INFANT VISUAL PREFERENCES: A REVIEW AND NEW THEORETICAL TREATMENT

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I. Introduction

The looking patterns of infants, young and old, are characterized by unmistakable tendencies to look longer at some stimuli as opposed to others. These so-called visual preferences were the object of intense study for many

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years. Indeed, the study of preferences was for awhile all but synonymous with the study of early visual perception. Lately, however, interest in visual preferences has waned decidedly. Rise and decline of scientific interest in a phenomenon are, of course, not unusual. Phenomena often lose interest value because they have been explained to everyone's satisfaction, but this was not the reason in the case of preference research. Between 1967 and 1978, several theories of preferences were developed and debated, but none of them gained wide acceptance. Thus, an explanation of the rise and decline of preference research must be sought elsewhere. Let us indulge then in a brief historical review in an attempt to pinpoint reasons.

The modern era of preference research began with the late Robert Fantz's refinement of the visual preference paradigm. Fantz was most interested in determining if the percepts of sensorially inexperienced neonates were the "great blooming, buzzing confusion" pictured by William James or something more refined. Specifically, he asked whether young infants could differentiate visual stimuli on the basis of differences in form. In his experiments, infants were shown pairs of stimuli that differed only in form (e.g., Fantz, 1958, 1961). For example, a bull's-eye was paired with a grating of the same area, luminance, and contrast. If an infant looked repeatedly at one target rather than the other, Fantz reasoned that the targets had been discriminated on the basis of differences in their form. Even newborns exhibited reliable preferences among such stimuli (Fantz, 1963), so Fantz had demonstrated that visually inexperienced infants had at least a rudimentary capacity to detect and discriminate forms (or patterns). This work was exciting and fundamentally important, and it understandably spawned an enormous amount of research designed to characterize these early visual capabilities. In the process, however, the experimental question changed. More often than not it became, What aspects of visual stimuli determine infants' preferences? The pursuit of this question motivated numerous experiments in the 1960s and 1970s. For example, several researchers analyzed bull's-eyes and gratings in order to determine the differences that caused bull's-eyes to be preferred (Fantz, Fagan, & Miranda, 1975; Fantz & Nevis, 1967; Miranda, 1970; Ruff & Birch, 1974; Ruff & Turkewitz, 1975). Others sought the determinants of infants' preferences for checkerboards of various check sizes (Cohen, 1972; Fantz & Fagan, 1975; Greenberg & Blue, 1975; Karmel, 1969; Miranda & Fantz, 1971).

The proliferation of data naturally led to attempts at synthesis. Several theoretical accounts of early visual preferences followed including discrepancy theory (Kagan, 1970), complexity theory (Berlyne, 1960; Dember & Earl, 1957), contour density theory (Karmel, 1969), size and number theory (Fantz & Fagan, 1975), and neural substrate theories (Fantz *et al.,* 1975: Haith, 1978; Karmel & Maisel, 1975).

The discrepancy, complexity, and contour density theories were optimal level theories; that is, a moderate level of stimulation was assumed to be most preferred at each age and the optimal level was assumed to shift with age. Two of these theories—discrepancy and complexity—originated from the view that infants' information-processing capacity grows with age. They proposed that different levels of stimulus complexity provide optimal stimulation at different ages. To define complexity, discrepancy theory referred to the interaction between the stimulus and the infant's previous experience with it or related stimuli. Complexity theory referred more directly to the stimulus by defining complexity in terms of predictability (Haith, Kessen, & Collins, 1969), number of elements (Brennan, Ames, & Moore, 1966), or number of angles (Munsinger & Weir, 1967). The contour density theory originated from Karmel's post hoc analysis of checkerboard preferences. Contour density was defined as the total length of contour in a stimulus divided by the total area. According to this theory, different amounts of contour density were most preferred at different ages.

The neural substrate theories and, to some extent, the size and number theory were maximal level theories; that is, the highest available level of stimulation was assumed to be most preferred at all ages. The neural substrate models of Fantz *et al.* (1975), Haith (1978), and Karmel and Maisel (1975) stated that young infants' preferences are governed by the response rate of neurons in the central visual system. Patterns that match the size and shape of these neurons' receptive fields evoke greater activity and thereby attract or hold fixation. Finer patterns become more preferred with age because the receptive fields of such neurons become smaller. The size and number model was developed by Fantz and Fagan (1975) from a post hoc analysis of their preference data. According to this theory, stimuli with large elements are preferred over those with smaller elements, and stimuli with more elements are preferred over those with fewer. However, the relative importance of the two variables changes with age, size being most important in younger infants and number in older infants.

By the mid-1970s then, the developmental literature was filled with data and theories on infants' visual preferences; no more active area of research existed in the field of infant visual perception. If the rate of publication on the topic is used as an index, developmental researchers appear to have begun to lose interest in preferences shortly thereafter. What went wrong? We believe two things did.

First, progress in understanding the phenomenon had been slow at best. All of the preference theories proposed by 1978 had encountered some obvious difficulties. In each case, the theories could not account for some existing data. Welch's (1974) results were inconsistent with discrepancy theory (see also Thomas, 1971), and Karmel's (1969) and McCall and Melson's

(1970) results contradicted complexity theory. The contour density and size and number theories could not explain why pattern arrangement (Fantz *et al.*, 1975) and line thickness (McCall & Melson, 1970) affected preference. In retrospect, the fact that these models lacked predictive power is not surprising because they had some critical shortcomings involving the characterizations of both the stimulus and the infant. In regard to the stimulus, the relevant dimensions were either not defined rigorously enough to allow unambiguous predictions (discrepancy and complexity theories) or not defined with the richness required to incorporate a broad range of stimuli (contour density and size and number). In regard to the characterization of the infant, the theories were vague about what changes in the infant cause changes in preferences. The discrepancy and complexity theories did not specify how one could measure the child's current schema or level of information-processing capacity. The contour density and size and number models described the relevant mechanisms—the neural receptive fields proposed by Haith and others—but the dimensions of the mechanisms could not be determined at a given age because no way was (or is) available to measure them in human infants.

The second event that we believe led to the decline of preference research is the following. Many developmentalists seem to have turned to other research problems perhaps because they recognized that an explanation of the development of preferences might not enrich our general understanding of the development of visual perception. To illustrate this point, let us construct a hypothetical example. Suppose that we became convinced that complexity theory was an adequate account of young infants' preferences (this implies, of course, that complexity could be rigorously defined and that the optimal level of complexity could be determined at each age). What would such a theory tell us about the development of vision in some general sense? Our guess is that it would not tell us very much at all. For instance, one could not ascertain from such an account even very simple things such as whether a 3 month old can see pattern information that newborns cannot. Thus, such an account of preferences would probably not illuminate anything about early visual perception other than preferences. Indeed, researchers did become more concerned in the mid-1970s with questions about visual processing per se. Preferential looking was still measured, but it was now thought of as a response index of various capabilities including visual acuity (Dobson & Teller, 1978), contrast sensitivity (Atkinson, Braddick, & Moar, 1977a), color vision (Peeples & Teller, 1975), depth perception (Fox, Aslin, Shea, & Dumais, 1980), and cross-modal perception (Spelke, 1976).

Thus, the study of the determinants of infants' visual preferences reached an early retirement, and the field moved on to examine visual capabilities per se. Progress in understanding how various capabilities develop was remarkable, a fact that is documented in several recent reviews (Aslin, 1985; Banks & Salapatek, 1983; Teller & Bornstein, 1985; Yonas & Owsley, 1985). Starting 4 years ago, one of us realized that our improved understanding of the development of basic visual mechanisms could serve the construction of more useful models of early visual preferences (Banks & Salapatek, 1981). We expand those ideas in this article. In so doing, we resurrect the once lively debate about what determines infants' visual preferences at different ages. We propose a quantitative model of preferences based on linear systems techniques and test it against data from several well-known preference experiments. The model's predictions agree quite well with observed preferences for a variety of stimuli. The success of this model implies that infants' visual preferences are governed simply by a tendency to look at highly visible patterns. This account of early preferential looking is thus consonant with our understanding of how the growth of basic sensory mechanisms affects visual perception during the first months of life.

II. Linear Systems Analysis and Its Application

Before presenting our model of infant pattern preferences, we need to describe the engineering technique upon which it is based: linear systems analysis. Our discussion will be brief and conceptual. For more comprehensive and rigorous treatments, the reader is referred to Cornsweet (1970), Gaskill (1978), or Georgeson (1979).

Linear systems analysis is based on Fourier's theorem. This powerful theorem implies that any two-dimensional, time-invariant visual stimulus can be exactly described by combining a set of more basic stimuli. (We will consider only achromatic stimuli, that is, stimuli with contours defined by a difference in luminance rather than by a difference in hue.) These basic stimuli are sine wave gratings, examples of which are shown in Fig. 1. A sine wave grating is a pattern of light and dark stripes whose intensity varies sinusoidally with position. Sine wave gratings are specified by four parameters: (1) spatial frequency, the number of pattern repetitions (or cycles) per degree of visual angle; (2) orientation, the grating's tilt to the left or right of vertical; (3) phase, the grating's position with respect to some reference position; and (4) contrast, which is related to the difference between maximum and minimum intensities of the grating. [Formally, contrast is defined as $(I_{max} - I_{min})/(I_{max} + I_{min})$, where I_{max} refers to the peak intensity of a light stripe and I_{min} is the intensity of the least intense part of a dark stripe.] Fourier's theorem implies then that even a complex, two-dimensional visual stimulus, such as the picture of a face, can be described exactly by the com-

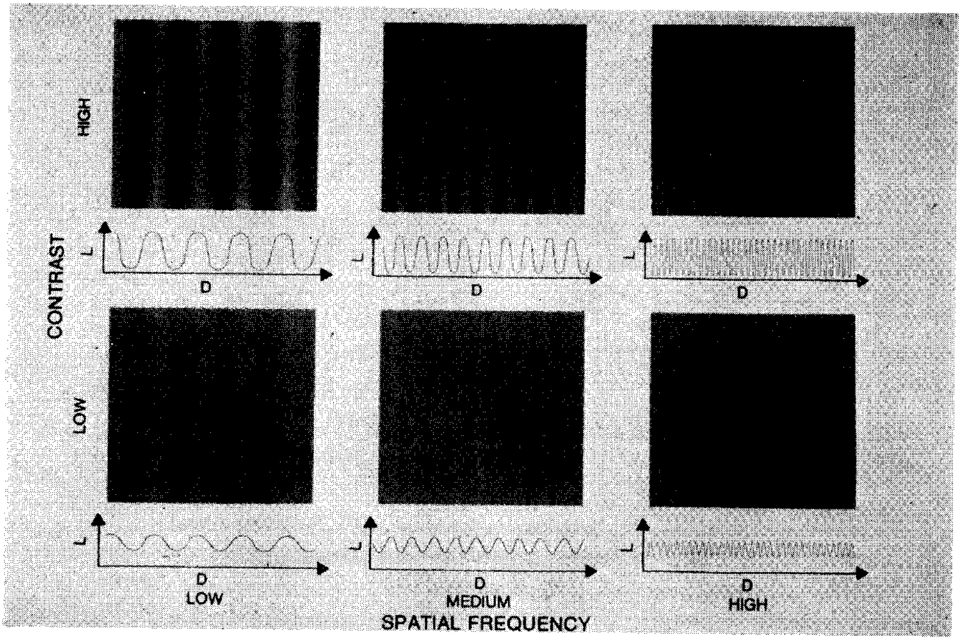

Fig. 1. *Six sine wave gratings differing in spatial frequency and contrast. From left to right, the gratings increase in spatial frequency. From bottom to top, they increase in contrast. If the figure is held at arm's length, the gratings have spatial frequencies of 1.5, 3, and 12 cycles/degree.*

bination of a set of gratings of various frequencies, orientations, phases, and contrasts.

