
Infant Visual Psychophysics

MARTIN S. BANKS

*School of Optometry and
Department of Psychology
University of California
Berkeley, California 94720*

JAMES L. DANNEMILLER

*Department of Psychology
University of Wisconsin
Madison, Wisconsin 53706*

I. INTRODUCTION

The mature visual system is a marvelous device. It gathers information about a wide variety of environmental properties, represents the information efficiently, and allows the perceiver to respond appropriately. All of these things occur reliably in spite of dreadfully complicating factors such as changes in the source of illumination, movement of objects under inspection or of the perceiver, changes in the context in which objects are presented, and so forth.

Recently, the development of the visual system has drawn much theoretical and empirical attention. This interest arises from our natural curiosity about how sophisticated devices come to be, but there are additional reasons. For one, the cognitive and social capabilities of young infants have also come under increasing scrutiny. The study of early cognitive and social skills generally involves visual stimulation, so it has become important to know what infants can and cannot see in order to ensure that immature performance can be ascribed to cognitive or social immaturities rather than to an inability to discern the stimuli used.

Another reason for the recent interest in infant vision arose from findings in the basic research field of neurophysiology and the clinical field of pediatric ophthalmology. The presence of ocular abnormalities early in

life (cataracts, crossed eyes, myopia, etc.) cause seemingly permanent deficits in various visual capabilities (e.g., Awaya, et al., 1973; Banks, Aslin & Letson, 1975; Freeman, Mitchell, & Millodot, 1972; Hubel & Wiesel, 1965; Wiesel & Hubel, 1965). This susceptibility of infants and young children to ocular abnormalities means that early diagnosis and treatment are required for effective eye care. Much research has, therefore, been devoted to describing how normal visual development proceeds, so that abnormality can be spotted, and to developing sensitive assessment techniques.

This volume presents work that was spawned by the recent interest in visual development. Our chapter has two fairly specific purposes. First, we describe and evaluate the psychophysical approach to the study of visual development. What is psychophysics? What are its strengths and weaknesses as a scientific methodology? What experimental techniques does the approach offer? How are psychophysical procedures implemented in infant research? Second, we review specific psychophysical findings concerning the development of pattern vision and temporal vision in human infants.

II. PSYCHOPHYSICS AND ITS TECHNIQUES

Psychophysics attempts to relate the physical properties of the external world to one's experience of it. The senses are considered the bridge between the external world and the inner world of experience, so psychophysics concentrates on sensory capabilities. The basic question asked in classical psychophysics is, what are the limits of sensory capability? Exploration of this question takes two routes: what is the smallest detectable energy (the absolute threshold)?; and, what is the smallest detectable change (the difference threshold)? These sound like rather uninteresting questions, but they are not because they are normally used as vehicles to explore the mechanisms that underlie sensory capabilities. We will return to this point shortly, but first we describe other defining characteristics of psychophysics.

Psychophysicists are most concerned with sensory mechanisms and those mechanisms are assumed to be low-level and indifferent to cognitive strategies. The performance of these mechanisms is also generally assumed to be dependent primarily upon the physical properties of stimulation. These two assumptions have led to two other common features of psychophysical research. First, because physical properties of stimula-

tion are assumed to be important, the field is characterized by its careful attention to stimulus measurement. In visual psychophysics, for example, the luminance, wavelength composition, size, temporal duration, and any other relevant physical dimension are usually specified precisely. The stimuli used are often quite simple as well. Second, because higher-level, cognitive mechanisms are not of primary interest, psychophysicists try to minimize their impact on performance by making the subject's task as simple as possible. Thus, the response asked for is generally very simple. ("Press this button if you see it, and the other button if you don't.") Subjects are also usually given any information that might aid performance without introducing experimental bias. Hence, they are typically given comprehensive instructions, lots of practice, rest periods as needed, and trial-by-trial feedback on their performance. To minimize the effects of variations in attentiveness, subjects are often allowed to initiate trials themselves.

Psychophysics is commonly portrayed as the discipline concerned with sensory thresholds. Indeed, the field's reliance on threshold data has been criticized on the grounds that sensory thresholds have little relevance for everyday perception. This point is certainly valid because the visual environment is populated by objects whose contours and features are well above threshold. Sensory thresholds only have a significant impact on perception in certain situations: for example, the ability to read a distant highway sign or to detect an aircraft in a dense fog (Ginsburg, 1978). Nonetheless, criticism of psychophysical research because it relies on threshold data misses the point of most research in this field. Sensory thresholds are generally measured not because the thresholds themselves are of interest but rather because they reveal the characteristics of underlying sensory mechanisms. In this sense, psychophysics resembles geophysics. A geophysicist maps the complex of direct and indirect shock waves produced by surface explosions in order to determine the shape, depth, and composition of underlying layers of rock. The psychophysicist maps the space of sensory experience under different conditions in order to ascertain the character of underlying sensory mechanisms.

This argument tells us why the psychophysicist attempts to relate the physical properties of stimulation to their sensory effects, but it does not tell us why the threshold region in the space of sensory experience is chosen. Why not a point 10 times higher than threshold? We believe thresholds are used because they are easy to find accurately and reliably. The subject can easily provide reliable data on the location of the transition from experience to no experience. It would be much more difficult to

design techniques that would reliably locate the region of sensory experience that is 10 times higher than threshold.¹

Let us describe a hypothetical psychophysical experiment to illustrate how thresholds are typically used to map sensory space and to reveal underlying mechanisms. The experiment involves determining the relationship between the wavelength and the visibility of a light. The experiment is most concerned with rod vision, so it is conducted under dim, scotopic illumination levels. Conceivably, one could use two strategies—input or output mapping—to chart this relationship between wavelength and visibility.

Output mapping strategies involve the presentation of a constant intensity value and the measurement of a variable output or response. In our example, one might present a dim, fixed-intensity flash of light and ask the subject to report a number corresponding to its perceived intensity. If this was done for a number of wavelengths, a curve plotting perceived intensity (a psychological dimension) as a function of wavelength (a physical dimension) could be determined. The problem with this strategy is that the characteristics of psychological scales, such as perceived intensity, are often difficult to ascertain. Are there floor and ceiling effects? Is the scale a ratio scale, an interval scale, or an ordinal scale?

The input mapping strategy, which is characteristic of psychophysical research, avoids this difficulty to a great extent. It involves varying the intensity of the stimulus in order to achieve some criterion output or response. In our example, we might present a variety of intensities at each wavelength and again ask the subject to report, for each intensity, a number corresponding to its perceived intensity. Following the input mapping strategy, we would summarize our findings by plotting the physical intensity required at each wavelength to elicit a constant perceived intensity. We could choose any level of perceived intensity to serve as criterion and thus avoid potential floor and ceiling effects and other sources of error. For reasons stated above, the best choice for the criterion level would probably be a threshold. Our summary graph would then plot the threshold intensity (a physical dimension) as a function of wavelength (another physical dimension). The beauty of this approach is that it

¹ This argument is not valid for all psychophysical experiments. At least one class of experimental questions is concerned with the actual value of thresholds. These are investigations of the visual system's optimal performance. For example, Green (1970) and Williams (1985) measured visual acuity and contrast sensitivity in adults and quantitatively related the threshold values to the spacing and size of photoreceptors. Another example is the experiment of Hecht, Schlaer, and Pirenne (1942). They measured the absolute threshold of the visual system under optimal conditions and then used the threshold value to deduce that a single quantum of light can be an effective visual stimulus.

sidesteps the problem of using indeterminant psychological scales; the only scales involved in the ultimate description are physical scales whose properties are known. The only assumption involved is that the criterion output—in this case, the threshold value—represents a similar sensory effect across wavelengths.²

It is interesting to note that input and output mapping strategies are both common in perceptual research. Input mapping is characteristic of adult and infant psychophysical research whereas output mapping is characteristic of most perceptual research concerned with higher-order mechanisms (e.g., Bornstein, Kessen, & Weiskopf, 1976; Ruff & Birch, 1974). The advantage of the input mapping strategy is its psychometric and logical simplicity. The disadvantage of the input mapping strategy is that it requires much more time to collect the data. In our hypothetical example, this strategy demands that several intensity levels at each wavelength be presented in order to find the intensity that elicits a criterion response. The output mapping strategy requires only one intensity level at each wavelength.

The hypothetical example developed above yields a psychophysical map of the relationship between the visibility and the wavelength of a light under dim illumination conditions. This map, which is called the scotopic (rod) spectral sensitivity curve, has proven very useful. The scotopic spectral sensitivity curve, once corrected for absorption by the ocular media, has the same shape as the curve that describes the way rhodopsin absorbs light of different wavelengths. It is reasonable to assume, then,

² The experimenter using an output mapping strategy has to be concerned with the rules that different subjects follow when relating input magnitude to response. For example, consider the use of the duration of fixation measure in studies of infant perception. Two infants may look for differing amounts of time at the same magnitude of a stimulus. So far, this creates no problems. Suppose, however, that when the stimulus is increased in magnitude, the two infants scale their fixation times according to different rules. One infant's fixation durations may increase fairly linearly with stimulus magnitude while the other infant's fixations may increase logarithmically. The underlying sensory responses are obscured by the indeterminate nature of the relationship between physical magnitude and response magnitude.

The use of an output mapping strategy in these studies bears some resemblance to a similar technique in audio engineering. For example, to determine the fidelity (frequency response) of a stereo system, an audio engineer can use the output mapping strategy of probing the system with a constant amplitude signal of various frequencies. The output amplitude at each of these frequencies is then measured and the effect (attenuation) of the system on each input frequency can be specified. The choice of an input amplitude is somewhat arbitrary because the system is approximately linear; the scale that relates input amplitude to output amplitude is a ratio scale, that is, the doubling of input amplitude leads to a doubling of response amplitude. No such *a priori* assumption can be made about the psychological scales that arise when the output mapping strategy is used in psychophysics.

that the psychophysical sensitivity curve and the absorption curve are intimately related. Since rhodopsin is the photopigment of rods, we can conclude that vision under dim illumination is mediated entirely by rods. This and many other examples illustrate the potential utility of using threshold data to determine the functional characteristics of sensory mechanisms.

The next topic we consider is methods used to measure thresholds. The term psychophysics generally refers to behavioral work. That is to say, psychophysical techniques are those that involve voluntary behavioral responses such as button presses and verbal reports. Electrophysiological techniques like visually evoked potentials and electroretinography are generally not considered psychophysical techniques. Psychophysics is also characterized by its emphasis on repeated measures. Specifically, most experiments involve hundreds or even thousands of trials per subject. For this reason, most psychophysical publications present data from only a handful of subjects.

The psychophysicist has several specific methods at his disposal: (1) method of adjustment; (2) method of limits; (3) method of constant stimuli; and (4) adaptive staircase techniques. These methods are distinguished by the manner in which the stimuli are presented and by the responses required of the subject. We discuss only two of them here—the method of constant stimuli and adaptive staircases—because the others are not currently applicable to infant research.

The method of constant stimuli is a very common psychophysical technique. This method places the control of stimulus level in the experimenter's hands. Several levels that span the subjects' estimated threshold are chosen beforehand. A number of trials are then presented at each level during the experimental session. Very frequently, the two-alternative forced-choice paradigm is used. In this paradigm the stimulus appears in one of two positions on each trial and the subject responds by indicating in which position (e.g., left) he/she thought the stimulus appeared. The subject's responses at each level are converted into a percentage correct score. Thus, percentage correct scores are obtained at each stimulus level. These percentages as a function of stimulus level are called the psychometric function. In the two-alternative, forced-choice procedure outlined above, the psychometric function generally extends from 50%, or chance performance, at low stimulus levels to 100%, or perfect performance, at high levels. The exact shape of the psychometric function depends on experimental conditions, but the cumulative normal distribution (ogive) is most frequently assumed.

Since psychometric functions change smoothly from 50%, the point at which the subject presumably cannot detect the stimulus, to 100%, the

point at which subject always detects the stimulus, how does one determine the location of threshold? Clearly the determination is somewhat arbitrary because any point between 50% and 100% would be a possibility. Most researchers have defined the 70% or 75% point as threshold, in part because the psychometric function is steepest in that region.³ Various techniques have been used to estimate either of these points. They can be estimated using graphical interpolation, but a more rigorous approach is to use a curve-fitting routine such as probit analysis (Finney, 1971).⁴

Adaptive staircase procedures (Wetherill & Levitt, 1965) are also commonly used for psychophysical measurement. These procedures differ from the method of constant stimuli in several respects. In staircase procedures, the level of the stimulus on each trial depends upon the observer's response(s) on the previous trial(s). Because stimulus levels are determined by the subject's performance, they tend to cluster around the point to be estimated on the psychometric function. For this reason, staircases allow accurate estimation of thresholds without requiring unreasonably large numbers of trials.

A large number of staircase procedures exist. Different versions are distinguished by four characteristics: (1) the rules used to determine changes from trial to trial in the level of the stimulus, (2) the step size by which the level is increased or decreased from trial to trial, (3) the rule used to terminate the staircase, and (4) the algorithm used to estimate threshold from the resulting data. The most common procedure is the two-down, one-up staircase of Wetherill and Levitt (1965). The change rule of this procedure requires two consecutive correct judgments before the stimulus level for the next trial is decremented (detection is made more difficult). Any incorrect judgment results in an increment in stimulus level on the next trial (detection is made easier). The step size of these increments and decrements is usually fixed, but several techniques have additional provisions for changing the step size as the staircase progresses (e.g., Pollack, 1968). The two-down, one-up staircase is generally terminated once a prespecified number of reversals (a change from incrementing to decrementing the level or vice versa) has occurred. Threshold is

³ The experimenter generally assumes that the shapes and slopes of psychometric functions are roughly the same for different stimuli. If this assumption is valid, the shape of derived sensitivity functions does not depend on the choice of threshold criterion. If this assumption is invalid, however, the shape of derived sensitivity functions varies with threshold criterion. This is a particular problem when the slopes of psychometric functions are shallow. Since shallow slopes are the rule in infant work, the validity of this assumption should be checked whenever possible.

⁴ Probit analysis is available on the SAS statistical package for IBM computers.

estimated simply by averaging the stimulus levels at each reversal. The two-down, one-up procedure estimates the 70.7% point on the subject's psychometric function. The statistical properties of staircase estimators have been reported by Rose, Teller, and Rendleman (1970).

It is important, of course, to use a psychophysical method that yields the most accurate estimate of threshold. In infant work, it is obviously desirable to require as few trials as possible. Two sorts of issues are important to evaluating whether the method of constant stimuli or adaptive staircases are better for infant psychophysical work. First the statistical accuracy of the procedures is important. We consider this issue by asking, under *ideal conditions*, how accurate are the two techniques in estimating threshold given a fixed number of trials? Second, the relative efficiencies of the techniques *in practice* are important. We consider this issue by asking, how useful are the two techniques in estimating thresholds under typical infant testing conditions?

We consider statistical accuracy under ideal conditions first. The accuracy of any psychophysical method depends on efficient placement of observations. This amounts to an efficient selection of stimulus levels. As might be expected, what constitutes efficient placement depends on the experimental question. For example, if one wants to estimate the slope of the psychometric function, it is best to distribute levels widely (Levitt, 1971). If, on the other hand, one wishes to determine a single point, such as the 70% point, it is better to cluster observations near the point being estimated (Levitt, 1971). The goal of most infant psychophysical work has been to estimate one point, so we will focus on that problem.

The method of constant stimuli makes optimal placing of observations difficult. The experimenter must choose the position and spacing of stimulus values prior to the experimental run. Since one often does not know the subject's capability beforehand, one has to make somewhat arbitrary choices. This presents a problem. One might, for example, choose stimulus levels that are all too low for the subject and only obtain points around the 50% level. A threshold could not be estimated with any accuracy in this case. Adaptive procedures, however, are designed to use information gained during the course of a session to improve the placing of stimulus levels. In that way, the majority of levels are placed near the threshold value so that most trials contribute significantly to the final computed value.

These considerations imply that adaptive staircases may estimate threshold in a given number of trials more accurately than the method of constant stimuli does. This is an empirical question, however, so let us investigate it in that fashion. There are two measures of accuracy that are important: bias and variability. Bias is simply the difference between the

true and estimated thresholds. Variability is the dispersion of individual cases of estimated thresholds about the mean threshold estimate. Bias can be partialled out if it is known, but variability cannot. Therefore, we concentrate here on the variability of threshold estimates.

Which method—method of constant stimuli with probit analysis or two-down, one-up adaptive staircase—yields the lesser variability in threshold estimates? Unfortunately, this question cannot be answered simply. One approach has been to use computer simulations to compare the two methods. These simulations are first approximations to these methods in actual use because most simulations make assumptions that are probably not true in actual psychophysical work. This is particularly true with infants because performance may not be stable across trials. Nonetheless, McKee, Klein, and Teller (1985) have argued that the variability of threshold estimates with adaptive staircase procedures can in principle be no less than the variability of threshold estimates from the method of constant stimuli with *optimum placement of trials*. Their computer simulations appear to support this assertion in that the variability of threshold estimates is about the same for the two methods when trials are placed optimally in the method of constant stimuli. But when trials are not placed optimally, adaptive staircases provide less variable threshold estimates than the method of constant stimuli. This occurs because staircases, given a reasonable number of trials, automatically place the majority of trials near the threshold value. In other words, adaptive staircases seem, on statistical grounds, to be a better choice than the method of constant stimuli.

The second important consideration is how these two procedures work in practice. We consider three problems that all argue in favor of using the method of constant stimuli, given our current state of knowledge. First, the criteria for rejecting poor experimental data sets are clearer with the method of constant stimuli: an infant who fails to respond near 100% correct with a highly visible target is probably not attending sufficiently to allow a meaningful estimate of threshold. The criteria for rejecting a poor staircase run are not as clear (see Manny & Klein, 1985), for a suggested criterion for rejecting poor staircase runs). Second, the upper asymptote of the infant's psychometric function may not be 100%. This presents no particular problems for the method of constant stimuli beyond those introduced if probit analysis is run with the assumption of an upper asymptote of 100%. However, asymptotes below 100% present problems for staircases. In particular, low asymptotes decrease the probability that two consecutive correct trials will occur as required by the rules of the two-down, one-up staircase. This reduces the probability that the staircase will converge quickly on the appropriate stimulus level. Finally, because

a two-down, one-up staircase converges on the 70.7% point on the psychometric function, a majority of the trials presented to the infant may be at or near threshold. We have used staircase procedures in our laboratory and our distinct impression is that infants' attention wanes when a number of near-threshold trials are presented consecutively. This is not as serious a problem with the method of constant stimuli because this method often presents numerous trials well above threshold. One way to alleviate the problem with the staircase procedure is to present levels well above threshold on a random schedule or when the experimenter thinks that they are necessary to maintain the infant's attention. These "easy" trials should not be used to compute changes in the direction of the staircase. Of course, if one has to present too many "easy" trials, the advantage of staircase procedures for required number of trials would diminish.

Human infants are, of course, nonverbal and this fact poses a number of problems for psychophysical testing. In particular, infants cannot be instructed to perform at the limit of their sensory capacity nor to respond in an unambiguous fashion. The developmentalist's only recourse is to rely on existing response systems. In psychophysical work, these response systems usually involve visual attending behaviors. These include general orienting behaviors to peripheral stimuli, such as eye movements and head turns, and visual following behaviors, such as smooth pursuit. Other responses, such as optokinetic nystagmus (OKN), electroretinography (ERG), and visually evoked potentials (VEP), have been used in related research but, according to our earlier definition, these are not conventional psychophysical response measures.

Two behavioral techniques that use visual orienting behaviors are most common in infant psychophysical work. They are the preferential looking technique (Fantz, 1958, 1965) and the forced-choice preferential looking technique (Teller, 1979). Both techniques rely on the tendency of young infants to fixate a patterned field rather than a blank field when given the choice. Fantz, Ordy, and Udelf (1962) and others have used the preferential looking technique (PL) to measure pattern detection thresholds. This is accomplished by simultaneously presenting a patterned field and a blank field of equal hue, luminance, and size. The infant's direction of first fixation, number of fixations, or total fixation time on each field is recorded. If significantly more or longer fixations are observed to the pattern, one can conclude that the infant can detect the pattern. The forced-choice preferential looking technique (FPL) is a variant of the PL technique. As in PL, two stimuli—a patterned and an unpatterned field—are generally presented on each trial, one to the left and one to the right. An adult observer, who is unaware of the location of the patterned stimu-

lus, is asked to judge its location based on the infant's behavior. The observer is allowed to use any aspect of the infant's behavior to make this judgment. In order to learn which behaviors are most informative for each infant, the observer is given practice and trial-by-trial feedback. So, if direction of first fixation is most informative for one infant, the observer should learn this and use that behavior to guide his judgments. If facial expressions are most informative for another infant and the observer notes this, that behavior would be used. When the observer in an FPL experiment is able to judge the pattern's location more often than expected by chance, one can conclude that the infant can detect the pattern.

