YOUNG INFANTS' BINOCULAR INTERACTION: EVOKED POTENTIAL MEASURES

by

James Vernon Odom

A Dissertation Submitted to
the Faculty of the Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Greensboro
1978

Approved by

M. Russell Harter
Dissertation Adviser

APPROVAL PAGE

This dissertation has been approved by the following committee of the Faculty of the Graduate School at the University of North Carolina at Greensboro.

Dissertation Adviser M. Russell Harter

Committee Members Walter L. Salingi

J. Allen Watson

Oct 20, 1978
Date of Acceptance by Committee

Oct 20, 1978
Date of Final Oral Examination

ABSTRACT

ODOM, JAMES VERNON. Young Infants' Binocular Interaction: Evoked Potential Measures. (1978)
Directed by: Dr. M. Russell Harter. Pp. 124.

The primary purpose of the dissertation was to determine the presence or absence of binocular interaction in young infants. The anaglyphic (color separation) method of splitting the visual field was employed to present a stimulus continuously to the right eye (continuous stimulus) while another stimulus was flashed (flashed stimulus) to the left eye with neither eye seeing the stimulus presented to the other. The continuous stimuli were darkness, a diffuse light (equal in space-averaged luminance to that of the patterns), a pattern of 20' dots and a pattern of 80' dots. The flashed stimuli were diffuse light, a pattern of 20' dots and a pattern of 80' dots.

The dependent measure was the electrical voltage changes recorded over the visual cortex (Oz referenced to the right ear) during the first 500 milliseconds following the flashed stimulus. Any changes in the visually evoked potential related to variations in the continuous stimuli were interpreted as indications of binocular interaction.

Data from the experiments were analyzed to examine intraocular and interocular effects. The presence of three suppression phenomena were examined: suppression by

continuous diffuse light relative to continuous darkness (luminance suppression); suppression by patterns relative to diffuse light, the magnitude of suppression increasing as pattern element size increases (pattern suppression); and suppression to patterns of a given element size by patterns with the same sized elements (size-specific suppression).

Prior to the present set of studies, neither the anaglyphic method nor redundant dot patterns had been used to study interocular suppression. Therefore, a first experiment with adults was necessary to demonstrate the feasibility of using the present procedures. Using eight adult subjects, all three forms of interocular suppression were demonstrated. A unique contribution of the first experiment was the demonstration that binocular size channels are not coded within binocular color channels, otherwise size-specific interocular suppression would not have been observed.

In the second experiment, three infants were tested. Each infant was tested for at least five separate replications of the experimental procedure. Ages at testing ranged from 20 days to 112 days. In young infants, an interaction between the flashed and continuously presented stimuli and pattern suppression were demonstrated statistically. The failure to demonstrate luminance suppression interocularly was attributed to inability of the young infants to maintain accommodation in darkness, resulting in extremely variable

VEPs in the dark conditions. The presence of interocular suppression in infants 20-112 days of age was interpreted as demonstrating the presence of binocular neurons in infants as young as 20 days postnatally, and indicating that binocular neurons may be present at birth in human infants.

ACKNOWLEDGMENTS

I would like to thank the members of my committee, Drs. Anthony DeCasper, Robert Eason, Walter Salinger, and James Watson for good questions and encouragement. Dr. Russell Harter, my chairman, deserves especial appreciation for his advice and example.

Any new research effort requires the aid of many people. For example, in the present experiment the testing of each infant required the presence of at least three adults (including the mother); further, many people consented to serve as pilot subjects. Therefore, I acknowledge the assistance of the following people: Melanie Bassett, John Black, Dennis Boring, Donald Bohlen, Patsy Bohlen, Carol Burnett, Bedford Clark, Charlene Clark, Abbe Godwin, Michael Hillegas, Marianne Jakmides, Janis McKeel, Douglas Mills, Patty Morrell, Barbara Onaczynski, Frederick Previc, Elizabeth Smith, Lucy Spencer, Leo Towle, and Janis Wright. Joanne Ferguson kindly typed the versions of the manuscript.

