mask." Taken together with narrowband phenomena in contrast matching (Arend & Lange 1980), this points to the existence of parallel broad and narrowband channels in suprathreshold vision, and rules out a scheme in which narrowband threshold channels act as an input stage to the broad channels.

In suprathreshold vision, there is some interesting evidence that particular phases of harmonically related SFs have preferred status in the visual system. Atkinson & Campbell (1974) found "monocular rivalry" in complex gratings formed by  $f+3f$ , that is, the lower and higher SF components alternated in the perceptual suppression of one another. However, these patterns proved most stable when the two components were in square wave or triangular wave phase. Furchner & Ginsburg (1978) further showed that a similar phase bias occurs when observers judge the appearance of such compound gratings. Finally, it may be possible to study the phase specificity of suprathreshold vision through adaptation techniques. De Valois (1977a) demonstrated different adaptation to two rectangular waveforms with identical power spectra but different phase spectra. In contrast to this finding, Jones & Tulunay-Keesey (1980) showed that adaptation to retinally stabilized counterphase flickering gratings generalizes across the relative phase of the test and adapting gratings, but this study may have been complicated by the fact that counterphase gratings seem to be detected by motion detectors (Sekuler et al 1978) which, of course, show no spatial phase sensitivity.

We will discuss further the problem of phase sensitivity in the next section in the context of texture discrimination, while we simply note here that recent results indicate that textural mechanisms are insensitive to the global phase spectrum but are sensitive to conspicuous local spatial information (Julesz & Caelli 1979). Foster & Mason (1980) attempted to refute even this more local claim for the case of figural perception. Their observers adapted to random arrays of micropatterns composed of T-like shapes or of disconnected perpendicular line segments and observed threshold elevation for the detection of a single T-shaped test figure. Adaptation was thus unselective for local cues, but this hardly seems surprising since threshold form vision is known to be phase-insensitive. Had they used a suprathreshold discrimination task instead of a detection task, it seems unlikely a phase-insensitive outcome would have resulted.

In summary, we know of no example in suprathreshold vision (except for contrast matching) where phase is ignored. How such an encoding of phase is carried out by the CNS is a mystery. Since we are not dealing with neurophysiological models, we only mention that no such neurophysiological mechanism has been found. Robson (1975) suggested that a mechanism using odd-symmetric and even-symmetric receptive fields could encode phase. However, as De Valois & De Valois (1980) point out, such a highly precise alignment of two receptive field centers has not yet been found, although, they add, neither has it been searched for by neurophysiologists.

### 3.2. Texture Discrimination: Beyond Autocorrelation

Preattentive or effortless texture discrimination (of side-by-side presented stochastic arrays without scrutinizing them) is an important link between spatial vision reviewed in the previous sections and the higher perceptual processes to be reviewed later. Indeed, Julesz (1962) observed that Markov texture pairs with identical second-order statistics (but different third- and higher-order statistics) usually could not be discriminated. Because the second-order probability distribution of color (luminance) values uniquely determines the autocorrelation function, hence the power spectrum, the indistinguishable iso-second-order textures have identical power spectra. Thus, it seemed, the preattentive visual system is insensitive to the phase (position) information. Since 1962, several non-Markov, two-dimensional texture classes were created with identical second-order statistics (see Figure 2) that were indistinguishable (Julesz et al 1973, Julesz 1975, Pratt et al 1978). [Some authors misunderstood the Julesz conjecture and mixed up second-order statistics with diagram statistics (that describe only adjacent samples); for details see Julesz 1978b].

In 1978 and since, several iso-second-order, even iso-third-order, texture classes were discovered that yielded strong texture discrimination based on local conspicuous features of quasi-collinearity, corner, closure, granularity, and connectivity (Caelli & Julesz 1978, Caelli et al 1978, Julesz et al 1978, Victor & Brodie 1978, Julesz 1980a). A typical distinguishable iso-third-order texture pair (that is also iso-second-order) (Julesz et al 1978) is shown in Figure 3, which demonstrates that texture granularity is a fourth-order statistical property. Figures 4A and 4B (Julesz 1980a) show iso-second-order texture pairs where discrimination is the result of conspic-

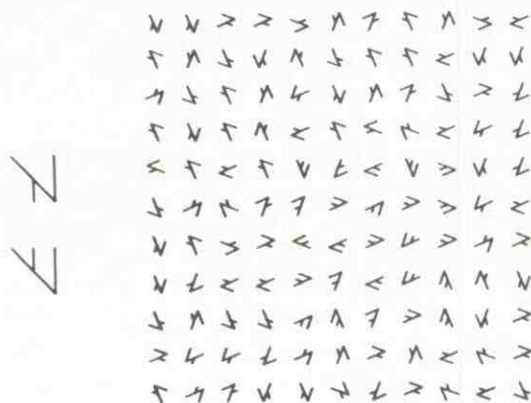


Figure 2 Indistinguishable texture pair with identical second-order statistics (hence identical power spectra). After Julesz (1980a).

uous local features of connectivity. Texture discrimination differs depending on whether the connected micropattern belongs to the target area or its surround. All these distinguishable iso-second-order texture pairs have identical Fourier amplitude (power) spectra and their phase spectra are both random (Julesz & Caelli, 1979).

Recently, Julesz (1980a) suggested that all these local, conspicuous features in distinguishable iso-second-order texture pairs can be reduced to only two features: elongated blobs (of given orientation, width, and length) and their terminators. He called these two fundamental textural atoms "textons." While Marr (1976) in his influential "primal sketch" model suggested the use of line segments and their terminators in machine vision, he borrowed these elements from existing neurophysiological results. The textons in iso-second-order textures, however, were discovered by psychological efforts of 18 years. It took that long to propose the modified-Julesz-conjecture: that preattentive texture discrimination cannot be performed globally by computing third- and higher-order statistics, but is the result of conspicuous feature differences in local texture elements (textons), or of differences in the first-order statistics of these textons.

Interestingly, Barlow (1953), who pioneered the notion that a receptive field might have behavioral significance, recently studied the detection of a rectangular random dot array surrounded by another with different probability distributions (Barlow 1978). To his surprise, detection performance did not change with the aspect ratio of the target rectangle, contrary to the fact that cortical cells are highly elongated. It appears that he used areas

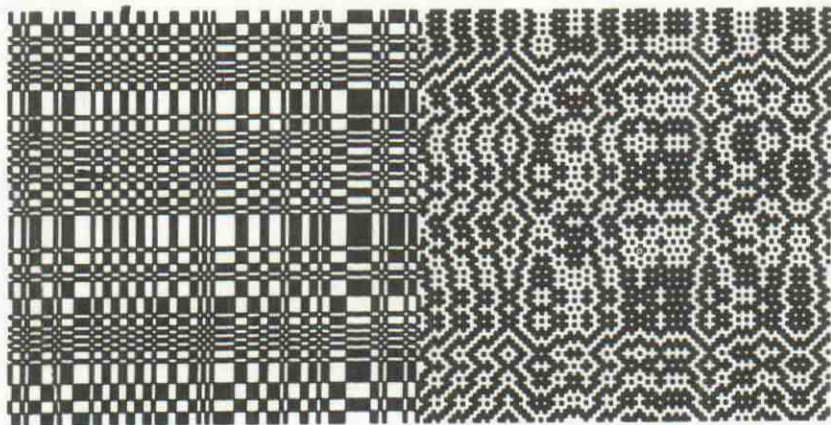


Figure 3 Distinguishable texture pair with identical third-order (hence identical second-order) statistics. Thus texture granularity is a fourth-order statistical property. From Julesz et al (1978).

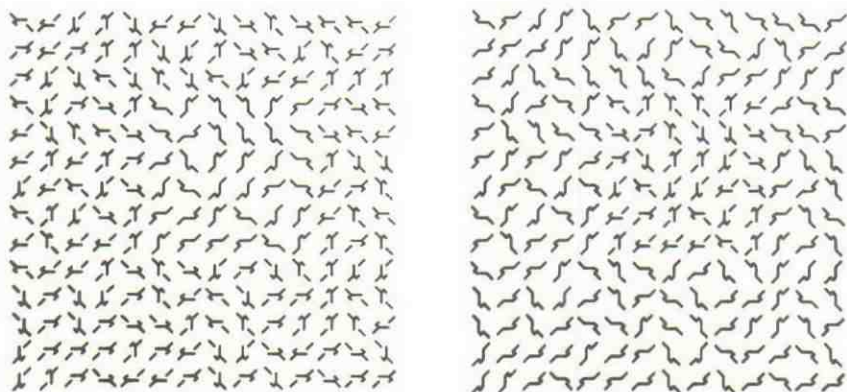


Figure 4 Distinguishable texture pair with identical second-order statistics (hence power spectra). (A) The unshared textons (terminators) belong to the target; (B) the unshared textons belong to the surround. From Julesz (1980a).

of random dots which were too large, and textons of elongated blobs manifest themselves only in small patches. Also, in Marr's primal sketch model real and virtual dipoles (between two place tokens) are treated equally, which led to incorrect predictions in texture discrimination (Marr 1977), as shown by Schatz (1978). It seems that in texture perception only three or more quasi-collinear place tokens act as real lines (Julesz 1980a).

In summary, texture discrimination is based on the number of unshared textons, but their exact positions are ignored (Caelli & Julesz 1979, Julesz 1980a). This position (phase) insensitivity to textons shows that texture perception is based on distributed attention. That attention is distributed in texture perception was first pointed out by Beck & Ambler (1972), who found that discrimination of T-s and  $\bar{T}$ -s did not depend on set size, but discrimination of L-s and T-s did.

There is a large literature on simple perceptual discrimination (finding a set of target letters in a set of background letters) according to which the effect of set size (indicating serial or focal attention) can completely disappear with practice—it becomes a parallel attention process (Rabbitt et al 1979). Julesz & Burt (1979) systematically presented 2, 3, . . . 8 target micropatterns embedded in an array of iso-second-order dual micropatterns either dispersed or grouped (for 160 msec, followed by erasure). They found that (a) if detection is based on a critical texton that is present in the target micropattern but absent in the surround, then there is no difference in detectability between the dispersed or grouped conditions; (b) If the critical texton is absent in the target micropattern (and thus belongs to the sur-

round), then the grouped condition is better perceived than the dispersed and probability of detection increases more rapidly with the number of target elements than in *a*. Furthermore, they found the presence of features (textons) in the target is more detectable than their absence, a finding noted in another texture paradigm by Beck (1973).

It is interesting that the perception of textons in the target area is a noncooperative process, but the perception of their absence in the target area is cooperative (defined here as better performance for the grouped than for the dispersed condition). A simple model based on pooled texton detector arrays of a critical size could explain these findings (Julesz & Burt 1979). Such a critical pooling (integration) area of textons has been suggested by Caelli & Julesz (1979), and earlier by Stevens (1978),—working on the perception of Glass patterns (Glass 1969, Glass & Switkes 1976)—who postulated the existence of integration areas covering about a dozen texture elements. The model by Julesz & Burt (1979) easily explains that the critical (unshared) texton in the few target micropatterns will activate one of the corresponding texton-detector arrays regardless of whether the micropatterns are dispersed or grouped. However, if the unshared texton belongs to the surround, then most of the texton detectors are activated and detection must be based on a significant deviation in the density of active texton detectors. Density reduction is greatest for the grouped condition.

Finally, Julesz & Burt (1979), using dual micropatterns with the same number of textons (see Figure 1), first found complete indiscriminability, but after several hundred trials discrimination became possible. Since in these experiments the foveal region was excluded and the brief exposure forced observers to keep their eyes on the center fixation point, the slow learning was restricted to the periphery. This learning was always based on detecting some existing texton that escaped attention prior to mastering the task. Such peripheral learning improvement was also observed by Johnson & Leibowitz (1979). This brings the texton theory close to some provocative findings by Treisman (1978), who found that the preattentive (parallel) system can easily cope with single (disjunctive) features, but only the attentive (serial) system can detect conjunction of features. Even after several hundred trials, RT for detecting conjunctions of "color" and "shape" still required a 27 msec/item slope, while single disjunctive features could be "overlearned," such that RT became independent of the number of items.

While the perceptual learning in the Julesz & Burt study was based on weak textons, formed by, say, the convex hull of the conspicuous textons in Figure 4, the conjunction targets of Treisman are conjunctions of textons, and thus more complex entities than textons. Conjunctions could be learned by the attentive (active) figure perception system, but not by the preattentive

(passive) texture system. A detailed model of active and passive attention and perceptual learning was proposed by Shiffrin & Schneider (1977).

In all the iso-second-order textures either the surround or both the target and surround were composed of many micropatterns in *random* orientations [since only a few different (dual) micropatterns exist that can yield iso-second-order textures when placed in *parallel*]. So the perceptual grouping observed in parallel micropattern textures by Beck (1967), Pomerantz (1980), Martin & Pomerantz (1978) and others is not discussed here.

It should be stressed that the observation that in iso-second-order textures the phase information is often ignored does not mean that one can freely manipulate the phase. Indeed, if one were to manipulate the phase in a compound sinusoidal grating, trying to exploit the phase insensitivity Graham & Nachmias (1971) found for threshold detection, this would drastically alter the first- (and second-) order statistics. Indeed, the suprathreshold discrimination of such textures composed of compound gratings can be very strong, not so much because of phase change, but because of the conspicuous difference in their first-order statistics of luminance.