We now consider the relationship between the results from PL and FPL experiments and infants' sensory thresholds. Any estimation of threshold requires information about what stimulus levels are above threshold and what levels are below threshold. Unfortunately, poor performance (negative results) is weak evidence that a stimulus is below threshold. Consequently, PL and FPL threshold estimates are ambiguous: they only indicate that threshold must be at the estimated value or lower. The difficulties arise because the dependent measures used (in PL, direction, number, or duration of fixations and in FPL, the adult observer's percentage correct) are at least two steps removed from the variable of interest, the sensory threshold. One step is between the infant's detection of the stimulus and the production of overt behavior in response to it. The other step is between the overt behavior and the actual dependent measure. These two steps, which we will call nonsensory factors, can be thought of as noisy channels in the transmission of information from the infant to the experimenter. They can only cause a loss of information (i.e., an elevation of the threshold estimate) and an increase in variability (i.e., a decrease in the slope of the psychometric function). These factors hamper the interpretation of infant psychophysical data because one generally cannot determine how much information is lost at each stage.

We can illustrate this ambiguity with an example. Consider a PL experiment in which an infant's number of fixations did not differ between a striped pattern and a blank field. The experimenter presumably wants to know if the striped pattern was below the infant's sensory threshold but cannot tell because she cannot answer the following questions. Could the infant simply not detect the stimulus? Or could he detect it, but failed to produce overt behavior indicative of detection? Because these ambiguities affect the estimation of sensory thresholds, it is very important to minimize the magnitude of information lost in these two steps. Consequently, developmental psychophysicists control behavioral state as well as possible in order to maximize the probability that overt behavior will be elicited by a detected stimulus. Likewise, sensitive dependent measures

are chosen to minimize information loss due to a mismatch between the overt behavior and the dependent measure. The FPL technique probably minimizes information loss due to this mismatch better than the PL procedure does. In PL experiments, the only useful overt behavior is the particular aspect of fixation recorded (say, first fixation). FPL experiments, in contrast, allow the observer to learn which behaviors are most informative for each infant and to guide his judgments accordingly. If some infants' most informative behaviors include other responses like the steadiness of fixation or facial expressions, the FPL procedure should be a more sensitive measure of threshold. Atkinson, Braddick, and Moar (1977a) have confirmed this expectation. They showed that lower contrast threshold estimates (higher contrast sensitivities) were obtained when the observer make an FPL judgment rather than a first fixation judgment.

We have discussed a number of important points in the last few paragraphs, so let us summarize them before moving on. The estimation of threshold requires information about which stimulus levels are above and below threshold. However, poor performance at low stimulus levels is ambiguous. It may indicate that the level is actually below threshold. But it might also result from information loss at two steps between the infant's threshold and the experimenter. It is very difficult to ascertain how much each step is responsible for the poor performance, so one must conclude that threshold estimates are lower-bound estimates of the true sensory threshold. Nonetheless, any psychophysical experiments should strive to minimize information loss at the two nonsensory steps.

The ambiguity of psychophysical threshold estimates in infants renders estimates of visual capacity at a given age uncertain. It also makes age comparisons quite difficult. This second point has not been fully appreciated in the infant psychophysical literature, so we describe it in some detail here. Suppose we conducted an FPL experiment to measure grating acuity thresholds in infants from 1 to 6 months of age. Suppose further that the thresholds obtained were 2 cycles/degree (c/deg) at 1 month and 6 c/deg at 6 months. Could we conclude that acuity improves by that amount over that age range? Not with any certainty. Performance in an FPL task may reflect the contribution of sensory thresholds (the variable of interest) and nonsensory factors. Consequently, a change in performance with age could be due to age changes in threshold, age changes in nonsensory factors, or both. Is it plausible that these nonsensory factors change with age and thus contaminate age comparisons? Unfortunately, it is. For example, it is plausible that the relationship between stimulus detection and the production of overt behavior changes. The behavioral repertoire and reactivity of human infants undergo significant changes with age (Kessen, Haith, & Salapatek, 1970). Thus, an age-related change

in performance cannot necessarily be ascribed to a change in sensory threshold.

If threshold measurements at one age and comparisons of thresholds across age are uncertain, the reader might wonder why one should bother to collect psychophysical data from infants at all.⁵ Not surprisingly, we believe that it is worth the effort. Even though psychophysical techniques yield uncertain estimates of sensory thresholds in infants, there are several ways to increase one's confidence that the threshold estimates reflect the behavior of sensory mechanisms rather than nonsensory factors. In the remainder of this section we briefly describe four approaches or sorts of information that are useful in this regard. We call them verification techniques. They are (1) the use of thresholds as relative rather than absolute information; (2) stimulus convergence; (3) response convergence; and (4) good performance relative to some known optimal performance. (The first technique does not have the same status as the others; indeed, we will describe cases in which it is subsumed under the second and third techniques.) We define these four techniques briefly here. More detailed discussions of them are provided in Sections III–VI below on visual acuity, contrast sensitivity, light and dark adaptation, and temporal vision.

First, consider the use of threshold data as relative rather than absolute information. The error introduced into threshold estimates by the intrusion of simple nonsensory factors may not be crucial for a large class of problems in visual development. Consider, for example, the often-replicated result that infants are less sensitive than adults in visual detection tasks. How much of this sensitivity difference is attributable to the intrusion of nonsensory factors such as low motivation to respond to a detected stimulus? If the problem under investigation involves an absolute comparison between infants and adults (e.g., stimulus intensity at threshold), one cannot answer this question without some means of estimating the magnitude of nonsensory contributions. However, if the problem involves a comparison between infants and adults in terms of relative,

⁵ Similar interpretive difficulties exist in all infant work. For example, when an infant fails to dishabituate to a novel stimulus in a habituation experiment, it is weak evidence that they cannot detect the stimulus change. Similarly, when an infant fails to search for a hidden object in an object permanence experiment, one cannot conclude with assurity that the infant does not know that the object still exists. Indeed, these sorts of interpretive difficulties exist, in a presumably less severe form, in adult psychophysical work, too. The relationship between an adult's true sensory threshold and his performance is known to vary with nonsensory factors such as perceptual set, response criterion, and stimulus-response compatibility. Psychophysicists who study adults do their best to minimize the impact of these factors, but one cannot measure how much all such factors contribute. Consequently, their effects on performance cannot be partialled out.

within-age sensitivity to different values along some stimulus dimension, then the effects of simple nonsensory factors present no particular problems. For example, consider scotopic spectral sensitivity. Here the question is a relative one: how sensitive are infants to different wavelengths of light at absolute threshold? Despite large differences between infants and adults in absolute sensitivity, the shapes of their scotopic spectral sensitivity curves (a relative comparison) are essentially identical (Powers, Schneck, & Teller, 1981). Of course, even these types of relative comparisons carry with them the assumption that some nonsensory factor such as motivation will not differentially interact with the stimulus dimension that constitutes the independent variable.

The concept of stimulus convergence was described by Yonas and Pick (1975). In the current context, stimulus convergence refers to the ability of a model of sensory mechanisms to predict thresholds for one sort of stimulus (e.g., faces) from thresholds obtained with another sort of stimulus (e.g., gratings). The same response measure (e.g., FPL) is used for both sorts of stimuli. If the predictions of the sensory model are accurate, our confidence that the data reflect sensory behavior is increased. In other words, the presence of stimulus convergence is reasonably persuasive evidence that infants' performance depends primarily on sensory rather than nonsensory factors and that the stimuli used tap the same sorts of sensory mechanisms. We give examples of such cases below under contrast sensitivity. The absence of stimulus convergence is more difficult to interpret because two possibilities exist: (1) stimulus convergence was not observed because of significant contributions by nonsensory factors (e.g., a stronger motivation to look at faces than at gratings), and (2) stimulus convergence was not observed because an inappropriate model of the sensory mechanisms involved was used.

The concept of response convergence was also described by Yonas and Pick (1975). In the current context, response convergence refers to the ability to obtain similar threshold estimates using different response measures. The same sorts of stimuli (e.g., gratings) are used for each response measure. Response convergence should be observed if the response measures reflect the behavior of the same sensory mechanisms. So, for example, FPL and visually evoked potentials (VEPs), if they reflect the behavior of the same sensory mechanisms, should yield similar estimates of visual acuity for gratings. If the thresholds are similar, one's confidence that the data reflect sensory behavior is increased because the contribution of nonsensory factors would presumably vary from one response measure to another. We provide examples of attempts to examine response convergence below under visual acuity, contrast sensitivity, and temporal vision. We argue in the first of those sections that several attempts to assess response convergence have been misguided. We suggest

a different strategy that should minimize problems encountered previously.

The final source of information that can increase one's confidence in infant threshold estimates is good performance relative to some theoretically optimal performance. The intrusion of nonsensory factors such as poor motivation to respond to a detected stimulus can only degrade performance. Consequently, if one could show that infants performed at the optimal level expected for sensory performance, we could safely conclude that nonsensory factors did not contaminate the results. A hypothetical example illustrates this. Suppose an FPL experiment yielded an acuity estimate of 2 c/deg at 1 month. One could conceivably calculate the maximum level of performance expected given the optical quality and photoreceptor density of the young eye. If the observed acuity was similar to the predicted optimum, our confidence in the accuracy of the threshold estimates would be strengthened considerably. We describe examples of this approach in our sections on visual acuity and temporal vision.

This concludes our general discussion of psychophysics and its application to the study of infant vision. The remainder of this chapter reviews developmental research that exemplifies the psychophysical approach.

One topic considered is the development of pattern vision. The ability to recognize, classify, and identify objects on the basis of pattern information is arguably the most complex and sophisticated of our visual capabilities. This point is corroborated by the difficulty computer scientists have had in producing general pattern recognition devices (e.g., Dodwell, 1970; Marr, 1982). For this reason, the study of the development of pattern vision has traditionally attracted more experimental and theoretical attention than any other topic in infant perception. We review basic findings concerning early pattern vision in the next three sections, visual acuity, contrast sensitivity, and light and dark adaptation. The last section, temporal vision, has been included because, in our opinion, spatial-temporal interactions are crucial to pattern vision.

In our discussion of each topic, we briefly review relevant adult psychophysical work and then describe and evaluate developmental studies. We concentrate on behavioral studies but occasionally include electrophysiological results that aid the interpretation of developmental findings.

III. VISUAL ACUITY

A fundamental visual function is to represent pattern information in a manner that allows the recognition and identification of objects and determination of their spatial layout. This function depends on the ability to

detect differences in intensity or wavelength composition because such differences create the contours of patterns in the first place. It is not enough, however, to just detect intensity or wavelength differences. Object recognition and determination of spatial layout also depend on the ability to encode the spatial distribution of such differences. The study of visual acuity concerns the accuracy of this encoding of spatial distribution.

Measures of visual acuity generally involve high-contrast black and white patterns. An observer's performance is assessed as the separation is varied between two contours within the pattern. The separation for which the subject is just able to detect or resolve the pattern serves as the measure of visual acuity and is expressed in degrees of visual angle.

Different acuity tasks use different sorts of patterns. We will discuss three: minimum visible acuity tasks, minimum separable acuity tasks, and vernier acuity tasks. The stimuli used in each of these tasks are depicted in Figure 1. As one might expect, the just-detectable separation of contours varies among these tasks.

Minimum visible tasks involve a single black line on a white background (or a single white line on a dark background). Adults can, under optimal conditions, detect such a line when its width is only $\frac{1}{2}$ sec of arc (Hecht & Mintz, 1939). Minimum visible acuity measurements, however, are highly dependent on the intensity discrimination capacity of the eye (Riggs, 1965). Consequently, they probably should not be regarded as measures of acuity.

Minimum separable acuity tasks require the subject to respond to a separation between elements of a pattern. The most common pattern is a series of alternating black and white stripes of equal width (a square wave grating). The finest grating the subject can resolve is taken as the measure of acuity. It is generally expressed in terms of spatial frequency, the number of pattern repetitions per degree of visual angle. (Other units for

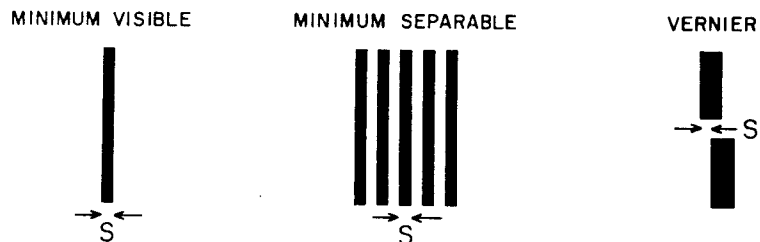


Figure 1. Stimuli typically used in minimum visible, minimum separable, and vernier acuity tasks. In each task, the measure of visual acuity is the minimum separation of contours that the subject can detect. Those separations (S) are indicated by the arrows.

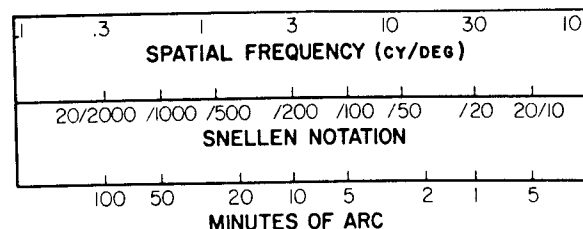


Figure 2. Scales for representing minimum separable acuity thresholds. From top to bottom the scales represent the spatial frequency in cycles per degree (or stripes per degree), Snellen notation, and stripe width in minutes of arc.

expressing acuity are displayed in Figure 2). Adult minimum separable acuity under optimal conditions is 45–60 c/deg, which corresponds to a stripe width of $\frac{1}{2}$ to $\frac{2}{3}$ min of arc.

Vernier acuity tasks require the subject to discriminate displacements of one line with respect to another. Generally, one must distinguish whether an upper vertical line is displaced to the left or right of a lower vertical line. The just-discriminable offset under optimal conditions is about 2 sec of arc for adults (Berry, 1948). This precision is remarkable because 2 sec is less than $\frac{1}{10}$ the diameter of photoreceptors in the fovea. Westheimer (1979, 1982) has argued that minimum separable and vernier acuity tasks actually tap different visual mechanisms. This is an intriguing idea to which we return below.

We would like to point out an important implication of the fact that different sorts of tasks yield widely different estimates of visual acuity. Because the resolution threshold varies from one pattern to another, one cannot use an acuity estimate obtained with one sort of pattern to predict the threshold for another sort of pattern. This has important implications for infant research. Several investigators have used estimates of minimum separable acuity (specifically, the angular subtense of one stripe when the grating is at threshold) to argue that the pattern elements in another stimulus (for example, the individual features in a schematic face) are resolvable. This is in general inappropriate because, as we have described here, acuity estimates actually vary strikingly from one pattern to another and hence cannot be used to predict one another in any simple way. Section IV on contrast sensitivity considers an approach that offers solutions to this problem.

One motivation for studying visual acuity (and, as we shall see, for studying the growth of visual acuity) is the expectation that it will provide insight into optical, anatomical, and physiological influences on visual performance. In tests of visual acuity, the visual system's ability to en-

code the spatial distribution of stimulation is pushed to the limit. Accurate processing is required from many stages beginning with the eye's optics and proceeding to central neural networks. Psychophysical estimates of acuity have helped delineate quantitative relationships between adults' visual performance on the one hand and optical and neural mechanisms on the other. A brief discussion of such work will provide a background and framework for much of the infant work on acuity development.

Two classical observations illustrate the influence of optical and neural factors on adults' visual acuity. First, minimum visible, minimum separable, and vernier acuity all depend heavily on the average luminance of the stimulus. For example, adults' minimum separable acuity increases more than 100-fold from dark scotopic to bright photopic conditions (Shlaer, 1937). Second, all three measures of acuity depend significantly on the retinal eccentricity of the target (retinal eccentricity refers to the angular distance from the fovea to the retinal region being tested). For example, adults' minimum separable acuity is highest in the fovea and falls dramatically, but steadily, as the target is moved into the periphery (Mandelbaum & Sloan, 1947). We consider the optical and neural factors that contribute to the luminance- and eccentricity-dependence of adults' visual acuity below.

The increase in acuity with higher luminance appears to be caused by both optical and neural factors. Consider first the contribution of optical factors. As luminance is increased, the pupil constricts. This improves the sharpness of the retinal image (and thereby improves visual acuity) because restricting light to the center of the cornea and lens minimizes the defocusing effects of spherical and chromatic aberrations (see Campbell & Gubisch, 1966, for details).⁶ Neural factors, however, are more important because dramatic improvements in acuity with increasing luminance are still observed even when pupil diameter (and hence optical quality) is held constant (Shlaer, 1937). Two neural mechanisms seem to be involved. First, the shift from rod to cone activation (which accompanies an increase in light level) enhances resolution because cones are packed much more densely than rods in the central retina and because cones do

⁶ The relationship between pupil diameter and visual acuity is actually somewhat more complicated. For large diameters (4–8 mm), any decrease in diameter improves visual acuity so long as the stimulus is fairly bright. Smaller diameters in this range are associated with higher acuity because they minimize spherical and chromatic aberrations. For bright stimuli and small diameters (1–2 mm), however, any decrease in diameter actually degrades acuity because it causes greater optical diffraction due to the pupillary aperture. Therefore, these optical factors—spherical and chromatic aberrations on the one hand and optical diffraction on the other—imply that the optimal pupil diameter for resolution of bright stimuli is roughly 2–4 mm. For an interesting discussion of the relationship between pupil diameter and visual acuity for stimuli of various luminances, see Campbell and Gregory (1960).

not pool their responses at higher-level neurons as much as rods do. (We describe the theoretical relationship between receptor density, pooling, and resolution in the next paragraph.) Second, there is physiological evidence that the receptive fields of retinal neurons change with light level. Barlow, Fitzhugh, and Kuffler (1957) and Enroth-Cugell and Robson (1966) observed that the antagonistic surround of retinal ganglion cells disappeared at low light levels and, consequently, that the resolution of the cells dropped. A third mechanism is also involved. At very low luminances, the intensity discrimination capacity of the visual system is poorer than at high luminances. This fact is illustrated by the increment threshold function (see Figure 9 in Section V). The detection or discrimination of acuity targets involves intensity discrimination, so it follows that acuity should be lower for light levels where intensity discrimination is lower.

Neural factors also seem to be primarily involved in the change in visual resolution from the fovea to the far periphery. The optical quality of the eye is much worse for the retinal periphery than for the fovea, but Green (1970) has shown nonetheless that optical quality does not constrain acuity in the periphery. He measured adults' minimum separable acuity at various eccentricities under two conditions: (1) using conventional gratings viewed under normal conditions, and (2) using laser-generated gratings that were formed directly on the retina and hence were impervious to optical degradation (except for degradation due to scattering which, presumably, is similar for the fovea and periphery). His results are summarized in Figure 3. Peripheral acuity was identical for the two conditions, suggesting that optical factors, despite their poor quality, do not constrain resolution in that part of the retina. Foveal acuity was somewhat higher for the laser gratings than for the conventional gratings. So despite the relatively good quality of foveal optics, optical quality partially constrains acuity for that part of the retina. Since optical factors apparently do not cause the fall in acuity with retinal eccentricity, neural mechanisms must. Which neural mechanisms are most significant? Green (1970) showed that, once optical factors were partialled out, acuity in the central 5° of the retina could be predicted precisely from the average separation of cones.

This is a particularly important observation, so let us examine it in some detail. The retinal image is digitized in a fashion because the photoreceptors sample the image at discrete points only (Williams, 1985). It can be shown mathematically that spatial information finer than the grain of the photoreceptor mosaic cannot be transmitted without distortion (Goodman, 1965; Snyder, 1979). Stated more precisely, the sampling frequency of the receptor mosaic (the density of receptors or, more specifi-

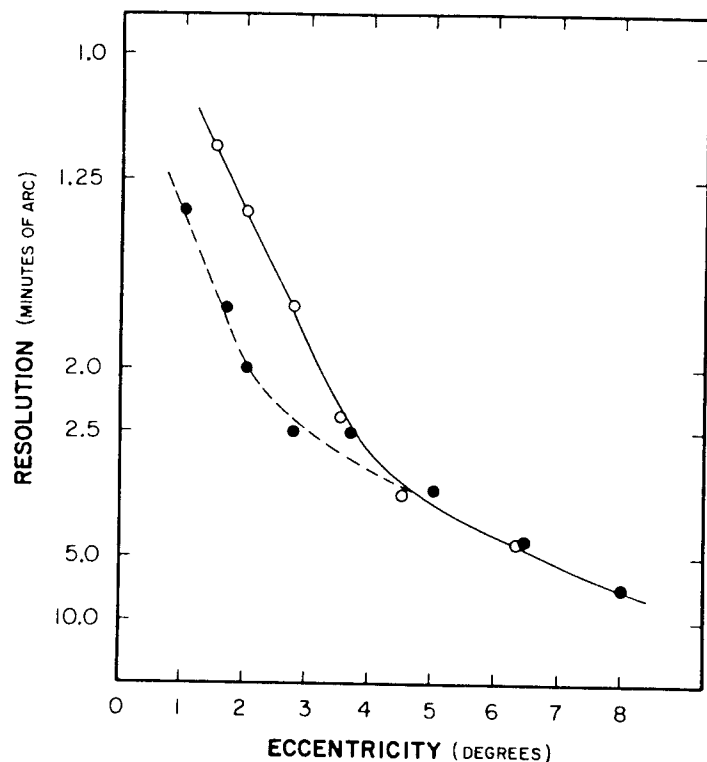


Figure 3. Adult minimum separable acuity at various positions eccentric from the fovea. The narrowest stripe width is plotted as a function of retinal eccentricity. The open circles are for laser-generated patterns that were formed directly on the retina. Filled circles are for conventional patterns. (Adapted from Green, 1970.)

cally, the reciprocal of twice the average separation between receptors) sets a limit on the highest spatial frequency (the finest pattern of stripes) that can be transmitted accurately. Consequently, it is not surprising that adults' minimum separable acuity does not exceed the limit imposed by the average separation of foveal cones. Of course, foveal acuity could be worse than the limit set by the mosaic. The fact that it is not indicates that acuity in the fovea is constrained primarily by the average separation of foveal cones and not by neural factors further upstream. Beyond 5°, Green found that acuity was actually somewhat worse than would be predicted from receptor density. The primary constraint then must be beyond the photoreceptor stage.