I especially wish to thank Bob Sweeley of the S. Galeski Optical Company who kindly donated the frames used to construct the glasses for the babies, a donation which greatly facilitated this research.

TABLE OF CONTENTS

		Page
APPROVAL PAGE		ii
ACKNOWLEDGMENTS		iii
LIST OF FIGURES		vi
CHAPTER		
I.	INTRODUCTION	1
	VEP Correlates of Binocular Interaction: Adult Data	1
	Infant VEPs	9
	Infant Binocularity: Behavioral Experiments	17
	Conclusion	23
II.	EXPERIMENT 1 (ADULT BINOCULAR INTERACTION): METHODS	26
III.	EXPERIMENT 1 (ADULT BINOCULAR INTERACTION): RESULTS	30
	Intraocular Effects	35
	Interocular Luminance Effects	36
	Interocular Effects of Pattern	36
	KH's Data	37
	Summary	37
IV.	EXPERIMENT 1 (ADULT BINOCULAR INTERACTION): DISCUSSION	39
	Relationship to Previous Research	39
	Physiological Bases of the Effects	42
	Interaction of Color and Size Channels	49
V.	EXPERIMENT 2 (INFANT BINOCULAR INTERACTION): METHODS	51
VI.	EXPERIMENT 2 (INFANT BINOCULAR INTERACTION): RESULTS	54
	Intraocular Effects	59
	Interocular Luminance Effects	60
	Interocular Effects of Pattern	60

Page

VII. EXPERIMENT 2 (INFANT BINOCULAR INTERACTION): DISCUSSION 62

Interocular luminance Suppression 63
Size-Specific Interocular Suppression . . . 64
Interocular Pattern Suppression 64
Relationship to a Critical Period for the Development of Binocularity 67
Relationship to Previous Research 70

BIBLIOGRAPHY 77

REFERENCE NOTES 78

REFERENCES 79

APPENDICES

APPENDIX A 96
Quantified Data: Adults 97

APPENDIX B 100
Adult Subjects' Visual Characteristics 101
Interrelationship of Measures of Visual Acuity of Adult Subjects 102

APPENDIX C 103
Adult Correlation Matrices: Intraocular Effects of Pattern 104
Adult Correlation Matrices: Interocular Effects of Luminance 105
Adult Correlation Matrices: Interocular Effects of Pattern 106

APPENDIX D 107
Quantified Data: KW 108
Quantified Data: JB 110
Quantified Data: MO 111

APPENDIX E 113
Group Average: Correlation Matrices 114
KW: Correlation Matrices 115
MO: Correlation Matrices 116
JB: Correlation Matrices 117

Page

APPENDIX F 118
Models Tested: Infant Data 119
PT: Flash Effects 120
N2: Luminance Effects 121
P4: Luminance Effects 122
P2: Pattern Effects 123
N2: Pattern Effects 124

LIST OF FIGURES

		Page
FIGURE 1:	VEPs of Adult Subjects	31
FIGURE 2:	Quantified Mean Adult Evoked Potential Amplitude	34
FIGURE 3:	VEPs of Infant Subjects	55
FIGURE 4:	Quantified Means of Infant Subjects	58

CHAPTER I

INTRODUCTION

One of the major areas of nativist-empiricist controversy has been depth perception. A binocular cue for the perception of depth is disparate input to the two retinae (Boring, 1942; Hochberg, 1962). For retinal disparity to serve as a cue for depth perception, there must be neural binocular interaction. The anatomical and physiological basis for binocular interaction has been extensively studied in the cat, and the type of binocular interaction which serves as the basis of depth perception is not observed before the cortical level (Bishop, 1973). The purpose of this research is to explore the feasibility of studying young infants' neural binocular interaction using visual evoked potentials (VEPs). The introduction will review the literature in three areas: VEPs as a measure of adult binocular interaction, VEPs as a measure of infant visual development, and the development of infant binocular interaction as indicated by behavioral experiments.