Finally, it should be noted that all the demonstrated strongly discriminable texture pairs had identical autocorrelation functions and thus power spectra. So any theory based on autocorrelation (Uttal 1975) is an oversimplification. A similar conclusion was reached by Uttal & Tucker (1977), who found that detection of dot targets in masking random dots increased with their complexity. However, this complexity scale, based on individual judgments, greatly deviated in some instances from a scale based on the autocorrelation of the dot patterns. Similarly, quasi-linear theories based on one-dimensional Fourier decompositions are unsuccessful because gratings have no terminators, and so such models fail to explain the strong discrimination in, say, Figure 4. Results of studies with patches of gratings might depend on how abruptly they taper off; the pendulum could swing back and perhaps in place of gratings local textures will be used again in vision research. The stimuli used by Wilson & Bergen (1979) and Regan & Beverley (1979) point toward this trend.

We noted that some authors misunderstood the  $n$ th-order statistics paradigm originally stated by Julesz (1962) for Markov textures and studied instead  $n$ gram transition probabilities. When they asked for the smallest  $n$  that could not yield discrimination of iso- $n$ gram texture pairs, they really studied texture pairs with different second-order statistics, although the nearest neighboring dots up to a distance  $n$  had the same second-order statistics (Julesz 1978b, 1980c). This question—to what distance can the visual system detect correlation in a densely packed dot texture—is interesting in its own sake and was studied by Purks & Richards (1977) and Pollack (1973). The techniques of Gagalowicz (1979) permit such a study for non-Markov textures.



The above review of texture discrimination with stochastic constraints covers much of the perceptual literature. It is a profitable strategy to limit one's interest to texture discrimination instead of studying texture recognition and to impose stochastic constraints without which ad hoc variations result in unpredictable percepts. Obviously, in practical problems such as textural analysis of biomedical images or aerial photographs, one has to abandon many of these constraints. Zucker (1976) suggested generating more natural looking textures by periodic structures, and some interesting algorithmic texture generators that imitate "cellular" textures were described by Schachter et al (1978). There is a huge literature on machine segmentation of texture domains and their automatic identification in biomedical imagery that occurs in pathology, hematology, immunology, genetics, radiology, and nuclear medicine. Subsequent to the book *Picture Processing and Psychopictorics* (edited by Lipkin & Rosenfeld 1970), much of the recent literature on texture analysis for biomedical applications has been reviewed by Pressman et al (1979).

We mention only briefly some texture similarity experiments of one-dimensional synthetic textures composed of the sum of a few sinusoidal gratings with randomly selected amplitudes. Richards & Polit (1974) found that similarity between these textures was predictable by a four SF-channel model. Harvey & Gervais (1980), using multidimensional scaling, also found four channels underlying texture similarity. These channels were of the Wilson & Bergen (1979) type, but Harvey & Gervais suggested that the four channels interact in an opponent process manner. They conclude that texture perception is based on SF analysis rather than on feature extraction. Of course, one-dimensional textures do not exist in nature (even the bark of a tree is made up of elongated structures with many breaks), and as Julesz & Caelli (1979) showed, even highly conspicuous textures in two dimensions (e.g. Figure 4) can have identical Fourier amplitude spectra (since differences in terminator numbers do not reveal themselves in these spectra). This shows again the limitations of the SF-channel approach in visual perception. The discovery of textons argues rather for a feature extraction approach.

### *3.3 Cross-Correlation Channels in Depth and Movement*

The importance of cross-correlation models in binaural audition was stressed by Licklider (1948) and Cherry (1953) and in insect vision by Reichardt (1957). Models in binocular vision, particularly in the global stereopsis of RDS, although related to cross-correlation, are more complex because areas of different disparities have to be segmented. However, there does exist a cross-correlation ion-like process in global stereopsis, as shown by measurements of the largest disparity jumps that can be correctly perceived as crossed or uncrossed (Tyler & Julesz 1980, Burt et al 1979). These

disparity limits increase monotonically with target area up to target areas in excess of  $100 \text{ deg}^2$ , and can be over  $2^\circ$  arc, but of course observers do not see a dense surface at such enormous depth. They perceive only a slight depth jump of a cloud of dots toward or away from the observer.

This process is very different from actual global stereopsis, where a dense surface is perceived, and can be regarded as a precursor process. This might be similar to stereopsis with wide bars, as reported by Richards & Kaye (1974), who found that the maximum disparity for seeing bars in depth (though diplopic) increases as the square root of bar area (bar width), and can also be degrees of arc. As we mentioned, these cross-correlation-like processes are very different from the global stereopsis of dense surfaces, since a measure of sensitivity requiring detailed depth resolution showed improvement with increases in target area only up to  $4 \text{ deg}^2$ , the area of the fovea, where it reaches an asymptote (Schumer & Julesz 1980a).

This foveal asymptote for target area is also obtained when the task is to detect a change from correlation to uncorrelation or vice versa (Julesz & Tyler 1976; Tyler & Julesz 1976, 1978). The presentation time required to detect a transition from correlation to decorrelation (from order to disorder) was only 2 msec while from decorrelation to correlation (from disorder to order) it was 20 msec. Interestingly, changes from uncorrelation to negative correlation and vice versa were also perceived, which can be explained only if one assumes that simultaneously with a binocular fusion process a binocular rivalry process operates as well. This rivalry process favors the negative correlation the most. The strength of this rivalry process relative to that of the fusion process varied with observers, being 10% or less (even zero). Interestingly, the finding by Julesz & Miller (1975) that SF-filtered RDS can be fused while masking noise having a different spectrum can be in rivalry at the same time argues also for two different processes operating in parallel.

In an important paper, Lappin & Bell (1976) showed that sensitivity ( $d'$ ) for observing the direction of a stroboscopic movement jump in a random-dot cinematogram is inversely proportional to the square root of correlated target area. They proposed a signal detection model based on the output of a cross-correlation process (really autocorrelation, since the moving areas contained the same random dots). Julesz & Chang (1980) measured the maximum perceivable displacement in random-dot cinematograms in which 16 successive 10 msec frames contributed to movement. They obtained an increase with  $(A)^{1/4}$  for maximum displacement. Thus if  $d'$ , the response strength, is inversely related to  $d_{\text{max}}^2$ , the maximum displacement, the results could be related to the Lappin & Bell model. In Julesz & Chang's study  $d_{\text{max}} > 25 \text{ min arc}$  (8 picture elements) was routinely achieved for  $3^\circ$

$\times 3^\circ$  target size. These results and those of Lappin & Bell are at variance with those of Braddick (1974), who found an asymptotic limit of  $d_{\max} = 15$  min arc. Some light was shed on these problems by Julesz & Chang, who found that without practice  $d_{\max}$  for movement detection in a random-dot cinematogram increased as  $(A)^{1/4}$ , while for shape recognition in the same stimulus  $d_{\max}$  seemed to be constant with area. However, with learning even  $d_{\max}$  for shape recognition reached almost the same value as for movement detection. Note, however, that even though  $d_{\max}$  for movement in random-dot cinematograms can be larger than the limit found by Braddick (1974), it is still an order of magnitude less than the limits found for apparent movement with monocularly recognizable forms, as discussed next.

### 3.4 Movement Perception

In Section 3.3, several experiments with random-dot cinematograms were reported. These can be regarded as studies of global movement perception, since the false target problem cannot be decided locally. Global movement perception tolerates only small displacements. On the other hand, local movement perception (for which the corresponding elements in successive frames can be locally determined by form recognition) tolerates large displacements. Since large displacements and highly central processes are hard to reconcile with the word "local" (although this terminology is used for global and local stereopsis by Julesz 1978a), we will use the terminology of Braddick (1974) and Anstis (1978) and call the global movement process short-range and the local one long-range.

Anstis, in his review, discusses the problem of the relationship between real movement (RM) and apparent movement (AM). We mention here only the theory of Braddick (1974), according to which AM is mediated by both the long- and short-range processes, while RM is mediated only by the short-range process. He finds that the short-range process and the long-range processes can be differentially studied using dichoptic presentation (Braddick & Adlard 1978). To summarize his results, for short-range movement motion perception precedes form perception (as in global stereopsis), while for long-range movement form perception precedes motion perception. For long-range movements, which occur only in AM, a form recognition mechanism labels some clusters of dots, and then the AM process looks for motion between similarly labeled clusters. While short-range AM has found wide application in television and movies, the phenomenon of long-range AM, interesting in its own right, does not seem to occur in real life situations. For an object in RM, the jumps in position between successive perceptual instants are never very large, but the tolerance of 15–30 min arc

permits the processing of unexpected jumps. Recently, Petersik & Pantle (1979) juxtaposed short- and long-range processes. When they perturbed the local elements the short-range process gave way to the long-range process and a holistic, group movement was experienced. Burt & Sperling (1980) juxtaposed motion of arrays of dots successively presented in adjacent rows. They studied displacement and ISI (interstimulus intervals) and determined those relationships that best favor AM. Because they assumed a scaling invariance principle to derive their model, we return to this work in Section 3.6.

Other evidence shows that there are short-range AM processes beyond the cyclopean retina for stereopsis (Julesz & Payne 1968). A dynamic RDS target in depth could be successively presented in two different positions or orientations to produce AM, but at somewhat higher presentation rates (but less than the simultaneity rate) observers saw a single, stable percept at the average position of the two actual targets. For example, in the case of two tilted cyclopean gratings tumbling clockwise and counterclockwise, a single vertical grating is seen in standstill. In this experiment, AM must have taken place after stereopsis had identified the targets. Since this AM shows a stage, binocular standstill, not observed with luminance targets, it must be different from the AM observed when monocular identification is possible, and perhaps reflects a spatial averaging process in stereopsis which is overridden when the form of the moving surface is available to monocular pathways.

Many interesting studies on motion perception were reviewed by Sekuler et al (1978). They discuss the evidence for direction-specific movement channels and review both psychological and neurophysiological evidence. The chapter by Sekuler et al attests to the hectic activity in recent years. They review research using drifting and counterphase gratings, with and without retinal stabilization, and using random-dot arrays as adaptation and test stimuli, summarizing over 100 papers.

Direction-selective motion mechanisms appear to operate best at low SF and high temporal frequency, that is, at high velocities ( $Vel = TF/SF$ ). Watson et al (1980) showed that the direction selectivity of mechanisms for movement begins to disappear at low target velocities. Under such conditions, targets moving in opposite directions summate their contrast in a compound detection task; also, discrimination of direction of individual components at low velocities is poor relative to detection. Both these results are expected of a single, directionally nonselective mechanism. That this result is not due to the use of low temporal frequencies alone, but depends on low velocity, is shown by Stromeyer et al (1979), who showed that test patterns of both quite low temporal and spatial frequency (thus of moderate velocity) give rise to direction-selective adaptation.

There is also evidence for a dichotomy between a flicker/motion sensitive system and a pattern sensitive system. The pattern system is most sensitive to high spatial but low temporal frequencies, while just the reverse is true for the flicker/motion system. Another difference is that the motion system is direction selective, while the pattern system is direction insensitive, even in its response to moving patterns. A typical finding in this regard is a recent report by Levinson & Sekuler (1980). They found direction-selective adaptation (to a moving dot array) when they tested (with dots) for threshold elevation using a flicker criterion, but found no directional selectivity when using a pattern threshold criterion. These results extend the findings of Keeseey (1972), who found different thresholds for flicker and pattern detection. Although it may be possible at threshold to separate mechanisms for pattern and motion, Burr (1980) has recently shown that blur in moving dots disappears only when exposure duration is long enough for dot motion to be seen, indicating that motion mechanisms are also responsible for the analysis of the spatial form of the moving target.

An interesting question is how motion channels, which like SF channels have mostly been studied in threshold experiments, pool their outputs when operating above threshold. There is some evidence for quite broad pooling of information similar to the broad suprathreshold channels in the SF domain (Nachmias & Weber 1975). Levinson et al (1980) showed that above motion threshold (but below pattern threshold) two sheets of dots drifting in different directions are indiscriminable from a single sheet moving in the average direction, and this holds up to differences as large as  $180^\circ$ . The same conclusion can be reached from the elegant study of Riggs & Day (1980), who adapted to alternately presented orthogonally moving gratings and dot textures. They tested the aftereffect with a disk that contained two adjacent orthogonal gratings (or dots) at standstill, and found that the adjacent test gratings did not appear to separate and move orthogonally, but instead moved in unison according to the vectorial addition of the two aftereffect velocities.

An NP-model of the orthogonal movement aftereffects first reported by Brewster (1845) and studied by MacKay (1957, 1965) was presented by Georgeson (1976). He hypothesized that sustained cortical cells which are sensitive to the orientation of contours are antagonistically coupled to transient cells, in the same cortical hypercolumn, which themselves are sensitive to movement at right angles to those contours. According to MacKay & MacKay (1976) the experimental findings of Georgeson do not support this hypothesis since the sustained contour analyzers alone could account for his results. However, they acknowledge that some antagonism between visual channels for pattern and movement is an attractive NP-type model for orthogonal movement aftereffects.

A major event in motion perception was the publication of Ullman's book (1979), *The Interpretation of Visual Motion*. Here, within the framework of machine vision, Ullman proves an important theorem that "given three distinct orthographic views of four noncoplanar points in a rigid configuration, the structure and motion compatible with the three views are uniquely determined." This theorem gives the minimal requirements to recover a 3-D structure without phantom localizations. (There is only one possible misinterpretation: An object rotating by some angle  $\alpha$  and its mirror image rotating by  $-\alpha$  have the same orthographic projections.) Such a powerful theorem has many applications in movement studies, and Ullman discusses many of the movement illusions, from the Mach illusion to Ames's trapezoidal window, in the light of his theory.