Figures 2 and 3 demonstrate this principle. They show how sine wave gratings can be added together to reproduce the checkerboard shown in the upper half of Fig. 2. The lower half is the Fourier or spatial frequency representation of the checkerboard, and is obtained by Fourier transformation of the pattern (Kelly, 1976, pp. 286–287). This particular representation is called an amplitude spectrum. It contains all the information necessary to specify the spatial frequency, contrast, and orientation of the checkerboard's constituent sine wave gratings. Phase is not represented in this type of plot. Each spot in the lower half of Fig. 2 represents a grating component. The spatial frequency of each component is indicated by the spot's distance from the center of the plot; the greater the distance, the higher the frequency. Contrast is represented by the area of the spot. Orientation is indicated by the angle between the horizontal axis and a line from the origin to the spot. According to Fourier's theorem, one can reconstruct the original checkerboard by adding together the grating components represented in the lower half of the figure. This process is called Fourier synthesis and

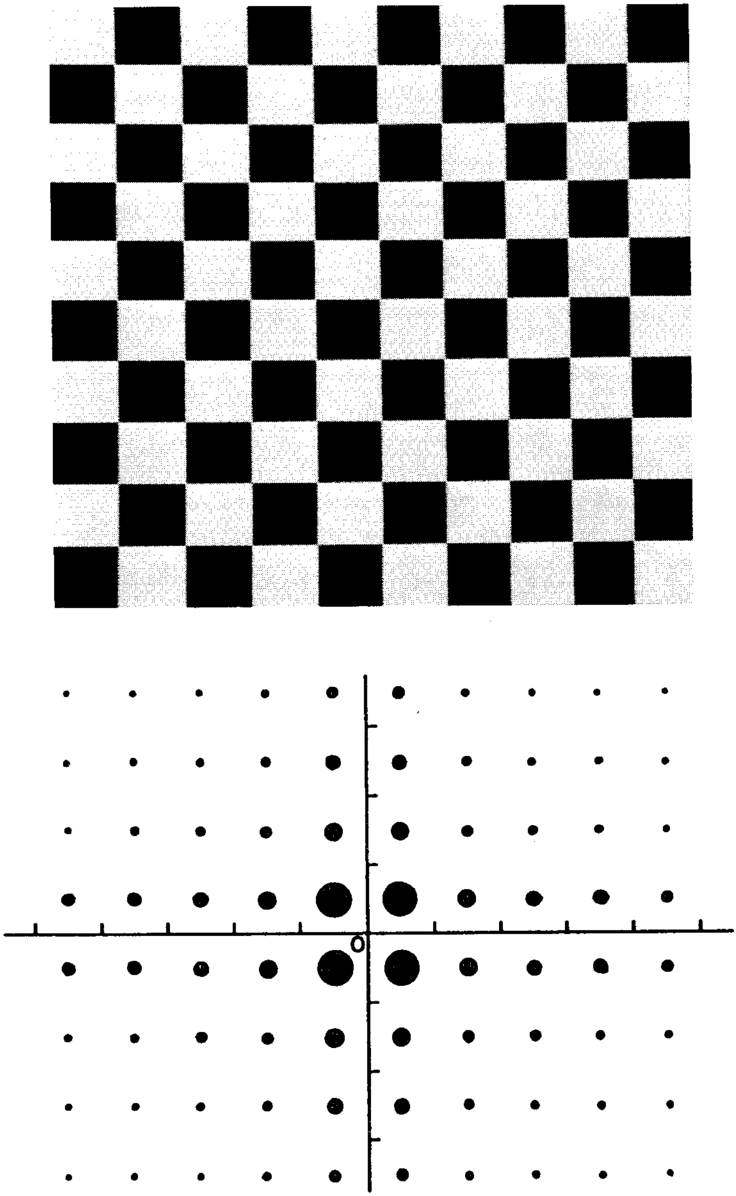

Fig. 2. A checkerboard and its spatial frequency components. Top: A 5 × 5 checkerboard. Bottom: The spatial frequency representation (amplitude spectrum) of the checkerboard. Each spot represents an individual sine wave component. Spatial frequency is indicated by the spot's distance from the origin. Orientation is represented by the angle between the spot and the origin. Contrast or amplitude is indicated by the spot's area.

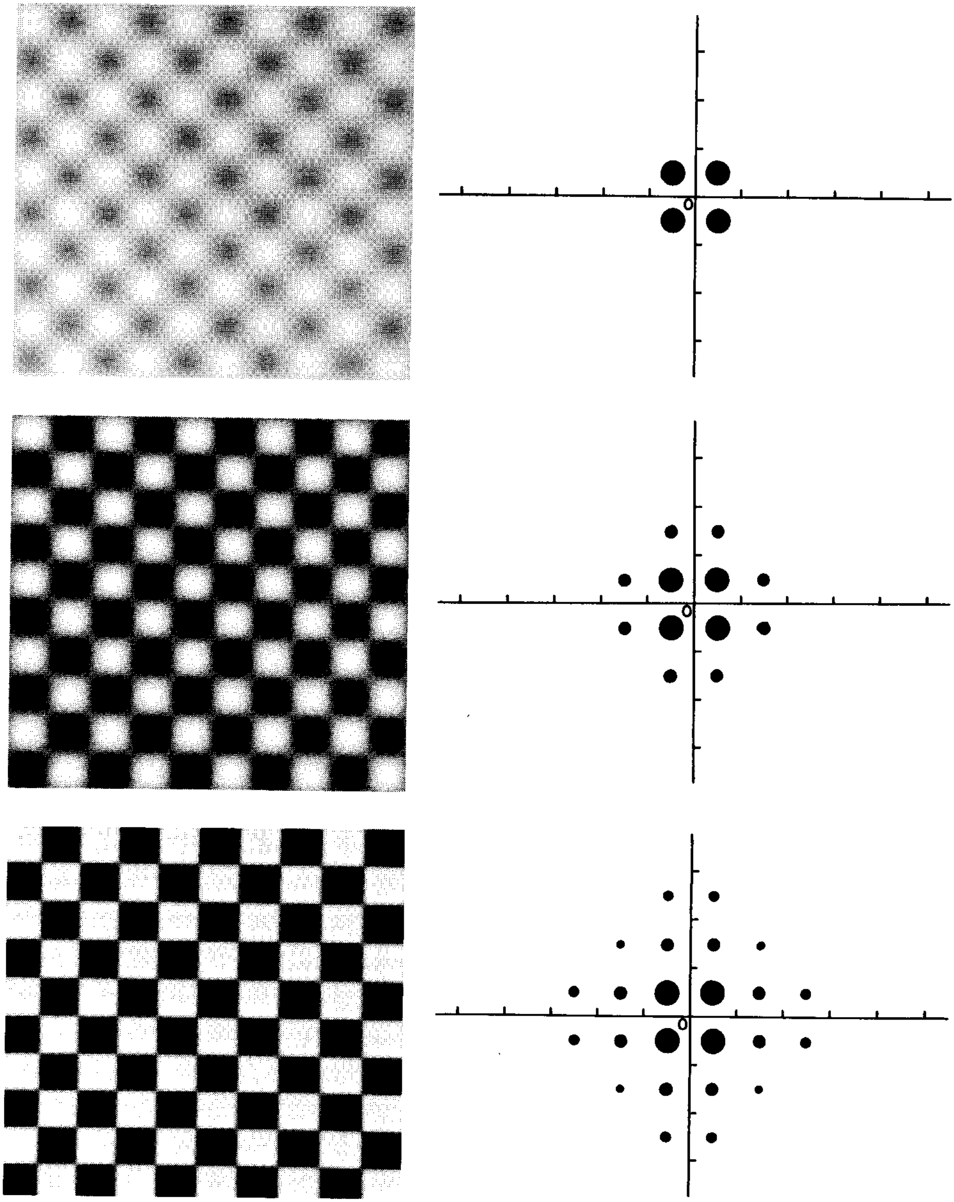

Fig. 3. Synthesis of a checkerboard. The graphs on the right are representations of the components that have been added to create the images on the left. From top to bottom in the figure, more and more spatial frequency components have been added. See text for details.

is illustrated by Fig. 3. From top to bottom, more and more of the checkerboard's components are added until the original pattern emerges. In the two top panels, the four gratings of lowest frequency have been added; these components are called the fundamentals. The basic structure of the checkerboard has already emerged, but the shape of each check has not. The two middle panels show what happens when the next eight gratings are added; some of the individual checks have begun to take shape. Finally, the next 12 components have been added in the lowest two panels; the resulting pattern is virtually indistinguishable from the original checkerboard. If we added all of the remaining components to this image, the checkerboard of Fig. 2 would be reconstructed precisely.

To this point, we have discussed how Fourier's theorem allows one to describe any two-dimensional stimulus in terms of sine wave gratings of various spatial frequencies, contrasts, orientations, and phases. We turn now to the analysis of real systems by considering how Fourier's theorem and linear systems analysis can be used to characterize the image-forming quality of a camera lens. We will use some engineering terms throughout this section because they make the discussion simpler. The term *input* will refer to the stimulus presented to a lens (or a visual system), the term *output* to the image created on the camera's film (or the perceptual response of a visual system), and the terms *transmission* and *filtering* to what goes on in between. The application of linear systems techniques allows an optical engineer to characterize the quality of a camera lens completely. In other words, an engineer can use these techniques to predict the lens' output no matter what the input is. Because any input can be represented by a set of sine wave gratings, linear systems techniques involve the measurement of how sine wave gratings of various frequencies are transmitted by the lens. The index of this measurement is the modulation transfer function, which is the proportion of input contrast at different spatial frequencies that is transmitted by the lens onto the camera's film. Lenses transmit low spatial frequencies very well and high spatial frequencies rather poorly. Thus, the modulation transfer function of a lens is like a low-pass filter; the proportion of input contrast transmitted onto the film is nearly 1 at low frequencies and nearly 0 at high frequencies.