VEP Correlates of Binocular Interaction: Adult Data

This section will review investigations which used VEPs as a measure of adults' binocular interaction. Harter (1977)

reviewed the methods by which VEPs have been used to study binocular interaction; therefore, this review will be limited to experiments which present a transient stimulus to one eye, usually by flashing it (flashed stimulus), and changes in the resulting VEP were observed as a function of the nature of the stimulus presented continuously to the other eye (continuous stimulus). In these studies the flashed stimulus was not visible to the eye receiving continuous stimulation, nor was the continuously presented stimulus visible to the eye viewing the flashed stimulus; therefore, any changes in monocular VEPs was a result of binocular interaction.

VEPs to diffuse flashes. Several experiments have examined the effects of presenting a continuous stimulus to the nonflashed eye on the VEPs evoked by diffuse flashes. Lehmann and Fender (1967, 1968) presented a diffuse flash as an evoking stimulus while a target (diffuse, dot, cross, or grid) was continuously presented to the nonflashed eye. The root mean square VEP amplitude was reduced as the target presented to the nonflashed eye increased in structure (diffuse to dot to cross to grid). As structure increased, so did the visual angle subtended by the pattern. The root mean square amplitude changes were attributable to changes in the amplitude of a component with a peak at 120 msec after the flash (Lehmann & Fender, 1968). Comparable results

were obtained as the continuous stimulus was changed from darkness to pattern (Lehmann, Beeler, & Fender, 1967). Absence of interocular effects in a subject with a split chiasma indicated that the effects are the result of the binocular innervation of cortical neurons (Lehmann & Fender, 1969).

Investigations which continuously present grids (Harter, Seiple, & Musso, 1974) and gratings (Harter, Conder, & Towle, Note 2) to the nonflashed eye have observed that VEPs to diffuse flashes are reduced in amplitude. Increasing the between-line distance increased the suppressing effects of pattern (Harter, Seiple, & Musso, 1974). VEPs evoked by diffuse flashes when the continuous stimulus is diffuse light are reduced in amplitude relative to diffuse flash evoked VEPs when the contralateral eye views darkness (Harter, Conder, & Towle, Note 2; see Paris & Prestrude, 1975).

VEPs to patterned stimuli. The VEPs to patterned stimuli are reduced in amplitude by the presentation of continuous stimulation to the other eye, either diffuse light or pattern. Harter, Conder, and Towle (Note 2) presented diffuse light or gratings as the evoking stimulus. The continuously presented stimulus was either darkness, diffuse light, or gratings. As the continuous stimulus was changed from darkness to diffuse light, a negative measure at

100 msec became more positive and another measure at 200 msec became more negative. Further, the response to evoking stimuli was more variable in darkness than when diffuse light was continuously viewed. VEP amplitude was further reduced when pattern was presented to the eye continuously stimulated.

Harter, Seiple, and Musso (1974) varied the between-line distance (diffuse, 15', 30', and 60') of dichoptically viewed grids for both the flashed stimulus and the continuous stimulus. The grids presented to both eyes were continuously visible. VEPs were elicited by a momentary increase in the intensity of the grid viewed by one or both eyes. Amplitudes of two measures, at 110 and 175 msec, reflected binocular interaction. The greater the between-line distance of the contralateral grid, the greater the reduction in VEP amplitude. This effect was greatest when the evoking stimulus was diffuse light. Harter, Towle, and Musso (1976), using checkered patterns, varied check size of the flash evoked pattern (12' or 35') and the continuously viewed pattern (9', 12', 18', 24', 35', 48', or 95'). Negative measures at 120 and 160 msec indicated a size-specific binocular interaction such that the smallest amplitude VEP was elicited when the continuously stimulated eye viewed a pattern with the same sized checks as the evoking stimulus. Both latencies also showed an effect of

the continuously viewed stimulus, similar to that observed by Harter, Seiple, and Musso (1974). Towle (Note 4) also observed size-specific suppression of VEP amplitude.