Ullman's computational theory goes beyond autocorrelation although it still uses linear summation of local elements. In a recent paper, Lappin et al (1980) criticized this theory by showing that no linear summation of local processes can account for the perception of rigid three-dimensional objects. Lappin et al showed that a rotating sphere portrayed by a random-dot cinematogram (with many more than 4 dots) was vividly perceived, and this percept was dramatically degraded by the introduction of even a slight amount of decorrelation. However, this dramatic effect only held for the percept of a three-dimensional object and not for planar surfaces.

The role of stationary and transitory channels in foveal versus peripheral vision was suggested by MacKay (1964). Fixation upon one dot in a field of many randomly scattered dots leads to a loss of positional and detail information in the periphery: the random-dot textures become more uniform in size and appear almost regular. Nelson (1974) reported a similar perceptual reorganization while staring at an ant hill. He perceived either stationary gravel texture in the fovea or the moving ants in a wide peripheral area.

### 3.5 Global Stereopsis

During the 20 years since the introduction of RDS into psychology (Julesz 1960), this field has grown vigorously and arborized in several directions. Problems of false (phantom) target elimination, cooperativity, hysteresis effects, parallel versus serial models, disparity averaging, cyclopean MTF, hypercyclopean SF channels, problems of fusion, diplopia, and rivalry, clinical testing for stereoblindness, and isoluminance color stereograms are some of the main research activities.

That global stereopsis of RDS is basically different from that of classical targets has been known conceptually and experimentally since 1960. Indeed, the elimination of false localizations in RDS—a prodigious feat in

random-line stereograms with vernier breaks (Julesz & Spivack 1967)—is not necessary in classical stereograms with conspicuous monocular cues. Furthermore, Fender & Julesz (1967) discovered a hysteresis effect under binocular retinal stabilization, and found 20 times larger cortical shifts for RDS than for simple line targets. This hysteresis for line targets was further corroborated for both nasal and temporal shifts by Diner (1978), and for RDS, under free viewing, a cortical shift in excess of  $4^\circ$  arc was measured by Hyson et al (1980). This stimulus complexity dependent hysteresis effect is the manifestation of a cooperative process at work.

This cooperativity was further corroborated by the findings that in ambiguous RDS, with several possible global states, a 4% unambiguous bias could initiate a disorder-order transition in a 50 msec brief flash, resulting in a single (the biased) global state (Julesz 1964), and this bias could exact its influence from 18 min arc disparity distance away (Julesz & Chang 1976). Since in 50 msec no vergence movements can be initiated and a 96% match for a serial search process would suffice, instead of the 100% match actually preferred by the stereopsis system, a parallel spring-coupled dipole model was proposed by Julesz & Chang (1976) in place of an earlier, serial cooperative model (Julesz 1971). This cooperative model eliminated false targets, found the biased organization, and exhibited hysteresis, a basic phenomenon of global stereopsis. Many other cooperative models of stereopsis have been proposed (Julesz 1963, Sperling 1970, Dev 1975, Nelson 1975, Marr & Poggio 1976, Mayhew & Frisby 1980b), but none of these explicitly exhibits hysteresis.

Most of these models assume that pools of binocular disparity detectors tuned to similar disparity values facilitate one another, while those tuned to values further apart are not combined or even inhibit each other. Such a global stereopsis unit is conceptually simple if one assumes that binocular disparity is encoded by a gamut of disparity detectors. Many relevant findings and models were reviewed by Julesz (1978a).

The false target problem has recently come under close scrutiny, derived from interest in the relation between luminance-domain channels and the mechanisms of stereopsis. An alternative to cooperative processing that has been considered, starting with the earliest demonstrations of random-dot stereopsis in 1960, is that large, spurious clusters in each random-dot image serve as conspicuous monocular cues which facilitate stereopsis (see Julesz 1961, discussion). Clusters could aid stereopsis in either of two distinct ways. First, it could be that conspicuous clusters help direct vergence eye movements and so cause the two stereo half-images to be brought into rough registration, whereupon finer disparity cues may be utilized. This view assumes that coarse features may be binocularly matched at quite large disparities.

The second possible benefit of coarse features has to do with their rarity. Large blobs in either eye's field may actually be unique within a reasonably large visual window, and so the false target problem for such blobs may be reduced to virtually nothing. Decisions about disparity in a local region based on large blobs might be made quite readily, and these decisions could then be used to influence finer disparity matches made on smaller, and possibly ambiguous, monocular features.

In addition, Richards (1977), using extremely narrow RDS targets in a tachistoscopic flash (violating the essence of RDS, which is the global distribution of information), found only a very small fusional area, and therefore argued that the false target problem might be rather overblown in the first place. His results, however, probably resulted from the use of targets too thin to be resolved by the stereoscopic system. Schumer & Julesz (1980b) recently showed that if the spatial configuration is optimized, discrimination thresholds of only a few minutes of arc at a pedestal of 50 min arc can be obtained with tachistoscopic RDS.

The critical issues, then, concern whether different size blobs are differentially utilized in stereopsis. Research on this question has tended to presume the translation of large blobs into low spatial frequencies, and of small features into high spatial frequencies. That SF channels might be utilized in stereopsis was demonstrated by Julesz & Miller (1975). They found that the fusion of a RDS made up of only a low SF spectrum is unaffected by high-frequency masking noise (and vice versa), but masking noise having a spectrum overlapping that of the stereogram disrupts stereopsis. Frisby & Mayhew (1977, Mayhew & Frisby 1978c) developed this idea into a particularly strong hypothesis (which Julesz and Miller cautiously avoided): binocular matches are made independently upon differently filtered images delivered by parallel and independent SF channels.

Mayhew & Frisby (1978c) tested this idea by studying contrast summation of two narrow bandpass filtered RDS with peak frequencies separated by a 4:1 ratio. They found that contrast threshold for stereopsis with the compound stereogram depended on the total power in the stereogram and not on the independent contrasts of the components, even taking probability summation into account. They conclude that there are probably early levels of stereopsis that are SF tuned, but that the final derivations of stable global percepts pool information over all of these channels. The early SF-tuned processes could be related to those binocular mechanisms shown to be SF-selective in threshold studies of dichoptic contrast summation (Blake & Levinson 1977) and masking (Legge 1979).

Surprisingly, neither of the stages in stereopsis seems to be orientation selective, since both masking and summation experiments with orientation filtered RDS show broad orientational interactions (Mayhew & Frisby



1978b,c). This conclusion was also drawn from the observation that the breaking up of diagonal connectivities in one half-image of a RDS impairs stereopsis no more than an equivalent amount of randomly introduced uncorrelation (Julesz 1964). These results are of special interest since physiologically identified candidates for fundamental disparity units are typically the orientation selective cortical receptive fields of visual areas 17 and 18 in cat and monkey as found by Pettigrew et al (1968), Hubel & Wiesel (1970), Poggio & Fischer (1977), von der Heydt et al (1978), Fischer & Krüger (1979), and Ferster (1979). However, the site of global stereopsis might not be only in area 17 (as Poggio's findings suggest) but might also be more central, for instance the medial temporal cortex, as the ablation studies in monkey by Cowey & Porter (1979) suggest. Interestingly, higher cortical areas show decreasing orientational tuning (Allman et al, in press). Some other early work on the neurophysiological basis of stereopsis was reviewed by Bishop (1973).

Particularly provocative is the view that channels tuned to lower SF code larger disparities while higher SF channels code small disparities and are capable of fine disparity resolution. Felton et al (1972) suggested such a connection when they reported that the bar width that gave the greatest disparity-specific adaptation increased with the adapting disparity, suggesting that broader bar widths are the strongest stimuli for those binocular mechanisms selective for large disparities. Richards & Kaye (1974) showed that the largest disparity for patent stereopsis increases with the width of the stimulus bars.

All these findings were incorporated into a new theory by Marr & Poggio (1979). They abandoned their earlier cooperative model and proposed a new model based on multiple SF channels associated with different disparity ranges, the use of vergence eye movements, and a buffer memory where the successful matches are stored. The key features of their model are that coarse SF channels encode large disparities, while fine SF channels encode only small disparities, and binocular matching takes place only between SF channels of the same coarseness. Furthermore, coarse channels control vergence movements and cause the left and right images to come within the codable disparity range of the fine channels, an idea earlier proposed by Sperling (1970).

Marr & Poggio assume SF channels to be the bar-masks of Wilson & Giese (1977) and compute the response of these channels to "white" noise, as might be used in a RDS. Marr & Poggio utilize zero crossings (the midpoints between adjacent light and dark patches) of the filtered image as the primitive matching elements because it allows them to use a powerful theorem by Logan (1977) that describes the distribution of zero crossings in a one-octave band-limited signal (Marr et al 1979). They find that only

5% of the time will a bar-mask filter with width  $w$  (of its excitatory region) contain two zero crossings, with the proviso that the gradients at the zero crossings have the same polarity. This proviso is essential since Julesz (1960) showed that contrast reversal of one stereo half-pair destroys stereopsis entirely. Thus, if binocular matches are made only within the disparity range  $\pm w/2$ , no false target will arise 95% of the time. After the largest blobs of  $w$  size are matched in the RDS, the vergence mechanism brings into the codable disparity range smaller SF channels that can match correspondingly smaller blobs without false targets.

This vergence movement-based scanning of the Marr-Poggio theory was disproved by Mayhew & Frisby (1979) and Schumer & Julesz (1980b). Mayhew & Frisby presented narrow-band filtered RDS for a brief flash. They claim to have refuted both the Felton et al (1972) proposal that low SF channels might feed only large disparity detectors and that high SF channels might feed only small ones, and the Marr-Poggio model based on this proposal. Both for filtered (10.8 c/deg center frequency) and unfiltered RDS, discrimination between 13' and 10.4' arc disparities was possible in less than 180 msec. Above 18' arc disparity even the unfiltered RDS required larger than 180 msec duration, indicating the need for vergence movements. Schumer & Julesz (1980b) found even stronger evidence against the Marr-Poggio theory. They presented a pair of dynamic RDS with  $\pm 50$  min arc disparities for 100 msec with one of the pair having a sinusoidally corrugated surface in depth while the other was flat. Even at such large disparities (three times the limit set by Marr and Poggio, based on 5% false matches), observers could easily discriminate between flat and mildly corrugated surfaces. Perhaps the vergence mechanism of this theory could be replaced by a cortical shift mechanism, but the Fender & Julesz (1967) kind of binocular cortical shift mechanism works only for slow pulling rates. Even if some other cortical mechanism might be evoked, its neural realization is an enigma, while a cooperative model based on lateral facilitation and inhibition is conceptually simple. But more importantly, it is most unlikely that bar-mask filters of 50 min arc width abound in the central  $10^\circ$  or so of the visual field, and the coarsest filters Marr and Poggio assume are more than three times narrower. This restores the false target problem with full force.

Let us stress that for large disparity RDS (outside Panum's fusional area) vergence strategies of correct eye movements, which can greatly improve with learning, have a crucial role. Small disparity static and dynamic RDS, within Panum's fusional area, do not require vergence movements, and can be fused within 80 msec in foveal regions (Julesz et al 1976). Further, the slow emergence of cyclopean targets in RDS is not due to their complexity but only to the magnitude of disparity they contain. Stereopsis for large disparity RDS does, however, improve with practice (Ramachandran &

Braddick 1973, Frisby & Clatworthy 1975, Saye & Frisby 1975, Maccracken et al 1977). The memory for vergence eye movements contains two steps. In the absence of monocular contours one has to learn to voluntarily make large vergence movements and then learn not to make a sudden vergence but to do it slowly, so that the Fender-Julesz hysteresis range does not collapse. This "cerebellar" learning is very different from the behavior of the 2 1/2-D sketch memory Marr & Poggio propose for smaller disparities.

So much space has been devoted to this model because it appeared to offer a "simpler" model of stereopsis than the cooperative model. However, this simplicity is illusory. Cooperativity (and hysteresis) is a much simpler notion than memory, based as it is on well specified nonlinear interactions. In favor of Marr and Poggio's theory it should be said that it shifted attention to the relationship between receptive field size and binocular disparity range and to how that relationship might bear on the elimination of false targets. Indeed, Burt et al (1979) observed markedly reduced limits for the maximum detectable brief depth-jump of a flat RDS in which large clusters of dots had been broken up. Schumer & Julesz (1980c) also found a large reduction in the maximum disparity pedestal at which stereopatterns (e.g. corrugated depth gratings) could be seen when clusters in the horizontal direction were broken up.

Thus, the evidence tends to favor the view that there exists an association between large disparities and low SF, though the complementary association between small disparities and high SFs, while logically plausible, lacks experimental support. Perhaps a connection between high SF channels and stereopsis is provided by a recently postulated disparity gradient limit of stereoscopic fusion by Burt & Julesz (1980), to be discussed in Section 3.6.

Mayhew & Frisby (1980a) proposed a model of global stereopsis based on simultaneous binocular matches and SF filtering. Disambiguation is based on possible matches in similar nonoriented SF filters followed by orientationally tuned nonlinear grouping processes. These nonlinear operations over a large global area constitute again a cooperative model. Mayhew & Frisby (1980b) also challenge the zero crossing assumption of Marr & Poggio (1979). They generated a stereogram composed of a triangle wave grating paired with a phase-varying ramp grating. Stereo pairs of this type present interesting ambiguities about which elements are to be selected for left-right matches. Instead of the zero-crossing matches of Marr & Poggio (1979), the visual system seems to use the peaks of the luminance profiles.