As we mentioned above, any input can be represented by the addition of various gratings. Thus, according to linear systems theory, the output of a linear system to any input can be represented by the addition of the responses to the input's constituent gratings. This statement is described more formally by the following equations:

$$A_0(f,g) = A_i(f,g) \cdot A_h(f,g) \qquad (1)$$
$$P_0(f,g) = P_i(f,g) + P_h(f,g) \qquad (2)$$

Equation (1) relates the amplitudes of the input and output sine wave grating components. $A_h(f,g)$ is the lens' two-dimensional modulation transfer function; it is the proportion of input contrast that is transmitted onto the film as a function of the spatial frequency in two dimensions (f and g). $A_i(f,g)$ is the amplitude spectrum of the input stimulus. Thus, the multiplication of the input's sine wave components, $A_i(f,g)$, by the appropriate weighting factor, $A_h(f,g)$, yields the amplitude spectrum of the output. Inverse Fourier transformation (the operation involved in Fourier synthesis) can then be used to synthesize the output, $A_0(f,g)$. Equation (2) relates the phases of the input and output spatial frequency components. Most optical systems and visual systems do not change the phase of a stimulus or its components during processing. Therefore, the phase transfer function of a system, $P_h(f,g)$, is generally zero, which implies that the output and input phases are identical. For this reason, we will disregard phase transfer functions and their effects henceforth.

Figure 3 can be used to illustrate how linear systems analysis is used to predict the output of an optical system to a particular input. Suppose that the modulation transfer function of the lens is a simple low-pass filter. That is, suppose that the lens transmits spatial frequencies lower than 2 cycles/degree (c/deg) perfectly and does not transmit higher spatial frequencies at all. In that case, Eq. (1) implies that the amplitude spectrum of the output contains all of the spatial frequencies of the original checkerboard except those above 2 c/deg. In other words, the output spectrum would be that of the top right graph in Fig. 3. One can then use inverse Fourier transformation to produce the predicted output. This is shown in the top left graph in Fig. 3. As can be seen, a lens that transmits only low spatial frequencies would produce a noticeably degraded version of the original checkerboard. The middle and bottom pairs of panels in Fig. 3 illustrate the outputs that would be obtained for modulation transfer functions cutting off at 4.5 and 7.2 c/deg, respectively.

Our real interest is the evaluation of visual systems, not optical systems, so we now turn to that topic. Linear systems analysis has been successfully applied for two decades or more to the investigation of visual performance (e.g., Cornsweet, 1970; Ratliff, 1965). According to linear systems theory, the output (perceptual response) associated with any input (two-dimensional, time-invariant stimulus) can be predicted if one knows the system's response to sine waves of various spatial frequencies. For the prediction to be precise, however, the visual system must satisfy certain conditions, a topic we return to below.

The contrast sensitivity function (CSF) is used instead of the modulation transfer function to represent the visual system's ability to detect and transmit information as a function of spatial frequency. The CSF is determined by measuring an observer's contrast sensitivity to sine wave gratings of various spatial frequencies. In practice, this is done by presenting gratings of a number of different spatial frequencies one at a time and determining the least contrast necessary for an observer to detect the grating at each of those frequencies. An example of a typical adult's CSF is shown in the lower portion of Fig. 4. Contrast sensitivity, the reciprocal of the minimum contrast required for detection, is plotted as a function of spatial frequency. Note that sensitivity is greatest for intermediate spatial frequencies (2–6 c/deg) and lower for low and high frequencies. The figure also presents a grating, varying in spatial frequency and contrast, to give the reader a feeling for what the CSF represents. The grating increases in spatial frequency from left to right and increases in contrast from top to bottom. The *physical* contrast of the grating is constant along any horizontal line in the photograph, but its *perceived* contrast is not. Clearly, the highest perceived contrast is for intermediate frequencies. Note the correspondence between your ability to detect the grating at different frequencies in the upper part of the figure and the CSF plotted in the lower part.

The CSF then is used in place of the modulation transfer function in Eq. (1) to predict the visual system's response to any pattern. There is a catch, however. The use of linear systems analysis requires that the system satisfy four conditions: linearity, isotropy, homogeneity, and state invariance. The mature visual system does not satisfy any of these assumptions exactly (Banks & Salapatek, 1981; Cornsweet, 1970); thus, the CSF cannot completely characterize how the adult visual system transmits two-dimensional stimuli. There is no compelling reason to expect that the infant visual system exactly satisfies these conditions either, but there are reasons to believe that they are more nearly satisfied in infants than in adults. For one thing, the infant visual system seems to be isotropic (that is, sensitivity seems to be equivalent for contours of any orientation) (Teller, Morse, Borton, & Regal, 1974). For another, the immature visual system may not violate the assumptions of linearity as seriously because the range of contrasts to which infants are sensitive is so small. In any event, the inaccuracies that might arise from violations of these four conditions can be minimized by measuring CSFs under certain conditions and by restricting the application of linear systems analysis to those situations in which the violations are small. The primary restrictions are (1) use of stimuli in which contrast is not significantly above threshold; (2) use of stimuli in which average luminances are within a restricted range; and (3) caution concerning which segment of the visual field is actually being studied. These points are discussed in greater detail by Banks and Salapatek (1981, pp. 28–29) and by Cornsweet (1970, pp. 324–339). If these restrictions are heeded, the CSF and linear systems analysis should be quite useful to the study of infant pattern vision.

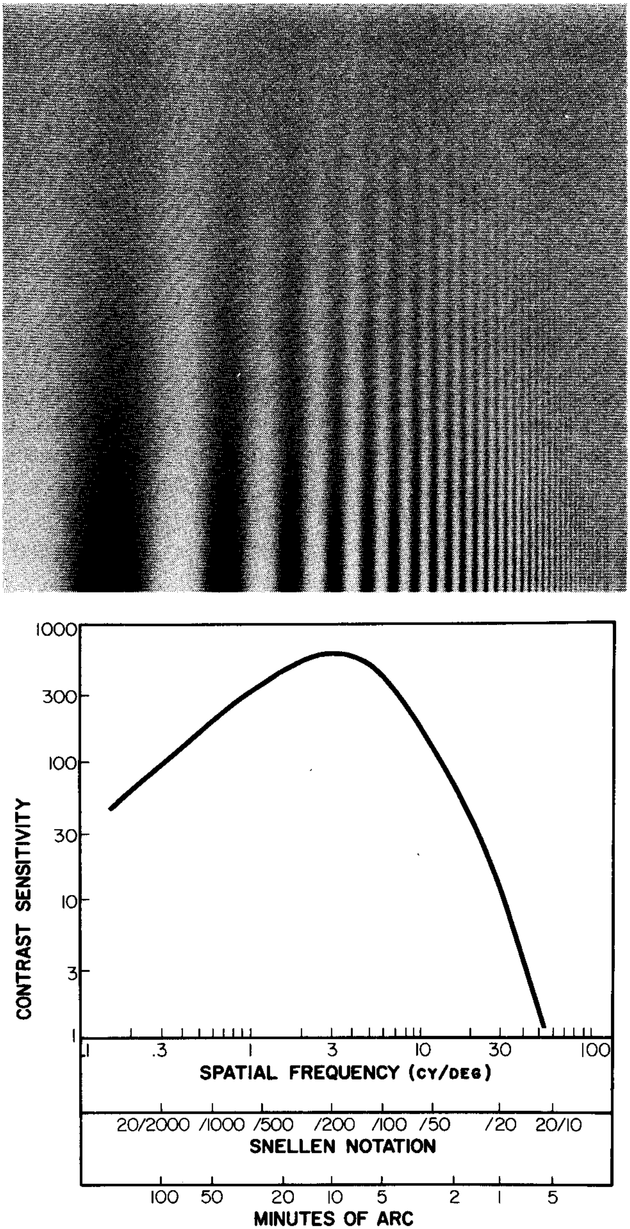

Fig. 4. A sine wave grating and a typical adult contrast sensitivity function (CSF). The upper part of the figure displays a sine wave grating in which spatial frequency increases from left to right and contrast increases from top to bottom. The lower part of the figure shows a typical adult CSF. Contrast sensitivity, the reciprocal of contrast at threshold, is plotted as a function of spatial frequency. Scales relating spatial frequency to Snellen equivalents and stripe width in minutes of arc are shown for comparison. If the figure is viewed from a distance of 1.5 m, the scales at the bottom indicate the actual frequency values of the grating in the upper part of the figure. (Adapted from Banks and Salapatek, 1981.)

III. Infant Contrast Sensitivity and Related Topics

The CSFs of young infants have been measured by three laboratories. Two of the groups, Atkinson *et al.* (1977a) and Banks and Salapatek (1978), have used preferential looking techniques primarily while the other, Pirchio, Spinelli, Fiorentini, and Maffei (1978), has used the visual evoked potential. The CSF data from these studies have been reviewed elsewhere, so we refer the interested reader to those sources for details (Banks & Dannemiller, 1985; Banks & Salapatek, 1983).

Atkinson *et al.* (1977a) and Banks and Salapatek (1978) used versions of the forced-choice preferential looking technique to test 1, 2, and 3 month olds. The contrast of sine wave gratings was varied systematically in order to determine the least contrast necessary to elicit 70 or 75% correct responding. The results from Banks and Salapatek are shown in Fig. 5. Contrast sensitivity increased significantly from 1 to 3 months, particularly at high spatial frequencies. Indeed, estimates of the highest detectable spatial frequency (the acuity cutoff) increased from 2 to 4 c/deg. The low-frequency falloff in sensitivity that is characteristic of adult CSFs is not observed at 1 month, but is at 2 and 3 months. The Banks and Salapatek data and the Atkinson *et al.* data agree remarkably well on the shape and height of the CSF at 2 and 3 months of age. They disagree concerning overall contrast sensitivity at 1 month, but agree on the shape of the CSF at that age.

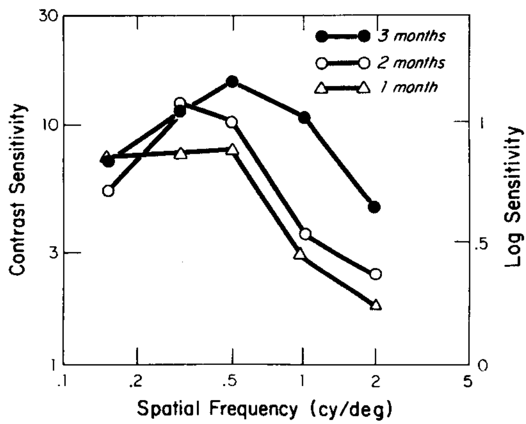

Fig. 5. The average CSFs for 1, 2, and 3 month olds as reported by Banks and Salapatek. The average contrast sensitivity for each age group is plotted as a function of spatial frequency. (From Banks and Salapatek, 1978.)

A comparison of the adult CSF in Fig. 4 and the infant functions in Fig. 5 reveals distinct differences. Clearly, infant CSFs are shifted to a lower band of spatial frequencies. Moreover, all infants appear to have a substantial deficit in overall contrast sensitivity relative to adults. Such comparisons motivate an important question: To what extent are these early deficits the result of nonvisual factors such as motivation?