The neural substrates of vernier acuity are less clear than those of minimum separable acuity. For one thing, vernier thresholds can be as

low as 2 sec of arc, a distance that is roughly 10 times smaller than the average separation of foveal cones! Obviously, then, simple hypotheses based on the grain of the receptor mosaic cannot account for these thresholds as they did for minimum separable thresholds. Vernier thresholds also behave differently than minimum separable thresholds in some circumstances. For instance, defocusing the stimulus reduces minimum separable acuity severely but does not influence vernier acuity much at all (Westheimer, 1979). For these and other reasons, Westheimer (1979, 1982) has argued that vernier acuity and minimum separable acuity actually tap different visual mechanisms. Barlow (1979) and Crick, Marr, and Poggio (1981) have advanced models of the neural substrates of vernier acuity that are, in fact, quite different from models of minimum separable acuity. Geisler (1984) has argued alternatively that special mechanisms are not required to explain why vernier acuity is affected by blur differently than grating acuity is.

A. Development

We now consider the development of visual acuity. There have been two fundamental motivations for studying acuity growth: (1) the expectation that such studies will provide insight into the relationship between visual performance and the optical, anatomical, and physiological development of the infant's visual system, and (2) the attempt to characterize the visual system's sensitivity to patterns at different ages. Concerning the second motivation, we will argue in the next section that acuity measurements actually do not provide a general index of pattern sensitivity. Nonetheless, visual acuity is an important aspect of pattern vision. Pattern elements that are smaller than the resolution limit cannot be detected. If such an element was the distinguishing feature of an object, the object obviously could not be correctly identified. Hence the second of the above-mentioned motivations should be stated more narrowly: acuity estimates may allow researchers to determine which high-contrast pattern elements or features are too small to be detected at different ages.

Casual observation suggests that visual acuity is quite low early in life and that it improves dramatically during the first year. For example, neonates seem to attend only to large objects whereas older infants notice quite small objects or features that even their parents have difficulty detecting. These casual observations are confirmed by the now extensive literature on infant visual acuity. The literature consists almost entirely of measurements of minimum separable acuity, but different response measures and different stimuli have been used. Consequently, one cannot summarize the literature by just stating acuity estimates for various ages

because, as in adults, the estimates of acuity depend on the responses and stimuli used.

In order to keep our review of this work reasonably brief, we have chosen to describe only three studies—each with a different response measure—in detail and to present the findings of other studies as supplements. Discussion of stimulus variables will be distributed throughout this section and the next. The three response measures represented—preferential looking (PL), optokinetic nystagmus (OKN), and visually evoked potentials (VEP)—account for virtually all of the acuity studies to date (for reviews, see Dobson & Teller, 1978; Maurer, 1975).

Our primary goal is to review psychophysical work, so we will present the PL study first. Allen (1978) used the forced-choice preferential looking technique (FPL) to measure acuity in infants from $\frac{1}{2}$ to 6 months. The infants were shown simultaneously two fields of equal size, luminance, and hue. The fields differed only in that one was a stationary, high-contrast square wave grating while the other was unpatterned. An adult observer tried to identify the grating's location based on the infant's behavior. The spatial frequency of the grating was varied from 0.38 (wide stripes) to 12 (narrow stripes) c/deg. The observer's percentage correct typically varied from about 50%, which is chance performance, for high spatial frequencies, to about 100% for low spatial frequencies. Allen estimated the spatial frequency required to achieve 75% correct responding by interpolation and this value was considered as the acuity estimate. These estimates are shown in Figure 4. The acuity estimates increased monotonically from 1.3 c/deg at $\frac{1}{2}$ month to 5 c/deg at 6 months. Allen's data agree reasonably well with those of other preferential looking studies (Atkinson Braddick, & Moar, 1977a, 1977b; Banks & Salapatek, 1978; Fantz et al., 1962; Gwiazda, Brill, Mohindra, & Held, 1978; Salapatek, Bechtold, & Bushnell, 1976; Teller, Morse, Borton, & Regal, 1974). Most have found that minimum separable acuity is roughly 1 c/deg at 1 month and 6 c/deg at 6 months. As we noted earlier, however, these acuity estimates are uncertain. They only represent lower-bound estimates of infants' resolution capabilities at different ages. Consequently, we cannot be confident that the values shown represent sensory thresholds *per se* or that thresholds change with age in the manner indicated. What we would like to know, then, is whether these estimates faithfully represent sensory thresholds at different ages. This is quite difficult to ascertain, but we can use the four verification techniques outlined earlier to attempt it.

The first of the four techniques—the use of thresholds as relative rather than absolute information—is not applicable here. Those who have measured visual acuity in infants have been most interested in determining the absolute acuity at different ages rather than in determining how acuity

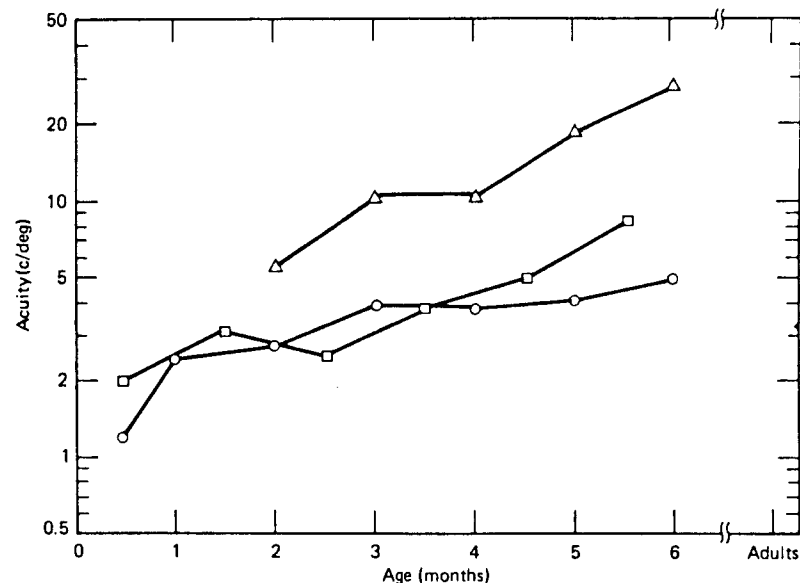


Figure 4. Minimum separable acuity estimates at different ages. The highest detectable spatial frequency is plotted as a function of age. Circles, acuity estimates from Allen's (1978) FPL experiment. Squares, acuity estimates from the Fantz, Ordy, and Udelf (1962) OKN experiment. Triangles, estimates from Sokol's (1978) VEP experiment. (From Banks, 1982.)

changes as a function of some other independent variable such as luminance. We must, consequently, concentrate on the remaining three approaches.

Some researchers have looked for stimulus convergence in infant acuity experiments (Atkinson, Braddick, & Moar, 1977c; Banks & Salapatek, 1981). They used a model of sensory mechanisms that is based on the contrast sensitivity function and linear systems analysis. Since that model is described in some detail in the next section, we will put off discussion of stimulus convergence until then.

Different response measures have been used to measure infant acuity, so we can examine the results for response convergence. If response convergence can be demonstrated convincingly, our confidence would increase that these response measures reflect the behavior of sensory mechanisms. We have chosen two studies—one that used OKN and one that used VEP—to highlight the use of different responses to measure infant acuity.

Fantz et al. (1962) used OKN to estimate acuity from birth to 6 months of age. OKN is the rhythmic pattern of slow pursuitlike eye movements

followed by saccadic refixations that is elicited when a subject looks at a repetitive moving pattern. As in most OKN procedures, Fantz et al. used a moving square wave grating that covered most of the infant's visual field. The spatial frequency of the grating was varied from 0.75 to 6 c/deg. The presence or absence of OKN was judged on-line by an adult observer. The highest spatial frequency for which reliable OKN was observed was taken as the acuity estimate. We have reanalyzed their results and plotted in Figure 4 the estimated spatial frequency at which 50% of the infants in each age group would yield reliable OKN. The acuity estimates increased fairly smoothly from about 2 c/deg at $\frac{1}{2}$ month to greater than 6 c/deg at 5½ months. These acuity values agree reasonably well with the OKN acuities observed by Enoch and Rabinowicz (1976) and Gorman, Cogan, and Gellis (1957, 1959). Dayton et al. (1964) reported OKN acuities of 4 c/deg for many newborns, a value higher than the others obtained. Banks and Salapatek (1981), however, have shown that their stimulus contained spatial frequencies lower than 4 c/deg, so Dayton et al. probably overestimated OKN acuity.

Sokol (1978) used the steady-state visually evoked potential (VEP) to measure infant acuity. The stimuli were checkerboards that reversed in phase 12 times/sec (6 Hz). Check size was varied from 7.5 to 90 min of arc and the amplitude of the VEP was noted for each size. Fifteen infants were tested, in most cases longitudinally, at monthly intervals from 2 to 6 months of age. Extrapolation to zero response amplitude on an amplitude versus check size plot allowed Sokol to estimate the threshold check size for each infant. (Campbell and Maffei, 1970, and Regan and Richards, 1971, have shown that such an extrapolation predicts adult psychophysical acuity thresholds.) The results from this experiment are also plotted in Figure 4. This figure shows the fundamental spatial frequency corresponding to threshold check size for each age. Estimated acuities increase monotonically from 5.7 c/deg at 2 months to 28 c/deg at 6 months. These results agree reasonably well with those of other steady-state VEP studies (Harris, Atkinson, & Braddick, 1976; Sokol & Dobson, 1976), sweep VEP studies (Norcia and Tyler, 1985), and of one transient VEP study (Marg, Freeman, Peltzman, & Goldstein, 1976). Other transient VEP studies have yielded lower estimates of acuity (Harter, Deaton, & Odom, 1977a, 1977b; Harter & Suitt, 1970).

Shimojo et al. (1984) have used FPL to measure vernier acuity from 2 to 9 months. They found that the smallest detectable offset was less than 3 min of arc by 6 months. Furthermore, the growth curve for vernier acuity was different than the growth curve for grating acuity. This may reflect the emergence of different resolution mechanisms.

Infant acuity experiments using different responses have often dis-

agreed on one point: many VEP studies obtained higher acuity estimates than PL and OKN studies, particularly after 3 months of age. This discrepancy suggests that response convergence (Yonas & Pick, 1975) may not obtain and raises the question of whether behavioral techniques, such as FPL, yield meaningful estimates of visual acuity.

Dobson and Teller (1978) considered the discrepancy between VEP and PL acuity estimates in some detail. They presented a number of possible explanations, two of which suggest that the differences are more apparent than real. We describe those two explanations here.

First, the discrepancy between VEP and PL acuities might be due to differences in the stimuli used in the two techniques. Specifically, the stimuli used in VEP studies, because they were modulated temporally, may yield higher acuity estimates, regardless of the response measure used, than the static gratings used in PL studies. This hypothesis is weakened somewhat by the results of two studies that compared PL acuities for both static and nonstatic stimuli. Dobson, Teller, and Belgum (1978) used FPL to measure visual acuity in 2-month-olds with two types of stimuli: (1) phase-alternating checkerboards similar to those used in many VEP studies and (2) static square wave gratings like those used in many PL studies. Similar acuity estimates were obtained with the two patterns, which suggests that temporal modulation does not lead to higher acuity estimates. Similarly, Atkinson et al. (1977b) measured FPL acuity in 1-, 2-, and 3-month-olds using static and drifting sinewave gratings. They too found no difference between stationary and moving gratings. Before concluding that Dobson and Teller's first hypothesis is false, we should point out that data from older infants would have been more relevant to the issue at hand because VEP and PL acuities generally do not differ significantly until after 3 months. In other words, we cannot rule out the possibility that VEP estimates are higher than PL estimates after 3 months of age because of differences in the stimuli used.⁷

Second, Dobson and Teller hypothesized that the discrepancy between VEP and other estimates of acuity may be due to the different scoring techniques the measures require. They argued that in PL studies, acuity is estimated by rather strict criteria, for example, the spatial frequency required to elicit 75% correct responding. VEP acuity, on the other hand, is usually estimated with much more generous criteria, for example, the spatial frequency for which VEP amplitude will be zero or just above

⁷ Sokol et al. (1986) showed that FPL estimates of grating acuity were increased by as much as 1 octave by flickering the square wave grating target. They observed higher acuities from 3 to 8 months, the age range tested. This finding suggests that some of the discrepancy between FPL and VEP acuity estimates may be caused by stimulus differences.

zero. They pointed out that use of more generous scoring criteria (60%, for example) in PL studies would increase acuity estimates by 1 to 1.5 octaves. In other words, much of the difference between acuities estimated by VEP and PL techniques may be attributable to differences in the scoring criteria used. Of course, this argument depends on the assumption that 75% in a PL experiment is somehow a stricter criterion than near-zero amplitude in a VEP. It is unclear to us how one would defend this assumption. PL studies provide percentage correct values as the dependent measure, while VEP studies provide changes in electrical potential. It is simply not clear how one should compare such different variables. That is to say, how many millivolts of change in electrical potential should be comparable to the 75% correct value? Until answers to such questions emerge, it will be difficult to assess response convergence in infant acuity measurements.

If we cannot compare thresholds meaningfully across response measures, how can we determine if they are tapping the same underlying mechanisms in infants? We propose that the best way is to examine whether they are influenced similarly by changes in stimulus parameters. For example, if VEP and PL acuity estimates are affected in quite different ways by changes in light level, they probably do not tap the same mechanisms. This is the most appropriate way to test for response convergence.

Unfortunately, very little is known about how various stimulus parameters affect VEP, PL, and OKN acuity estimates in infants. In the absence of such information, we resort to consultation of the adult literature for clues about the substrates of these measures. Some adult work has concluded that VEP, OKN, and psychophysical acuity estimates are, in some circumstances, affected in different ways by changes in stimulus parameters; this implies that the three responses tap somewhat different mechanisms in adults. For example, Regan (1978) has argued that VEP and psychophysical measures are affected differently by changes in stimulus parameters. Specifically, he showed that pattern-reversal VEPs in adults exhibit two components: (1) a pattern component due to the phase-reversing changes in the pattern and (2) a local flicker component due to changes in luminance over time. The relative magnitude of the two VEP components varies significantly with both the size of the pattern elements and the rate of phase reversal. Researchers using VEP to estimate acuity generally fix the rate of phase reversal and manipulate the size of pattern elements. Consequently, the choice of temporal frequency influences the estimate of acuity. Changes in temporal frequency also affect psychophysical estimates of acuity (Robson, 1966) but not in the same manner as

they affect VEP estimates. In other words, spatial-temporal interactions in the VEP appear to be different than those observed in psychophysical tasks. This suggests that the two techniques may tap somewhat different mechanisms.

Cannon (1983), however, has offered a more optimistic view of the correlation between VEP and psychophysical estimates of pattern detection capabilities. He used a novel VEP technique to measure detection thresholds in adults. The details of the technique are beyond the scope of this chapter, but a few of Cannon's observations are worth mentioning here. He measured VEP and psychophysical detection thresholds but, unlike other researchers, he presented precisely the same stimulus in both tasks: a sinewave grating phase reversing 20 times/sec (10 Hz). VEP thresholds were consistently higher than psychophysical thresholds, but they were nearly perfectly correlated. Specifically, as Cannon changed a subject's optical correction or changed the spatial frequency of the stimulus (as in contrast sensitivity measurements, see Section IV), VEP and psychophysical thresholds varied in unison. These results suggest that at least one VEP technique may reveal the same mechanisms as psychophysical techniques.

One might argue from Regan's and Cannon's findings that high correlations between VEP and behavioral estimates of infant acuity would be observed if the appropriate temporal frequency for phase reversal were chosen. Unfortunately, one cannot use adult data to guide such a choice. Moskowitz and Sokol (1980) have shown that significant spatial-temporal interactions exist in infant VEPs and, most importantly, that these interactions change with age. Thus, a choice of temporal frequency based on adult work could yield an inaccurate estimate of visual acuity for the particular age tested.

Little is known of the substrates of OKN acuity in infants, so we must consult the adult literature once again for clues. Several adult studies suggest that OKN acuity reflects different visual mechanisms than psychophysical acuity. For example, Pearson (1966) and Reinecke and Cogan (1958) have shown that adults' OKN acuity estimates are not well-correlated with psychophysical estimates. Furthermore, Schor and Narayan (1981) have shown that OKN and psychophysical acuity estimates are affected differently by changes in stimulus parameters. They examined the effects of a number of stimulus parameters in eliciting involuntary OKN in adults. As in the infant studies described above, the stimulus was a drifting grating. They found that the highest velocity at which OKN could be elicited was the same as the highest detectable velocity in a psychophysical task. They also found that the acuity cutoff for OKN was

well below the psychophysical acuity for some conditions.⁸ Specifically, psychophysical acuity was unaffected by changes in stimulus field size, whereas OKN acuity was considerably lower for large fields than for small fields. (OKN acuity appeared to match the psychophysical acuity for the most peripheral part of the retina stimulated by the drifting grating.) To summarize, the fact that OKN and psychophysical acuities are affected differently in adults by changes in stimulus parameters implies that the two types of acuity reflect somewhat different mechanisms.

We have seen that VEP, OKN, and psychophysical estimates of adult acuity are often affected differently by variations in stimulus parameters such as rate of temporal modulation and field size. This means the three response measures may tap somewhat different visual mechanisms in adults. It is possible, however, that a careful choice of parameters, exemplified by Cannon (1983), may reveal similar underlying processes. At this stage we cannot judge whether VEP, OKN, and PL acuity estimates in infants converge. We will not be able to do so until more is learned about how various stimulus parameters, such as those examined in the adult studies mentioned above, affect the techniques' estimates of infants' visual capability. It is worth restating in this context, however, that VEP, OKN, and PL acuities do not appear to diverge until after about 3 months. Although similarity of acuity estimates is not sufficient evidence by itself, it might mean that the three response measures reflect the same mechanism early in infancy and different mechanisms later on. Stated another way, it is possible that response convergence is present before 3 months but not later.

The final verification technique that could aid the interpretation of psychophysical data on infant acuity is good performance relative to some known optimal performance. In the current context this could be demonstrated by showing that infants' visual performance approximates the best performance possible given the structural and functional quality of the young eye. We now examine this possibility. Specifically, we examine infants' performance relative to the optical quality, photoreceptor spacing, and neural processes of the young system.

First, consider optical quality. The sharpness of the retinal image depends on the quality of the cornea, lens, and other optic media. Consequently, infants' performance in acuity tasks might attain the highest level the optics allows. This hypothesis, however, does not seem to account for the data adequately (Dobson & Teller, 1978; Salapatek & Banks, 1978).

⁸ Schor and Narayan adopted a strict definition of OKN. To distinguish involuntary OKN (the desired response) from voluntary pursuit, they computed the frequency of the fast phase. Fast phase frequencies less than 1 Hz were considered pursuit and were discarded.

Several sorts of optical errors can affect acuity: spherical aberration, chromatic aberration, diffraction due to the pupil, and clarity of the optic media, but all of these errors appear to be far too small in young infants to account for their low acuity values (see Salapatek & Banks, 1978, for details).

Infants' performance might, however, be constrained by another optical error—accommodative error. This hypothesis is plausible because accommodation, like acuity, improves notably with age (Banks, 1980). If accommodative error were an important constraint, one would expect young infants' acuity to vary with target distance. On the contrary, several investigators have shown that infants' acuity does not vary with distance (Atkinson et al., 1977a; Fantz et al., 1962; Salapatek et al., 1976). Thus, accommodative error also does not appear to be a significant limitation to infant acuity.

These considerations imply that the quality of the retinal image exceeds the acuity observed in young infants and, therefore, that acuity does not reach the optimal level expected from optical factors alone.