Another interesting area of research that again illustrates a fundamental difference between global stereopsis of RDS and monocularly recognizable stereograms involves isoluminant color stereograms. While till 1971 it seemed futile to try to overcome the optical registration problems necessary

to present isoluminance colored RDS (Julesz 1971), this technical feat was solved by Lu & Fender (1972). They showed that a 100x100 cell RDS with 40x40 cell center target would not yield depth around the isoluminance setting, even though the individual cells were clearly perceived in color and resolved in shape. This was the more curious since Ramachandran et al (1973) and Comerford (1974), who used monocularly recognizable stereograms, found stereopsis under isoluminance conditions. The complex optical problems of registration were made unnecessary by an ingenious invention by Gregory (1977), who confirmed both findings, i.e. no depth under isoluminance for RDS, depth under the same condition for classical stereograms. Finally, Ramachandran & Gregory (1978) showed that even stroboscopic movement perception would cease for random-dot cinematograms under isoluminance.

These findings were carefully retested by de Weert (1979), and he also concluded that for classical color line stereograms depth could not be eliminated at any luminance setting, while for cyclopean stereograms stereopsis could be made to disappear even when the setting deviated from isoluminance.

Whether these findings mean that the "cyclopean retina" is colorblind, or merely that RDS are more sensitive to a dramatic reduction of contrast than classical stereograms, is a problem worth studying. The first possibility is of special interest in light of findings that the cerebral cortex contains modules functionally specialized for color, depth, motion, etc (Zeki 1978).

Other interesting work related to stereopsis is reviewed in other sections, particularly in Section 4.0, on hypercyclopean channels. Here we stress only the maturity this field has achieved. We have reached a stage in the study of global stereopsis where models of great complexity and generality can be proposed and tested.

We hope that findings reviewed here also counter the opinion expressed by De Valois & De Valois (1980) "... that while Julesz random-dot stereograms are very useful analytic tools, they nonetheless constitute an artificially difficult problem for the visual system." That detailed depth resolution can be obtained in briefly flashed RDS in the order of about 1° arc disparities shows the robustness of this technique as well.

### *3.6 Scaling Invariance Principles in Depth and Movement Perception*

To our knowledge, a scaling invariance principle was first stated by Tyler (1973) in the context of stereopsis of sinusoidally wiggling vertical lines. Disparity at the limit of fusion changed inversely with SF. Therefore, this limit did not change as the observation distance was varied, which defines the principle of scaling invariance. For stereograms composed of vertical

lines wiggling in square wave fashion, however, Tyler (1975) failed to observe disparity scaling. The scaling principle also holds for global stereopsis (Tyler 1974, Burt et al 1978). For motion perception in random-dot cinematograms disparity scaling also holds, since Bell & Lappin (1973) increased the size of the picture elements together with that of the target area and did not observe any change in performance.

It is only recently that the deeper reason for the scaling principle has been understood for stereopsis. Burt & Julesz (1980) observed a fundamental and simple law for stereopsis that surprisingly was not explicitly stated before in mathematical terms, although qualitatively it had been noted from Helmholtz (1925) to Braddick (1970). When two dots at different distances from the observer and far from each other (in the x-y plane) can both be fused, then when the distance between the two is reduced while keeping their disparity constant, one of the two dots becomes diplopic. Burt & Julesz observed that if the disparity gradient (the ratio between the disparity difference and the distance) between the dots is larger than one, fusion ceases, even if the disparity difference is well within Panum's classical fusional area. For dot separations as small as 4' of arc, fusion was lost at 4' disparity, or less than one-third of the value reported by Ogle (1964) for the width of Panum's area in the fovea. Such a disparity gradient limit implies scaling invariance. This disparity gradient limit explains why two dots on a horizontal line cannot be fused so that the order of the dots is reversed in one eye with respect to the other. Such a "folding back" on itself of the fusion space results in a disparity gradient  $>2$ , outside the bounds for fusion. Similarly it explains why in Panum's limiting case one image must become diplopic since here the disparity gradient equals 2. This supports the argument by Kaufman & Lane (1979) that in Panum's limiting case depth is due to eye vergence rather than multiple fusion. Perhaps this principle of a disparity gradient limit elucidates why high SF channels (activated by nearby samples in the x-y plane) cannot encode large disparities between these samples.

The scaling invariance principle for movement perception was used as a guide by Burt & Sperling (1980) to derive a mathematical model of AM. They created an ambiguous display composed of dots, where apparent motion between dots could be perceived along many possible paths. For any given path, given by  $d_i$  and by  $t_i$ , the distance and time interval between successive elements of path  $P_i$ , they associated a stimulus strength  $S_i$  for motion. From scaling invariance, which they observed, it follows that  $S_i$  is a separable function of  $d$  and  $t$ , and they derive a logarithmic relationship between the  $t$  value where AM is equally likely to be perceived along paths  $i$  and  $j$  and  $d_i$  and  $d_j$ . They also observed that when successive elements along a path differ in orientation or size, the perceived motion along this

path was not necessarily weaker than motion along a path composed entirely of identical elements. They account for their results by postulating motion analyzing channels in the visual system that are not feature selective and that differ in spatial but not in temporal characteristics. It is particularly interesting that the postulated motion-detecting channels are indifferent to element orientation, similar to the channels for global stereopsis as discussed in Section 3.4.

### *3.7 Depth and Movement*

Our emphasis on stereopsis is based on its importance as a model system for cooperativity and as a tool for operationally skipping early stages, but not on its importance as the most powerful depth cue. Gibson (1950) emphasized that the most powerful depth cue was monocular movement parallax, since even one-eyed observers could estimate the direction in which an airplane was flying. Gibson proposed that the optical flow pattern was sufficient to determine the direction in which one was moving. In important papers, Lee (1974) and Nakayama & Loomis (1974) elaborated on Gibson's proposal and provided mathematical descriptions of the information available in optical flow patterns. Nakayama & Loomis also showed how a particular higher-order variable of optical flow might be extracted by velocity-sensitive neurons. Recently, Regan & Beverley (1978) proposed that changing-size tuned channels might locally extract information that would enable the visual system to construct global flow patterns without using distant interactions. Furthermore, Regan & Cynader (1979) found neurons in the cat cortex that operate only when a pair of nearby edges move in opposite directions, but are not sensitive to movement per se since they are not active when the edges move in the same direction. In a further observation, Regan & Beverley (1979) found that inspecting a radial flow pattern depressed visual sensitivity to changes in the size of a small test square, but only when the square was located near the focus of the adapting flow pattern. They regard this as evidence that their neurophysiological local channels tuned to expansion-contraction can find the fixed point in any global flow pattern. Once again, here is a rare case when a type PP model seems to be complemented by a type NP model.

Temporal factors in stereopsis were studied by Morgan (1975) and independently by Ross & Hogben (1975). They found a Pulfrich-like effect with AM in the horizontal direction (instead of RM as in the classical Pulfrich illusion). That dimming one eye's view was equivalent to retarding that view was first shown with dynamic RDS by Julesz & White (1969). In an AM study Burr & Ross (1979) presented spots of light moving stroboscopically against a background of dynamic noise. Binocular delay of the moving dots (without real binocular disparity, only disparity on the AM-generated interpolated positions) yielded vivid stereoscopic depth. Further, temporal delay

combined additively with spatial disparity. The threshold temporal delay of 160  $\mu$ sec corresponded to 2 sec arc virtual disparity (which is the smallest stereoacuity that can be achieved with real disparity under optimal laboratory conditions). Since frames were presented every 50 msec, the stereoscopic system could calculate delays of 0.25% of the presentation period!

Williams & Lit (1980) studied the Hess effect, a monocular analog of the Pulfrich effect. When images of a pair of vertically aligned targets of unequal luminance move horizontally across the retina of a stationary eye, the brighter target appears to lead the dimmer. This is an interesting phenomenon and could be studied with gratings having different SF, since the MTF of the human visual system dims gratings with higher SFs. Indeed, Campbell & Maffei (1979) observed that when two gratings were rotated with the same velocity, the one with the higher SF seemed to slow down, and at low contrast even appeared at a standstill, while the lower SF grating seemed to rotate.

#### 4.0 HYPERCYCLOPEAN CHANNELS

The search for multiple channels, so successfully carried out a decade ago in the luminance domain, has lately brought similar findings beyond the "cyclopean retina" of Julesz (1971). Indeed, the study of aftereffects to adaptation, and of detection and discrimination thresholds following adaptation and during masking, that worked so admirably for the luminance stage, seem to work for the hypercyclopean stage as well.

Because cyclopean methodology skips earlier receptor and transducer stages and selectively stimulates the rich network of the CNS, it might reveal general properties of brain organization as a processor of information. Indeed, the many retinal and LGN stages specialized for processing luminance information are "blind" to the cyclopean information portrayed by RDS, particularly dynamic RDS (Julesz 1971, Ross 1974, Breitmeyer et al 1975).

Traditionally, research in vision and audition has examined how the prothetic continua of brightness (luminance) or loudness (pressure) are converted into the metathetic continua of spatial-extent, SF, or pitch (Stevens 1975). In cyclopean research the input variable is already a metathetic quantity (e.g. binocular disparity) and the output (e.g. segregated areas at a certain depth) also consists of metathetic quantities. It would therefore seem that problems of local-global interactions, nonlinearity-linearity, cooperativity-memory, etc could be more generally studied at the hypercyclopean level than at the hypocyclopean level.

It took only 4 years from the introduction of the random-dot stereogram methodology into psychology by Julesz (1960) until Papert (1964) produced a cyclopean figural aftereffect of tilt and found that RDS-produced edges

yielded as large aftereffects as conventional edges. A similar cyclopean figural aftereffect of contour displacement was reported by Walker & Krüger (1972). The first three-dimensional repulsion aftereffect of perceived depth in RDS was observed by Blakemore & Julesz (1971), but they could not draw conclusions about the nature of the stereoscopic mechanisms involved because there are a number of underlying alternative mechanisms that could account for their findings. As has been pointed out by Ganz (1966), Blakemore & Sutton (1969), Anstis (1975) and Nelson (1975), the presence of figural aftereffects suggests the existence of two or more channels along which stimuli are represented. In this view an aftereffect is based on the imbalance in the overall response distribution following fatigue or adaptation of a subset of these channels. What is left unspecified by the Blakemore & Julesz finding is the specific nature of these stereoscopic channels.

A relevant study was performed by Tyler (1975), who reported aftereffects of tilt and size following prolonged viewing of a RDS portraying a corrugated sinusoid in depth (disparity grating). He also observed a perceived shift in the SF of a test disparity grating after adapting to a disparity grating of slightly different SF. Tyler inferred—by analogy to similar findings with luminance gratings by Campbell & Maffei (1971), Blakemore & Sutton (1969) and Blakemore et al (1970)—the existence of hypercyclopean channels selective for the orientation and SF of depth patterns. Schumer & Ganz (1979a) studied the subthreshold summation of disparity gratings with  $f$  and  $3f$  corrugation frequencies and showed that at detection threshold each hypercyclopean channel is sensitive only to corrugated gratings of a specific frequency. Further, this threshold does not depend on the relative phase (spatial position) of the two disparity gratings. These cyclopean channels appear to interact with each other according only to probability summation. Schumer & Ganz also found that disparity gratings can selectively adapt stereoscopic channels tuned to the SF of disparity modulation. These channels are bandpass, but are more broadly tuned than the analogous channels in the luminance domain. The hypercyclopean channel bandwidth revealed by adaptation is 2-3 octaves (Schumer & Ganz 1979a), while hypocyclopean channel bandwidths measured by adaptation (Blakemore & Campbell 1969) and by filtered masking noise (Stromeyer & Julesz 1972) are about 1-1.5 octaves.

The masking noise paradigm was tried in the hypercyclopean domain by Tyler & Julesz (1978) using a narrowband compound disparity grating to mask a disparity grating. They found sharper critical bands than Schumer & Ganz, and thus the suprathreshold masking experiments reveal more global hypercyclopean channels in the spatial domain than do threshold experiments with adaptation. This is in contrast to the luminance masking experiments which yield similar critical bands to the values obtained by



adaptation. Whether frequency beats "sharpen" the channel bandwidth estimates of Tyler & Julesz (1978) as was the case with "sharp" luminance channels (see Section 2.1) remains to be seen.

Both the adaptation and masking results with luminance gratings suggest antagonistic center-surround hypercyclopean receptive fields, which would explain the bandpass phenomena. Anstis et al (1978) observed a hypercyclopean Craik-O'Brien-Cornsweet illusion in which a spatial disparity transient causes a perceived global depth shift between two sides of a RDS surface which are actually of the same disparity. This also suggests lateral inhibitory interactions among pools of disparity units. Let us stress that the disparity-grating-frequency tuned hypercyclopean channels should not be confused with the SF-tuned channels in the luminance domain that are utilized in stereopsis, and which were discussed in Section 3.5.

Up to this point, the similarity between hypercyclopean-frequency-tuned channels and those in the luminance domain is striking. If these hypercyclopean channels were to be linear in disparity, then the Fourier transform of their SF tuning curve would give their disparity weighting function (receptive field profile) in the spatial domain. Indeed, a powerful depth (disparity) averaging effect in stereopsis helps to probe the linearity of this system in the disparity domain. The definition of linearity requires that if a hypercyclopean channel is stimulated by a spatiotemporal disparity signal that falls within its critical band, then another spatiotemporal disparity signal having the same average disparity distribution elicits the same output.

A number of studies with classical line stereograms have revealed disparity averaging (Tyler 1971, Richards 1972, Stigmar 1970, Foley 1976). Foley (1976, Birch & Foley 1979) showed that contributions to disparity averaging mechanisms are weighted according to the relative luminances of the target lines. Foley & Richards (1978) observed disparity averaging for binocular lines with disparities as great as  $4^\circ$  arc and for mixtures of nonsymmetric disparities. The averaging of signals from disparity detector pools is a phenomenon foreign to both known physiological findings as well as to psychophysically based models of stereopsis. All these models assume that disparity detectors, when activated, convey fixed disparity values to higher centers, though the hysteresis effect of Fender & Julesz (1967) clearly argues for an alternative interpretation.