Evoked potential measurements can answer this question to some extent because they are presumably less susceptible to motivational effects than are behavioral techniques. Using visual evoked potentials, Pirchio *et al.* (1978) measured CSFs in one infant from $2\frac{1}{2}$ to 6 months of age. They also measured two points on the CSF in a number of infants from 2 to 10 months. The results for the infant tested longitudinally revealed a steady increase in contrast sensitivity, particularly at high frequencies, from $2\frac{1}{2}$ to 6 months. The $2\frac{1}{2}$-month data were quite similar to the 2- and 3-month results of Atkinson *et al.* and Banks and Salapatek. The results from the infants tested cross-sectionally by Pirchio *et al.* confirmed this. Harris, Atkinson, and Braddick (1976) measured the CSF in one 6 month old, using both the visual evoked potential and preferential looking. In spite of differences in some of the stimulus parameters and the obvious differences in response measures, the two techniques yielded similar estimates of the CSF. Their data suggest that adult contrast sensitivity is only two times higher than that of 6 month olds.

The similarity of visual evoked potential and behavioral results suggests that the poor contrast sensitivity reported for young infants reflects mostly visual rather than nonvisual motivational factors. Thus, the pattern information to which young infants are sensitive is probably a small fraction of the information available to adults.

These developmental CSF data have been used to predict sensitivity (that is, detection thresholds) to a variety of patterns. These demonstrations include quantitative predictions of "face acuity" (Atkinson *et al.,* 1977b), qualitative predictions of acuity for irregular versus regular gratings (Banks and Salapatek, 1981), quantitative predictions of acuity for square wave gratings versus rectangular wave gratings (Banks and Salapatek, 1981), and quantitative predictions of contrast sensitivity for rectangular wave gratings of different duty cycles (Banks and Stephens, 1982). The accuracy of these predictions illustrates the utility of the CSF and linear systems analysis for characterizing the sensitivity of the developing visual system to different sorts of patterns.

Up to this point, we have simply presented a technique that allows one to predict input–output relationships, without pinpointing the types of processing that actually occur in the visual system. In order to develop a plausible preference model, however, one must consider processing mechanisms as well. Therefore, in the next section we describe recent work on the development of feature-selective visual mechanisms. Results from this work determine some of the characteristics of the preference model presented later on.

All mature sensory systems seem to possess many parallel pathways, each specialized to convey information about a particular set of stimuli. In the visual system, different sorts of pattern information from the same location in the visual field are signaled by different neurons. For instance, different cells in the primary visual cortex of cats and monkeys respond exclusively to stimuli of particular orientations (Hubel & Wiesel, 1962, 1968). Such cells also respond selectively to different bands of spatial frequency, one cell responding to low spatial frequencies and another to high frequencies (Campbell, Cooper, & Enroth-Cugell, 1969; Albrecht, DeValois, & Thorell, 1980). A number of psychophysical demonstrations have suggested that human adults process pattern information in parallel with mechanisms that are analogous to these cortical cells. Different mechanisms appear to be tuned to different orientations and spatial frequencies (Braddick, Campbell, & Atkinson, 1978). These mechanisms have been called orientation channels and spatial-frequency channels even though any given mechanism probably responds selectively to both orientation and spatial frequency.

Several investigators have argued the importance of these channels to pattern recognition and identification (e.g., Ginsburg, 1978; Marr, 1982; Pollen, Lee, & Taylor, 1971). Nonetheless, their development has only recently been investigated. Derrington and Fuchs (1981) reported that the spatial-frequency specificity of kitten cortical cells increases postnatally. Blakemore and Van Sluyters (1975) and Bonds (1979) reported a similar finding for orientation specificity.

Banks, Stephens, and Hartmann (1985) used a masking paradigm to measure the spatial-frequency selectivity of channels in human infants and adults. Detection thresholds were measured for sine wave gratings presented in either the presence or absence of a narrow-band noise masker. (The masker was a stimulus, continuously present, that was intended to render the grating less detectable when it was presented.) At all ages the masker caused an increase in the threshold for detecting the grating when the spatial frequencies of the masker and sine wave grating were similar. However, when the masker and grating differed in frequency by two octaves (a factor of four), the grating's threshold was unaffected by the masker in 3 month olds and adults. This result indicates that pattern information whose frequency content differs by two octaves is processed by separate channels and, therefore, constitutes evidence for multiple spatial-frequency channels with narrow bandwidths. In $1\frac{1}{2}$ month olds, however, the masker increased the grating's threshold even when the grating and masker differed by two octaves. Consequently, separate, narrow-band channels were not demonstrated at that age. Banks *et al.* used these data to estimate channel bandwidths at different ages. The estimates were slightly less than ± 1.3 octaves for 3 month olds and adults. A bandwidth could not be estimated at $1\frac{1}{2}$ months because no frequency-selective masking was observed. These results imply that spatial-frequency channels are quite unselective early in life but acquire adult-like specificity by 3 months. Banks *et al.* (1985) conducted a second experiment, using a different paradigm, to test the reliability of this age-related shift. The results corroborated those of the first experiment.

To date, the development of orientation selectivity has not been investigated in humans. In cats, spatial frequency and orientation selectivity develop at similar rates. We assume, therefore, that spatial frequency and orientation selectivity develop at similar rates in humans, too. Thus, in our preference model we assume that no spatial frequency- or orientation-selective channels operate before 2 months of age. After that age, we assume the presence of ± 1.0-octave spatial-frequency channels and ± 15-degree orientation channels.

Another important feature of our preference model concerns the shape of the filtering function $A_h(f,g)$ that should be used for different ages and stimulus contrasts. Banks and Salapatek (1981) assumed that the CSF of the appropriate age should be used at all stimulus contrasts. Recent evidence suggests, however, that this assumption should be questioned. The adult psychophysical literature illuminates important differences between threshold and suprathreshold processing. Georgeson and Sullivan (1975), for example, examined the perception of spatial contrast near threshold and above. They asked adults to adjust the contrast of a sine wave grating of one spatial frequency (the "comparison" grating) until it appeared to match the contrast of a sine wave grating of a different frequency (the "standard" grating). The standard was a grating of 5 c/deg, a value near the peak of the adult CSF. When the contrast of the standard was near threshold, adults set the contrast of the comparison gratings to higher values that were predictable from the CSF. This result is expected since the CSF is a threshold function that describes the minimum contrast required to detect gratings of different frequencies. The most interesting result in this experiment, however, occurred when the contrast of the standard was set to a value well above threshold. Adults in this situation adjusted the contrast of the comparison to the same physical value as the contrast of the standard. This is an unexpected result because the optical imperfections of the eye cause two gratings of equal contrast but different spatial frequencies to produce different retinal image contrasts. In other words, when adults set 5 and 20 c/deg gratings to equal physical contrasts, they were accepting as equal in perceived contrast two gratings with retinal image contrasts differing by a factor of 4.7 (Campbell & Gubisch, 1966). Georgeson and Sullivan called this phenomenon "contrast constancy." The phenomenon implies that the adult CSF does not describe the relative perceived contrasts of suprathreshold gratings. The function that does is much flatter than the CSF.

According to current theory, multiple spatial-frequency channels are needed to achieve contrast constancy (Hess, 1983; Georgeson & Sullivan, 1975). Because such channels appear to develop by 3 months, Stephens and Banks (1985) examined the development of contrast constancy in young infants. Two sine wave gratings, differing in spatial frequency by a factor of 3, were presented simultaneously to $1\frac{1}{2}$ and 3 month olds. The contrast of one grating was varied in order to estimate the contrasts at which fixation preference for the two gratings was equal. The equal preference points for $1\frac{1}{2}$ month olds were predictable from their CSFs. The 3 month olds' equal preference points were also predictable from CSFs but only for low-contrast stimuli. At high contrasts, equal preference occurred when the gratings were of the same physical contrast. Thus, if one accepts the assumption that equal preference in infants is analogous to perceived contrast matches in adults, Stephens and Banks' data imply that contrast constancy is observed at 3 months but not $1\frac{1}{2}$ months. In other words, the CSF is an adequate description of the relative perceived contrast of gratings among $1\frac{1}{2}$ month olds for both near-threshold and suprathreshold stimuli. Things are more complicated for 3 month olds: The CSF adequately describes the relative perceived contrast of gratings at low contrasts, but the function needed for high contrasts is flatter than the CSF. For this reason, we assume in our preference model that the CSF is the appropriate filter to use for infants less than 2 months of age regardless of stimulus contrast. We assume further that the CSF is the appropriate filter to use for older infants so long as near-threshold stimuli are involved; a flatter function is required for suprathreshold contrasts.

We should discuss one final point before describing the details of the linear systems preference model. One might not expect the linear systems approach to yield accurate predictions of infants' preferences among suprathreshold patterns. For one thing, the assumptions of linear systems analysis are more likely to be violated when applied to suprathreshold rather than threshold stimuli. Specifically, the assumption of linearity is probably violated. We do not know how seriously this assumption is violated, so we use a practical approach to the problem. We assume that the assumption is not seriously violated and use the linear systems equations to predict infants' preferences among suprathreshold patterns. If the predictions turn out to be accurate, our assumption must have been correct that the violations of the linearity assumption were not serious.

IV. Linear Systems Preference Model

With the background from Sections II and III, we now describe the linear systems preference model. This model is an elaboration of the one presented by Banks and Salapatek in 1981. Its domain is the visual preferences of infants from birth to 3 months of age, though it could be extended to older infants once more is known about their contrast sensitivity and frequency/orientation channels. By visual preference we mean the tendency to look longer at one pattern over another when given the choice. Unfortunately, this definition of preference obscures many telling features of infants' looking behavior, such as the particular eye movements used and the lower probability of looking with repeated presentations (Haith, 1980), but the definition is consistent with the majority of experiments that were suitable for reanalysis. The model does not incorporate the effect of repeated stimulus presentations as in habituation experiments. The interested reader should refer to Dannemiller and Banks (1983, 1985), Slater, Earle, Morison, and Rose (1985), and Slater and Morison (1985) for discussions of this topic. We should also emphasize that a clear distinction between preference and discrimination is necessary. The model presented here only concerns preferences, that is, infants' tendency to fixate one pattern over another. When the model predicts that two patterns are equally preferred, it does not imply that they are indiscriminable. Thus, the model does not yield predictions concerning discrimination per se. The reasons for drawing this distinction between preference and discrimination are described by Banks and Salapatek (1981, pp. 38–39).

The linear systems preference model assumes that infant pattern preferences are governed by the pattern information available to decision centers in the central nervous system. There are three facets to this assumption.

1. The pattern information available to central decision centers is a small fraction of the information impinging on the infant's eye; considerable information is lost in processing by the optic media, retina, and central visual pathways. This loss of information can be thought of as filtering.