Another mechanism that might account for the early acuity deficit and subsequent growth is a broad class of neural mechanisms. A number of the anatomical and physiological mechanisms known to influence adult acuity are potentially involved in early acuity development. One such mechanism is the spacing of photoreceptors. Recall that the average angular separation between foveal cones predicts adults' minimum separable acuity. Smaller separations (higher density) near the center of the fovea lead to higher acuity; larger separations (lower density) in the parafovea lead to somewhat lower acuity in that part of the retina (Green, 1970). Foveal cone separation is known to decrease postnatally in humans (Abramov et al., 1982; Hendrickson & Yuodelis, 1984; Mann, 1964) and monkeys (Hendrickson & Kupfer, 1976), so receptor spacing probably contributes to age-related changes in infants' minimum separable acuity. Indeed, I. Abramov (personal communication) has estimated that the average separation of foveal cones decreases by a factor of roughly 10–20 from birth to adulthood. Furthermore, the average newborn's eye is about 33% shorter than an adult's eye (Larsen, 1971). Since the size of the retinal image (expressed in micrometers) is roughly proportional to eye length, this means that retinal images are roughly one and one-half times larger in adults than in newborns. This difference combined with the change in photoreceptor spacing predicts that neonates' acuity should be 15–30 times lower than adults'. These factors then might account for most of the roughly 45-fold increase in minimum separable acuity over the same age range. (Other evidence suggests, however, that the change in photoreceptor spacing is smaller than the 10- or 20-fold figure given by

Abramov [Yuodelis & Hendrickson, in press].) This is an exciting hypothesis, which, if correct, would imply that neonates' acuity approaches the highest level expected on anatomical grounds. Some additional information, however, is sorely needed before we can relate these numbers with confidence. No one is certain of the part of the retina infants use in acuity tasks. If they do not use the fovea, then one should not use anatomical data from the foveal region to assess the contribution of receptor spacing. Thus, measurements of minimum separable acuity as a function of retinal eccentricity are needed, along with more quantitative estimates of receptor density for different eccentricities, before one can evaluate the receptor spacing hypothesis in infants. Unfortunately, nothing is known of the relationship between infants' minimum separable acuity and retinal eccentricity. Lewis, Maurer, and Kay (1978) found that newborns could detect a narrower light bar against a dark background when it was presented near the fixation point than when it was presented in the periphery, but their task measured minimum visible acuity, which is in general not predictable from the dimensions of the receptor mosaic.

A broad class of neural mechanisms may also constrain acuity early in life: the spatial tuning of neurons at different levels of the visual system. The size of a neuron's receptive field limits its spatial resolution, larger fields exhibiting lower acuity (e.g., Enroth-Cugell & Robson, 1966). The size of retinal ganglion cell receptive fields decreases significantly postnatally in cats (Rusoff & Dubin, 1977), so one would expect a concomitant increase in visual acuity. Mitchell, Giffin, Wilkinson, Anderson, and Smith (1976) have shown that kittens' acuity improves considerably postnatally, but no quantitative links between ganglion cell receptive fields and behavioral acuity have been drawn. The spatial resolution of lateral geniculate and cortical neurons also improves postnatally in cats and monkeys (e.g., Blakemore & Vital-Durand, 1980; Derrington & Fuchs, 1979). This too should affect visual acuity. There are, of course, no physiological data on receptive field sizes in developing humans, but several lines of evidence suggest that receptive field development may be similar in human and macaque infants (Boothe, 1981).

We have considered the issue of how meaningful psychophysical estimates of infant acuity are. In particular, we examined whether response convergence is observed and concluded that it is too early to know. We also examined whether infants' performance attains the optimal levels expected on optical, anatomical, and physiological grounds. Preliminary evidence suggests that neonates' performance approaches the optimal level predicted given the spacing of photoreceptors and the length of the eye at that age. Additional experimentation is needed, however, to confirm this.

B. Summary

One form of visual acuity—minimum separable acuity—is by all accounts quite poor early in life and grows steadily until at least 6 months of life. The acuity estimates at different ages can be used to calculate roughly which high-contrast objects or features in the environment are too small to be resolved. Unfortunately, different response measures yield different estimates of acuity, particularly after 3 months. It is possible that the measures tap different visual mechanisms in infants, but more experimental and theoretical attention must be devoted to this issue before firm conclusions can be drawn.

Various neural factors such as the grain of the photoreceptor mosaic and the spatial tuning of retinal, geniculate, and cortical receptive fields may determine early visual resolution and its subsequent development. Not enough is known currently to pinpoint which of these are the major determinants. Nonetheless, it appears that the primary limitation to early acuity is not the quality of the retinal image but rather the nervous system's ability to process that image.

IV. CONTRAST SENSITIVITY

Measurements of visual acuity index the visual system's ability to resolve small objects at high contrast. This is an important aspect of the system's pattern detection capabilities, but most visual scenes actually consist of objects of many different sizes at varying contrast levels. Hence acuity measurements alone are a poor index of the visual system's ability to detect ordinary pattern information. This point is substantiated by the observation that many visual functions do not require fine pattern information at all. For example, the use of visual information to regulate posture is unaffected when the information is defocused (Leibowitz, Schupert-Rodemer, & Dichgans, 1979). A better index of the ability to detect pattern information is provided by the contrast sensitivity function (CSF). This function represents the visual system's sensitivity to everything from very coarse to very fine spatial patterns. Specifically, the CSF relates the contrast required to just detect a sinewave grating (a repeating series of stripes whose luminance varies sinusoidally) to the grating's spatial frequency (the number of stripes per degree of visual angle).

The top half of Figure 5 shows a sinewave grating whose spatial frequency increases from left to right and whose contrast increases from top to bottom. Note that your ability to detect the grating varies with spatial frequency; intermediate frequencies are the easiest to detect. The

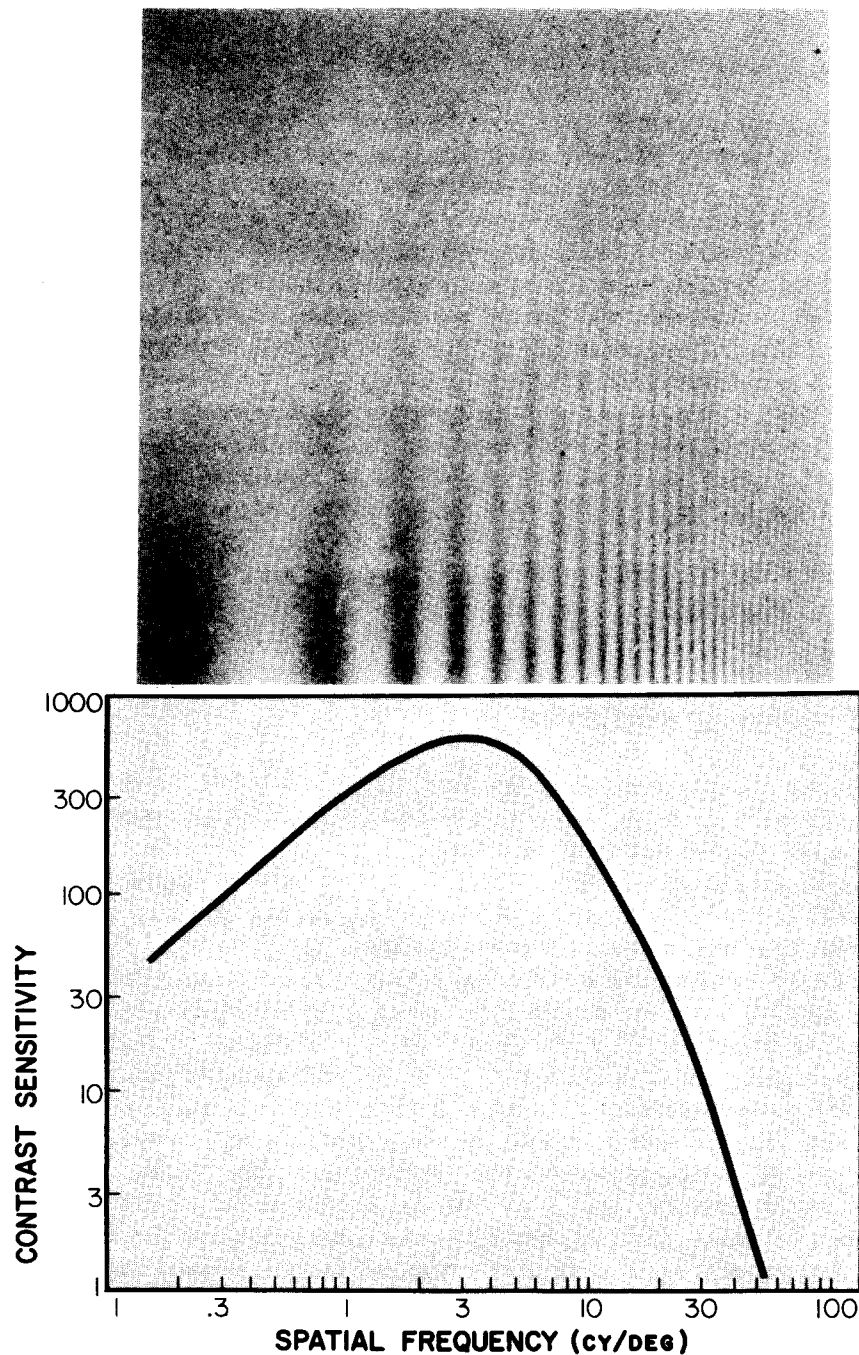


Figure 5. Sinewave grating and typical adult contrast sensitivity function (CSF). Top, a sinewave grating whose spatial frequency increases from left to right and contrast increases from bottom to top. Bottom, a typical adult CSF. Contrast sensitivity, the reciprocal of contrast at threshold, is plotted as a function of spatial frequency. (Adapted from Banks & Salapatek, 1981.)

lower half of Figure 5 represents the CSF of a typical adult. It shows how sensitivity varies with spatial frequency. Notice the bandpass characteristic: sensitivity is higher to intermediate than to low or high spatial frequencies.

The CSF has been extremely useful to the study of adult pattern vision. There are two reasons for this. First, the CSF can be used in conjunction with Fourier's theorem and linear systems analysis to characterize the visual system's sensitivity to a wide variety of patterns. Fourier's theorem implies that any two-dimensional pattern can be represented by its spatial frequency content (see Banks & Salapatek, 1981; Cornsweet, 1970; Gaskill, 1978). Thus, even a complex pattern such as the picture of a face can be exactly reproduced by combining a set of sinewave gratings of various spatial frequencies, contrasts, phases, and orientations. Linear systems analysis utilizes this fact to allow, in principle, the prediction of sensitivity to any pattern once the CSF of a visual system is known. The validity of linear systems analysis depends, however, on certain assumptions about the system under study. The adult visual system does not satisfy these assumptions in detail but, with certain restrictions, the approach has been very successful in predicting sensitivity to quite a variety of patterns (Banks & Salapatek, 1981; Cornsweet, 1970). This generalization capability has allowed researchers to synthesize a wide variety of observations.

The second reason that CSFs have been useful is related to the first. CSFs can reveal the properties of some important aspects of pattern vision. These include visual acuity, intensity discrimination, low-frequency attenuation, and multiple feature-selective channels. We will describe each of these below.

Many of the infant studies concerning CSFs have been designed to capitalize on the generalizability afforded by linear systems analysis and to reveal the properties of the above-mentioned aspects of pattern vision. In other words, the theoretical background for much of the infant work is based on rules and phenomena uncovered in previous adult work. We outline this background here by presenting a few illustrative examples from the adult literature.

The CSF has been a useful index of adults' visual acuity. The point at which the high-frequency side of the CSF intersects the abscissa is called the high-frequency cutoff and is an estimate of visual acuity. Are acuity estimates derived from the CSF in this manner more useful than other measures of acuity? Yes, because one can use the CSF to predict accurately adults' ability to resolve various sorts of acuity targets. The converse is not true. An example of how the CSF approach can be used to predict resolution thresholds for a variety of targets illustrates this. Adults

exhibit remarkable resolution when the acuity target is a single black line on a white background (minimum visible acuity). The narrowest detectable line in this case is only a few seconds of arc wide (Hecht & Mintz, 1939). On the other hand, the high-frequency cutoff of the adult CSF is about 45 c/deg, so the narrowest resolvable stripes in a sinewave grating are roughly $\frac{2}{3}$ min wide (Campbell & Green, 1965). Despite this apparent contradiction between minimum visible and minimum separable acuities, Campbell, Carpenter, and Levinson (1969) showed that the narrowest detectable single line can actually be predicted from a straightforward application of the CSF and linear systems analysis.

Bodis-Wollner (1972) provided a striking example that illustrates how the CSF may pick up visual dysfunctions that measurements of acuity do not. He reported case histories of patients who were experiencing great difficulty reading and performing other pattern recognition tasks. These perceptual problems were apparently caused by cortical pathology. The visual acuity of these people was normal and hence suggested no dysfunction. Their CSFs, however, revealed a large deficit for intermediate spatial frequencies. These deficits probably caused the reading disturbances because, subsequent to treatment, the midfrequency deficit lessened and normal reading ability returned.

The CSF has also been a useful indicant of intensity discrimination in adults. Intensity differences generally define patterns in the first place, so the discrimination of intensities is a fundamental aspect of pattern vision. Each point on the CSF represents the contrast necessary to just detect that an intensity difference is present. Is the CSF a better index of this capacity than other measures? Again a positive answer is justified. Adult psychophysical studies have revealed that no single value can characterize intensity discrimination capabilities. For example, discriminability depends critically on stimulus size and on illumination level (Vos, Lazet, & Bouman, 1956). Van Mecteren (1967) has shown, however, that CSFs measured at different illumination levels can be used to predict intensity discrimination thresholds for various background illumination levels and spots of various sizes.

Yet another important property revealed in CSF measurements is low-frequency attenuation. The attenuation of sensitivity to low spatial frequencies seems to reflect lateral inhibitory processes in early stages of the visual system. These processes serve to attenuate the visual system's response to gradual intensity changes and thereby emphasize sudden or sharp intensity changes (e.g., an edge). Consider the function of lateral inhibition in pattern vision. In order to simplify processing of the astronomical amount of information entering the eye, the visual system must filter out certain types of information. Lateral inhibitory networks tend to

filter out gradual intensity changes (diffuse shadows, gradual changes in lighting, etc.). Hence the pattern information that passes through lateral inhibitory networks appears to be the most "valid" information, namely the position and shape of contours which define patterns in the first place. The argument that the low-frequency falloff of the CSF reflects lateral inhibitory processing is supported by several physiological and psychophysical studies. For example, physiological experiments have found that the sensitivity of lateral inhibition among retinal ganglion cells is less for low than for high luminances (Barlow et al., 1957). Adult psychophysical experiments have shown that the slope of the low-frequency CSF falloff is also less for low than for high luminances (Van Nes & Bouman, 1967). Stated another way, at high luminances where lateral inhibition is strong, the low-frequency falloff of the adult CSF is pronounced. At low luminances where inhibition is weak, the low-frequency falloff is much less distinct.

A. Development

The utility of the CSF in adult work has led developmental researchers to measure these functions in infants as well. Three laboratories have published reports of CSF development during early infancy (Atkinson et al., 1977a; Banks & Salapatek, 1978; Pirchio, Spinelli, Fiorentini, & Maffei, 1978). The methods of the three differ, so we will describe them briefly.

Atkinson et al. (1977a) used the FPL technique (and a first fixation measure) to test 1-, 2-, and 3-month-olds. On each trial sinewave gratings appeared on one of two oscilloscopes; the other oscilloscope presented a uniform field of the same hue and average luminance. Each display subtended 15°. The gratings were either stationary or drifting. The results—the contrast necessary to elicit 70% correct responding as a function of spatial frequency—revealed a large increase in contrast sensitivity, primarily at high spatial frequencies, from 1 to 2 months and essentially no change from 2 to 3 months. The low-frequency falloff in sensitivity that is characteristic of adult CSFs was not observed consistently at 1 month but was at 2 and 3 months.

Banks and Salapatek (1978) used the first fixation version of the preferential looking technique to measure CSFs in 1-, 2-, and 3-month-olds. They used a projection system to present much larger stimuli (48° × 40°) than Atkinson et al. (1977a). The grating and uniform fields were again equal in hue and average luminance, but they were adjacent to one another. The observer always waited until the infant was fixating midline before presenting the stimuli. Consequently, the grating in the Banks and

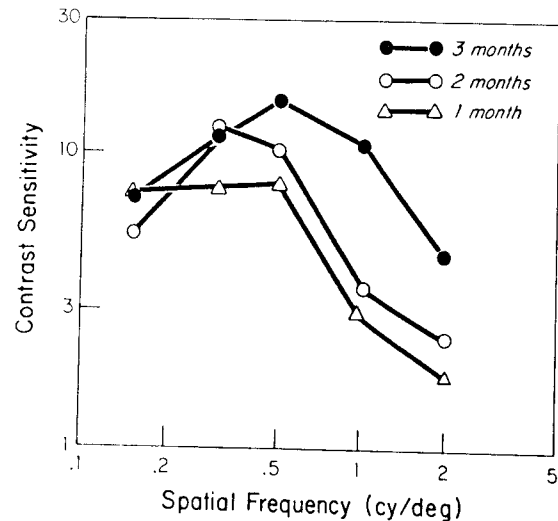


Figure 6. Average CSFs for 1-, 2-, and 3-month-old infants as reported by Banks and Salapatek (1978). Average contrast sensitivity is plotted as a function of spatial frequency. (From Banks & Salapatek, 1978.)

Salapatek study would, when first presented, have appeared close to the infant's fixation point. The sinewave gratings were always static. The results are shown in Figure 6. Again there is an increase with age in contrast sensitivity, primarily at high spatial frequencies, but not as large an increase as observed by Atkinson et al. The low-frequency falloff was again not observed consistently at 1 month but was at 2 and 3 months.

These two behavioral experiments agree substantially on the shape and height of the CSF at 2 and 3 months of age. They also agree on the shape of the CSF at 1 month but disagree on the overall sensitivity at that age. The disagreement may be due to the differences in the field sizes employed. This argument is supported by findings that 1-month-olds do not appear to process pattern information presented within a frame (e.g., Milewski, 1976, 1978). Moreover, Atkinson et al. (1983) observed higher grating acuities in 1- and 2-month-old infants when the targets were large rather than small.

The infant functions in Figure 6 are quite distinct from the adult CSF in Figure 5. Clearly, infant CSFs are shifted to a lower band of spatial frequencies. Infants also appear to have a substantial deficit in overall contrast sensitivity relative to adults. These differences prompt an important question: to what extent are the early deficits due to nonsensory factors such as motivation? We use the four verification techniques outlined earlier to explore this question.

First, note that the shape of the CSF depends on relative threshold values. Thus, shape comparisons obey our first verification technique: the use of thresholds as relative rather than absolute information. We believe, then, that comparisons of CSF shape are not as susceptible to contamination by nonsensory factors as comparisons of contrast thresholds at a given spatial frequency might be.

Second, consider whether response convergence exists. Evoked potential measurements are useful in this regard because they presumably are not as subject to motivational factors as behavioral techniques might be. Pirchio et al. (1978) used steady-state VEPs to measure CSFs in one infant from 2½ to 6 months of age. They also measured two points on the CSF (the high-frequency cutoff and the peak) in a number of infants from 2 to 10 months. The sinewave gratings were presented in 7 to 25° fields, depending on the infant's age. The gratings were flickered in counterphase fashion at a rate of 8 Hz. Pirchio et al. estimated threshold by plotting VEP amplitude versus contrast and extrapolating to find the contrast yielding zero amplitude. The results for the infant tested longitudinally are shown in Figure 7. Results from other infants (not shown in Fig. 7) indicated that the high-frequency cutoff increased from 2 c/deg at 2

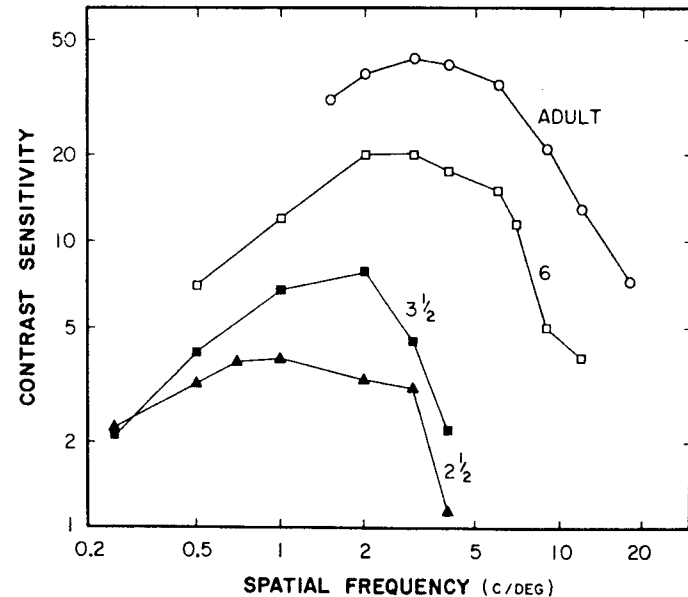


Figure 7. CSFs for one infant and one adult as reported by Pirchio, Spinelli, Fiorentini, and Maffei (1978). The infant's age in months is shown to the right of each of the infant functions. (From Banks, 1982.)

months to about 20 c/deg by 10 months and that peak contrast sensitivity improved from 4 to about 40 over the same age range.