Several factors affect the interocular suppression of VEPs evoked by patterned stimuli, including background illumination of the flash, the luminance of the continuous stimulus, the relative contrast of the flashed and continuous stimulus, and the relative loci of stimulation in the two eyes. Lehmann, Koukkou, and Dittrich (1977) varied the background illumination of the flashed stimulus, nature of the flash (diffuse, dot, or grid), and the nature of the continuously presented target (none, diffuse, dot, or grid). Cluster analysis of intercorrelations of the wave forms of the VEPs elicited by the ten stimulus combinations employed indicated three cluster levels. The first level clustered conditions according to the presence or absence of background illumination of the flashed eye, indicating the importance of background luminance of the flash.

Harter, Towle, Zakzrewski, and Moyer (1977) varied the level of illumination of the continuous stimulus, the between-line distance of flashed and continuously viewed grids, the eye flashed and quality of the subjects' stereoacuity. Binocular interaction was found only under conditions of high illumination of the continuous pattern. In the high luminance condition the effects of size of the continuously

viewed pattern and size-specific interaction were evidenced by amplitude changes in measures between 150 and 260 msec after stimulus onset. The differences between good and poor binocularity groups were most obvious when small (15') checks were the evoking stimulus. The VEPs of the poor and good stereoacuity groups were reduced in amplitude as the between-line distance of the continuous stimulus increased, but the effect was greater for the good binocularity group. The good binocularity group showed greater size-specific interocular suppression. It appears that suppression of pattern flashes occurs only when the continuous stimulus is relatively bright compared to the flashed stimulus. Moreover, the suppressing effects of increased element size of the continuous stimulus appear to be functionally different than the size-specific interocular effects. Size-specific suppression appears more closely related to the mechanism of stereopsis than does the suppression due to the element size of the continuous stimulus, though both types of suppression are greater in the good binocularity group.

Spekreijse, van der Tweel, and Regan (1972) examined VEPs to the appearance and disappearance of 15' checks presented to one eye as a function of the contrast of 15' checks continuously presented to the other eye. Suppression of the VEP amplitude was most evident when the continuous stimulus was of greater contrast than the transient stimulus.

The use of hemifield stimulation and varying the fusion of transient and continuous stimuli indicated that suppression occurred only with stimulation of corresponding retinal regions. Varying the relative orientation of the checks did not alter suppression, indicating that the corresponding regions of suppression did not interact on a point-to-point basis. Harter (1977; see Westendorf & Fox, 1977) also reported that the regions of suppression did not require point-to-point correspondence, although the same region of the retinae must be stimulated. VEP suppression resulting from continuous stimulation of the contralateral eye is virtually complete in 1.5 seconds, indicating that it is a central rather than a peripheral process (Harter, 1977).

Summary. VEPs evoked by either diffuse or patterned flashes are affected by stimulation presented continuously to the nonflashed eye. Binocular interaction is evidenced at latencies from 100-250 msec. Diffuse light presented to the nonflashed eye reduces the amplitude of VEPs to flashes presented to the other eye relative to the VEP amplitude evoked by the same stimulus when the nonflashed eye views darkness. Pattern continuously presented to the nonflashed eye further reduces VEP amplitude, the amplitude being smaller the larger the size of the pattern elements. VEPs evoked by pattern are reduced in amplitude not only by contralateral luminance and increasing pattern element size; the greatest

reduction in VEP amplitude occurs when the continuous stimulus and the flashed stimulus have the same pattern element size. The interocular suppression effects resulting from continuous stimulation of one eye require binocular cortical neurons; size-specific suppression is loosely related to mechanisms of stereopsis. VEPs show greater amplitude reduction if the continuous stimulus relative to the flashed stimulus is brighter, has greater contrast, and is presented to the same retinal area.

Psychophysical experiments. A number of psychophysical experiments have examined interocular suppression of a pattern viewed by one eye when the other eye has been adapted by a pattern having the same spatial frequency (Blakemore & Campbell, 1969; Lema & Blake, 1977; Blake & Fox, 1972; Cosgrove, Kohl, Schmidt, & Brown, 1974; Sharpe, 1974; Ware & Mitchell, 1974; Pantle & Sekuler, 1968). These studies did not investigate the size specificity of interocular suppression in that the spatial frequency of the adapting stimulus was not varied.