Disparity averaging with RDS was first shown by Kaufman et al (1973), who presented the two combined half-images of a RDS to one eye, but a weighted mixture of the two half-images to the other eye, and varied the ratio of their brightnesses but kept their total brightness constant. As the ratio of the brightnesses varied (but was different from 1), depth was seen. Perceived depth depended on the disparity of the cyclopean target, but also increased linearly with the brightness ratio for smaller disparities (4-8 min

arc). For slightly larger disparities (9-10 min arc), however, perceived depth jumped rapidly to full depth as soon as small imbalances in the half-field brightnesses were introduced.

Disparity averaging with RDS was studied in detail by Schumer (1979, Schumer & Ganz 1979b), using the technique of portraying multiple surfaces by even and odd rows of a RDS, respectively. He found that threshold for a corrugated sinusoid presented simultaneously and spatially overlapping with a flat surface was exactly twice the threshold for a corrugated sinusoid presented alone. This follows if the sinusoid and flat surface average to produce an effective stimulus with one-half the amplitude of the sinusoid alone. Further, disparity averaging was found to hold above threshold. The discrimination of a sinusoidal from a square wave disparity grating was first measured and found to occur well above detection threshold. It was then shown that in order to discriminate a sinusoid presented simultaneously with a flat surface from a square wave, the sinusoid again required twice the amplitude of the just-discriminable sinusoid when presented alone. Thus the combined surfaces were perceived according to disparity averaging.

What are the disparity limits of this averaging? The Kaufman et al (1973) study mentioned earlier showed linear weighting of disparity information up to about 8 min arc. Recently, Schumer & Julesz (1980d) used a different method to establish limits for disparity averaging. A split-screen display was used to test the discriminability of a sinusoidal disparity grating from a similar grating, but of twice the amplitude, and presented simultaneously with a flat RDS surface. As expected, discrimination was impossible at low amplitudes, but at about 4 min arc, the percept of the sine plus flat surface became discriminable by the presence of small protruding "nipples" at the peaks and troughs. This shows a sudden departure from the regime of disparity averaging and entry into a nonlinear domain of disparity processing.

Schumer & Julesz (1980b) measured forced-choice discrimination between flat and sinusoidal corrugated surfaces with large mean disparities (depth pedestals) using presentation times of 100 msec. Sensitivity was measured for a range of pedestal sizes and corrugation frequencies. It was found that the hypercyclopean MTF for disparity changes its shape (gets narrower) as the disparity pedestal increases, showing further the nonlinear behavior of the stereopsis system beyond the limits of disparity averaging. It is this nonlinear range between 4-50 min arc disparities where the nonlinear excitatory and inhibitory interactions between disparity detectors are taking place and where cooperative models of stereopsis are suggested.

We have seen how disparity domain interactions lead to hypercyclopean aftereffects, depth averaging, etc which Nelson (1977) described in a scholarly paper on "the plasticity of correspondence." The paper is a treasure

chest of perceptual literature related to binocular vision, as is his earlier paper on a cooperative model of stereopsis (Nelson 1975). He discusses several new "induced effects" (based on vertical disparity) which are one of the most important plastic phenomena of stereopsis. Arditi (1979) studied the induced effect and noted that oblique structures in the stereograms are necessary to obtain it.

The selective stimulation of the cyclopean retina has yielded many hypercyclopean results that are analogous to hypocyclopean findings. This fact gives us confidence in the psychological methods used to explore both processing stages. This fact is also reassuring in that some general principles of brain functioning have been revealed that go far beyond luminance processing. On the other hand, hypercyclopean phenomena exhibit some complex properties—cooperativity and plasticity—that are less prevalent at earlier processing stages. They seem to be the next logical step to study. Furthermore, the ubiquitous microcomputer brings the real-time generation of dynamic RDS within the reach of any laboratory. That one can operationally skip several processing stages by psychological means alone—merely by utilizing binocularity—is a lucky break and should continue to be exploited by psychologists and neurophysiologists whenever possible.

## 5.0 EPILOGUE

We have focused on select topics that we feel constitute a new, unified trend in visual perception. We hope that our review has benefited from this unifying principle and shows where progress was made and what the unsolved problems might be. Among important findings and ideas that we could not review here are the interesting global theories of perception ranging from the brush-fire model of Blum (1973) to the relativistic model of movement foreshortening by Caelli et al (1978). Unfortunately, in these global theories the perceptual atoms are not defined, so they do not fit in our main theme. Also omitted is the Lie-algebra theory of Hoffman (1977, 1978) which is based on local operators, but these operators are so general that countless perceptual or neurophysiological atoms could be proposed as candidates, and those suggested by Hoffman are rather speculative, as discussed by Caelli (1977), Bruter (1977), Dodwell (1977), and Fregnac (1977).

The interesting field of perceptual constancies was also omitted except for scaling invariance in movement and depth perception. The crucial problems of foveal attention and eye movements were only hinted at, and temporal factors in vision were only briefly treated. While we discussed some top-down processes and learning phenomena, we only did so to emphasize that even in the earliest processing stages central processes do participate.

Within our own speciality we had to skip important work on binocular

rivalry and binocular summation, infant perceptual development, amblyopia and stereoblindness, diagnosis of impaired stereopsis by evoked potentials elicited by dynamic RDS and random-dot correlograms, hemispheric localization and horopter problems in global stereopsis, psychoanatomic studies (the tracing of the information flow by RDS).

We hope that the work we reviewed gave a sense of the new collaborative spirit which appears to be infusing diverse areas of vision research that not long ago were pursued rather independently. It seems that this cohesion reflects more than some analogies between different descriptive levels, but rather signifies an appreciation of how these levels organize in an integrated system.

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#### Literature Cited

- Albrecht, D. G., De Valois, R. L., Thorell, L. G. 1980. Visual cortical neurons: are bars or gratings the optimal stimuli? *Science* 207:88-90
- Allman, J. M., Baker, J. F., Newsome, W. T., Petersen, S. E. 1980. The cortical visual areas of the owl monkey: Topographic organization and functional correlates. In *Multiple Cortical Somatic Sensory-Motor, Visual and Auditory Areas and Their Connectivities*, ed. C. N. Woolsey. Clifton, NJ: Humana. In press
- Anstis, S. M. 1975. What does visual perception tell us about visual coding. In *Handbook of Psychobiology*, ed. M. S. Gazzaniga, C. Blakemore. New York: Academic
- Anstis, S. M. 1978. Apparent movement. See Held et al 1978, pp. 655-73
- Anstis, S. M., Howard, I. P., Rogers, B. 1978. A Craik-O'Brien-Cornsweet illusion for visual depth. *Vision Res.* 18:213-17
- Arditi, A. R. 1979. *An explanation of the induced size effect in binocular vision*. PhD thesis. New York Univ., NY
- Arend, L. E., Lange, R. V. 1979. Phase-dependent interaction of widely separated spatial frequencies in pattern discrimination. *Vision Res.* 19:1089-92
- Arend, L. E., Lange, R. V. 1980. Narrow-band spatial mechanisms in apparent contrast matching. *Vision Res.* 20: 143-47
- Armington, J. C., Krauskopf, J., Wooten, B. R., eds. 1978. *Visual Psychophysics and Physiology*. New York: Academic. 488 pp.
- Atkinson, J., Campbell, F. W. 1974. The effect of phase on the perception of compound gratings. *Vision Res.* 16:337-44
- Barlow, H. B. 1953. Summation and inhibition in the frog's retina. *J. Physiol.* 119:69-88
- Barlow, H. B. 1978. The efficiency of detecting changes of density in random dot patterns. *Vision Res.* 18:637-50
- Beck, J. J. 1967. Perceptual grouping produced by line figures. *Percept. Psychophys.* 2:491-95
- Beck, J. J. 1973. Similarity grouping of curves. *Percept. Mot. Skills* 36:1331-41
- Beck, J. J., Ambler, B. 1972. Discriminability of differences in line slope and line arrangement as a function of mask delay. *Percept. Psychophys.* 12:33-38
- Bekesy, G. von. 1929. Auditory thresholds. Transl. E. G. Wever 1960. *Experiments in Hearing*. New York: McGraw-Hill
- Bell, H. H., Lappin, J. S. 1973. Sufficient conditions for the discrimination of motion. *Percept. Psychophys.* 14:45-50
- Bergen, J. R., Wilson, H. R., Cowan, J. D. 1979. Further evidence for four mechanisms mediating vision at threshold: sensitivities to complex gratings and aperiodic stimuli. *J. Opt. Soc. Am.* 69:1580-86
- Biederman, I. 1980. On the semantics of a glance at a scene. See Kubovy & Pomerantz 1980

- Birch, E. E., Foley, J. M. 1979. The effects of duration and luminance on binocular depth mixture. *Perception* 8:263-67
- Bishop, P. O. 1973. Neurophysiology of binocular single vision and stereopsis. In *Handbook of Sensory Physiology*, ed. R. Jung, 7(3A):256-305. Berlin: Springer
- Blake, R., Levinson, E. 1977. Spatial properties of binocular neurones in the human visual system. *Exp. Brain Res.* 27: 221-32
- Blakemore, C. 1978. Maturation and modification in the developing visual system. See Held et al 1978, pp. 377-436
- Blakemore, C., Campbell, F. W. 1969. On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. *J. Physiol.* 203:237-60
- Blakemore, C., Julesz, B. 1971. Stereoscopic depth aftereffect produced without monocular cues. *Science* 171:286-88
- Blakemore, C., Nachmias, J., Sutton, P. 1970. The perceived spatial-frequency shift: Evidence for frequency-selective neurones in the human brain. *J. Physiol.* 210:727-50
- Blakemore, C., Sutton, P. 1969. Size adaptation: A new aftereffect. *Science* 166: 245-47
- Blum, H. 1973. Biological shape and visual science. *J. Theor. Biol.* 38(1):205-87
- Braddick, O. J. 1970. Binocular fusion and perceptual processing. *Ophthalmol. Opt.* 10:993-1003
- Braddick, O. J. 1974. A short-range process in apparent motion. *Vision Res.* 14:519-27
- Braddick, O. J., Adlard, A. 1978. Apparent motion and the motion detector. In *Visual Psychophysics and Physiology*, ed. J. C. Armington, J. Krauskopf, B. R. Wooten. New York: Academic
- Braddick, O. J., Campbell, F. W., Atkinson, J. 1978. Channels in vision: Basic aspects. See Held et al 1978, pp. 3-38
- Breitmeyer, B. G. 1973. A relationship between the detection of size, rate, orientation and direction in the human visual system. *Vision Res.* 13:41-58
- Breitmeyer, B. G., Julesz, B. 1975. The role of on and off transients in determining the psychophysical spatial frequency response. *Vision Res.* 15:411-15
- Breitmeyer, B. G., Julesz, B., Kropfl, W. 1975. Dynamic random dot stereograms reveal an up-down anisotropy and a left-right isotropy between cortical hemifields. *Science* 187:269-70
- Brewster, D. 1845. Notice on two new properties of the retina. *Trans. Br. Assoc.*, p. 8
- Brindley, G. S. 1960. Two more visual theorems. *Q. J. Exp. Psychol.* 12:110-12
- Bruter, C. P. 1977. On Hoffman's work. *Cah. Psychol.* 20:183-95
- Burr, D. C. 1980. Motion smear. *Nature* 284:164-65
- Burr, D. C., Ross, J. 1979. How does binocular delay give information about depth? *Vision Res.* 19:523-32
- Burt, P., Julesz, B. 1980. A disparity gradient limit for binocular fusion. *Science* 208:615-17
- Burt, P., Julesz, B., Kropfl, W. 1979. Disparity limits set by element and target shape in random-dot stereograms. *Invest. Ophthalmol. Visual Sci.* 18:174 (Suppl.)
- Burt, P., Sperling, G. 1980. Time, distance, and feature trade-offs in visual apparent motion. *Psychol. Rev.* In press
- Burt, P., Sperling, G., Julesz, B. 1978. The range of stereopsis. *J. Opt. Soc. Am.* 68:1365
- Caelli, T. M. 1977. Criticism of the LTG/NP Theory of perceptual psychology. *Cah. Psychol.* 20:197-204
- Caelli, T. M., Hoffman, W., Lindman, H. 1978. Subjective Lorentz transformations and the perception of motion. *J. Opt. Soc. Am.* 68:402-11
- Caelli, T. M., Julesz, B. 1978. On perceptual analyzers underlying visual texture discrimination: Part I. *Biol. Cybern.* 28:167-75
- Caelli, T. M., Julesz, B. 1979. Psychophysical evidence for global feature processing in visual texture discrimination. *J. Opt. Soc. Am.* 69:675-78
- Caelli, T. M., Julesz, B., Gilbert, E. N. 1978. On perceptual analyzers underlying visual texture discrimination: Part II. *Biol. Cybern.* 29:201-14
- Campbell, F. W., Cooper, G. F., Enroth-Cugell, C. 1969. The spatial selectivity of the visual cells of the cat. *J. Physiol.* 203:223-35
- Campbell, F. W., Maffei, L. 1971. The tilt after-effect: A fresh look. *Vision Res.* 11:833-40
- Campbell, F. W., Maffei, L. 1979. Stopped visual motion. *Nature* 278:192
- Campbell, F. W., Robson, J. G. 1968. Application of Fourier analysis to the visibility of gratings. *J. Physiol.* 197:551-66
- Cannon, M. W. Jr. 1979. Contrast sensation: A linear function of stimulus contrast. *Vision Res.* 19:1045-52
- Carlson, C. R., Anderson, C. H., Moeller, J. R. 1980. Visual illusions without low spatial frequencies. *Invest. Ophthalmol. Visual Sci.* 19:165 (Suppl.)