The findings of Pirchio et al. are both similar and dissimilar to those of the behavioral studies (Atkinson et al., 1977a; Banks & Salapatek, 1978). They are dissimilar in the absolute contrast sensitivity values observed; Banks and Salapatek, for example, reported a peak sensitivity of 13 for 2-month-olds while Pirchio et al. observed a peak sensitivity of only 4. One really should not, however, expect the absolute sensitivity values to agree between two response measures for reasons described in Section III on visual acuity. The VEP and behavioral studies are similar in the relative sensitivity values reported, that is, the shapes of the CSFs and spatial frequencies at which sensitivity is highest are nearly identical. They are also similar in that the peak sensitivity of adult functions is roughly 20 times higher than those of 2- and 3-month functions. In other words, infants' sensitivity deficits, expressed relative to adult sensitivity values, are about the same in behavioral and electrophysiological studies.

Harris et al. (1976) have also found clear similarities between VEP and FPL measures. They actually measured CSFs in one 6-month-old using both techniques. Despite differences in some of the stimulus parameters and the obvious differences in response measures, the two techniques yielded similar estimates of the CSF. It should be noted that the 6-month-old's CSF exhibited only a twofold deficit in high-frequency sensitivity relative to adults. It appears, then, that the CSF may be nearly adultlike by 6 months.

Comparisons of behavioral and VEP measurements thus suggest that response convergence exists for indices of contrast sensitivity. This bolsters the argument that the sensitivity deficits young infants exhibit in behavioral experiments are due in large part to sensory factors rather than to nonsensory, motivational factors.

We can also ask if stimulus convergence exists for contrast sensitivity measurements. Recall that the CSF has been used in adult work to predict acuity thresholds for a variety of targets. Atkinson et al. (1977c) and Banks and Salapatek (1981) demonstrated that similar predictions can be drawn from infant CSFs. Banks and Salapatek reanalyzed two experiments—Dayton et al. (1964) and one described by Fantz, Fagan, and Miranda (1975)—which had used atypical patterns to estimate visual resolution. These experiments were of particular interest because both obtained higher resolution values than others that used more conventional stimuli. In both cases, application of linear systems analysis and the CSF for the appropriate age group revealed that higher acuities were actually predictable given the patterns they used. Hence the results of Dayton et al. and Fantz et al. were actually consistent with other investigators' estimates.

Atkinson et al. (1977c) developed a unique measure of acuity using facial photographs. Two faces, one focused and one defocused to varying degrees, were presented to 1- to 3-month-olds in a discrimination task. When one face was badly defocused, infants preferentially fixated the focused version. Atkinson and colleagues varied the amount of defocus to find the point at which infants preferred the focused face on 70% of the trials. Once they obtained these thresholds, the experimenters used CSF measurements from another experiment (Atkinson et al. 1977a) in an attempt to predict the amount of just-detectable defocus. The predictions were quite accurate given the inherent variability of infant data. Thus, the CSF and a simple application of linear systems analysis allowed the prediction of a unique estimate of visual acuity. The success of this experiment argues that the use of "necological" stimuli such as sinewave gratings has not badly misrepresented infants' visual sensitivity.

These two reports (Atkinson et al. 1977c; Banks & Salapatek, 1981) illustrate that stimulus convergence is observed among stimuli that probe the visual acuity of young infants. Banks and Stephens (1982) have examined stimulus convergence in another situation. Specifically, they used the CSF approach to predict contrast sensitivity for patterns coarser than the resolution limit. They measured 10-week-olds' contrast thresholds for five types of rectangular wave gratings. The spatial frequency of the gratings was always 1 c/deg, but the gratings differed in duty cycle (the relative widths of light and dark stripes). An adult was also tested with rectangular wave gratings of 7 c/deg. Figure 8 summarizes Banks and Stephens' infant and adult results and shows some of the stimuli employed. The infant and adult results were very similar except for a large difference in contrast sensitivity. In both cases, sensitivity varied systematically with duty cycle. Banks and Stephens used linear systems theory to derive predicted contrast sensitivities as a function of duty cycle. The predicted functions—the solid lines—fit the infant and adult data very well. The close match between the predicted and observed functions illustrates that stimulus convergence holds for stimuli coarser than the resolution limit of young infants. It also exemplifies the utility of linear systems analysis and the CSF in predicting infants' contrast thresholds for various sorts of grating patterns.

We have shown that both response convergence and stimulus convergence are present in measures of infants' contrast sensitivity. These observations corroborate the view that these CSF measurements reveal the behavior of sensory mechanisms rather than nonsensory, motivational factors. To the extent that this view is correct, we can conclude that the pattern information to which young infants are sensitive is only a fraction of the information available to adults. This fraction increases steadily from birth to 6 months, when contrast sensitivity approaches adult val-

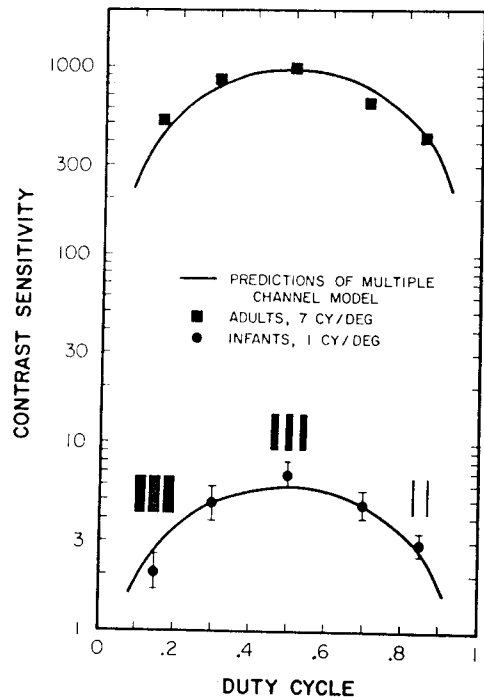


Figure 8. Average contrast sensitivity for rectangular wave gratings differing in duty cycle. Infant data are represented by circles. The sensitivity values are for 1c/deg gratings. Adult data are represented by squares. Those sensitivity values are for 7 c/deg gratings. The two curves represent linear systems predictions assuming multiple channel processing. They are identical in shape but have been shifted vertically for best fit. (Adapted from Banks & Stephens, 1982.)

ues. (This conclusion is more justifiable for the shape of the CSF than for its height, but the similarity across response measures of infant-adult differences in CSF height argues that the estimates of overall sensitivity cannot be badly in error.)

It is interesting to note that Boothe, Williams, Kiorpes, and Teller (1980) examined CSF development in macaque monkeys, a species whose mature visual system is very similar structurally and functionally to that of human adults (Boycott & Dowling, 1969; DeValois, Morgan, & Snodderly, 1974). Boothe et al. reported age-related changes very similar to those observed in humans, except that CSF development occurs more rapidly in macaques.

An important question concerning CSF development is, are the observed age differences determined primarily by changes in optical quality or by changes in neural mechanisms? An optical quality explanation is

somewhat attractive because young infants' deficits are most pronounced for high spatial frequencies, and high-frequency sensitivity suffers more from optical aberrations and accommodative errors than does low-frequency sensitivity (Green, Powers, & Banks, 1980). Nonetheless, it is very unlikely that optical aberrations or accommodation contribute significantly to early contrast sensitivity deficits. The reasoning behind this conclusion was detailed in the previous section, in which we considered whether optical aberrations or accommodative errors constrain visual resolution to its low levels early in life. Age differences in the CSF, therefore, are most likely determined by neural development.

Before discussing the implications of CSF development to the growth of visual perception, we should make an important qualification. The CSFs reported in the infant literature were generally measured using stationary gratings of moderate luminance. It is quite possible, even likely, that the use of flickering, high-luminance gratings would yield higher contrast sensitivity (Dobson et al., 1983; Sokol et al., 1986). Given this, we should apply the existing CSF data to the visibility of static stimuli of moderate luminance only.

To summarize the infant CSF work reviewed thus far, the evidence is reasonably persuasive that the young infant is sensitive to a much lower and perhaps more restricted range of spatial frequencies than the adult visual system is. Similarly, the range of contrasts to which infants are sensitive is quite restricted early on. The ranges of detectable frequencies and of detectable contrasts increase steadily during the first half-year. Neural mechanisms appear to be more responsible than optical structures for the early deficits and subsequent growth. It appears, then, that the young visual system is sensitive initially to only a fraction of the information to which the adult system is sensitive and that this fraction increases steadily through at least the first half-year of life.

Banks and Salapatek (1981) have referred to the fraction of pattern information to which young infants are sensitive as their "window." Evidently the window is quite restricted early in life, but before concluding that young infants must be virtually blind, two points should be kept in mind.

1. Concerning infants' low overall contrast sensitivity relative to adults': the contours of many common objects have contrasts greater than the threshold contrasts indicated in Figures 6 and 7. Faces, for example, often exhibit contrasts of 0.7 to 0.8 between the skin and hair, a value high enough to be detected by young infants. Thus, even though infants' contrast sensitivity is quite low relative to adults', it is sufficient for the detection of many typical intensity gradients in the environment. Further-

more, as Atkinson and Braddick (1982) point out, one should not conclude from poor sensitivity in a threshold task that contrasts well above threshold must look much fainter to infants than to adults. A contrast sensitivity deficit does not necessarily imply a drop in apparent contrast for suprathreshold stimuli. This point is illustrated by the work of Georgeson and Sullivan (1975) with normal adults and Hess and Bradley (1980) with amblyopic adults.

2. Concerning the shift of infants' sensitivity to low spatial frequencies relative to adults': the spatial frequencies of the sinewave components in an object change systematically with viewing distance. As the object is brought closer, its angular subtense increases and the major components are translated toward lower frequency values. The infants' low-frequency window is best suited for perceiving objects in the immediate rather than the distant visual environment. As the window grows with age, infants' ability to perceive distant objects (or small near objects) should increase correspondingly. Interestingly, Ginsburg (1978) has demonstrated that adult pattern recognition is not affected significantly when high spatial frequencies are deleted. His demonstrations emphasize the utility of low-frequency information in the recognition of all but very small objects (e.g., fine print).

As mentioned earlier, the CSF allows one in principle to predict sensitivity to a variety of patterns. It also reveals three important aspects of pattern vision: visual acuity, intensity discrimination, and low-frequency attenuation. We now discuss these points in the context of infant work.

We have already described work that shows that infant and adult CSFs allow quite accurate predictions of acuity thresholds for various kinds of targets. CSFs thus appear to provide a flexible, reasonably general index of the growth of visual resolution.

The CSF also reveals the intensity discrimination capacity of the visual system. Each point on the function represents the intensity difference (or contrast) necessary for an infant to detect the presence of nonuniformity. Peeples and Teller (1978) measured intensity discrimination in 2-month-olds. They found that 2-month-old infants could discriminate stripes (square wave gratings) whose intensity differed by only 12% from the background intensity. This corresponds to a contrast sensitivity of 17.5. The predicted contrast sensitivity, based on Banks and Salapatek's (1978) CSF data from 2-month-olds, is 14.0, a reasonably close match considering the differences in procedures. Clearly, however, a single value cannot portray the contrast sensitivity or intensity discrimination ability of the developing visual system because those abilities depend highly on stimulus size and shape. For example, Banks and Stephens (1982) showed that

the contrast sensitivity of 10-week-olds varies with the relative widths of light and dark stripes in a pattern.

The third aspect of pattern vision revealed in CSFs is low-frequency attenuation. Recall that this attenuation is a product of contour-enhancing lateral inhibitory processing. Figure 6 suggests that low-frequency attenuation develops between 1 and 2 months. Atkinson et al. (1977a) examined this by testing a number of 1- to 3-month-olds at three low spatial frequencies. The results clearly showed that the low-frequency falloff is generally not present before 2 months of age. The implication is that lateral inhibition is not functional until that age. This hypothesis is supported by two observations. First, physiological studies have established that the magnitude of lateral inhibition among retinal ganglion cells is less for low than for high luminances (Barlow et al., 1957). Consequently, if the low-frequency falloff in the CSF is caused by lateral inhibition, one would expect the falloff to become shallower at low luminances. Banks and Salapatek (1981) tested this in 2-month-olds. They measured CSFs at two luminances and found a shallower falloff slope at the lower luminance. Second, physiological studies of kitten retinal ganglion cells have found that lateral inhibitory mechanisms are not adultlike until 8 to 9 weeks, which is considerably delayed relative to the development of excitatory mechanisms (Hamasaki & Sutija, 1979; Rusoff & Dubin, 1977). A similar developmental sequence has been observed in rabbit ganglion cells (Bowe-Anders, Miller, & Dacheux, 1975). Thus, the contour-enhancing properties of early visual processing may not emerge in humans until about 2 months after birth.

Another fundamental property of pattern vision that can be revealed in CSF experiments is the existence of multiple, feature-selective channels. All sensory systems possess many parallel pathways, each specialized to carry information about a particular type of stimulus. 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 visual cortex respond selectively to stimuli of different orientations (Hubel & Wiesel, 1962, 1968). Furthermore, such cells respond selectively to different sizes (or bands of spatial frequency), one cell responding to large pattern elements (low frequencies) and another to small pattern elements (high frequencies) (Albrecht, DeValois, & Thorell, 1980). A number of psychophysical experiments in adults have suggested that pattern information is processed in parallel by "channels" analogous to the cortical cells mentioned above. Different channels appear to be tuned to different orientations and spatial frequencies (reviewed by Braddick, Campbell, & Atkinson, 1978). The evidence for spatial frequency tuning among these channels lies in the fact that spatial frequencies interact in

detection, adaptation, and masking experiments, but only if they lie within about 1 octave (a factor of two) of each other. Importantly, these channels appear to be involved in the perception of size (Blakemore & Sutton, 1969).

Despite the importance of these processes to pattern recognition (Ginsburg, 1978; Marr, 1982) and the electrophysiological evidence that channel specificity develops postnatally in kittens (Derrington & Fuchs, 1981), the development of spatial frequency and orientation channels in humans has only recently been investigated. Banks, Stephens, and Hartmann (1985) used a masking paradigm to measure the frequency bandwidth of channels in 1½-month-olds, 3-month-olds, and adults. They found at all ages that a narrowband noise masker whose spatial frequency was similar to the frequency of a sinusoidal test grating caused an increase in the grating's threshold. However, when the masker and grating differed in frequency by 2 octaves (a factor of four), the grating's threshold was unaffected by the masker in 3-month-olds and adults. This indicates that pattern information whose frequency content differs by 2 octaves is processed by separate channels and, therefore, constitutes evidence for multiple spatial frequency channels. In 1½-month-olds, the masker affected the grating's threshold even when they differed by 2 octaves and, consequently, separate channels were not demonstrated over this range of frequencies. Banks et al. used their data to estimate channel bandwidth as a function of age. The estimates were ± 1.3 octaves for 3-month-olds and adults. A bandwidth could not be estimated for 1½-month-olds because no frequency-selective masking was observed. The results imply that the spatial frequency tuning (or size tuning) of such channels is quite broad early in life and becomes adultlike by 3 months. A second experiment, using a different paradigm, substantiated this age-related shift (Banks et al., 1985).

Stephens and Banks (1985) examined the development of contrast constancy, a perceptual phenomenon that is characteristic of the mature visual system. As the term contrast constancy implies, adults are able to judge the contrast of an object and its features veridically as the object undergoes changes in distance. Models of contrast constancy assume the presence of narrowband spatial frequency channels. An implication of the findings of Banks et al. (1985) is that contrast constancy should not be present at 1½ months but may be at 3 months. Stephens and Banks used a preference procedure to test this implication. Indeed, 3-month-olds exhibited contrast constancy and 1½-month-olds did not.

In mature animals, spatial frequency-tuned responding is not observed before the level of the visual cortex. Therefore, the results of Banks et al. (1985) and Stephens and Banks (1985) may reflect cortical development in

humans. If spatial frequency channels are broadly tuned early in life, one might expect the ability to discriminate patterns according to size to improve correspondingly with age. Unfortunately, no data on the development of size discrimination *per se* exist, so this hypothesis cannot be evaluated. One might also expect various pattern recognition and stereovision capabilities to improve with age, but such expectations depend on the precise role spatial frequency channels are assumed to serve (e.g., Ginsburg, 1978; Marr, 1982; Pollen, Lee, & Taylor, 1971).

B. Summary

The CSF and linear systems analysis have only recently been applied to the study of visual development. Already the CSF has proven to be a useful general index of pattern detection capabilities. It has also illuminated several important aspects of pattern vision and how they change with age.

Several important questions remain to be explored. For one, how do spatial-temporal interactions influence infants' detection of pattern? This is an important question which we consider in our discussion of temporal vision. Another important question for future research concerns the encoding of spatial relations among detected contours. The potential importance of this is illustrated by an example from the adult amblyopia literature. (Amblyopia is a developmental anomaly in which visual acuity and some pattern discrimination capabilities are reduced.) Frequently one cannot predict adult amblyopes' acuity for letters (Snellen acuity) from their CSFs. Specifically, the Snellen acuity is usually worse than predicted. Pass and Levi (1982) may have discovered why. They measured conventional CSFs in amblyopic adults and found a small but reliable high-frequency deficit relative to normal adults. They also measured thresholds for the identification of spatial relations among detectable patterns. The amblyopes exhibited a large deficit in this task. This suggests that, in addition to a contrast sensitivity deficit, amblyopes also have a spatial encoding deficit. Similar sorts of experiments in infants might reveal important properties of the developing visual system.

Finally, one wonders how useful contrast sensitivity measurements might be to the study of pattern discrimination. Recently two laboratories (Banks & Ginsburg, 1985; Banks & Salapatek, 1981; Gayl, Roberts, & Werner, 1983) have used the CSF and linear systems analysis to investigate suprathreshold pattern preferences. Generally, the results exhibit close correlations between predicted and observed preferences and thus offer hope that this approach may be useful in this arena as well.

V. LIGHT AND DARK ADAPTATION

Up to this point we have considered infants' visual capabilities at fixed levels of illumination. Of course, the environment actually presents stimuli across an extremely large range of light levels. The mature visual system is able to maintain reasonably proficient pattern vision for a substantial portion of this range. Ripps and Weale (1969) have estimated that the useful range of light levels is 10 log units. In other words, we can still discern patterns when the light is 10,000,000,000 times more intense than the smallest amount of light detectable in the dark. This remarkable feat is accomplished by adjusting the visual system's sensitivity according to the ambient level of illumination. Such adjustments are usually not obvious subjectively because they occur so efficiently. They become obvious only when light level changes suddenly and drastically. On those occasions, the visual system is temporarily blinded but readapts fairly rapidly so that pattern vision is possible once again. The processes of adapting to increases and decreases in illumination are called light and dark adaptation, respectively.

Before describing research on light and dark adaptation, let us discuss the perceptual task of recognizing objects presented under different levels of illumination. An appreciation of this task is important to understanding adaptation. An object is generally defined by differences in intensity (or hue) between the object and its background or between features within the object. The apparent brightness or luminance of an object or a feature within an object depends both on its reflectance (the percentage of incident light reflected) and the amount of light falling on it. Consequently, two adjacent parts of an object with different reflectances will always differ in luminance and form a contour, if they are bathed in the same light. If the amount of light falling on the object is changed, the *ratio* of the luminances does not change. So, the luminance ratio defining the contour would be the same under sunlight or moonlight. The mature visual system capitalizes on this invariance: light and dark adaptation operate to insure that the visual system responds to luminance ratios rather than absolute luminances. In this way, contours remain approximately equally visible for a large range of illumination levels.

This property is illustrated by Weber's Law, which states that the smallest intensity increment needed for a target to be detected against an otherwise uniform background is a constant percentage of the background's intensity. Weber's Law is illustrated by the increment threshold function (ITF), which plots the logarithm of the just-detectable increment intensity against the logarithm of the background intensity. The lower function in Figure 9 is a typical adult increment threshold function.

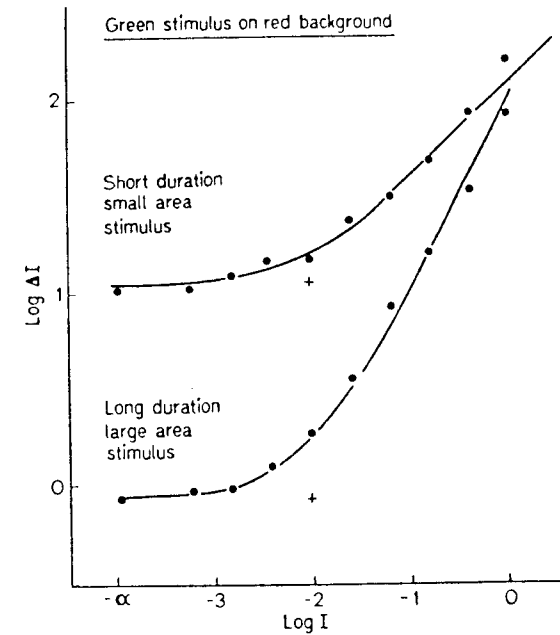


Figure 9. Adult increment threshold functions for different stimulus conditions. Both functions plot the logarithm of increment intensity at threshold as a function of the logarithm of background intensity. The lower curve represents thresholds when the test spot is 55 min in diameter and 1 sec in duration. The upper curve represents thresholds when the test spot is 5.2 min in diameter and 7 msec in duration. The separation of the functions has been reduced by 1 log unit for ease of presentation. (From Barlow, 1972.)