Maudabocus and Ruddock (1973) varied the wavelength and spatial frequency of the adapting stimulus. The adapting pattern was projected to one retina via a laser at 5 log units above threshold for three minutes. During the following two minutes, the contrast threshold of the test pattern (4 or 7 c/d) was measured. The more similar the spatial

frequencies of the adapting and test stimuli, the higher the contrast threshold of the test stimulus, irrespective of the wavelength of the adapting stimulus. Abadi (1976) varied the spatial frequency of a continuously presented adapting pattern of constant contrast and measured the contrast of a test stimulus presented to the other eye. The more similar the spatial frequencies of the adapting and test stimuli, the higher the contrast of the test stimulus required to suppress the adapting stimulus.

Ware and Mitchell (1974) compared the interocular suppression of subjects with good and poor stereoacuity. The adapting and test stimuli were of the same spatial frequencies. Suppression was greater for those with good binocularity.

In summary, psychophysical studies with adults which have examined interocular suppression concur with VEP studies. Interocular suppression is size-specific and its presence is related to normal binocular vision.

Infant VEPs

This section will review those experiments which have examined the effects of binocularly presented transient patterns, flashed or pattern appearance-disappearance, on infants' VEPs. The effects of diffuse flashes have been reviewed by Ellingson (1967).

VEPs have several potential advantages relative to behavioral techniques in the study of infant visual processes. Young infants have few coordinated behavior patterns, looking and sucking being the exception, and those which are present are not comparable to the behaviors used to study adult visual processes. Absence of behavioral discrimination by infants among patterns is ambiguous. In the case of differential fixation, it may represent a lack of preference for one stimulus over another, not a lack of discrimination. In the case of more global responses or fixation, it may represent a deficit in motor ability or sensorimotor integration rather than sensory or perceptual immaturity. The VEP represents neural activity and does not require a motor response; therefore, it is presumably a more direct measure of both the infants' sensory abilities and neural maturation. The VEP methodology is the same for both adults and infants providing a greater comparability of results between adults, children, and infants. Lastly, adults' VEPs correlate highly with their verbal reports of visual functioning (see Regan, 1972), lending credibility to the methodology.

Infants' VEPs to patterned stimuli have been used to investigate infants' basic visual functions, especially visual acuity, and the relationship of VEPs and pattern preferences. Based on the results of these experiments, hypotheses have been proposed relating VEPs to neural development.

VEPs and the development of visual acuity. Harter and Suitt (1970) studied the VEPs of a single infant from 21-155 days of age. Checkered stimuli, with checks from 20' to 133', and a diffuse flash were presented binocularly. The amplitude changes of an early positive measure (P2) and of a negative potential (N2) indicated that the check size which evoked the largest amplitude response decreased with age, reflecting changes in visual acuity with age. Based on the check size evoking the greatest VEP amplitude, the subject's acuity was estimated as 20/500 at one month and as 20/250 at three months. The changes in acuity were attributed to changes in refractive error and macular development. It was noted that the estimates of acuity agreed with available behavioral data on visual acuity.

Harter, Deaton, and Odom (1977a) simultaneously recorded the VEPs and looking behavior to a diffuse flash and to checkered stimuli with checks subtending 11.24' to 180'. Ten infants 6-45 days of age were subjects. Extrapolating to threshold from obtained VEPs to pattern, the estimated visual acuity of infants 27-45 days old was 20/200. Refractive error was estimated as +1.66 diopters. VEPs to pattern reversal (Sokol & Dobson, 1976) and constant luminance pattern appearance (Marg, Freeman, Peltzman, & Goldstein, 1976) have indicated that the visual acuity of infants reaches 20/20 by six months of age. The greatest

improvements in acuity occur during the first two months (Marg, Freeman, Peltzman, & Goldstein, 1976). Banks (1977), using a logarithmic scale of Marg's data, argued that the rate of acuity development is constant between one and six months of age.