2. The CSF is assumed to be a good description of the filtering characteristics of the visual system before 2 months of age. Thus, from birth to 2 months, our model uses the CSF to filter stimuli of all contrasts. For older infants, the model uses the CSF to filter stimuli with near-threshold contrasts and a flatter function to filter suprathreshold stimuli. These filtering functions are displayed in Fig. 6. Data obtained by Banks and Salapatek (1978) and Stephens and Banks (1985) were chosen to derive these functions because their stimulus conditions (field size and average luminance) were similar to those in most preference experiments.

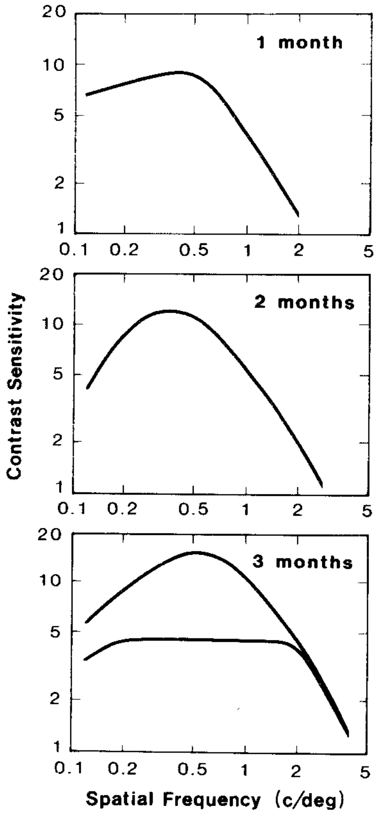

Fig. 6. The filtering functions used in the linear systems preference model. The functions were derived from the CSFs of Banks and Salapatek (1978) and the contrast matching data of Stephens and Banks (1985). Each function is represented by a smooth curve. The lower curve for the 3 month olds is the flat filtering function used for high contrasts.

3. The model assumes that infants tend to direct their eyes toward and hold fixation on or near the most "salient" pattern, once filtered by the appropriate filtering function. Salience has been defined in a variety of ways in the preference literature. The linear systems model presented here uses an explicit decision rule to determine the salience, or preference value, of any two-dimensional, time-invariant pattern. The rule, which we call the square root of sums rule, makes some physiological and psychophysical sense. It assumes that each stimulus is filtered by the appropriate filtering function and then channeled into spatial-frequency and orientation channels. In the case of infants less than 2 months of age, we have assumed that only one frequency/orientation channel exists (Banks *et al.*, 1985), so all the information is channeled into it. The output of that channel is deter-

mined by integrating the absolute values of the amplitude spectrum. In the case of infants older than 2 months, we assume that several frequency/orientation channels exist (Banks *et al.*, 1985), so the information is channeled into several ±1-octave, ±15-degree channels. This channeling is portrayed in Fig. 7. The output of each channel is determined by integration. The resultant is then squared and added to the squared output of the other channels. Finally, the square root of this sum is computed and this number is the predicted preference value. The square root of sums rule is similar to one used by Ginsburg (1978) in adult work, and can be used to compute a preference value for any two-dimensional, time-invariant pattern.

Let us summarize how the linear systems model works before describing the results of our reanalyses of preference experiments. A preference value is computed for each stimulus in an experiment by presenting the stimulus to a computer version of the model. Let us trace one stimulus through the steps involved. The Fourier transform of the stimulus is computed first, yielding an amplitude spectrum (see Figs. 2 and 3), which is simply the magnitude, spatial frequency, and orientation of each of the stimulus' constituent sine wave gratings. The amplitude spectrum is then multiplied by the appropriate filtering function (Fig. 6). The result is that components to which the infants are quite sensitive are transmitted and those to which infants are insensitive are attenuated. This filtered spectrum is then presented to the decision rule. For infants younger than 2 months, the filtered amplitude spectrum is integrated and the resultant is the predicted prefer-

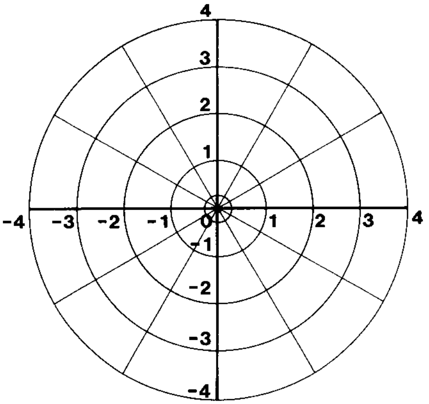

Fig. 7. Schematic of the frequency/orientation channels used in the linear systems preference model. The coordinates of the figure are the same as those in Figs. 2 and 3. The thin lines represent the boundaries of different frequency/orientation channels. The frequency bandwidths are ±1.0 octave and the orientation bandwidths are ±15 degrees. All components falling within a given channel are integrated.

ence value. For infants older than 2 months, the filtered amplitude spectrum is channeled into spatial-frequency/orientation channels (Fig. 7), and the spectrum within each channel is integrated. The resultant is squared and added to the squared outputs of all the other channels. Finally, the square root of the sum is computed and that number is the predicted preference value. We compute predicted preference values for each stimulus in a preference experiment and can use those numbers to predict the pattern of results.

V. Reanalyses of Preference Experiments

We have used the linear systems model to reanalyze several well-known preference experiments. The experiments are (1) the checkerboard studies conducted by several investigators, (2) the size and number studies of Fantz and Fagan (1975), (3) the contour density studies of Maisel and Karmel (1978), and (4) the matrix studies of Salapatek (1975). We chose these particular experiments for reanalysis because the experiments were reasonably well known, the observed preferences were robust, and the stimuli were fairly easy to analyze with the computation facilities we had at the time. We also describe reports by Gayl, Roberts, and Werner (1983) and Slater *et al.* (1985), who used linear system techniques to predict preferences.

As it turns out, the contour density model of Karmel (1969) bears some resemblance to the linear systems model, so we consider contour density predictions in several sections, too. Simply stated, the similarity between the contour density and linear systems models is the following. The contour density of a pattern is generally increased by adding more elements with shorter interelement distances, a process roughly equivalent to increasing the dominant spatial frequencies. Generally, then, the contour density of a pattern is roughly proportional to the spatial frequencies of the dominant Fourier components. This relationship is by no means perfect, however, so there are ways to contrast the predictions of contour density and linear systems models, as we will see.

A. CHECKERBOARDS

As mentioned in Section I, several researchers have presented checkerboards of various check sizes to infants and found that the most preferred check size decreases with age. The results of these experiments are summarized in Fig. 8, which is based on Fig. 2.3 of Karmel and Maisel (1975). The solid symbols represent the most preferred check size as a function of age. The consistency of these results is remarkable in view of the fact that they were drawn from different experiments using different procedures.

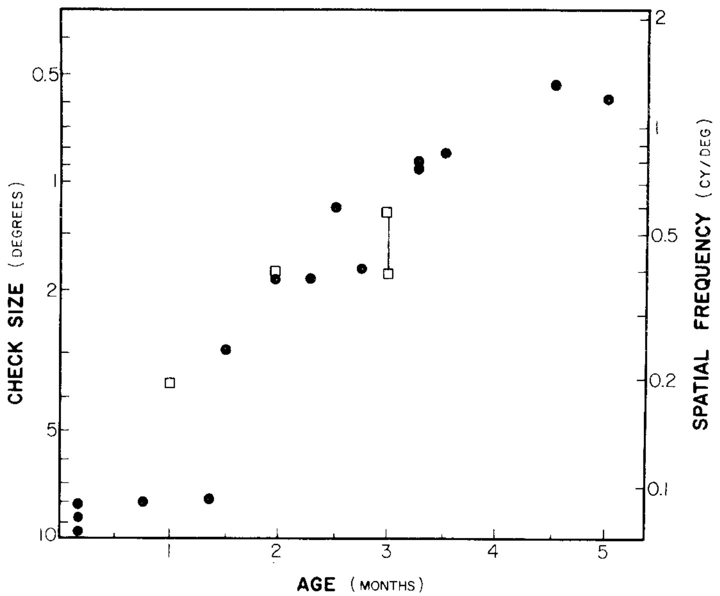

Fig. 8. Preferences for checkerboards with different check sizes as a function of age. The most preferred check size is plotted on the left ordinate and the corresponding spatial frequency of the fundamental component on the right ordinate. The filled symbols represent the results of different experiments as analyzed by Karmel and Maisel (1975). The open squares represent the predictions of the linear systems model. The two squares for 3 month olds represent the prediction when the CSF serves as the filtering function (top square) and the prediction when a flatter function (see Fig. 6) is used (bottom square).

We presented checkerboards of different check sizes to our computer implementation of the model and computed a predicted preference value for each. The resulting predictions are displayed as open symbols in Fig. 8. Notice that a range of predictions is indicated for the 3 month olds. The upper end of the range is the prediction if one assumes that the CSF is the appropriate filtering function; the lower end is the prediction if one assumes a flatter filtering function (see Fig. 6). The predictions match the observed preferences faithfully. Thus, the linear systems model seems to predict age-related changes in checkerboard preferences rather well.

As mentioned above, Karmel (1969) used a post hoc analysis to determine hypothetical functions that best described the relationship between checkerboard preferences and contour density at different ages. Obviously, the resulting agreement between observed and predicted preferences was good. Consequently, Karmel and colleagues used the derived hypothetical functions to predict preferences for patterns other than checkerboards. We will describe those analyses for each set of stimuli considered below.

B. SIZE AND NUMBER

We have also reanalyzed the size and number study of Fantz and Fagan (1975). These investigators had proposed that the size and number of pattern elements in a checkerboard were the primary determinants of checkerboard preferences. They argued that a model that combined the effects of size and number of elements would predict preferences better than either complexity or contour density alone. To examine this, they used the set of stimuli shown in Fig. 9. The size and number of pattern elements were varied independently in these stimuli. The relative preferences of 5, 10, 15, 20, and 25 week olds were measured by presenting all possible pairings of the stimuli. When the number of elements was equated (e.g., 2–2 vs 2–1 in Fig. 9), the member with larger elements was preferred. When element size was equated (e.g., 2–1 vs 8–1), the member with more elements was preferred. There were, however, some interesting developmental trends. The size variable was a better predictor of preference than the number variable at 5 weeks, and the reverse was true from 10 to 25 weeks.

We used the 1-month filtering function to reanalyze Fantz and Fagan's 5-week data and the 3-month functions to reanalyze their 10-week data. Using the curvilinear function of Fig. 6, we obtained correlations between the predicted and observed preferences of 0.92 and 0.95 for the 5-week and 10-week data, respectively. The correlation was 0.97 for 10 week olds when the flat filtering function of Fig. 6 was used. Obviously, the model provided an excellent fit between predicted and observed preferences. Figure 10 summarizes this relationship. The left panel represents the 5-week data and predictions, and the right panel the 10-week data and predictions. The predicted preference value for each stimulus is indicated by the abscissa and the observed looking time by the ordinate. The agreement between predicted and observed preferences was very good. Thus, the linear systems model predicts preferences among size and number stimuli quite well.