Weber's Law holds where the slope of this function is 1.0; thus it appears to hold over a large range of intensities in adults.

Several mechanisms contribute to adaptation in adults (see Barlow, 1972). First, pupillary changes modulate the amount of light falling on the retina in an appropriate, albeit insignificant, manner. The area of the adult pupil in bright light is about $\frac{1}{16}$ th its area in darkness. Therefore, pupillary changes aid adaptation but are really quite insignificant given the total dynamic range of the visual system. Second, the presence of two types of photoreceptors, rods and cones, aid adaptation by dividing the total dynamic range roughly in half. Rods are about 4 log units (10,000-fold) more sensitive than cones, so they function over the range of dim light levels while cones operate at high levels. Even this staggering of sensitivity cannot fully account for light adaptation in adults. Additional photochemical and neural mechanisms must, therefore, contribute (Barlow, 1972).

Adult psychophysical research has shown that several properties of the

visual system change when luminance is raised or lowered. These changes are presumably byproducts of the neural mechanisms of light and dark adaptation. For instance, the temporal summing properties of the visual system change with luminance; the highest detectable flicker rate (critical flicker frequency) increases from roughly 2 Hz at scotopic levels of illumination to about 60 Hz at photopic levels (Hecht & Verrijp, 1933; Kelly, 1961). This implies that the visual system summates (or integrates) inputs over longer durations at low light levels than at high light levels. The spatial summing properties of the visual system also change with luminance. This is exemplified by the large increases in visual acuity that accompany higher levels of illumination (Shlaer, 1937). Thus, the visual system seems to summate (or integrate) inputs over larger spatial intervals at scotopic light levels than at photopic levels.

These changes in temporal and spatial summation aid adaptation by increasing sensitivity at low light level, where input signals are relatively weak, and by decreasing sensitivity at high light levels, where input signals are so strong that they would otherwise saturate neural responses. The effect of increasing temporal and spatial summation at low light levels is illustrated by the two increment threshold functions (ITFs) of Figure 9. The upper curve shows an adult's ITF when the stimulus is a small (5.2-min diameter), short-duration (7 msec) spot on an otherwise uniform background. The lower curve is the ITF when the stimulus is a large (55-min diameter), long-duration (1 sec) spot on a uniform background. Because one spot is small and short in duration, it impedes the visual system's ability to summate an input over space and time. That is not the case for the other spot. The figure shows the impact of this difference on visual performance. At low background intensities, when temporal and spatial summation are needed to enhance sensitivity, thresholds for the small, brief spot are much higher than thresholds for the large, long spot. At high background intensities, when temporal and spatial summation are normally not so useful, thresholds are similar. Notice also that Weber's Law holds for the large, long-duration stimulus but not for the small, short one. This means that Weber's Law is valid for certain conditions only. In everyday settings, those conditions should correspond to relatively large, nonflickering features.

A. Development

Developmentalists have only recently studied the effects of illumination changes on pattern vision. Consequently, the experimental questions to date have been elementary. We describe some experiments that explored the development of light adaptation directly. We also describe experi-

ments that provide circumstantial evidence that neural mechanisms involved in adaptation change with luminance.

Two studies have directly examined light adaptation in infants using increment threshold functions. Hansen and Fulton (1981) and Dannemiller and Banks (1983) measured increment threshold functions at a number of ages in order to examine the extent to which adaptation occurs to different levels of illumination. Hansen and Fulton measured increment thresholds in the scotopic range (low light levels at which rods operate) using the FPL procedure. Although only one infant was tested at each age, two developmental trends were evident. First, increment thresholds at all background intensities decreased with age. Second, thresholds decreased more at low background intensities than at high, so the slopes of the increment threshold functions increased steadily from about 0.62 at 2 weeks to an adultlike value of 0.90 at 12 weeks. Thus, adultlike adaptation (Weber's Law) did not appear, at least for scotopic stimuli, until 12 weeks of age.

Dannemiller and Banks (1983) presented both scotopic and photopic (cone vision) levels to a much larger number of infants. They also used the FPL procedure. Their results are summarized in Figure 10. They observed the same two developmental trends. First, increment thresholds declined in general with age. Second, increment threshold function slopes increased with age; slopes of 0.56 and 0.79 were observed at 7 and 12 weeks, respectively. Adult slopes in the same apparatus over the same luminance range were 0.88 on the average, fairly close to Weber's Law.

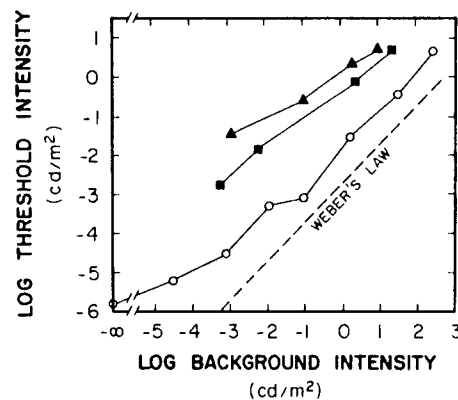


Figure 10. Increment threshold functions for 7-week-olds, 12-week-olds, and adults as reported by Dannemiller and Banks (1983). The logarithm of increment intensity at threshold is plotted as a function of the background intensity. Weber's Law is illustrated by the dashed line. Circles, adult increment threshold function. Squares, 12-week functions. Triangles, 7-week functions. (Adapted from Banks, 1982.)

Hence, the two groups of investigators concur that adultlike changes in visual sensitivity with changes in background intensity do not occur until 3 to 4 months of age.

Dannemiller and Banks considered several explanations for the postnatal changes in increment threshold function slopes they and Hansen and Fulton observed. First, adaptation mechanisms *per se* may be immature at birth and improve up to 3 to 4 months. Dannemiller and Banks argued that this account is possible but unlikely. Specifically, immaturities in most adaptation mechanisms should cause neural responses to saturate at high light levels. Saturation would cause an increase rather than a decrease in ITF slope. A second possibility is that adaptation mechanisms are mature before 3 to 4 months but other sensory and/or nonsensory factors that can affect increment threshold functions may change. They favored the second class of explanations. In particular, Dannemiller and Banks considered two hypotheses to be reasonable explanations of the shallower slopes observed in infant increment threshold functions.⁹

First, they considered the possibility that the spatial and temporal properties of the stimulus may have affected the ITF slopes. Recall that the slope of the adult ITF is shallower for small, short-duration test spots than for large, long-duration spots. The test spot in the Dannemiller and Banks experiment was very long in duration, so this probably did not lower ITF slopes. The test spot was also fairly large, but data from Hamer and Schneck (1984) suggest that infants' spatial summation areas are quite large, so perhaps the Dannemiller and Banks (and Hansen and Fulton) stimulus was small for infants. If this explanation is correct, the slopes of infant ITFs for relatively large test spots should be similar to adult slopes for smaller spots. A comparison of Figures 9 (the upper curve for small test spots) and 10 supports this explanation.

Dannemiller and Banks' second explanation for the shallower infant slopes involves differences in the relationship between stimulus intensity and response magnitude among retinal neurons (Dowling & Ripps, 1971; Naka & Rushton, 1966). A lower gain on this function would elevate absolute threshold and prolong the portion of the ITF in which threshold is unaffected by background luminance. These effects would produce a shallower slope. Both of these effects are compatible with known infant visual psychophysics: ITF slope is apparently lower in infants than in adults, and Powers et al. (1981) have reported that 1- and 3-month-olds'

⁹ They tentatively rejected the hypothesis that nonsensory factors caused the slope changes because their psychometric data did not support that idea. Specifically, there was no evidence for different contributions of nonsensory factors at different background intensities.

absolute thresholds are roughly 2.0 and 1.0 log units higher, respectively, than adults'.

Both of these explanations—one based on large spatial summation areas and one on a shallow intensity–response function—are reasonably consistent with current data on early adaptation. The first explanation is supported by Dannemiller's (1983) observations. If age-related changes in summation area are responsible for the reduced slopes of infant ITFs, then ITF slopes should be 1.0 at all ages when large test spots are used. Dannemiller (1983) observed adultlike slopes when 6- and 12-week-olds were tested with large, 8° diameter test spots. The same infants exhibited lower slopes when tested with smaller, 2° test spots. Brown (1984) also observed adultlike slopes with large test spots. These results favor the hypothesis that light adaptation mechanisms are reasonably mature early in life because Weber's Law holds once stimulus size is sufficiently large. Further research is required to ascertain whether changes in the intensity–response function also contribute to changes in the infant's ITF. Physiological experiments with infrahuman species may be the only means of testing the intensity–response function account.

Some circumstantial evidence exists that neural mechanisms of adaptation are functional early in life. In adults, adaptation is accompanied by several changes in visual function. For example, spatial and temporal resolution both decrease as the visual system adapts to lower luminance levels. If neural mechanisms of adaptation were reasonably mature early in life, we would expect to see such adaptive, luminance-related changes in young infants. The temporal and spatial summing properties of the 2-month-old's visual system actually do seem to change with luminance in much the same way as they do in adults.

Three research groups have examined the relationship between luminance and critical flicker frequency (CFF), an index of temporal resolution. Heck and Zetterström (1958) and Horsten and Winkelman (1962, 1964) used flicker electroretinography and Regal (1981) used a behavioral technique. The results of these experiments all suggested that CFF increases as luminance is raised by 2 months of age, if not earlier. Indeed, the relationship between luminance and CFF appeared quite adultlike by 2 months.

Dobson, Salem, and Carson (1983) have examined the relationship between luminance and visual acuity in 2-month-olds. They observed a 1-octave increase in acuity as luminance was raised from 0.10 to 10.0 candelas per meter squared (cd/m^2). These changes in acuity with increasing luminance were very similar to those observed in adults. Similarly, Fiorentini, Pirchio, and Spinelli (1980) have studied the luminance dependence of infants' spatial CSFs. As luminance was diminished from 6.0 to

0.06 cd/m², a threefold reduction in acuity and a diminution of the low-frequency falloff was observed for infants younger than 4½ months. Adults showed a similar diminution of the low-frequency falloff but a larger, 10-fold reduction in acuity.

These studies indicate that adaptive changes in temporal and spatial summation probably accompany changes in luminance by 2 months of age, if not earlier.

We now consider what is known about dark adaptation processes in early infancy. Only two studies have examined dark adaptation in infants less than 6 months of age. Hansen, Fulton, Leitzman, and Harris (1984) used pupillography to study the kinetics of dark adaptation. They found that the rates of dark adaptation (presumably for the rod system) were similar in young infants and adults. Dannemiller (1985) used a psychophysical technique to demonstrate that the very early phase of dark adaptation (from 0 to 5 sec) yielded very similar reductions in threshold for 6- and 12-week-olds and adults. This too implies that the rate of early dark adaptation is similar in young infants and adults. The early phase of dark adaptation is significant because it is probably controlled by neural mechanisms rather than by the photopigment regeneration kinetics responsible for the later stages of dark adaptation. Taken together, these two studies suggest that dark adaptation, like light adaptation, may be adultlike by 3 months, if not earlier.

B. Summary

Experiments on the development of light adaptation suggest that, for whatever reason, detection thresholds (expressed relative to background intensity) are affected more by changes in background intensity during the perinatal period than afterward. At 1 month, the increment intensity required for the detection of small spots is a much higher percentage of the background intensity at low light levels than it is at high levels. At 3 to 4 months, however, increment threshold is nearly a constant percentage of background intensity across a large range of light levels. Evidence suggests that younger infants' increment thresholds are also nearly a constant percentage of background intensity so long as large spots are used. Thus, very early in life, the visual system appears to capitalize on the invariance of relative intensities in the environment by responding to luminance ratios. The early phase of dark adaptation also appears to be mature soon after birth.

Studies of the development of light and dark adaptation are in their infancy. There are several aspects of adaptation that have not been investigated developmentally. However, our current sketchy understanding is

that some aspects of light and dark adaptation are adultlike by 1 to 2 months of age, if not earlier.

VI. TEMPORAL VISION

Most research on infant vision has disregarded or at least minimized the time-varying or temporal aspects of visual stimulation. In reality, the eye picks up information in a series of eye movements moving from one object to another, and those objects are frequently not stationary themselves. Consequently, from moment to moment, the eye may pick up entirely different distributions of light. Some temporal resolution is required to encode such distributions separately. For this reason, the temporal response properties of the visual system are important to the perception of patterns in everyday situations. We will consider two aspects of temporal vision: the perception of flicker and the effects of spatial-temporal interactions on perception. Both of these topics have been examined extensively in adults (for reviews, see Kelly, 1972; Sekuler, 1975). In keeping with our general organization, we will first review some basic findings in the adult literature before turning to developmental work.

The temporal resolution of the mature visual system is, in a sense, rather poor. Consider, for example, the picture we perceive on a television screen. Each spot on the screen is illuminated by an electron beam that scans the whole screen 60 times a second. Thus, each spot is briefly illuminated once every 1/60 sec or 17 msec. The fact that we perceive a nonflickering picture rather than a single moving spot shows that the visual system integrates light over time periods of 17 msec or longer. The integration time of the visual system is exemplified by Bloch's Law. This law states that the light intensity of a stimulus required to evoke a threshold response is inversely proportional to stimulus duration, so long as the duration is less than some critical duration. Stated another way, the visual effect for brief, near-threshold flashes depends on the product of intensity and duration. The critical duration is roughly 30 msec for photopic stimuli and 100 msec or longer for scotopic stimuli (Roufs, 1972). Thus, the adult visual system appears to pool information in 30-msec bins for bright stimuli and in bins of 100 msec or longer for dim stimuli. This observation accounts for the apparent stability of flickering television images.

Another index of the temporal summing properties of the visual system is the critical flicker frequency (CFF), which is the highest rate of flicker that can be perceived as time varying. CFF in adults depends on experimental conditions, but it is roughly 60 Hz under optimal conditions. As with Bloch's critical duration, CFF depends critically on stimulus

luminance. It increases roughly linearly with the logarithm of intensity from values near 2 Hz at very dim levels to about 60 Hz at bright, photopic levels (Hecht & Shlaer, 1936). Thus, temporal resolution is considerably better under photopic conditions.

Measurements of CFF index the visual system's ability to resolve very rapid, high-contrast flicker. This is an important aspect of temporal vision, but real visual scenes actually produce varying rates of flicker at varying contrasts. A more general index of temporal processing is provided by the temporal analog of the spatial contrast sensitivity function—the temporal contrast sensitivity function (temporal CSF). This function represents an observer's sensitivity to unpatterned, sinusoidally flickering stimuli as a function of flicker frequency. The adult temporal CSF varies with experimental conditions, but, in most cases, it exhibits a bandpass characteristic. This is illustrated by Figure 11 which shows adult temporal CSFs for a wide range of average illuminances. At most illuminances, sensitivity is greater at intermediate frequencies (5–20 Hz) than at low or high frequencies. Sensitivity, particularly at high frequencies, is higher for high illuminances than for low illuminances. The temporal CSFs in

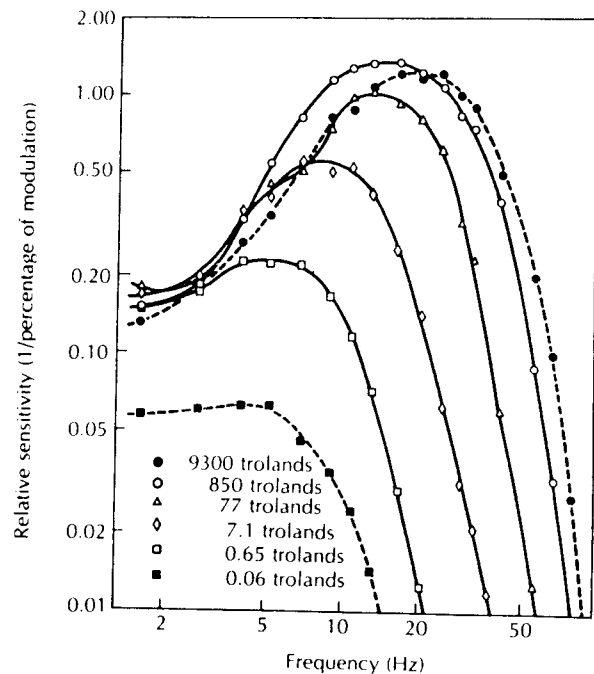


Figure 11. Adult temporal contrast sensitivity functions for different illuminances. Contrast sensitivity is plotted as a function of flicker frequency. (From Cornsweet, 1970.)

Figure 11 have proven useful for two reasons. First, they have revealed some important properties of the visual system. For example, the temporal delay of lateral inhibition is revealed by the low-frequency falloff of these functions (Kelly, 1971). Second, these temporal CSFs have been used successfully in conjunction with linear systems analysis to predict sensitivity to a wide variety of temporal stimuli. For example, DeLange (1958) showed that sensitivity to stimuli flickering in square-wave or rectangular-wave fashion could be predicted from these sinusoidal data. Cornsweet (1970) also demonstrated that stimulus durations for which Bloch's Law is valid are predictable from temporal CSFs. This means that temporal CSFs provide a useful general index of temporal processing for unpatterned stimuli. We consider temporal processing of patterned stimuli later on in our discussion of spatial-temporal interactions.

A. Development

We now turn to the development of temporal vision. First, we consider the development of flicker perception. Infant CFFs have been examined in both electrophysiological and behavioral studies. Even though behavioral studies are generally emphasized in this chapter, we will review both electrophysiological and behavioral work in this section and look for correlations among the two measures.

The most informative of the electrophysiological studies have used the electroretinogram (ERG), a measure of changes in electrical potential in the retina when it is exposed to light (for details, see Armington, 1974; Maurer, 1975). The ERG in adults exists at quite high flicker frequencies. Indeed, CFFs measured psychophysically and with the ERG correspond quite well so long as relatively intense stimuli are used (Dodt & Wadsten, 1954; Heck, 1957). In infants, the ERG has been used mostly to examine the response to single flashes, but a few studies have used flickering stimuli to measure the CFF. Heck and Zetterström (1958) measured CFFs in 1-day-old to 2-month-old infants. The stimulus field, which was large and unpatterned, was flashed on and off at various rates. Their results are shown in Figure 12. They found ERGs in response to a large flickering stimulus at all ages tested. CFF increased both with age and luminance. At the highest luminance, CFF improved from about 15 Hz at 1 day of age to 65 Hz, or nearly adultlike performance, by 2 months. CFF increased monotonically with luminance at all ages.

Horsten and Winkelman (1964) also used the ERG to investigate CFF at a number of ages. They too observed an increase of the CFF with increasing luminance for all ages tested. Surprisingly, however, no differences across age were reported. CFF at the highest luminance was about 70 Hz

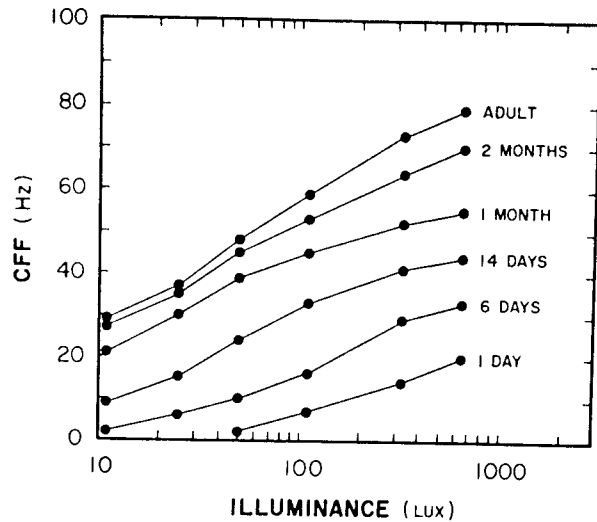


Figure 12. Critical flicker frequency as a function of flash illuminance as reported by Heck and Zetterström (1958). The highest flicker frequency to elicit a recordable ERG is plotted as a function of both flash illuminance and age. (From Banks, 1982.)

from birth to adulthood. The difference in their findings from those of Heck and Zetterström is most probably due to differences in recording technique, since the stimuli and subject populations appeared quite similar between the two experiments.

In summary, flicker ERG experiments disagree on the state of temporal resolution during the neonatal period but agree that adultlike resolution occurs by 2 months. Hence the retina is able to signal rapid temporal changes with adultlike precision by 2 months of age. This does not tell us, however, what the young visual system as a whole is capable of resolving.

The VEP has been used to investigate the temporal resolution of stages beyond the infant's retina (Ellingson, 1960; Vitova & Hrbek, 1972). The VEP, unfortunately, may not be a good index of temporal resolution. Regan (1972) has noted that the range of temporal frequencies that elicits a strong VEP in adults is different than the range of frequencies that the same adults perceive as flickering. In particular, the highest flicker frequency that elicits a VEP does not generally correspond with an adult's psychophysical CFF. Consequently, we will not review VEP work concerned with the development of temporal resolution.

Two behavioral studies of infant flicker perception have appeared. Nystrom, Hansson, and Marklund (1975) tested two age groups: 6-week-olds and 10-week-olds. They employed a preference paradigm. Two unpatterned, flickering stimuli were presented on every trial. In general, all possible pairings of 1, 5, 10, 20, and 100 Hz were presented to each infant.