Because several nonneural factors which affect visual acuity, including refractive error (shape of the cornea), pupillary size, and accommodation (Harter, Deaton, & Odom, 1977b), have not been considered sufficient to account for changes in visual acuity, macular and central neural maturation have been used as explanatory mechanisms to account for improved visual acuity (Harter, Deaton, & Odom, 1977a, 1977b). One major nonneural factor has not been considered, however--sagittal length of the eye. The length of the eye increases in a manner similar to improvement in visual acuity (see Larsen, 1971; Rusoff & Dubin, 1977).

VEPs and pattern preferences. Harter and Suitt (1970) noted that the check size evoking the largest amplitude VEP corresponded to the check sizes reported in behavioral studies as being preferred by infants of the same age, suggesting that developmental trends in infant looking behavior were a function of changes in visual acuity. The relationship of check size to VEP amplitude could be described as an inverted U-shaped function after 70 days of age.

Karmel, Hoffmann, and Fegy (1974) studied the VEPs of 33 infants 55-107 days of age. The stimuli were a diffuse flash and checkered stimuli with checks from 20' to 5°. The check size evoking the largest amplitude P2 decreased as a function of age and P2 latency (neurological age). The mathematical functions relating the check size evoking maximal amplitude P2 and age were very similar to the functions derived from earlier studies relating check size eliciting maximal looking preference and age. The fact that smaller sized checks elicited greater amplitude VEPs and more looking with increasing age was attributed to the presumed decreasing modal receptive field size in the infant retina, so that the optimal stimulus for "exciting" cortical neurons would decrease in element size with age.

Hoffmann (Note 3; see Karmel & Maisel, 1975) investigated the relationship of check size to VEPs in infants 28-96 days of age. Subjects were divided into groups based on neurological age (P2 latency). Three VEP measures were significantly related to pattern, P2, a later positive measure (P4), and a later negative measure (L-N). P2 was quantified at both a fixed latency and by identification of the positive peak. P4 and L-N were both quantified by the use of a fixed latency. Using the identification procedure, P2 amplitude was greatest to 80' checks for both age groups. Using the fixed latency procedure P2 was greatest

to 5° and 40' for the long latency (neurally younger) and short latency (neurally older) groups, respectively; P4 was greatest to 40' and 5° checks; and L-N was greatest to 80' and 5°. Mathematical functions were calculated for each of the three measures, as determined in each latency group, relating the measure's amplitude and check size. The function relating P2 and check size for the short latency group and the functions relating P4 and L-N to check size in the long latency group were similar to functions relating looking preference and check size in groups aged, respectively, 4-6 weeks and 10-12 weeks.

Harter, Deaton, and Odom (1977a, 1977b) measured both the VEPs and percentage of time looking (PTL) at patterns in infants 6-45 days of age, enabling them to directly compare the relationship of VEP amplitude and looking behavior. The early positive measure (P2), while related to pattern size, was unrelated to PTL. A later positive measure (P4) was unrelated to either pattern or PTL in infants 6-26 days old. However, in older infants (27-45 days), larger check sizes evoked greater P4 amplitude and P4 amplitude correlated .92 with PTL. P2 amplitude was largest to 11.24' and 22.5' in both the 6-26 and 27-45 day old groups. In the 27-45 day old group, P4 was largest to 90' and 180' checks.

VEPs and neural development. The differential relationship of VEP measures and visual preference observed by Hoffmann (Note 3, 1978) and Harter, Deaton, and Odom (1977a) have led to hypotheses about the relationship of VEP measures to infant neural development and the relationship of that development to visual behavior. Hoffmann tentatively identified the neurological substrates of P2, P4, and L-N. P2 was identified as reflecting the cortical activity of the geniculostriate system and a late negative measure (L-N was identified as reflecting the cortical activity of the collicular system. P4 was presumed to reflect other subcortical processes, possibly the pulvinar. P4 and L-N amplitudes were correlated significantly, reflecting the interrelationship of the superior colliculus and pulvinar. The identification of P2 and L-N with geniculostriate and collicular systems, respectively, was based on a study of VEPs in kittens (Rose & Lindsley, 1968). Identification of P4 with the pulvinar was based on its relationship to L-N. Given that P4 and L-N were related to the visual behavior of infants in their second month and that P2 was related to the visual behavior of infants in their third month, it was proposed that changes in visual preference during this period are attributable to a shift in the control of visual behavior from subcortical to cortical structures (see Bronson, 1974).