We also computed predictions for Karmel's (1969) contour density model. The correlations between the observed looking times and the predicted preferences based on contour density were 0.98 and 0.69 for the 5 and 10 week olds, respectively. Thus, the contour density model also predicts preferences among size and number stimuli accurately for younger but not older infants.

C. MAISEL AND KARMEL STUDY

The experiments we have discussed thus far involved only linear, nonconcentric patterns. To broaden our survey, we next examined the model's ability to predict preferences among different sorts of patterns. We chose

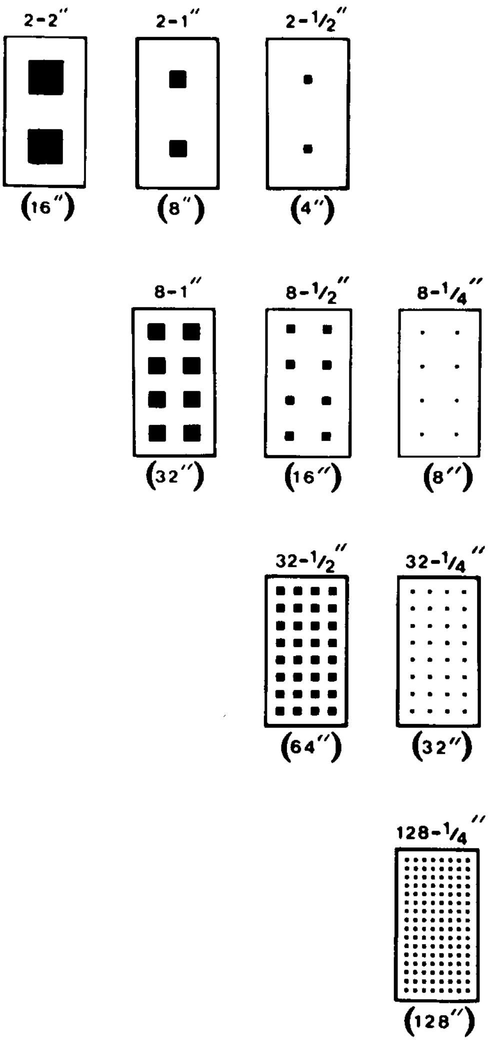

Fig. 9. Stimuli used in the size and number experiment of Fantz and Fagan. The numbers at the top of each stimulus indicate the number and size of elements. The numbers at the bottom are the total length of contour. (From Fantz and Fagan, 1975.)

Maisel and Karmel's (1978) data on preferences of 5 and 9 week olds for bull's-eyes varying in the size and number of concentric rings, concentric squares varying in the size and number of squares, and checkerboards varying in size and number. Maisel and Karmel presented three versions of each of these stimuli. (They actually presented a fourth type of pattern, a propeller pattern, but we did not analyze these data because at the time we did

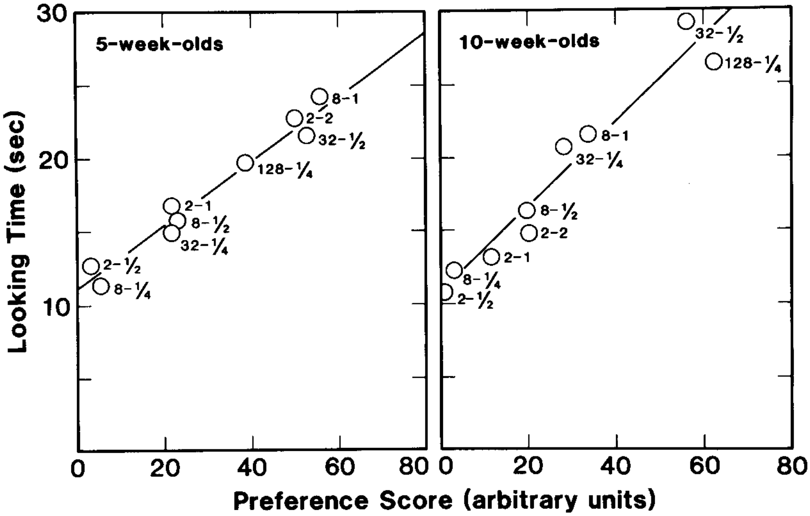

Fig. 10. The observed and predicted preferences among size and number stimuli for 5 and 10 week olds. Observed looking time for each stimulus is plotted as a function of the preference value predicted by our model. Each data point is labeled as in Fig. 9.

not have the facilities to compute the Fourier transform of these stimuli accurately.) Each trial consisted of a simultaneous presentation of one of the patterns paired with an unpatterned stimulus. Maisel and Karmel found that the younger infants preferred the bull's-eye, checkerboard, and concentric squares of lowest contour density. The older infants preferred those of intermediate density. The only obvious effect of configuration, when contour density was equated, was a preference for checkerboards over the other patterns. We used the 1-month and 2-month filtering functions of Fig. 6 to reanalyze the 5-week-old and 9-week-old data, respectively. We did not compute separate correlations for each age because of the small number of stimuli presented. The predictions were again quite good; the correlation between the observed and predicted most preferred stimulus was 0.96. The contour density correlation was 0.80.

D. MATRIX STUDIES

Finally, we examined some of Salapatek's (1975) matrix studies. Specifically, we reanalyzed his matrix studies 3 and 4, which were conducted with 2 month olds.

The matrix studies were developed to examine young infants' abilities to discriminate patterns and shapes. The stimuli presented in matrix study 3 are shown in Fig. 11. Notice that each stimulus had a uniform half com-

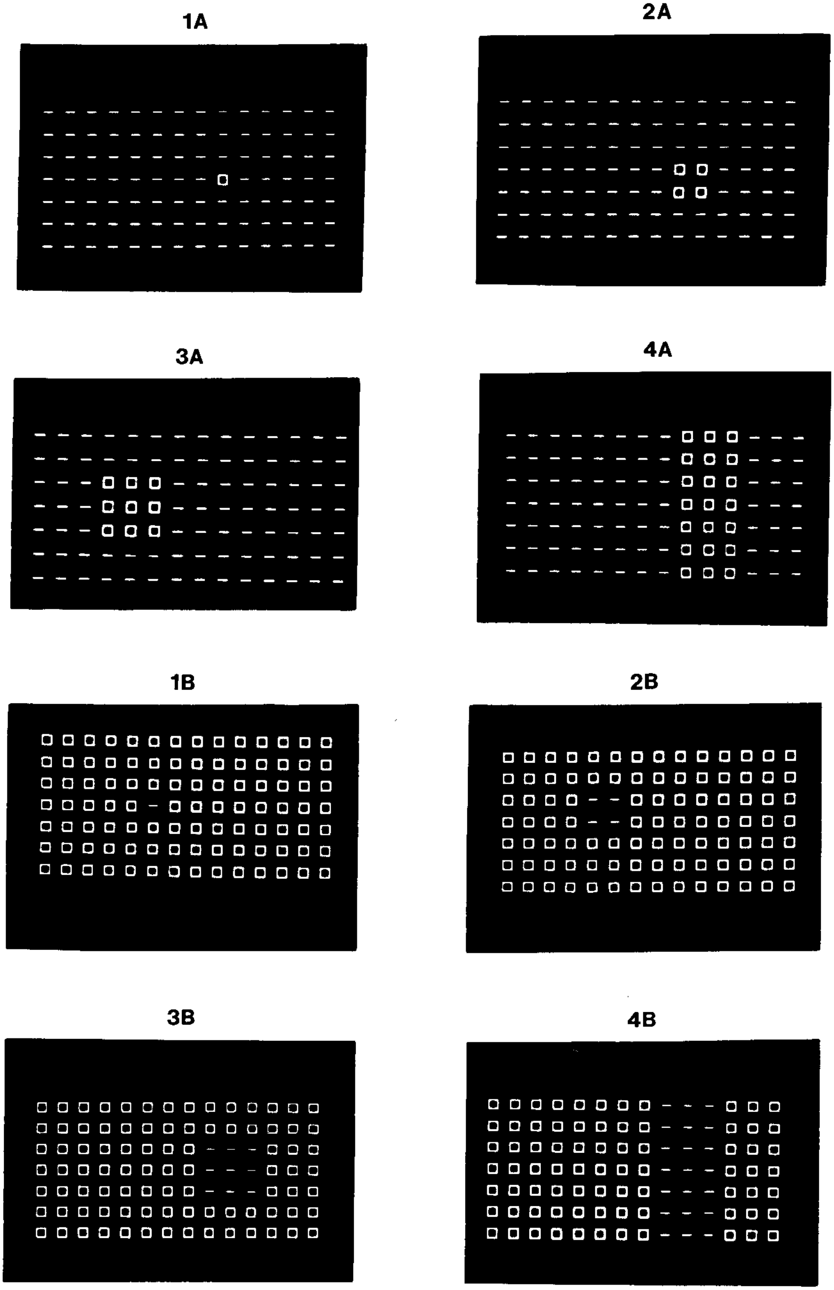

Fig. 11. *The stimuli used in Salapatek's matrix study 3. (Adapted from Salapatek, 1975.)*

posed of line segments (1A, 2A, 3A, and 4A) or squares (1B, 2B, 3B, and 4B) and a half with a discrepant embedded matrix. Salapatek hoped that infants would preferentially fixate the side with the discrepancy whenever they could discriminate the discrepant and background elements. The size of the discrepant matrix varied from one to 7 × 3. Prior to the presentation of each matrix stimulus, the infant's line of sight was centered with a fixation stimulus. Then the fixation stimulus was replaced by one of the matrix stimuli and the direction of first fixation was scored. The 2 month olds did not preferentially fixate either half when the discrepant matrix was a single or 2 × 2 matrix embedded in a field of lines or squares (1A, 2A, 1B, and 2B). However, differential looking was observed with the 3 × 3 and 3 × 7 matrices. Infants looked *toward* the embedded square matrix (numbers 3A and 4A) and *away from* the embedded line matrices (3B and 4B). Stated another way, the infants always preferred the side with more squares whether they were discrepant or not. This behavior is distinctly different from that of older subjects. Three year olds and adults looked toward the discrepant matrices whether they were composed of squares or lines.