- Carpenter, R. H. S., Blakemore, C. 1973. Interactions between orientations in human vision. *Exp. Brain Res.* 18:287-303
- Cherry, E. C. 1953. Some experiments on the recognition of speech with one and with two ears. *J. Acoust. Soc. Am.* 25:975-79
- Comerford, J. P. 1974. Stereopsis with chromatic contours. *Vision Res.* 14:975-82
- Coren, S., Girgus, J. S. 1978. Visual illusions. See Held et al 1978, pp. 549-68
- Cowey, A., Porter, J. 1979. Brain damage and global stereopsis. *Proc. R. Soc. London Ser. B* 204:399-407
- Dev, P. 1975. Perception of depth surfaces in random-dot stereograms: A neural model. *Int. J. Man-Mach. Stud.* 7: 511-28
- De Valois, K. K. 1977a. Independence of black and white: Phase specific adaptation. *Vision Res.* 17:209-15
- De Valois, K. K. 1977b. Spatial frequency adaptation can enhance contrast sensitivity. *Vision Res.* 17:1057-65
- De Valois, R. L. 1973. Central mechanisms of color vision. See Bishop 1973, pp. 209-53
- De Valois, R. L., De Valois, K. K. 1980. Spatial vision. *Ann. Rev. Psychol.* 31: 309-41
- de Weert, C. M. M. 1979. Colour contours and stereopsis. *Vision Res.* 19:555-64
- Dichgans, J., Brandt, T. 1978. Visual-vestibular interaction: Effects on self-motion perception and postural control. See Held et al 1978, pp. 755-804
- Diner, D. 1978. *Hysteresis in human binocular fusion: A second look.* PhD thesis. Calif. Inst. Technol., Pasadena
- Dodwell, P. C. 1977. Criteria for a neurophysiological theory of perception. *Cah. Psychol.* 20:175-82
- Dodwell, P. C. 1978. Human perception of patterns and objects. See Held et al 1978, pp. 523-49
- Estevez, O., Cavonius, C. R. 1976. Low-frequency attenuation in the detection of gratings: sorting out the artefacts. *Vision Res.* 16:497-500
- Felton, T. B., Richards, W., Smith, R. A. 1972. Disparity processing of spatial frequencies in man. *J. Physiol.* 225: 349-62
- Fender, D. H., Julesz, B. 1967. Extension of Panum's fusional area in binocularly stabilized vision. *J. Opt. Soc. Am.* 57: 819-30
- Ferster, D. 1979. *Neurons sensitive to binocular depth in areas 17 and 18 of the cat visual cortex.* Soc. Neurosci. 9th ann. meet., Abstr. 783
- Fischer, B., Krüger, J. 1979. Disparity tuning and binocularity of single neurons in cat visual cortex. *Exp. Brain Res.* 35:1-8
- Foley, J. M. 1976. Binocular depth mixture. *Vision Res.* 16:1263-67
- Foley, J. M. 1978. Primary distance perception. See Held et al 1978, pp. 181-214
- Foley, J. M., Legge, G. E. 1979. Contrast detection and discrimination. *Invest. Ophthalmol. Visual Sci.* 18:250-51 (Suppl.)
- Foley, J. M., Richards, W. A. 1978. Binocular depth mixtures with non-symmetric disparities. *Vision Res.* 18:251-56
- Foster, D. H., Mason, R. J. 1980. Irrelevance of local position information in visual adaptation to random arrays of small geometric elements. *Perception* 9: 217-21
- Fox, R. 1978. Visual masking. See Held et al 1978, pp. 629-54
- Fregnac, Y. 1977. Contradictions between L.T.G. model and neurophysiology. *Cah. Psychol.* 20:209-11
- Frisby, J. P., Clatworthy, J. L. 1975. Learning to see complex random-dot stereograms. *Perception* 4:173-78
- Frisby, J. P., Mayhew, J. E. W. 1977. Global processes in stereopsis: some comments on Ramachandran and Nelson (1976). *Perception* 6:195-206
- Frome, F. S., Levinson, J. Z., Danielson, J. T., Clavdetscher, J. E. 1979. Shifts in perception of size after adaptation to gratings. *Science* 206:1327-29
- Fuortes, M. G. F., Hodgkin, A. L. 1964. Changes in time scale and sensitivity in the omatidia of Limulus. *J. Physiol.* 172:239-63
- Furchner, C. S., Ginsburg, A. P. 1978. "Monocular rivalry" of a complex waveform. *Vision Res.* 18:1641-48
- Gagalowicz, A. 1979. *Stochastic texture fields synthesis from a priori given second-order statistics.* Proc. Pattern Recognition and Image Processing Conf., Aug. 6-8, Chicago, pp. 376-81
- Ganz, L. 1966. Mechanism of the figural aftereffects. *Perception* 73:128-50
- Ganz, L. 1978. Sensory deprivation and visual discrimination. See Held et al 1978, pp. 437-88
- Georgeson, M. A. 1976. Antagonism between channels for pattern and movement in human vision. *Nature* 259:413-15
- Georgeson, M. A., Sullivan, G. D. 1975. Contrast constancy: deblurring in human vision by spatial frequency channels. *J. Physiol.* 252:627-56
- Gibson, E. J. 1978. Perceptual aspects of the reading process and its development. See Held et al 1978, pp. 731-52

- Gibson, J. J. 1950. *The Perception of the Visual World*. Boston: Houghton Mifflin
- Gibson, J. J. 1979. *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin
- Ginsburg, A. P. 1975. Is the illusory triangle physical or imaginary? *Nature* 257:219-20
- Ginsburg, A. P., Cannon, M. W., Nelson, M. A. 1980. Suprathreshold processing of complex visual stimuli: Evidence for linearity in contrast perception. *Science* 208:619-21
- Glass, L. 1969. Moire effect from random dots. *Nature* 243:578-80
- Glass, L., Switkes, E. 1976. Pattern recognition in humans: Correlation which cannot be perceived. *Perception* 5:67-72
- Gouras, P. 1970. Trichromatic mechanisms in single cortical neurons. *Science* 169:489-92
- Graham, N. 1977. Visual detection of aperiodic spatial stimuli by probability summation among narrowband channels. *Vision Res.* 17:637-52
- Graham, N. 1980a. Psychophysics of spatial-frequency channels. See Kubovy & Pomerantz 1980
- Graham, N. 1980b. Spatial frequency channels in human vision: Detecting edges without edge detectors. See Harris 1980
- Graham, N., Nachmias, J. 1971. Detection of grating patterns containing two spatial frequencies: A comparison of single-channel and multiple-channel models. *Vision Res.* 11:251-59
- Graham, N., Robson, J. G., Nachmias, J. 1978. Grating summation in fovea and periphery. *Vision Res.* 18:815-25
- Graham, N., Rogowitz, B. E. 1976. Spatial pooling properties deduced from the detectability of FM and quasi-AM gratings: a reanalysis. *Vision Res.* 16:1021-26
- Green, D. M., Luce, R. D. 1975. Parallel psychometric functions from a set of independent detectors. *Psychol. Rev.* 82:483-86
- Gregory, R. L. 1977. Vision with isoluminant colour contrast: 1. A projection technique and observations. *Perception* 6:113-19
- Gregory, R. L., Harris, J. 1974. Illusory contours and stereo depth. *Percept. Psychophys.* 15:411-16
- Hamerly, J. R., Quick, R. F., Reichert, T. A. 1977. A study of grating contrast judgement. *Vision Res.* 17:201-8
- Harmon, L. D., Julesz, B. 1973. Masking in visual recognition: effects of two-dimensional filtered noise. *Science* 180:1194-97
- Harris, C. S., ed. 1980. *Visual Coding and Adaptability*. Hillsdale, NJ: Erlbaum. In press
- Harvey, L. O. Jr., Gervais, M. J. 1980. Visual texture perception and Fourier analysis. *Percept. Psychophys.* In press
- Hatwell, Y. 1978. Form perception and related issues in blind humans. See Held et al 1978, pp. 489-520
- Heeley, D. W. 1979. A perceived spatial frequency shift at orientations orthogonal to adapting gratings. *Vision Res.* 19:1229-36
- Hein, A. 1980. The development of visually guided behavior. See Harris 1980
- Held, R. 1980. The rediscovery of adaptability in the visual system: Effects of extrinsic and intrinsic chromatic dispersion. See Harris 1980
- Held, R., Leibowitz, H. W., Teuber, H.-L., eds. 1978. *Handbook of Sensory Physiology*, Vol. 8: *Perception*. Berlin: Springer
- Helmholtz, H. von. 1909. *Physiological Optics*, ed. Opt. Soc. 1925, transl. from 3rd German ed. Republished by Dover, NY
- Henning, G. B., Hertz, B. G., Broadbent, D. 1975. Some experiments bearing on the hypothesis that the visual system analyses spatial patterns in independent bands of spatial frequency. *Vision Res.* 14:1039-42
- Hering, E. 1878. *Zur Lehre vom Lichtsinn*. Vienna: Gerold's Sohn
- Hines, M. 1976. Line spread function variation near the fovea. *Vision Res.* 16:567-72
- Hochberg, J. 1980. Levels of perceptual organization. See Kubovy & Pomerantz 1980
- Hoekstra, J., van der Goot, D. P. J., van den Brink, G., Bilsen, F. A. 1974. The influence of the number of cycles upon the visual contrast threshold for spatial sine wave patterns. *Vision Res.* 14:365-68
- Hoffman, W. C. 1977. An informal, historical description (with bibliography) of the "L.T.G./N.P." *Cah. Psychol.* 20:135-74
- Hoffman, W. C. 1978. The Lie transformation group approach to visual neurophysiology. In *Formal Theories of Visual Perception*, ed. E. L. J. Leeuwenberg, H. F. J. M. Buffart. New York: Wiley
- Hubel, D. H., Wiesel, T. N. 1959. Receptive fields of single neurones in the cat's striate cortex. *J. Physiol.* 148:574-91
- Hubel, D. H., Wiesel, T. N. 1962. Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *J. Physiol.* 160:106-54

- Hubel, D. H., Wiesel, T. N. 1968. Receptive fields and functional architecture of monkey striate cortex. *J. Physiol.* 195: 215-43
- Hubel, D. H., Wiesel, T. N. 1970. Cells sensitive to binocular depth in area 18 of the Macaque monkey cortex. *Nature* 255: 41-42
- Hubel, D. H., Wiesel, T. N., Stryker, M. P. 1978. Anatomical demonstration of orientation columns in macaque monkey. *J. Comp. Neurol.* 177:361-80
- Hyson, M. T., Julesz, B., Fender, D. H. 1980. Vergence eye movements and postulated cortical compensations during the fusion of horizontally misaligned random dot stereograms. In *Recent Advances in Vision*. Tech. Dig., OSA Meet., Sarasota, Fla.
- Ingle, D. 1978. Mechanisms of shape-recognition among vertebrates. See Held et al 1978, pp. 267-96
- Johansson, G. 1978. Visual event perception. See Held et al 1978, pp. 675-712
- Johansson, G., von Hofsten, C., Jansson, G. 1980. Event perception. *Ann. Rev. Psychol.* 31:27-63
- Johnson, C. A., Leibowitz, H. W. 1979. Practice effects for visual resolution in the periphery. *Percept. Psychophys.* 25: 439-42
- Jones, R. M., Tulunay-Keesey, U. 1980. Phase selectivity of spatial frequency channels. *J. Opt. Soc. Am.* 70:66-70
- Julesz, B. 1960. Binocular depth perception of computer-generated patterns. *Bell Syst. Tech. J.* 39:1125-62
- Julesz, B. 1961. Binocular depth perception and pattern recognition. *London Symp. Inf. Theory*, 4th, ed. C. Cherry, pp. 212-24. London: Butterworth
- Julesz, B. 1962. Visual pattern discrimination. *IRE Trans. Inf. Theory* IT-8 84-92
- Julesz, B. 1963. Towards the automation of binocular depth perception (AUTO-MAP-1). *Proc. IFIPS Congr., Munich, 1962*, ed. C. M. Poppelwell. Amsterdam: North-Holland
- Julesz, B. 1964. Binocular depth perception without familiarity cues. *Science* 145: 356-62
- Julesz, B. 1971. *Foundations of Cyclopean Perception*. Chicago: Univ. Chicago Press
- Julesz, B. 1975. Experiments in the visual perception of texture. *Sci. Am.* 232: 34-43
- Julesz, B. 1978a. Global stereopsis: Cooperative phenomena in stereoscopic depth perception. See Held et al 1978, pp. 215-56
- Julesz, B. 1978b. Visual texture discrimination using random-dot patterns: Comments. *J. Opt. Soc. Am.* 68:268-70
- Julesz, B. 1980a. Spatial nonlinearities in the instantaneous perception of textures with identical power spectra. In *The Psychology of Vision*, ed. C. Longuet-Higgins, N. S. Sutherland. *Philos. Trans. R. Soc. London* 290:83-94
- Julesz, B. 1980b. Spatial frequency channels in one-, two-, and three dimensional vision: Variations on a theme by Bekegy. See Harris 1980, pp. 263-316
- Julesz, B. 1980c. Figure and ground perception in briefly presented iso-dipole textures. See Kubovy and Pomerantz 1980
- Julesz, B., Breitmeyer, B., Kropff, W. 1976. Binocular-disparity-dependent upper-lower hemifield anisotropy and left-right hemifield isotropy as revealed by dynamic random-dot stereograms. *Perception* 5:129-41
- Julesz, B., Burt, P. 1979. *Cooperativity of nearby micropatterns in texture discrimination*. Presented at Psychon. Soc. Meet., Phoenix
- Julesz, B., Caelli, T. 1979. On the limits of Fourier decompositions in visual texture perception. *Perception* 8:69-73
- Julesz, B., Chang, J. J. 1976. Interaction between pools of binocular disparity detectors tuned to different disparities. *Biol. Cybern.* 22:107-19
- Julesz, B., Chang, J. J. 1979. Symmetry perception and spatial-frequency channels. *Perception* 8:711-18
- Julesz, B., Chang, J. J. 1980. Perceptual learning in random-dot cinematograms. *J. Opt. Soc. Am.* In press
- Julesz, B., Gilbert, E. N., Shepp, L. A., Frisch, H. L. 1973. Inability of humans to discriminate between visual textures that agree in second-order statistics—revisited. *Perception* 2:391-405
- Julesz, B., Gilbert, E. N., Victor, J. D. 1978. Visual discrimination of textures with identical third-order statistics. *Biol. Cybern.* 31:137-40
- Julesz, B., Hesse, R. I. 1970. Inability to perceive the direction of rotational movement of line segments. *Nature* 225:243-44
- Julesz, B., Miller, J. E. 1975. Independent spatial frequency tuned channels in binocular fusion and rivalry. *Perception* 4:125-43
- Julesz, B., Payne, R. A. 1968. Differences between monocular and binocular stroboscopic movement perception. *Vision Res.* 8:433-44
- Julesz, B., Spivack, G. J. 1967. Stereopsis