The 100 Hz stimulus was assumed to appear nonflickering because it was well above adults' CFF. Nystrom et al. observed that both groups of infants preferentially fixated the higher of the two frequencies presented, with one notable exception: When the 100 Hz stimulus was presented, the other frequency was always preferentially fixated (the younger group also preferred 10 to 20 Hz). This one finding shows that infants as young as 6 weeks can demonstrate behaviorally the ability to detect flicker frequencies of at least 20 Hz. Unfortunately, frequencies between 20 and 100 Hz were not presented, so this study shows only that CFF is 20 Hz or higher at a young age.

Regal (1981) conducted a more systematic investigation in order to estimate CFF as a function of age. He tested 1-, 2-, and 3-month-olds cross-sectionally and longitudinally using the FPL technique. On each trial, two unpatterned, flickering stimuli were presented. One was always flickered at 75 Hz, a value higher than the adult CFF and, presumably, higher than the infant CFF, too. The observer judged the location of the lower frequency stimulus on each trial. The average luminance of the flickering stimuli and the background was 34 cd/m². The results are summarized in Figure 13. Correct responding rates of 75% were achieved on

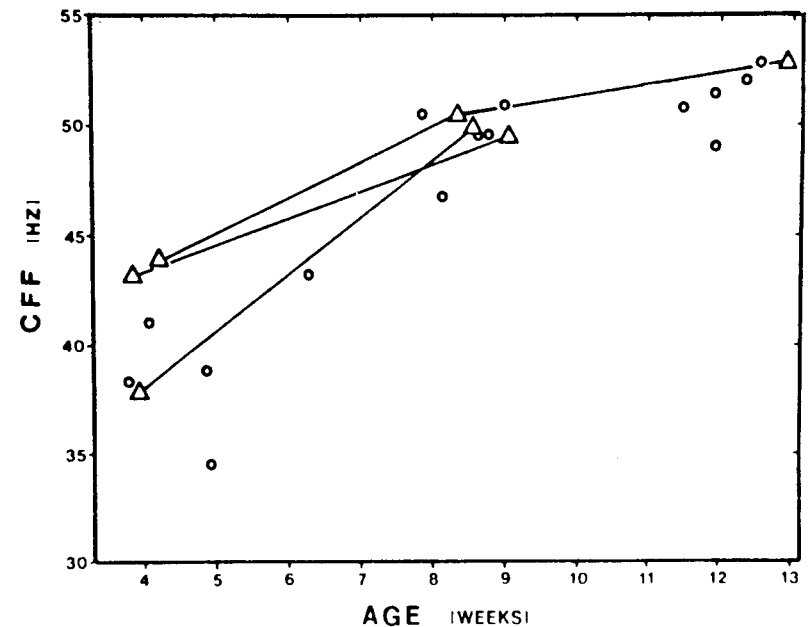


Figure 13. Critical flicker frequency as a function of age as reported by Regal (1981). The highest flicker frequency to elicit 75% correct responding in a behavioral paradigm is plotted. O, Cross-sectional data; Δ, longitudinal data. (From Regal, 1981.)

the average at 41 Hz for 1-month-olds, 50 Hz for 2-month-olds, 51 Hz for 3-month-olds, and about 53 Hz for adults. Consequently, Regal concluded that CFF is essentially adultlike by 2 months of age. This astonishing result is an example of good performance relative to an expected optimum. In this case, quite young infants' performance in a behavioral task approaches that of well-motivated, practiced adults. Consequently, such a finding suggests that FPL provides meaningful estimates of flicker thresholds. It also tends to bolster confidence that FPL is a sensitive index of sensory thresholds in general.

Regal (1981) also examined the influence of stimulus luminance on CFF. Specifically, he tested three 2-month-olds at two different luminances. CFF fell from 50 Hz at 34 cd/m² to 34 Hz at 3.4 cd/m². These values were quite similar to those obtained in adults under the same luminance conditions. This suggests that the relationship between stimulus luminance and temporal resolution may be adultlike by 2 months. Of course, this relationship would have to be examined over a wider range of luminances before this statement could be made with confidence.

Note that response convergence has been observed rather convincingly for these flicker experiments. Specifically, ERG recordings (which are presumably not affected by motivational factors) and behavioral investigations agree that adultlike temporal resolution is present by 2 months and perhaps that resolution changes with luminance in an adultlike fashion at that age. This observation, in conjunction with the finding of good performance relative to an optimum, implies that behavioral measures provide reasonably accurate estimates of temporal resolution early in life.

To date, no infant work has examined sensitivity to flicker rates well below the CFF. Of course, this could be accomplished by measuring the temporal CSF of infants. As in adult work, such measurements may be useful for revealing important properties of the visual system and for predicting sensitivity to a wide variety of temporal stimuli.

The temporal vision studies reviewed thus far have concerned infants' perception of very simple, unpatterned temporal stimuli. However, as we mentioned above, most of the temporal variation in visual stimulation is associated with motion of one pattern(s) with respect to another. Thus, in the remainder of this section we consider how spatial-temporal interactions affect perception in human infants.

Visual scientists have examined spatial-temporal interactions by combining sinewave grating and sinewave flicker stimuli. The resulting stimulus is a sinewave grating whose contrast flickers in counterphase fashion. Robson (1966) used such stimuli to demonstrate complex spatial-temporal interactions in adults. For high spatial frequencies, the greatest sensitivity

occurred at fairly low temporal frequencies. For low spatial frequencies, sensitivity was greatest at higher temporal frequencies.

Kelly (1979) has argued that counterphase flickering gratings represent an unnatural situation. In most everyday situations, pattern information of different spatial frequencies moves across the retina at a constant velocity rather than at a constant flicker rate. Accordingly, Kelly measured adults' contrast sensitivity to sinewave gratings drifting at fixed velocities. He found that one sensitivity profile fit the data for a wide range of velocities. He concluded from this and other results that the visual system is designed to respond to drifting rather than flickering pattern information.

Researchers have examined infants' processing of both simple spatial-temporal interactions and moving stimuli. Moskowitz and Sokol (1980), for example, measured VEPs from 2 to 6 months using counterphase flickering checkerboards. Check size and flicker rate were varied orthogonally to ascertain the character of spatial-temporal interactions. They found that the spatial response function depended on flicker rate. That is, at high flicker rates, VEP amplitude was greatest for large checks but, at low flicker rates, it was greatest for smaller checks. Moskowitz and Sokol also observed that this spatial-temporal interaction changed with age. Most notably, the largest VEP amplitude was observed for higher temporal and higher spatial frequencies with increasing age. Their data for 3- and 4-month-olds are both similar and dissimilar from their adult data. For large check sizes, the temporal frequency at which the maximum VEP response occurs is 3–5 Hz for both 3- to 4-month-olds and adults. For smaller check sizes, however, the peak response occurs at a flicker frequency of 5 to 6 Hz in 3- to 4-month-olds and 3 Hz in adults. Thus, the Moskowitz and Sokol results for large check sizes are congruent with the above-mentioned flicker studies using unpatterned stimuli. Smaller check sizes, however, reveal a dissimilarity between infant and adult temporal selectivity.

Caution is required before using such VEP data to infer what the development of spatial-temporal interactions may be for visual thresholds measured using other techniques. As Regan (1972) has argued for adult VEPs, the observed spatial-temporal interactions may be caused by the peculiar temporal summing properties of the VEP itself. For this reason, Karmel, Lester, McCarvill, Brown, and Hoffmann (1977) explored the relationship between visual preference and VEP for flickering patterns. In their preference experiment, they presented simultaneously two identical checkerboards flickering in an on-and-off fashion at different rates to 3-month-olds. They found the longest fixation durations for a flicker frequency of about 5 Hz. In the VEP experiment, only one checkerboard

was present at a time. The largest VEP amplitude was for 5-Hz flicker, suggesting a link between the VEP and visual preference. Unfortunately, check size in the VEP study was only about one-half the check size in the preference study, so the two experiments were not directly comparable.

Our knowledge of the development of motion perception *per se* is quite limited. Many researchers have reported that infants prefer to fixate moving as opposed to static patterns (e.g., Carpenter, 1974), but few have examined this in detail. Atkinson et al. (1977b) compared 1-, 2-, and 3-month-olds' contrast sensitivity and visual acuity for static and drifting sinewave gratings. The drifting gratings were moved so as to produce a local flicker rate of 3 Hz. Therefore, velocity and spatial frequency were inversely proportional. Thresholds under the two temporal conditions were estimated using FPL for a low spatial frequency grating (0.2 c/deg), a midfrequency grating (0.4 c/deg for 1-month-olds and 0.9 c/deg for 2- and 3-month-olds) and for the highest detectable frequency (the visual acuity cutoff). The results revealed higher sensitivity at all ages to drifting than to static gratings for low and intermediate spatial frequencies. In contrast, the acuity cutoffs for drifting and static gratings were similar. The adults yielded qualitatively similar results: drift enhanced sensitivity to 0.2 to 0.9 c/deg but did not to 4.8 c/deg, a spatial frequency similar to the acuity cutoffs of 2- and 3-month-olds.

It is tempting to conclude that movement enhances the visibility of coarse but not fine patterns in infants. Unfortunately, these data may not be conclusive on this point. Since Atkinson et al. used a constant local flicker rate of 3 Hz to set the drift rate of their gratings, the *velocity* of drift was quite low for higher spatial frequencies, like those at the acuity cutoff. Consequently, we do not know if higher velocities would have yielded higher sensitivities. Future research in this area might follow Kelly's (1979) observation that measurements of contrast sensitivity at a constant local flicker rate represent an unnatural situation because different spatial frequencies are tested at different velocities. In the real world, all of the spatial frequency components of a moving object move at the same velocity. Thus, we might learn more about basic elements of motion perception if velocity, rather than flicker rate, were held constant in such experiments.

B. Summary

The investigation of the development of temporal vision has just begun but already interesting observations have appeared. For example, temporal resolution, unlike spatial resolution, appears to be essentially mature by 2 or 3 months of life. Preliminary evidence, however, suggests that

spatial-temporal interactions are not mature by this age. This latter finding is not surprising given the deficits 2- and 3-month-olds exhibit in pattern vision *per se*. The development of motion perception is an important topic that warrants more experimental attention.

VII. CONCLUSIONS

We have discussed a wide variety of topics in this chapter. We do not intend to provide a comprehensive summary here. Rather, two points are made that are based on much of the foregoing material. One point concerns the meaningfulness of psychophysical data in infants and the other concerns the relationship between infant and adult visual capabilities.

Despite the obvious virtues of psychophysical approaches to the study of visual development, we argued in the psychophysics section above that threshold estimates relying on behavioral techniques are ambiguous. The reason is that poor performance (negative results) is weak evidence that a stimulus is undetectable and threshold estimation requires information about which stimulus levels are undetectable. The resulting ambiguity hampers not only the interpretation of data at one age but also the interpretation of age effects. These are serious problems that must be addressed in infant psychophysical work.

We presented four verification techniques that might aid the interpretation of infant psychophysical data. They were: (1) the use of thresholds as relative rather than absolute information, (2) stimulus convergence, (3) response convergence, and (4) good performance relative to some known optimal performance. We described how each of these techniques has been used to assess how well infant psychophysical data reflect the behavior of sensory mechanisms. In many cases, use of the techniques yielded confirmatory evidence. For example, response convergence and stimulus convergence appeared to obtain in contrast sensitivity measurements. A cautious reader, however, may have found the arguments concerning response and stimulus convergence somewhat circular. A hypothetical example illustrates this potential circularity. Suppose we measure a sensitivity function using a technique (say FPL) whose validity is unknown. If we measure the same function using another technique (say VEP) whose validity is also unknown, what can we hope to achieve? In other words, why should similar results from the two techniques increase our confidence in the techniques unless we already know that one of them is valid? We believe that the presence of response convergence between two previously uncertain techniques tends to substantiate the validity of both techniques. The reasoning is as follows. If the two techniques are

quite different at the output end (which FPL and VEP are), then one would expect that nonsensory variables such as motivation would influence the techniques quite differently. When similar rather than dissimilar findings emerge, the most plausible interpretation is that both techniques are measuring sensory rather than nonsensory effects. It also implies that one's model of how the two techniques are related (e.g., do they tap the same mechanisms?) must be reasonably valid. A similar line of reasoning applies to stimulus convergence. Any time such linkages are found, all components of the linkage become more believable.

The second point we describe here concerns the relationship between the development of pattern vision and temporal vision. We have reviewed a number of psychophysical findings concerning these visual capabilities. By all accounts, pattern vision capabilities early in life are quite poor by adult standards. Visual acuity, for example, is roughly 45-fold lower in 1-month-olds than in adults. Furthermore, acuity continues to improve until at least 6 months of age. In contrast, temporal resolution is very good in 1-month-olds and essentially adultlike one month later. The conjunction of poor spatial resolution and good temporal resolution that exists during the first several months is analogous to what is observed in the peripheral retina of the adult visual system (Banks, 1982). Specifically, at retinal eccentricities of 20 to 30°, adults' minimum separable acuity is about 2 c/deg, yet their temporal resolution (CFF) is about the same as for the fovea. This analogy between infant vision and adult peripheral vision, if correct, may mean that postnatal visual development is most marked for the fovea and parafovea. Further study is required, however, to assess the validity of this analogy.

ACKNOWLEDGMENTS

Preparation of this chapter was supported by NIH Research Grant HD-12572 and by NIMH Research Scientist Development Award MH-00318 to M.S.B. The authors thank Bill Geisler for comments on the section on psychophysical techniques and Dick Aslin for general editorial comments.

REFERENCES

- Abramov, I., Gordon, J., Hendrickson, A., Hainline, L., Dobson, V., & LaBossiere, E. (1982). The retina of the newborn human infant. *Science*, *217*, 265–267.
- Albrecht, D. G., DeValois, R. L., & Thorell, L. G. (1980). Visual cortical neurons: Are bars or gratings the optimal stimuli? *Science*, *207*, 88–90.
- Allen, J. (1978). *Visual acuity development in human infants up to 6 months of age*. Unpublished doctoral dissertation, University of Washington, Seattle.
- Armington, J. C. (1974). *The electroretinogram*. New York: Academic Press.
- Atkinson, J., & Braddick, O. (1982). Sensory and perceptual capacities of the neonate. In P. Stratton (Ed.), *Psychobiology of the human newborn*. New York: Wiley.
- Atkinson, J., Braddick, O., & Moar, K. (1977a). Development of contrast sensitivity over the first 3 months of life in the human infant. *Vision Research*, *17*, 1037–1044.
- Atkinson, J., Braddick, O., & Moar, K. (1977b). Contrast sensitivity of the human infant for moving and static patterns. *Vision Research*, *17*, 1045–1047.
- Atkinson, J., Braddick, O., & Moar, K. (1977c). Infants' detection of image defocus. *Vision Research*, *17*, 1125–1126.
- Atkinson, J., Pimm-Smith, E., Evans, C., & Braddick, O. (1983). The effects of screen size and eccentricity on acuity in infants using preferential looking. *Vision Research*, *23*, 1479–1483.
- Awaya, S., Miyake, Y., Amaizumi, Y., Shiose, Y., Kanda, T., & Komuro, K. (1973). Amblyopia in man suggestive of stimulus deprivation amblyopia. *Japanese Journal of Ophthalmology*, *17*, 69–82.
- Banks, M. S. (1980). The development of visual accommodation during early infancy. *Child Development*, *51*, 646–666.
- Banks, M. S. (1982). The development of spatial and temporal contrast sensitivity. *Current Eye Research*, *2*, 191–198.
- Banks, M. S., Aslin, R. N., & Letson, R. D. (1975). Sensitive period for the development of human binocular vision. *Science*, *190*, 675–677.
- Banks, M. S., & Ginsburg, A. P. (1985). Early visual preferences: A review and new theoretical treatment. In H. W. Reese (Ed.), *Advances in child development and behavior*. New York: Academic Press.
- Banks, M. S., & Salapatek, P. (1978). Acuity and contrast sensitivity in 1-, 2-, and 3-month-old human infants. *Investigative Ophthalmology & Visual Science*, *17*, 361–365.
- Banks, M. S., & Salapatek, P. (1981). Infant pattern vision: A new approach based on the contrast sensitivity function. *Journal of Experimental Child Psychology*, *31*, 1–45.
- Banks, M. S., & Stephens, B. R. (1982). The contrast sensitivity of human infants to gratings differing in duty cycle. *Vision Research*, *22*, 739–744.
- Banks, M. S., Stephens, B. R., & Hartmann, E. E. (1985). The development of basic mechanisms of pattern vision. Spatial frequency channels. *Journal of Experimental Child Psychology*, *40*, 501–527.
- Barlow, H. B. (1972). Dark and light adaptation: Psychophysics. In D. Jameson & L. Hurvich (Eds.), *Handbook of sensory physiology: Vol. 7, Pt. 4. Visual psychophysics*. Berlin & New York: Springer-Verlag.
- Barlow, H. B. (1979). Three theories of cortical function. In R. D. Freeman (Ed.), *Developmental neurobiology of vision*. New York: Plenum.
- Barlow, H. B., Fitzhugh, R., & Kuffler, S. W. (1957). Dark adaptation, absolute threshold and Purkinje shift in single units of the cat's retina. *Journal of Physiology (London)*, *137*, 327–337.
- Berry, R. N. (1948). Quantitative relations among vernier, real depth, and stereoscopic depth acuities. *Journal of Experimental Psychology*, *38*, 708–721.
- Blakemore, C., & Sutton, P. (1969). Size adaptation: A new aftereffect. *Science*, *166*, 245–247.
- Blakemore, C., & Vital-Durand, F. (1980). Development of the neural basis of visual acuity in monkeys. Speculation on the origin of deprivation amblyopia. *Transactions of the Ophthalmological Societies of the United Kingdom*, *99*, 363–368.
- Bodis-Wollner, I. (1972). Visual acuity and contrast sensitivity in patients with cerebral lesions. *Science*, *178*, 769–771.
- Boothe, R. G. (1981). Development of spatial vision in infant macaque monkeys under conditions of normal and abnormal visual experience. In R. N. Aslin, J. R. Alberts, &

- M. R. Petersen (Eds.), *The development of perception: Psychobiological perspectives: Vol. 2. The visual system*. New York: Academic Press.
- Boothe, R. G., Williams, R. A., Kiorpes, L., & Teller, D. Y. (1980). Development of contrast sensitivity in infant *Macaca nemestrina* monkeys. *Science*, *208*, 1290–1292.
- Bornstein, M. H., Kessen, W., & Weiskopf, S. (1976). Color vision and hue categorization in young human infants. *Journal of Experimental Psychology: Human Perception and Performance*, *2*, 115–129.
- Bowe-Anders, C., Miller, R. F., & Dacheux, R. (1975). Developmental characteristics of the receptive organization in the isolated retina-eyecup of the rabbit. *Brain Research*, *87*, 61–65.
- Boycott, B. B., & Dowling, J. E. (1969). Organization of primate retina: Light microscopy. *Philosophical Transactions of the Royal Society of London, Series B*, *255*, 109–184.
- Braddick, O., Campbell, F. W., & Atkinson, J. (1978). Channels in vision: Basic aspects. In R. Held, H. W. Leibowitz, & H. L. Teuber (Eds.), *Handbook of sensory physiology: Vol. 8. Perception*. Berlin & New York: Springer-Verlag.
- Brown, A. (1984). *Scotopic field sensitivity in 2-month-old infants*. Paper presented at the Association for Research in Vision and Ophthalmology, Sarasota.
- Campbell, F. W., Carpenter, R. H. S., & Levinson, J. Z. (1969). Visibility of aperiodic patterns compared with that of sinusoidal gratings. *Journal of Physiology (London)*, *204*, 283–298.
- Campbell, F. W., & Green, D. G. (1965). Optical and retinal factors affecting visual resolution. *Journal of Physiology (London)*, *181*, 576–593.
- Campbell, F. W., & Gregory, A. H. (1960). Effect of size of pupil on visual acuity. *Nature*, *140*, 1121–1123.
- Campbell, F. W., & Gubisch, R. W. (1966). Optical quality of the human eye. *Journal of Physiology (London)*, *186*, 558–578.
- Campbell, F. W., & Maffei, L. (1970). Electrophysiological evidence for the existence of orientation and size detectors in the human visual system. *Journal of Physiology (London)*, *207*, 635–652.
- Cannon, M. W., Jr. (1983). Contrast sensitivity: Psychophysical and evoked potential methods compared. *Vision Research*, *23*, 87–95.
- Carpenter, G. C. (1974). Visual regard of moving and stationary faces in early infancy. *Merrill-Palmer Quarterly*, *20*, 181–194.
- Cornsweet, T. N. (1970). *Visual perception*. New York: Academic Press.
- Crick, F. H. C., Marr, D. C., & Poggio, T. (1981). An information-processing approach to understanding the visual cortex. In F. O. Schmitt, F. G. Worden, G. Adelman, & S. G. Dennis (Eds.), *The organization of the cerebral cortex*. Cambridge MA: MIT Press.
- Dannemiller, J. L. (1983). *The development of light adaptation in human infants*. Doctoral dissertation, University of Texas, Austin.
- Dannemiller, J. L. (1985). The early phase of dark adaptation in human infants. *Vision Research*, *25*, 207–212.
- Dannemiller, J. L., & Banks, M. S. (1983). The development of light adaptation in the human infant. *Vision Research*, *23*, 599–609.
- Dayton, G. O., Jr., Jones, M. H., Aiu, P., Rawson, R. H., Steele, B., & Rose, M. (1964). Developmental study of coordinated eye movements in the human infant. I. Visual acuity in the newborn human: A study based on induced optokinetic nystagmus recorded by electrooculography. *Archives of Ophthalmology*, *71*, 865–870.
- DeLange, H. (1958). Research into the dynamic nature of the human fovea-cortex systems with intermittent and modulated light. I. Attenuation characteristics with white and colored light. *Journal of the Optical Society of America*, *48*, 777–784.