Salapatek asked what stimulus properties determined the 2 month olds' unexpected preferences. He explored two hypotheses: (1) the infants may simply have chosen the brighter of the two sides since the side with more squares was always brighter than the side with more lines; and (2) the infants may have chosen the side with greater contour density since squares have more contour than lines. Matrix study 4 was conducted to test the first hypothesis. The stimuli used are shown in Fig. 12. Note that stimuli 3A and 3B were identical to two of the stimuli in study 3. Stimuli 3AR and 3BR in

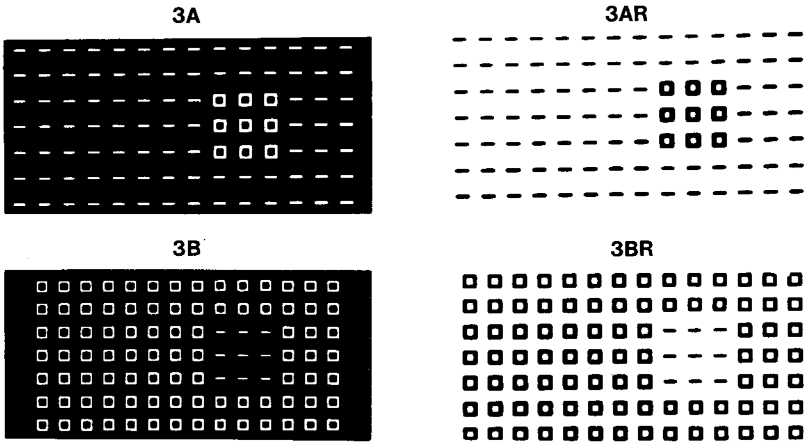

Fig. 12. The stimuli used in Salapatek's matrix study 4. (Adapted from Salapatek, 1975.)

study 4 were also similar to 3A and 3B in study 3, but they were reversed in brightness. Salapatek reasoned that if infants were simply looking to the brighter of the two sides, they should look toward the side with more squares in stimuli 3A and 3B and toward the side with more lines in 3AR and 3BR. The results clearly disconfirmed this hypothesis. Infants preferentially fixated the side with more squares in all of the stimuli. Salapatek concluded that infants simply preferred to fixate the side with greater contour density.

We reanalyzed these experiments in the following fashion. The stimuli in Figs. 11 and 12 were divided at midline. Each of those half stimuli was then presented to our preference model. We assumed that the infants' tendency to fixate one half over the other was determined solely by the difference in preference values for the two halves. The predictions and observed data are summarized in Fig. 13. The ordinate plots the percentage of first fixations toward the side with the discrepant matrix. The abscissa plots the predicted preference value for the side with the discrepancy; positive values mean that fixation should be toward the discrepant matrix, and negative values mean they should be away from the discrepancy. Notice that the model predicts that infants should prefer the halves with more squares in all of the 3 × 3

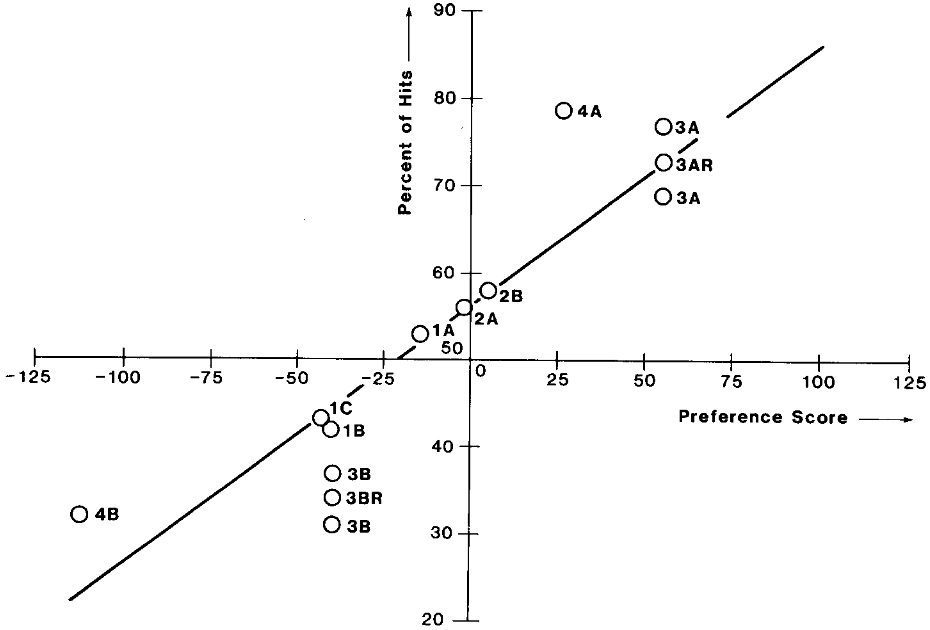

Fig. 13. The observed and predicted preferences among the stimuli of matrix studies 3 and 4. The percentage of hits is plotted as a function of the difference of preference values for the two sides of the stimulus. The percentage of hits is the percentage of first looks to the side with the discrepant embedded matrix. Each data point is labeled as in Figs. 11 and 12.

and 3 × 7 stimuli even when that reflects a preference for the nondiscrepant side. Once again the agreement between the predicted and observed preferences was rather good; the correlation between the predictions and the data was 0.90. We also calculated the contour density predictions; they too were quite accurate, yielding a correlation of 0.93.

E. OTHER REANALYSES

As mentioned above, Gayl *et al.* (1983) and Slater *et al.* (1985) have also used linear systems techniques to examine infants' preferences among suprathreshold patterns. Gayl *et al.* reanalyzed Karmel's (1969) data. In that experiment, Karmel presented two types of checkerboards, regular and random, to 13 and 20 week olds. Each type was presented with four different check sizes. Karmel presented the stimuli in all possible pairings and measured infants' mean looking time for each. The results are summarized in Fig. 14. Interestingly, the most preferred check size among regular checkerboards was considerably larger than the optimal check size among random check patterns.

To reanalyze these data, Gayl *et al.* used a linear systems approach very

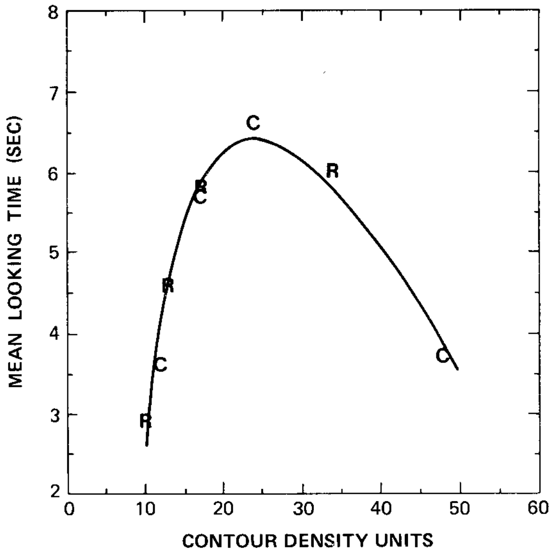

Fig. 14. The looking times observed by Karmel (1969) for regular and random checkerboards. Mean looking time for each stimulus is plotted as a function of contour density. The symbols C and R represent checkerboards and random check patterns, respectively. The line through the data points indicates Karmel's (1969) best-fitting function. (From Gayl et al., 1983.)

similar to the one described here and by Banks and Salapatek (1981). The similarity is illustrated by the following quotation: "the amount of time an infant spends looking at a complex pattern is some function of how well the infant sees the pattern, and . . . how well the infant sees the pattern can be estimated by considering the spatial frequency components of the pattern in relationship to the infant's spatial frequency sensitivity" (p. 34). Gayl *et al.* chose the 3-month CSF of Banks and Salapatek (1978) as the filtering function for Karmel's 13 week olds. Once the various stimuli were filtered, three different decision rules were employed to compute preference values. The first rule was identical to a rule considered by Banks and Salapatek (1981) and the second was identical to our square root of sums rule assuming no frequency/orientation channels. The third rule was similar to our square root of sums rule assuming the presence of multiple frequency/orientation channels. The first two rules simply did not predict Karmel's preference data very well. The third rule was much more successful, yielding a correlation of 0.95 between the predicted and observed looking times. This close relationship is illustrated in Fig. 15.

As mentioned above, Karmel (1969) derived his estimates of the optimal contour density at 13 and 20 weeks by analyzing these regular and random

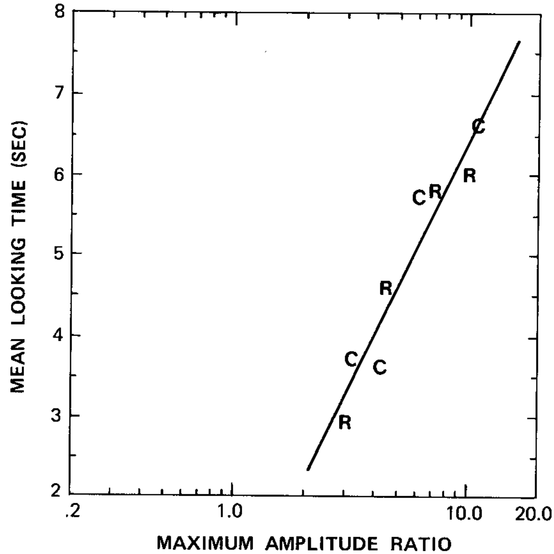

Fig. 15. The observed and predicted preferences among regular and random checkerboards as reported by Gayl et al. Mean looking time for each stimulus is plotted as a function of the preference value predicted by their model. The symbols C and R represent checkerboards and random check patterns, respectively. (From Gayl et al., 1983.)

checkerboard data in a post hoc fashion. Thus, it is not meaningful to ask whether the contour density model can adequately account for these data.

How similar is the Gayl *et al.* model to ours? It appears to be quite similar. As we mentioned, the decision rule they chose for 3 month olds is very similar to our rule for infants of that age. Unfortunately, one cannot ascertain the bandwidths of the frequency/orientation channels from their report, so we are not certain that our rules are similar in detail. One obvious difference between our model and theirs is the choice of filtering functions. They chose the 3-month CSF of Banks and Salapatek (1978), and we chose functions ranging from Banks and Salapatek's 3-month CSF to the flatter function of Stephens and Banks (1985). Our experience, however, is that the curvilinear CSF and the flattened function yield reasonably similar predictions of *relative* preferences among stimuli, so this difference between our model and theirs may not be significant.

Slater *et al.* (1985) directly compared a linear systems model with Karmel's contour density model. To newborns they presented five pairs of stimuli that were identical in contour density but dissimilar in the distribution of spatial frequency components. These stimuli were patterns of stripes with different widths and spacings. The number of stripes was held constant, so the contour densities of the stimuli were identical. Slater *et al.* used a simple version of Banks and Salapatek's (1981) model to compute linear systems predictions. For all five pairings, infants preferentially fixated the stimulus predicted by the linear systems model. Consequently, Slater *et al.* concluded that the linear systems model provided a better account of newborns' preferences than the contour density model did.

VI. Evaluation of Preference Models

Most of the older preference models—discrepancy, complexity, and size and number—were not able to predict young infants' preferential looking for a reasonably diverse set of patterns. The contour density model was somewhat more successful. Nonetheless, the generic linear systems model predicted preferences more accurately than any of the older models for all of the stimuli considered. In this sense, linear systems models provide a better account of early preferences. Let us consider some of the reasons for this. As we noted in Section I, the discrepancy and complexity models were simply not explicit enough to test rigorously. The proponents of these models never stated clear definitions of stimulus complexity or discrepancy. They also never pinpointed measurable changes in infants' processing capabilities that caused age-related shifts in preference. The size and number model of Fantz and Fagan (1975) was more explicit but very limited in scope; they never stated how their model could be extended to stimuli other than check patterns. The contour density model of Karmel (1969) was commendably explicit and, as we have shown, able to account for an impressive array of preference data. In general, however, the predictions of the contour density model have not been as accurate as those of the linear systems model. Indeed, when Slater *et al.* (1985) constructed stimuli to oppose the predictions of the two models, their version of the linear systems model was clearly superior.