- based on vernier acuity cues alone. *Science* 157:563-65
- Julesz, B., Tyler, C. W. 1976. Neuronotropy, an entropy-like measure of neural correlation in binocular fusion and rivalry. *Biol. Cybern.* 22:107-19
- Julesz, B., White, B. W. 1969. Short-term visual memory and the Pulfrich phenomenon. *Nature* 222:639-41
- Kahneman, D., Henik, A. 1980. Perceptual organization and attention. See Kubovy & Pomerantz 1980
- Kaufman, L., Bacon, J., Barroso, F. 1973. Stereopsis without image segregation. *Vision Res.* 13:137-47
- Kaufman, L., Lane, B. C. 1979. Depth perception relative to convergence distance. *Invest. Ophthalmol. Visual Sci.* 18:174 (Supple.)
- Keesey, U. T. 1972. Flicker and pattern detection: A comparison of thresholds. *J. Opt. Soc. Am.* 62:446-48
- Kelly, D. H. 1966. Frequency doubling in visual responses. *J. Opt. Soc. Am.* 56:1628-33
- Kelly, D. H. 1979. Motion and vision. II. Stabilized spatio-temporal threshold surface. *J. Opt. Soc. Am.* 69:1340-49
- King-Smith, P. E., Kulikowski, J. J. 1975. The detection of gratings by independent activation of line detectors. *J. Physiol.* 247:237-71
- Koenderink, J. J., van Doorn, A. J. 1979. Spatiotemporal contrast detection threshold surface is bimodal. *Opt. Lett.* 4:32-34
- Kubovy, M., Pomerantz, J. R., eds. 1980. *Perceptual Organization*. Hillsdale, NJ: Erlbaum. In press
- Kuffler, S. W. 1953. Discharge patterns and functional organization of mammalian retina. *J. Neurophysiol.* 16:37-68
- Kulikowski, J. J., King-Smith, P. E. 1973. Spatial arrangement of line, edge and grating detectors revealed by sub-threshold summation. *Vision Res.* 13:1455-78
- Kulikowski, J. J., Tolhurst, D. J. 1973. Psychophysical evidence for sustained and transient detectors in human vision. *J. Physiol.* 232:149-62
- Lappin, J. S., Bell, H. H. 1976. The detection of coherence in moving random-dot patterns. *Vision Res.* 16:161-68
- Lappin, J. S., Doner, J. F., Kottas, B. L. 1980. Minimal conditions for the visual detection of structure and motion in three dimensions *Science* 209:717-19
- Lee, D. N. 1974. Visual information during locomotion. In *Perception: Essays in Honor of James J. Gibson*, ed. R. B. MacLeod, H. L. Pick Jr. Ithaca: Cornell Univ. Press
- Legge, G. E. 1976. Adaptation to a spatial impulse: implication for Fourier transform models of visual processing. *Vision Res.* 16:1407-18
- Legge, G. E. 1978. Space domain properties of a spatial frequency channel in human vision. *Vision Res.* 18:959-69
- Legge, G. E. 1979. Spatial frequency masking in human vision: Binocular interactions. *J. Opt. Soc. Am.* 69:838-47
- Levinson, E., Coyne, A., Gross, J. 1980. Synthesis of visually perceived movement. *Invest. Ophthalmol. Visual Sci.* 19:105 (Supple.)
- Levinson, E., Sekuler, R. 1980. A two-dimensional analysis of direction specific adaptation. *Vision Res.* 20:103-7
- Levinson, J. Z., Frome, F. S. 1979. Perception of size of one object among many. *Science* 206:1425-26
- Licklider, J. C. R. 1948. The influence of interaural phase relations upon the masking of speech by white noise. *J. Acoust. Soc. Am.* 20:150-59
- Limb, J. O., Rubinstein, C. B. 1977. A model of threshold vision incorporating inhomogeneity of the visual field. *Vision Res.* 17:571-84
- Lipkin, B. S., Rosenfeld, A., eds. 1970. *Picture Processing and Psychopictorics*. New York: Academic
- Logan, B. F. Jr. 1977. Information in the zero-crossings of bandpass signals. *Bell Syst. Tech. J.* 56:487-510
- Lu, S., Fender, D. H. 1972. The interaction of color and luminance in stereoscopic vision. *Invest. Ophthalmol.* 11:482-90
- MacAdam, D. L. 1970. *Sources of Color Science*. Cambridge, Mass: MIT Press
- Maccracken, P. J., Bourne, J. A., Hayes, W. N. 1977. Experience and latency to achieve stereopsis: a replication. *Percept. Mot. Skills* 45:261-62
- MacKay, D. M. 1957. Moving visual images produced by regular stationary patterns. *Nature* 180:849-50
- MacKay, D. M. 1964. Central adaptation in mechanisms of form vision. *Nature* 203:993-94
- MacKay, D. M. 1965. Visual noise as a tool of research. *J. Gen. Psychol.* 72:181-97
- MacKay, D. M., MacKay, V. 1976. Antagonism between visual channels for pattern and movement? *Nature* 263:312-14
- Macleod, I. D. G., Rosenfeld, A. 1974. The visibility of gratings: Spatial frequency channels or bar-detecting units? *Vision Res.* 14:909-15

- Maffei, L. 1978. Spatial frequency channels. See Held et al 1978, pp. 39-66
- Maffei, L., Fiorentini, A. 1973. The visual cortex as a spatial frequency analyzer. *Vision Res.* 13:1255-67
- Magnussen, S., Kurtenbach, W. 1980. Adapting to two orientations: Disinhibition in a visual aftereffect. *Science* 207:908-9
- Marr, D. 1976. Early processing of visual information. *Philos. Trans. R. Soc. London Ser. B* 275:483-524
- Marr, D. 1977. Artificial intelligence—a personal view. *Artif. Intell.* 9:37-48
- Marr, D., Hildreth, E. 1979. *Theory of edge detection*. MIT Artif. Intell. Lab. Memo No. 518
- Marr, D., Poggio, T. 1976. Cooperative computation of stereo disparity. *Science* 194:283-87
- Marr, D., Poggio, T. 1979. A theory of human stereopsis. *Proc. R. Soc. London Ser. B* 204:301-28
- Marr, D., Ullman, J. M., Poggio, T. 1979. Bandpass channels, zero-crossings, and early visual information processing. *J. Opt. Soc. Am.* 69:914-16
- Martin, R. C., Pomerantz, J. R. 1978. Visual discrimination of texture. *Percept. Psychophys.* 24:420-28
- Mayhew, J. E. W., Frisby, J. P. 1978a. Suprathreshold contrast perception and complex random textures. *Vision Res.* 18:895-98
- Mayhew, J. E. W., Frisby, J. P. 1978b. Stereopsis in humans is not orientationally tuned. *Perception* 7:431-36
- Mayhew, J. E. W., Frisby, J. P. 1978c. Contrast summation effects in stereopsis. *Perception* 7:537-50
- Mayhew, J. E. W., Frisby, J. P. 1979. Convergent disparity discriminations in narrow-band-filtered random-dot stereograms. *Vision Res.* 19:63-71
- Mayhew, J. E. W., Frisby, J. P. 1980a. The computation of binocular edges. *Perception* 9:69-86
- Mayhew, J. E. W., Frisby, J. P. 1980b. *Computational and psychophysical studies towards a theory of human stereopsis*. Special issue of *Artificial Intelligence on computer vision* (Monogr.)
- Mitchell, D. E. 1980. The influence of early visual experience on visual perception. See Harris 1980. In press
- Morgan, M. J. 1975. Stereoillusion based on visual persistence. *Nature* 256:639-40
- Movshon, J. A., Thompson, I. D., Tolhurst, D. J. 1978. Spatial summation in the receptive fields of simple cells in the cat's striate cortex. *J. Physiol.* 283:53-77
- Nachmias, J., Sanbury, R. 1974. Grating contrast: Discrimination may be better than detection. *Vision Res.* 15:899-910
- Nachmias, J., Weber, A. 1975. Discrimination of simple and complex gratings. *Vision Res.* 15:217-23
- Nakayama, K., Loomis, J. M. 1974. Optical velocity patterns, velocity-sensitive neurons, and space perception: a hypothesis. *Perception* 3:63-80
- Nelson, J. I. 1974. Motion sensitivity in peripheral vision. *Perception* 3:151-52
- Nelson, J. I. 1975. Globality and stereoscopic fusion in binocular vision. *J. Theor. Biol.* 49:1-88
- Nelson, J. I. 1977. The plasticity of correspondence: after effects, illusions and horopter shifts in depth perception. *J. Theor. Biol.* 66:203-66
- Nelson, T. M., Bartley, S. H., Bourassa, C. M., Ball, R. J. 1971. What is a channel? *J. Gen. Psychol.* 84:133-77
- Ogle, K. N. 1964. *Researches in Binocular Vision*. New York: Hafner
- Osgood, C. E., Heyer, A. W. 1952. A new interpretation of figural after-effects. *Psychol. Rev.* 59:98-118
- Oyama, T. 1978. Figural aftereffects. See Held et al 1978, pp. 569-94
- Pantle, A., Sekuler, R. 1968. Size-detecting mechanisms in human vision. *Science* 162:1146-48
- Papert, S. 1964. Stereoscopic synthesis as a technique for localizing visual mechanisms. *MIT Q. Prog. Rep.* 73:239-44
- Petersik, J. T., Pantle, A. 1979. Factors controlling the competing sensations produced by a bistable stroboscopic display. *Vision Res.* 19:143-54
- Pettigrew, J. D., Nikara, T., Bishop, P. O. 1968. Binocular interaction on single units in cat striate cortex: Simultaneous stimulation by single moving slit with receptive fields in correspondence. *Exp. Brain Res.* 6:391-410
- Pfaffman, C. 1941. Gustatory afferent impulses. *J. Cell Comp. Physiol.* 17:243-58
- Plateau, J. A. F. 1850. Quatrieme note sur de nouvelles applications curieuses de la persistence des impressions de la retine. *Bull. Acad. Sci. Belg.* 16:254-60
- Poggio, G. F., Fischer, B. 1977. Binocular interaction and depth sensitivity in striate and prestriate cortex of behaving Rhesus monkey. *J. Neurophysiol.* 40:1392-1405
- Pollack, I. 1973. Discrimination of third-order Markov constraints within visual displays. *Percept. Psychophys.* 13:276-80