- Derrington, A. M., & Fuchs, A. F. (1979). Spatial and temporal properties of X and Y cells in the cat lateral geniculate nucleus. *Journal of Physiology (London)*, *293*, 347–364.
- Derrington, A. M., & Fuchs, A. F. (1981). The development of spatial-frequency selectivity in kitten striate cortex. *Journal of Physiology (London)*, *316*, 1–10.
- DeValois, R. L., Morgan, H. C., & Snodderly, D. M. (1974). Psychophysical studies of monkey vision. III. Spatial luminance contrast sensitivity tests of macaque and human observers. *Vision Research*, *14*, 75–81.
- Dobson, V., Salem, D., & Carson, J. B. (1983). Visual acuity in infants—The effect of variations in stimulus luminance within the photopic range. *Investigative Ophthalmology & Visual Science*, *24*, 519–522.
- Dobson, V., & Teller, D. Y. (1978). Visual acuity in human infants: A review and comparison of behavioral and electrophysiological studies. *Vision Research*, *18*, 1469–1483.
- Dobson, V., Teller, D. Y., & Belgum, J. (1978). Visual acuity in human infants assessed with stationary stripes and phase-alternated checkerboards. *Vision Research*, *18*, 1233–1238.
- Doty, E., & Wadensten, L. (1954). The use of flicker electroretinography in the human eye. *Acta Ophthalmologica*, *32*, 163–180.
- Dodwell, P. C. (1970). *Visual pattern recognition*. New York: Holt.
- Dowling, J. E., & Ripps, H. (1971). S-potentials in the Skate retina. *Journal of General Physiology*, *58*, 163–189.
- Ellingson, R. J. (1960). Cortical electrical responses to visual stimulation in the human infant. *Electroencephalography and Clinical Neurophysiology*, *12*, 663–677.
- Enoch, J. M., & Rabinowicz, I. M. (1976). Early surgery and visual correction of an infant born with unilateral eye lens opacity. *Documenta Ophthalmologica*, *41*, 371–382.
- Enroth-Cugell, C., & Robson, J. G. (1966). The contrast sensitivity of retinal ganglion cells of the cat. *Journal of Physiology (London)*, *187*, 517–552.
- Fantz, R. L. (1958). Pattern vision in young infants. *Psychological Record*, *8*, 43–47.
- Fantz, R. L. (1965). Visual perception from birth as shown by pattern selectivity. *Annals of the New York Academy of Sciences*, *118*, 793–814.
- Fantz, R. L., Fagan, J. F., III, & Miranda, S. B. (1975). Early visual selectivity as a function of pattern variables, previous exposure, age from birth and conception, and expected cognitive deficit. In L. B. Cohen & P. Salapatek (Eds.), *Infant perception: From sensation to cognition: Vol. 1. Basic visual processes*. New York: Academic Press.
- Fantz, R. L., Ord, J. M., & Udelf, M. S. (1962). Maturation of pattern vision in infants during the first six months. *Journal of Comparative Physiological Psychology*, *55*, 907–917.
- Finney, D. J. (1971). *Probit analysis*. London & New York: Cambridge University Press.
- Fiorentini, A., Pirchio, M., & Spinelli, D. (1980). Scotopic contrast sensitivity in infants evaluated by evoked potentials. *Investigative Ophthalmology & Visual Science*, *19*, 950–955.
- Freeman, R. D., Mitchell, D. E., & Millodot, M. A. (1972). Neural effect of partial visual deprivation in humans. *Science*, *175*, 1384–1386.
- Gaskill, J. D. (1978). *Linear systems, Fourier transforms, and optics*. New York: Wiley.
- Gayl, I. E., Roberts, J. O., & Werner, J. S. (1983). Linear systems analysis of infant visual pattern preferences. *Journal of Experimental Child Psychology*, *35*, 30–45.
- Geisler, W. S. (1984). Physical limits of acuity and hyperacuity. *Journal of the Optical Society of America A*, *1*, 775–782.
- Georgeson, M. A., & Sullivan, G. D. (1975). Contrast constancy: Deblurring in human vision by spatial frequency channels. *Journal of Physiology (London)*, *252*, 627–656.
- Ginsburg, A. P. (1978). *Visual information processing based on spatial filters constrained by biological data*. Ph.D. dissertation, University of Cambridge.

- Goodman, J. W. (1965). *Introduction to Fourier optics*. New York: McGraw-Hill.
- Gorman, J. J., Cogan, D. G., & Gellis, S. S. (1957). An apparatus for grading the visual acuity of infants on the basis of optokinetic nystagmus. *Pediatrics*, *19*, 1088–1092.
- Gorman, J. J., Cogan, D. G., & Gellis, S. S. (1959). A device for testing visual acuity in infants. *Sight-Saving Review*, *29*, 80–84.
- Green, D. G. (1970). Regional variations in the visual acuity for interference fringes on the retina. *Journal of Physiology (London)*, *207*, 351–356.
- Green, D. G., Powers, M. K., & Banks, M. S. (1980). Depth of focus, eye size, and visual acuity. *Vision Research*, *20*, 827–835.
- Gwiazda, J., Brill, S., Mohindra, I., & Held, R. (1978). Infant visual acuity and its meridional variation. *Vision Research*, *18*, 1557–1564.
- Hamasaki, D. I., & Sutija, V. G. (1979). Development of X- and Y-cells in kittens. *Experimental Brain Research*, *35*, 9–23.
- Hamer, R., & Schneck, M. E. (1984). Spatial summation in dark-adapted human infants. *Vision Research*, *24*, 77–85.
- Hansen, R. M., & Fulton, A. B. (1981). Behavioral measurement of background adaptation in infants. *Investigative Ophthalmology & Visual Science*, *21*, 625–629.
- Hansen, R. H., Fulton, A., Leitzman, D., & Harris, S. (1984). *Pupillographic assessment of rhodopsin regeneration in human infants*. Paper presented at the Association for Research in Vision and Ophthalmology, Sarasota.
- Harris, L., Atkinson, J., & Braddick, O. (1976). Visual contrast sensitivity of a 6-month-old infant measured by the evoked potential. *Nature (London)*, *264*, 570–571.
- Harter, M. R., Deaton, F. K., & Odom, J. V. (1977a). Maturation of evoked potentials and visual preference in 6–45 day old infants: Effects of check size, visual acuity, and refractive error. *Electroencephalography and Clinical Neurophysiology*, *42*, 595–607.
- Harter, M. R., Deaton, F. K., & Odom, J. V. (1977b). Pattern visual evoked potentials in infants. In J. E. Desmedt (Ed.), *Visual evoked potentials in man: New developments*. London & New York: Oxford University Press (Clarendon).
- Harter, M. R., & Suitt, C. D. (1970). Visually-evoked cortical responses and pattern vision in the infant: A longitudinal study. *Psychonomic Science*, *18*, 235–237.
- Hecht, S., & Mintz, E. U. (1939). The visibility of single lines at various illuminations and the basis of visual resolution. *Journal of Genetic Physiology*, *22*, 593–612.
- Hecht, S., & Schlaer, S. (1936). Intermittent stimulation by light. V. The relation between intensity and critical frequency for different parts of the spectrum. *Journal of General Physiology*, *19*, 965–979.
- Hecht, S., Schlaer, S., & Pirenne, M. H. (1942). Energy, quanta, and vision. *Journal of General Physiology*, *25*, 819–840.
- Hecht, S., & Verriep, D. C. (1933). The influence of intensity, color and retinal location on the fusion frequency of intermittent illumination. *Proceedings of the National Academy of Sciences of the U.S.A.*, *19*, 522–535.
- Heck, J. (1957). The flicker electroretinogram of the human eye. *Acta Physiologica Scandinavica*, *39*, 158–166.
- Heck, J., & Zetterström, B. (1958). Analyse des photopischen Flimmerelektroretinogramms bei neugeborenen. *Ophthalmologica*, *135*, 205–210.
- Hendrickson, A., & Kupfer, C. (1976). The histogenesis of the fovea in the macaque monkey. *Investigative Ophthalmology*, *15*, 746–756.
- Hendrickson, A., & Yuodelis, C. (1984). The morphological development of the human fovea. *Ophthalmology*, *91*, 603–612.
- Hess, R. F., & Bradley, A. (1980). Contrast perception above threshold is only minimally impaired in human amblyopia. *Nature (London)*, *287*, 463–464.
- Horsten, G. P., & Winkelman, J. E. (1962). Electrical activity of the retina in relation to histological differentiation in infants born prematurely and at full term. *Vision Research*, *2*, 269–276.
- Horsten, G. P. M., & Winkelman, J. E. (1964). Electro-retinographic critical fusion frequency of the retina in relation to the histological development in man and animals. *Ophthalmologica*, *18*, 515–521.
- Hubel, D. H., & Wiesel, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *Journal of Physiology (London)*, *160*, 106–154.
- Hubel, D. H., & Wiesel, T. N. (1965). Binocular interaction in striate cortex of kittens reared with artificial squint. *Journal of Neurophysiology*, *28*, 1041–1059.
- Hubel, D. H., & Wiesel, T. N. (1968). Receptive fields and functional architecture of monkey striate cortex. *Journal of Physiology (London)*, *195*, 215–243.
- Karmel, B. Z., Lester, M. L., McCarvill, S. L., Brown, P., & Hoffmann, M. J. (1977). Correlation of infants' brain and behavior response to temporal changes in visual stimulation. *Psychophysiology*, *14*, 134–142.
- Kelly, D. H. (1961). Flicker fusion and harmonic analysis. *Journal of the Optical Society of America*, *51*, 917–918.
- Kelly, D. H. (1971). Theory of flicker and transient responses. I. Uniform fields. *Journal of the Optical Society of America*, *61*, 537–546.
- Kelly, D. H. (1972). Flicker. In D. Jameson & L. M. Hurvich (Eds.), *Handbook of sensory physiology: Vol. 7, Pt. 4. Visual psychophysics*. Berlin & New York: Springer-Verlag.
- Kelly, D. H. (1979). Motion and vision. Stabilized spatio-temporal threshold surface. *Journal of the Optical Society of America*, *69*, 1340–1349.
- Kessen, W., Haith, M. M., & Salapatek, P. H. (1970). Human infancy: A bibliography and guide. In P. H. Mussen (Ed.), *Carmichael's manual of child psychology* (3rd ed.,). Vol. 1, New York: Wiley.
- Larsen, J. S. (1971). The sagittal growth of the eye. IV. Ultrasonic measurement of the axial length of the eye from birth to puberty. *Acta Ophthalmologica*, *49*, 873–886.
- Leibowitz, H. W., Shupert-Rodemer, C., & Dichgans, J. (1979). The independence of dynamic spatial orientation from luminance and refractive error. *Perception and Psychophysics*, *25*, 75–79.
- Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America*, *49*, 467–477.
- Lewis, T. L., Maurer, D., & Kay, D. (1978). Newborns' central vision: Whole or hole? *Journal of Experimental Child Psychology*, *26*, 193–203.
- Mandelbaum, J., & Sloan, L. L. (1947). Peripheral visual acuity: With special reference to scotopic illumination. *American Journal of Ophthalmology*, *30*, 581–588.
- Mann, I. C. (1964). *The development of the human eye*. London: British Medical Association.
- Manny, R. E., & Klein, S. A. (1985). A three-alternative tracking paradigm to measure vernier acuity of older infants. *Vision Research*, *25*, 1245–1252.
- Marg, E., Freeman, D. N., Peltzman, P., & Goldstein, P. J. (1976). Visual acuity development in human infants: Evoked potential measurements. *Investigative Ophthalmology*, *15*, 150–153.
- Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. San Francisco, CA: Freeman.
- Maurer, D. (1975). Infant visual perception: Methods of study. In L. B. Cohen & P. Salapatek (Eds.), *Infant perception: From sensation to cognition: Vol. 1. Basic visual processes*. New York: Academic Press.
- McKee, S. P., Klein, S. A., & Teller, D. Y. (1985). Statistical properties of forced-choice

- psychometric functions: Implications of probit analysis. *Perception and Psychophysics* 37.
- Milewski, A. E. (1976). Infants' discrimination of internal and external pattern elements. *Journal of Experimental Child Psychology*, 22, 229-246.
- Milewski, A. E. (1978). Young infants' visual processing of internal and adjacent shapes. *Infant Behavior and Development*, 1, 359-371.
- Mitchell, D. E., Giffin, F., Wilkinson, F., Anderson, P., & Smith, M. L. (1976). Visual resolution in young kittens. *Vision Research*, 16, 363-366.
- Moskowitz, A., & Sokol, S. (1980). Spatial and temporal interaction of pattern-evoked cortical potentials in human infants. *Vision Research*, 20, 699-707.
- Naka, K., & Rushton, W. (1966). S-potentials from luminosity units in the retina of fish (Cyprinidae). *Journal of Physiology (London)*, 185, 587-599.
- Norcia, A. M., & Tyler, C. W. (1985). Spatial frequency sweep VEP: Visual acuity during the first year of life. *Vision Research* 25, 1399-1408.
- Nystrom, M., Hansson, M. B., & Marklund, K. (1975). Infant preference for intermittent light. *Psychological Research Bulletin, Lund U.*, 15, 1-11.
- Pass, A. F., & Levi, D. M. (1982). Spatial processing of complex stimuli in the amblyopic visual system. *Investigative Ophthalmology & Visual Science*, 23, 780-786.
- Pearson, R. M. (1966). The objective determination of vision and visual acuity. *British Journal of Physiological Optics*, 23, 107-127.
- Peebles, D. R., & Teller, D. Y. (1978). White-adapted photopic spectral sensitivity in human infants. *Vision Research*, 18, 49-59.
- Pirchio, M., Spinelli, D., Fiorentini, A., & Maffei, L. (1978). Infant contrast sensitivity evaluated by evoked potentials. *Brain Research*, 141, 179-184.
- Pollack, I. (1968). Methodological determination of the PEST (Parametric Estimation by Sequential Testing) procedure. *Perception and Psychophysics*, 3, 285-289.
- Pollen, D. A., Lee, J. R., & Taylor, J. H. (1971). How does the striate cortex begin the reconstruction of the visual world? *Science*, 173, 74-77.
- Powers, M. K., Schneck, M., & Teller, D. Y. (1981). Spectral sensitivity of human infants at absolute visual threshold. *Vision Research*, 21, 1005-1016.
- Regal, D. M. (1981). Development of critical flicker frequency in human infants. *Vision Research*, 21, 549-555.
- Regan, D. (1972). *Evoked potentials in psychology, sensory physiology and clinical medicine*. London: Chapman & Hall.
- Regan, D. (1978). Assessment of visual acuity by evoked potential recording: Ambiguity caused by temporal dependence of spatial frequency selectivity. *Vision Research*, 18, 439-443.
- Regan, D., & Richards, W. A. (1971). Independence of evoked potentials and apparent size. *Vision Research*, 11, 679-684.
- Reinecke, R., & Cogan, D. (1958). Standardization of objective visual acuity measurements. *Archives of Ophthalmology*, 60, 418-421.
- Riggs, L. A. (1965). Visual acuity. In C. H. Graham (Ed.), *Vision and visual perception*. New York: Wiley.
- Ripps, H., & Weale, R. A. (1969). Visual adaptation. In H. Davson (Ed.), *The eye* (Vol. 2). New York: Academic Press.
- Robson, J. G. (1966). Spatial and temporal contrast-sensitivity functions of the visual system. *Journal of the Optical Society of America*, 56, 1141-1142.
- Rose, R. M., Teller, D. Y., & Rendleman, P. (1970). Statistical properties of staircase estimates. *Perception and Psychophysics*, 8, 199-204.
- Roufs, J. A. J. (1972). Dynamic properties of vision. I. Experimental relationships between flicker and flash thresholds. *Vision Research*, 12, 261-278.
- Ruff, H. A., & Birch, H. G. (1974). Infant visual fixation: The effect of concentricity,

- curvilinearity, and the number of directions. *Journal of Experimental Child Psychology*, 17, 460-473.
- Rusoff, A. C., & Dubin, M. W. (1977). Development of receptive-field properties of retinal ganglion cells in kittens. *Journal of Neurophysiology*, 40, 1188-1198.
- Salapatek, P., & Banks, M. S. (1978). Infant sensory assessment: Vision. In F. D. Minifie & L. L. Lloyd (Eds.), *Communicative and cognitive abilities—Early behavioral assessment*. Baltimore, MD: University Park Press.
- Salapatek, P., Bechtold, A. G., & Bushnell, E. W. (1976). Infant visual acuity as a function of viewing distance. *Child Development*, 47, 860-863.
- Schor, C., & Narayan, V. (1981). The influence of field size upon the spatial frequency response of optokinetic nystagmus. *Vision Research*, 21, 985-994.
- Sekuler, R. (1975). Visual motion perception. In E. C. Carterette & M. P. Friedman (Eds.), *Handbook of perception: Vol. 5. Seeing*. New York: Academic Press.
- Shimojo, S., Birch, E. E., Gwiazda, J., & Held, R. (1984). Development of vernier acuity in infants. *Vision Research* 24, 721-728.
- Shlaer, S. (1937). The relation between visual acuity and illumination. *Journal of General Physiology*, 21, 165-188.
- Snyder, A. W. (1979). The physics of vision in compound eyes. In H. Autrum (Ed.), *Handbook of sensory physiology: Vol. 7, Pt. 6A. Vision in invertebrates*. Berlin & New York: Springer-Verlag.
- Sokol, S. (1978). Measurement of infant acuity from pattern reversal evoked potentials. *Vision Research*, 18, 33-40.
- Sokol, S., & Dobson, V. (1976). Pattern reversal visually evoked potentials in infants. *Investigative Ophthalmology*, 15, 58-62.
- Sokol, S., Augliere, R., & Moskowitz, A. (1986). *Preferential looking estimates of infant visual acuity for stationary and phase-alternating gratings*. Paper presented at the meeting of the Association for Research in Vision and Ophthalmology, Sarasota.
- Stephens, B. R., & Banks, M. S. (1985). The development of contrast constancy. *Journal of Experimental Child Psychology*, 40, 528-547.
- Teller, D. Y. (1979). The forced-choice preferential looking procedure: A psychophysical technique for use with human infants. *Infant Behavior and Development*, 2, 135-153.
- Teller, D. Y., Morse, R., Borton, R., & Regal, D. (1974). Visual acuity for vertical and diagonal gratings in human infants. *Vision Research*, 14, 1433-1439.
- van Meeteren, A. (1967). *Spatial sinewave response of the visual system* (Institute for Perception TNO Rep. No. IZF-1966-7).
- Van Nes, F. L., & Bouman, M. A. (1967). Spatial modulation transfer in the human eye. *Journal of the Optical Society of America*, 57, 401-406.
- Vitova, Z., & Hrbek, A. (1972). Developmental study on the responsiveness of the human brain to flicker stimulation. *Developmental Medicine and Child Neurology*, 14, 476-486.
- Vos, J. J., Lazet, A., & Bouman, M. A. (1956). Visual contrast thresholds in practical problems. *Journal of the Optical Society of America*, 46, 1065-1068.
- Westheimer, G. (1979). The spatial sense of the eye. *Investigative Ophthalmology & Visual Science*, 18, 893-912.
- Westheimer, G. (1982). The spatial grain of the perifoveal visual field. *Vision Research*, 22, 157-162.
- Wetherill, G. B., & Levitt, H. (1965). Sequential estimation of points on a psychometric function. *British Journal of Mathematical and Statistical Psychology*, 18, 1-10.
- Wiesel, T. N., & Hubel, D. H. (1965). Comparison of the effects of unilateral and bilateral eye closure on cortical unit responses in kittens. *Journal of Neurophysiology*, 28, 1029-1040.

- Williams, D. R. (1985). Aliasing in human foveal vision. *Vision Research* 25, 195-2.
- Yonas, A., & Pick, H. L. (1975). An approach to the study of infant space perception. In L. B. Cohen & P. Salapatek (Eds.), *Infant perception: From sensation to cognition: Vol. 2. Perception of space, speech, and sound*. New York: Academic Press.
- Yuodelis, C. & Hendrickson, A. (in press). A qualitative and quantitative analysis of the human fovea during development. *Vision Research*.