Although three versions now exist, the differences among the linear systems models do not appear to be important. The version presented here is the most explicit (and recent) of the three, however, so we will not discuss the others henceforth.

The linear systems model presented here offers several advantages over other previous preference models. (1) It utilizes a rich description of visual stimuli based on Fourier's theorem. It also puts to use powerful engineering techniques that allow one, in principle, to relate any two-dimensional, time-invariant stimulus to its response. (2) It uses empirical data (such as CSFs and channel bandwidths) to determine the age-related changes in processing that underlie shifts in preference. Almost all of the model's parameters have been set by empirical observations of the age changes in basic visual mechanisms. The only exceptions are the orientation bandwidths of channels in infants older than 2 months (there are no data, so we assumed adult-like bandwidths), and the choice of decision rule (in the absence of relevant data, we have chosen a simple and plausible one). (3) Most importantly, the model has proven so far to provide quite accurate predictions of actual preference data from birth to 3 months of age.

The linear systems model might share important features with the neural substrate models of Fantz *et al.* (1975), Karmel and Maisel (1975), and Haith (1980). It proposes, just as the neural models do, that infants' tendency to look at one pattern over another is governed by how well the pattern passes through the infant's filtering function. The linear systems view uses the CSF and contrast matching data to describe this filtering function. The neural substrate models use the size and shape of hypothetical receptive fields. Presumably, the size and shape of the CSF (and the suprathreshold filtering function) are dependent on receptive field size and shape at various levels in the visual system. Thus, the filtering functions of the linear systems model could be manifestations of the visual cortical receptive fields proposed by Haith and others.

The success of the linear systems model to date is surprising in some ways. For one thing, one might expect predictions based on linear systems equations to break down under suprathreshold conditions due to violations of the assumption of linearity. Our results, and those of Gayl *et al.* and Slater *et al.,* imply that the violations are simply not serious enough to affect the predictions greatly. Another surprise stems from the types of analyses used to test the model. All of the analyses that Gayl *et al.,* Slater *et al.,* and we have presented were based on between-subjects comparisons. Clear individual differences exist among infant preferences (Thomas & Jones-Molfese, 1977) and CSFs (Atkinson *et al.,* 1977a; Banks & Salapatek, 1981), so one might not expect between-subjects analyses to yield such high correlations. As Gayl *et al.* pointed out, within-subject experiments would presumably improve the accuracy of predictions even further.

Our results suggest an interesting research question: To what extent are "cognitive" variables such as stimulus significance, meaningfulness, or familiarity required to explain early preferences? This question could not be pursued rigorously in the past because "sensory" variables could not be controlled effectively. An example will clarify this point. Suppose one wanted to know when infants first exhibit a preference for faces because of their social significance. Showing that infants of a certain age preferred facelike over nonfacelike stimuli would not be convincing because critics could argue that the facelike stimuli simply passed better through the peripheral stages of visual processing (perhaps because they were high in contrast, the features were somewhat regularly spaced, etc.). To examine such a question experimentally, one would have to construct two stimuli, one facelike and one not, that passed equally well through peripheral processing. But one would not know how to construct such stimuli without a clear, quantitative model of the sensory aspects of pattern processing. The linear systems model might be useful in this regard. Its development has been based on empirical observations of the development of basic mechanisms of pattern vision. It has been tested with abstract, nonrepresentational patterns. It postulates nothing about the significance, meaningfulness, or familiarity of a visual stimulus. Thus, the model would not predict a strong preference for a face over a similar, but nonfacelike, stimulus except to the degree that the face provided spatial frequency information that fit the infant's filtering function better. One could use the linear systems model as a guide in constructing stimuli that minimized differences in how well they were transmitted in peripheral processing. Such stimuli would allow one to investigate infants' perceptions of faces as social objects more rigorously. Our argument here assumes, of course, that the linear systems model provides an accurate characterization of filtering in peripheral stages of processing. This assumption is at least plausible given how well linear systems techniques portray sensitivity to various sorts of patterns (Atkinson *et al.,* 1977b; Banks & Salapatek, 1981; Banks & Stephens, 1982).

As Banks and Salapatek (1981) have pointed out, simple sensory-based models, like the one described here, cannot adequately account for preferences in older infants: their preferences are assuredly influenced by the significance of a stimulus since certain stimulus configurations, such as Mom's face, acquire particular significance. It will be of particular interest to delimit the ages for which the linear systems model does and does not work. A clear failure to predict preferences at a certain age will imply that processes other than simple optical and neural filtering by the peripheral visual system have become significant to the infant's perceptual world.

VII. Some Final Thoughts about the Rules for Preferences

The success of the linear systems model in predicting infant pattern preferences suggests an intriguing question: Why should young infants' visual behavior obey such simple rules? In other words, why should infants look at patterns they can see well rather than patterns they cannot? There is no obvious way to explore this question experimentally, but we would like to offer two related hypotheses.

The first hypothesis was stated originally by Fantz (1961). He put it this way: "It is . . . reasonable to suppose that the early interest of infants in form and pattern in general, as well as in particular kinds of pattern, play an important role in the development of behavior by focusing attention on stimuli that will later have adaptive significance" (p. 72). This hypothesis is attractive because patterned regions in the visual field are in fact much more likely than unpatterned regions to contain information that will become significant to the infant (e.g., faces, drop-offs, furniture). We would like to extend Fantz' hypothesis to incorporate our finding that infants prefer to fixate high-contrast, low-frequency contours over anything else. What does such pattern information normally correspond to in the infant's environment? Most objects are seen because of the contrast between their surface and the background. So a preference for high-contrast contours should generally correspond to a tendency to fixate object boundaries. What about the preference for low spatial frequencies? As Banks and Salapatek (1981) observed, the spatial frequencies contained within an object change systematically with the distance between the infant and the object. As an object is brought closer, its angular size increases and its constituent sine wave components shift toward lower frequencies. Thus, a preference for low spatial frequencies corresponds to a tendency to fixate near rather than distant objects. Such a behavioral strategy is reasonable because young infants cannot direct effective action toward objects more than a meter away.

Furthermore, objects of concern, such as the face of a parent interacting with them, are generally presented at close range.

The second hypothesis about the teleology of early visual preferences is different from, but not contradictory to, the first. Briefly stated, the hypothesis is that preferential looking toward highly visible patterns is a useful strategy for providing visual stimulation that is needed to guide the development of the central visual system.

This hypothesis evolved from recent observations of how visual experience influences the development of central visual structures. The microstructure of the human visual cortex is strikingly immature at birth (e.g., Conel, 1939–1959). We do not know, of course, what the physiological properties of the cortex are at this age, but one suspects that they are quite immature, too. Indirect evidence from other species supports this claim. For example, the visual cortex of kittens is anatomically immature at birth and so are the physiological properties of individual cortical cells. Among physiological properties, the orientation (Blakemore and Van Sluyters, 1975), disparity (Pettigrew, 1974), and spatial-frequency (Derrington and Fuchs, 1981) selectivities of single cells are ill defined until 5–7 weeks after birth.

There is overwhelming evidence that particular types of visual experience are required for adultlike definition to emerge. Blakemore and Van Sluyters (1975), for example, traced the development of orientation selectivity in kittens reared with normal visual experience and with no visual experience. Before 4 weeks, the cortical cells of normally reared and binocularly deprived kittens were essentially indistinguishable. After 4 weeks, the cells in deprived animals became less and less responsive and selective compared to cells in normal animals. Blakemore and Van Sluyters next reared kittens in a variety of restricted environments in order to determine what sorts of visual experience were necessary to keep cortical development on its normal course. The necessary ingredients for normal binocularity and orientation selectivity were high-contrast, elongated contours presented to both eyes simultaneously. In support of this conclusion, Blakemore (1976) reported that reducing the illumination into one eye had no discernible effect on cortical development so long as both eyes experienced the same contour information.

Blakemore and Van Sluyters (1975) proposed a model of innate and experiential influences on the development of single cortical cells. They noted that most cortical cells in young kittens are not as selective as they are in adults. Those that are reasonably selective tend to be monocular. Blakemore and Van Sluyters argued that cortical cells must eventually acquire strict, adultlike preferences for similar environmental features presented to the two eyes. In other words, a given cortical cell must ultimately prefer similar orientations, spatial frequencies, and directions of motion for both eyes. Their model proposed that binocular visual experience with elongated contours provides vigorous, correlated neuronal activity, and that this activity is required for the acquisition of similar stimulus preferences for a narrow range of features.

If experience with patterned visual stimulation, correlated between the eyes, is a necessary condition for normal cortical development, how can an immature organism ensure that it receives an adequate diet of such stimulation? A few sensorimotor strategies come to mind. For one, it would be beneficial to focus or accommodate the eyes to provide sharp images to the retina; apparently, even young infants are capable of focusing with moderate accuracy (Banks, 1980; Braddick, Atkinson, French, & Howland, 1979). Second, it would be important to orient the two eyes toward roughly the same position in space in order to guarantee that a given feature falls on nearly corresponding regions on the two retinas, something neonates are equipped to do (Slater & Findlay, 1975). Finally, it would be useful to fixate (i.e., direct the foveas toward) regions in the visual environment that contain large, high-contrast contours. But the reader might raise questions about this claim. Why does the infant profit from orienting the *foveas* toward pattern stimulation? Such a fixation strategy would tend to maximize the amount of pattern information to which the foveal and parafoveal retina was exposed. But why might that be important? First, as Haith (1978) emphasized, the majority of the visual cortex is devoted to foveal and parafoveal processing, so this fixation strategy would ensure that most of the cortex would be exposed to patterned stimulation. Second, the requirements for spatial resolution and for the acquisition of similar feature preferences are probably greater for cortical cells subserving the fovea as opposed to the eccentric retina. For these reasons, we speculate that patterned stimulation of the central retina is important to the guidance of cortical development.

How would one determine which regions of the visual field provide the most adequate stimulation? It seems reasonable that measures of visual sensitivity could tell us which regions should be stimulating and which should not. If the filtering functions presented in Fig. 6 are valid estimates of how sensitive infants are to various sorts of information, then infants, when given a choice, should prefer to fixate pattern information that passes easily through those filtering functions. In other words, they should follow the rules the linear systems model claims they do.

In summary, our second hypothesis is that young infants' looking behavior reflects a fixation strategy that tends to expose the central retina to quite visible pattern information in order to provide the stimulation required for normal cortical development.

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