Harter, Deaton, and Odom (1977a), also, attributed P2 and P4 to separate neural processes. P2 and P4 amplitudes were greatest to 11-22' and 90-180' checks respectively in 27-45 day old infants suggesting that they represented two aggregates of neurons. One aggregate tuned to higher spatial frequencies was reflected by P2; another tuned to lower spatial frequencies was reflected by P4. The differential relationship of the two measures to PTL suggested that P2 might reflect subcortical activity or the first stages of processing at the cortex and P4 might reflect cortical activity. The specific structures presumed to underlie the components were not stated.

Given this paper's concern with the development of binocularity, the relationship between the development of visual acuity, changes in pattern preferences and the development of binocularity is of particular interest. In cats, the development of visual acuity is related to the critical period for the development of binocular cortical neurons (Freeman & Marg, 1975). The visual acuity of the kitten as measured by VEPs reaches adult levels at the end of the critical period, suggesting that the critical period for humans is ended at six months of age, because by that age adult acuity levels are reached (Marg, Freeman, Peltzman & Goldstein, 1976; see Sokol & Dobson, 1975).

Summary. Major changes occur in the visual behavior of infants during the second month as reflected behaviorally

(Salapatek, 1975; Karmel & Maisel, 1975; Fantz, Fagan, & Miranda, 1975) and electrophysiologically (Harter, Deaton, & Odom, 1977a, 1977b; Hoffmann, Note 3, 1978; Karmel & Maisel, 1975). The changes have been attributed to a shift from subcortical to cortical control of vision (Bronson, 1974; Karmel & Maisel, 1975; Harter, Deaton, & Odom, 1977a, 1977b). Given that the binocular interaction reflected by adults' VEPs is cortical in origin, infant binocular interaction as measured by VEPs should reflect cortical functioning. Several suggestions regarding the neural origins of infant VEP components have been made (Karmel & Maisel, 1975; Harter, Deaton, & Odom, 1977a, 1977b; Hoffmann, 1978). Binocularity is presumably of cortical origin (Bishop, 1974); therefore, differences in the relationship of VEPs to binocularity might aid in determining the neural origin of VEP components.

Infant Binocularity: Behavioral Experiments

This section will review studies which examine infants' binocular vision. Most of the experiments examining infant binocularity have been conducted by researchers interested in the development of binocular depth perception (stereopsis). Two basic procedures have been used: comparison of infant performance under binocular and monocular viewing conditions and the use of techniques which attempt to eliminate all but binocular depth cues.

Comparison of monocular and binocular viewing conditions. Walk (1968), using the visual cliff apparatus, compared the performance of infants in the normal procedure (binocular condition) and with an eye patch over one eye (monocular condition). Infants in the monocular condition performed as well as infants in the binocular condition at a visual depth of 25 cm. However, at a depth of 12.7 cm infants younger than 9 months turned consistently toward the uncovered eye, i.e., did not show a preference for the shallow side, revealing a monocular weakness.

Fantz (1961) studied depth perception using the visual preference technique. He used either solid balls or pictures of the balls. The balls were either smooth or textured under direct or indirect lighting. Stimuli were viewed either monocularly or binocularly. Only the textured sphere viewed under direct lighting was preferred to a circle. The preference was found at all ages, one to six months, under monocular viewing conditions. Infants in the binocular condition showed no preference for the directly lighted, textured sphere prior to three months of age, indicating that prior to three months of age infants either lack or have poor binocularity. A subsequent comparison of monocular and binocular viewing of a three-dimensional face and an outline of a face yielded similar results (Fantz, 1965, 1966).