- Pomerantz, J. R. 1980. Perceptual organization in information processing. See Kubovy & Pomerantz 1980
- Pomerantz, J. R., Kubovy, M. 1980. Perceptual organization: An overview. See Kubovy & Pomerantz 1980
- Pratt, W. K., Faugeras, O. D., Gagalowicz, A. 1978. Visual discrimination of stochastic texture fields. *IEEE Trans. Syst. Manage. Cybern.* 8:796-804
- Pressman, N. J., Haralick, R. M., Tyrer, H. W., Frost, J. K. 1979. Texture analysis for biomedical imagery. In *Biomedical Pattern Recognition and Image Processing*, ed. K. S. Fu, T. Pavlidis. Berlin: Dahlem Konferenzen
- Purkinje, J. A. 1820. Beiträge für nähren Kenntniss des Schwindles aus heautognostischen Daten. In *Purkyne's sebrana spisy* (opera omnia), ed. K. J. Lhotak, 2:15-37. Prague (1937)
- Purks, S. R., Richards, W. 1977. Visual texture discrimination using random patterns. *J. Opt. Soc. Am.* 67:765-71
- Quick, R. F. Jr. 1974. A vector-magnitude model of contrast detection. *Kybernetik* 16:65-67
- Quick, R. F. Jr., Mullins, W. W., Reichert, T. A. 1978. Spatial summation effects on two-component grating thresholds. *J. Opt. Soc. Am.* 68:116-21
- Quick, R. F. Jr., Hamerly, J. R., Reichert, T. A. 1976. The absence of a measurable "critical band" at low suprathreshold contrasts. *Vision Res.* 16:351-56
- Rabbitt, P., Cumming, G., Vyas, S. 1979. Improvement, learning and retention of skills at visual search. *Q. J. Exp. Psychol.* 31:441-59
- Ramachandran, V. S., Braddick, O. 1973. Orientation-specific learning in stereopsis. *Perception* 2:371-76
- Ramachandran, V. S., Gregory, R. L. 1978. Does colour provide an input to human motion perception? *Nature* 275:55-56
- Ramachandran, V. S., Rao, V. M., Vidyasagar, T. R. 1973. The role of contours in stereopsis. *Nature* 242:412-14
- Regan, D., Beverley, K. I. 1978. Looming detectors in the human visual pathway. *Vision Res.* 18:415-21
- Regan, D., Beverley, K. I. 1979. Visually guided locomotion: Psychophysical evidence for a neural mechanism sensitive to flow patterns. *Science* 205:311-13
- Regan, D., Cynader, M. 1979. Neurons in area 18 of cat visual cortex selectively sensitive to changing size: Nonlinear interactions between responses to two edges. *Vision Res.* 19:699-711
- Reichardt, W. 1957. Autokorrelations-Auswertung als Funktionsprinzip des Zentralnervensystems. *Z. Naturforsch.* 12: 448-57
- Richards, W. 1972. Response functions for sine- and square-wave modulations of disparity. *J. Opt. Soc. Am.* 62:907-11
- Richards, W. 1977. Stereopsis with and without monocular contours. *Vision Res.* 17:967-70
- Richards, W., Kaye, M. G. 1974. Local versus global stereopsis: Two mechanisms? *Vision Res.* 14:1345-47
- Richards, W., Polit, A. 1974. Texture matching. *Kybernetik* 16:155-62
- Riggs, L. A., Day, R. H. 1980. Visual aftereffects derived from inspection of orthogonally moving patterns. *Science* 208:416-18
- Robson, J. G. 1966. Spatial and temporal contrast sensitivity functions of the human eye. *J. Opt. Soc. Am.* 56:1141
- Robson, J. G. 1975. Receptive fields: neural representation of the spatial and intensive attributes of the visual image. In *Handbook of Perception*, ed. E. C. Carterette, M. P. Friedman, 5:81-112. New York: Academic
- Robson, J. G. 1980. Neural images: The physiological basis of spatial vision. See Harris 1980. In press
- Robson, J. G., Graham, N. 1978. Probability summation and regional orientation in sensitivity across the visual field. *Invest. Ophthalmol. Visual Sci.* 17:221 (Suppl.)
- Rogowitz, B. E., Nachmias, J. 1979. Phase-dependent masking and facilitation: Evidence for the non-linear processing of amplitude-modulated gratings. *Eur. Conf. Visual Percept., Noordwijkerhout, The Netherlands*
- Ross, J. 1974. Stereopsis by binocular delay. *Nature* 248:363
- Ross, J., Hogben, J. H. 1975. Short-term memory in stereopsis. *Vision Res.* 14:1195-201
- Ross, J., Johnstone, J. R. 1980. Phase and detection of compound gratings. *Vision Res.* 20:189-92
- Sachs, M. B., Nachmias, J., Robson, J. G. 1971. Spatial-frequency channels in human vision. *J. Opt. Soc. Am.* 61: 1176-86
- Savoy, R. L., McCann, J. J. 1975. Visibility of low-spatial-frequency sine-wave targets: Dependence on numbers of cycles. *J. Opt. Soc. Am.* 65:343-49
- Saye, A., Frisby, J. P. 1975. The role of monocularly conspicuous features in facilitating stereopsis from random-dot stereograms. *Perception* 4:159-71
- Schachter, B. J., Rosenfeld, A., Davis, L. S. 1978. Random mosaic models for tex-

- tures. *IEEE Trans. Syst. Man Cybern.* 8:694-702
- Schatz, B. 1978. *The computation of immediate texture perception*. Comp. Sci. Dep. Rep. No. 152, Carnegie-Mellon Univ., Pittsburgh, Pa.
- Schumer, R. A. 1979. *Mechanisms in human stereopsis*. PhD thesis. Stanford Univ., Stanford, Calif.
- Schumer, R. A., Ganz, L. 1979a. Independent stereoscopic channels for different extents of spatial pooling. *Vision Res.* 19:1303-44
- Schumer, R. A., Ganz, L. 1979b. Disparity averaging in random dot stereopsis. *J. Opt. Soc. Am.* 69:1479
- Schumer, R. A., Julesz, B. 1980a. *Limited area integration of binocular disparity detectors in global stereopsis*. Presented at Topical Meet. Recent Adv. in Vision, Opt. Soc. Am., Sarasota, Fla., p. SB2
- Schumer, R. A., Julesz, B. 1980b. Maximum disparity limit for detailed depth resolution. *Invest. Ophthalmol. Visual Sci.* 19:106-7 (Suppl.)
- Schumer, R. A., Julesz, B. 1980c. Disparity limit in dynamic random-dot stereograms without low spatial frequencies. In preparation
- Schumer, R. A., Julesz, B. 1980d. The range of disparity-averaging in random-dot stereograms. In preparation
- Sekuler, R. 1974. Spatial vision *Ann. Rev. Psychol.* 25:195-232
- Sekuler, R., Ganz, L. 1963. Aftereffect of seen motion with a stabilized retinal image. *Science* 139:419-20
- Sekuler, R., Pantle, A., Levinson, E. 1978. Physiological basis of motion perception. See Held et al 1978, pp. 67-96
- Shapley, R. M., Tolhurst, D. J. 1973. Edge detectors in human vision. *J. Physiol.* 229:165-83
- Shaw, R., Turvey, M. T. 1980. Coalitions as models for ecosystems: A realist perspective on perceptual organization. See Kubovy & Pomerantz 1980
- Shepard, R. N. 1980. Psychophysical complementarity. See Kubovy & Pomerantz 1980
- Shiffrin, R. M., Schneider, W. 1977. Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychol. Rev.* 84:127-90
- Sokoloff, L., Reivich, M., Kennedy, C., Des Rosiers, M. H., Patlak, C. S., Pettigrew, K. D., Sakurada, O., Shinohara, M. 1977. The [<sup>14</sup>C]deoxyglucose method for the measurement of local cerebral glucose utilization: theory, procedure, and normal values in the conscious and anesthetized albino rat. *J. Neurochem.* 28:897-916
- Sperling, G. 1970. Binocular vision: A physical and a neural theory. *J. Am. Psychol.* 83:461-534
- Sperling, G., Sondhi, M. M. 1968. Model for visual luminance discrimination and flicker detection. *J. Opt. Soc. Am.* 58:1133-45
- Stevens, K. A. 1978. Computation of locally parallel structure. *Biol. Cybern.* 29:19-28
- Stevens, S. S. 1975. *Psychophysics: Introduction to its Perceptual, Neural, and Social Prospects*. New York: Wiley
- Stigmar, G. 1970. Observations on vernier and stereo acuity with special reference to their relationship. *Acta Ophthalmol.* 48:979-98
- Stromeyer, C. F. III. 1978. Form-color aftereffects in human vision. See Held et al 1978, pp. 97-142
- Stromeyer, C. F. III, Julesz, B. 1972. Spatial frequency masking in vision: Critical bands and spread of masking. *J. Opt. Soc. Am.* 62:1221-32
- Stromeyer, C. F. III, Klein, S. 1975. Evidence against narrow-band spatial frequency channels in human vision: The detectability of frequency modulated gratings. *Vision Res.* 15:899-910
- Stromeyer, C. F. III, Klein, S. 1974. Spatial frequency channels in human vision as asymmetric (edge) mechanisms. *Vision Res.* 14:1409-20
- Stromeyer, C. F. III, Madsen, J. C., Klein, S. 1979. Direction-selective adaptation with very slow motion. *J. Opt. Soc. Am.* 69:1039-41
- Sullivan, G. D., Georgeson, M. A., Oatley, K. 1972. Channels for spatial frequency selection and detection of single bars by the human visual system. *Vision Res.* 12:383-94
- Sutherland, S. 1961. Figural aftereffects and apparent size. *Q. J. Exp. Psychol.* 13:222-28
- Teller, D. 1980. Locus questions in visual science. See Harris 1980
- Teuber, H.-L. 1978. The brain and human behavior. See Held et al 1978, pp. 879-920
- Thomas, J. P. 1970. Model of the function of receptive fields in human vision. *Psychol. Rev.* 77:121-34
- Thomas, J. P., Barker, R. A., Gille, J. 1979. A multidimensional space model for detection and discrimination of spatial patterns. In *Modeling and Simulation*, Vol. 10: Proc. 10th Ann. Pittsburgh Conf., ed. W. G. Vogt, M. H. Mickle

- Tolhurst, D. J. 1972. Adaptation to square-wave gratings: Inhibition between spatial frequency channels in the human visual system. *J. Physiol.* 226:231-48
- Treisman, A. 1978. The psychological reality of levels of processing. In *Levels of Processing and Human Memory*, ed. L. S. Cermak, F. I. M. Craik. Hillsdale, NJ: Erlbaum
- Tyler, C. W. 1971. Stereoscopic depth movement: Two eyes less sensitive than one. *Science* 174:958-61
- Tyler, C. W. 1973. Stereoscopic vision: Cortical limitations and a disparity scaling effect. *Science* 181:276-78
- Tyler, C. W. 1974. Depth perception in disparity gratings *Nature* 251:140-42
- Tyler, C. W. 1975. Stereoscopic tilt and size aftereffects. *Perception* 4:187-92
- Tyler, C. W., Julesz, B. 1976. The neural transfer characteristic (Neuronropy) for binocular stochastic stimulation. *Biol. Cybern.* 23:33-37
- Tyler, C. W., Julesz, B. 1978. Binocular cross-correlation in time and space. *Vision Res.* 18:101-5
- Tyler, C. W., Julesz, B. 1980. On the depth of the cyclopean retina. *Exp. Brain Res.* 40. In press
- Ullman, S. 1979. *The Interpretation of Visual Motion*. Cambridge, Mass: MIT Press
- Ullman, S. 1980. Against direct perception. *Behav. Brain Sci.* In press
- Uttal, W. R. 1975. *An Autocorrelation Theory of Form Detection*. Hillsdale, NJ: Erlbaum
- Uttal, W. R., Tucker, T. E. 1977. Complexity effects in form detection. *Vision Res.* 17:359-66
- van Doorn, A. J., Koenderink, J. J., Bouman, M. A. 1972. The influence of the retinal inhomogeneity on the perception of spatial patterns. *Kybernetik* 10:223-30
- van Meeteren, A. 1978. On the detective quantum efficiency of the human eye. *Vision Res.* 18:257-67
- van Nes, F. L., Koenderink, J. J., Nas, H., Bowman, M. A. 1967. Spatiotemporal modulation transfer in the human eye. *J. Opt. Soc. Am.* 57:1082-88
- Victor, J. D., Brodie, S. E. 1978. Discriminable textures with identical Buffon-needle statistics. *Biol. Cybern.* 31: 231-34
- Virsu, V., Rovamo, J. 1979. Visual resolution, contrast sensitivity, and the cortical magnification factor. *Exp. Brain Res.* 37:475-94
- von der Heydt, R., Adorjani, C., Hanny, P., Baumgartner, G. 1978. Disparity sensitivity and receptive field incongruity of units in the cat striate cortex. *Exp. Brain Res.* 31:523-45
- Walker, J. T., Kruger, M. W. 1972. Figural aftereffects in random-dot stereograms without monocular contours. *Perception* 1:187-92
- Watson, A. B. 1979. Probability summation over time. *Vision Res.* 19:515-22
- Watson, A. B. 1980. Summation of grating patches implies many frequency-selective detectors at one retinal location. *Invest. Ophthalmol. Visual Sci.* 19 (Suppl.):45
- Watson, A. B., Nachmias, J. 1980. Summation of asynchronous gratings. *Vision Res.* 20:91-94
- Watson, A. B., Thompson, P. G., Murphy, B. J., Nachmias, J. 1980. Summation and discrimination of gratings moving in opposite directions. *Vision Res.* 20:341-47
- Weisstein, N., Harris, C. S. 1980. Masking and the unmasking of distributed representations in the visual system. See Harris 1980
- Weisstein, N., Harris, C. S., Berbaum, K., Tangney, J., Williams, A. 1977. Contrast reduction by small localized stimuli: Extensive spatial spread of above-threshold orientation selective masking. *Vision Res.* 17:341-50
- Williams, J. M., Lit, A. 1980. Luminance dependent latency as measured by the Hess effect. *Invest. Ophthalmol. Visual Sci.* 19:166 (Suppl.)
- Wilson, H. R., Bergen, J. R. 1979. A four mechanism model for threshold spatial vision. *Vision Res.* 19:19-32
- Wilson, H. R., Giese, S. C. 1977. The significance of frequency gradients in binocular grating perception. *Vision Res.* 16:983-90
- Wilson, H. R., Phillips, G., Rentschler, I., Hilz, R. 1979. Spatial probability summation and disinhibition in psychophysically measured line-spread functions. *Vision Res.* 19:593-98
- Wohlgemuth, A. 1911. On the after-effect of seen movement. *Br. J. Psychol. Monogr. Suppl.* (PhD thesis). Cambridge: Univ. Press
- Yin, R. K. 1978. Face perception: A review of experiments with infants, normal adults, and brain-injured persons. See Held et al 1978, pp. 593-608
- Zeki, S. M. 1978. Functional specialisation in the visual cortex of the rhesus monkey. *Nature* 274:423-28
- Zucker, S. W. E. 1976. On the structure of texture. *Perception* 5:419-36

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