Bower (1965) conducted an investigation of depth perception using infants 40-60 days of age. Three groups were taught to turn their heads upon presentation of a cube at a given distance; one group was trained under binocular conditions, another under monocular conditions, and a third with projections of real objects. After training, infants were tested to determine if they could discriminate the conditioned stimulus from stimuli of the same shape subtending the same retinal angle. The binocular and monocular groups performed comparably on the posttest. Binocular cues did not improve performance of this age group, suggesting that infants in their second month use monocular cues rather than retinal disparity to discriminate the relative depth of objects subtending the same retinal angle.

Experiments eliminating monocular cues. Adults who possess normal stereoacuity perceive a three-dimensional object when viewing separate two-dimensional projections. The visual field is split by the use of polarized lenses and the separate two-dimensional images are projected using different polarization. The perception of depth is presumed to rely solely on binocular cues. If the images projected are shadows of a three-dimensional object, the mechanism is called a stereoscopic shadow caster, and the adult percept is one of a single, solid object (virtual object) hanging in space.

Bower, Broughton, & Moore (1970a, 1970b), using a stereoscopic shadow caster, studied infants in their first month. Infants as young as eight days reached for the virtual object and cried when it was not grasped, implying that binocular depth perception is innate (see Bower, 1971; Bower, 1975). Bower's conclusions have been questioned on several bases. First, directed reaching of the kind reported by Bower has not been observed by others prior to several months of age. Second, crying by young infants could be accounted for by either increasing conflict of accommodation and convergence or increasing binocular rivalry as the virtual object is brought close to the infant (Gordon & Yonas, 1976). Given that infants less than two months show poor convergence (Wickelgren, 1967, 1969; Aslin, 1977) and accommodation (Haynes, White, & Held, 1965), make these suggestions seem reasonable.

Gordon and Yonas (1976) used a stereoscopic shadow caster to study the response of infants 20-26 weeks of age to binocular cues for depth. When the image projected by the shadow caster was beyond the infants' reach, they tended to lean farther forward (which makes the image appear to be closer), make fewer reaches, and the proportion of reaches which included grasping movements was less. The results were interpreted to indicate that infants five months or older perceive disparity. There was no evidence of

frustration (crying) at failure to touch the object, but Bower (1971) mentions that infants older than five months fail to show this behavior.

Random patterns presented dichoptically by means of polarized light through polarized lenses may give rise to stereopsis if portions of the pattern are displaced horizontally (vertical disparities do not give rise to stereopsis) and the person has binocular vision.

Typically, subjects are permitted to scan the stereograms while making judgments of depth. Permitting scanning of the figures introduces the monocular cues of relative convergence. Only flash presentation of the stereograms totally eliminates the use of monocular cues (Richards, 1977). Investigations of infant disparity detection have continuously presented the stereograms, thereby confounding their interpretation by failing to eliminate the cues of relative convergence.

Bower (1970) indicated that 20-30 percent of the young infants tested looked longer at stereograms with horizontal disparities than those lacking disparity. Atkinson and Braddick (1976) used both visual preference and dishabituation of high amplitude sucking to assess the ability of four two-month-old infants to discriminate disparity using stereograms. Both measures indicated that two of the four infants had stereopsis; only one of the four showed

stereopsis on both tests. Appel and Campos (1976) used stereograms and measured the dishabituation of high amplitude sucking and heart rate deceleration in two-month-old infants as stimuli were changed from disparity to nondisparity or from nondisparity to disparity. Infants failed to show statistically significant response reduction in either condition; however, the difference between the response amplitude in the habituation phase and the dishabituation phase was significant for both heart rate and sucking as conditions changed from nondisparity to disparity but not as conditions were changed from disparity to nondisparity. The results were interpreted as indicating the presence of disparity detection in two-month-olds.

Aslin (1977) investigated infants' ability to detect disparity by measuring the presence of the saccadic response to prism-induced disparity. If one is fixating an object and a prism is placed in front of one eye, the perceived location of the object changes and one makes a saccadic movement in the direction of the perceived change, if one can detect binocular disparity. Infants were three, four and one-half, and six months old. Prisms which altered the visual image of one eye by 2.5^{o} or 5^{o} were employed. Only six-month-olds made a saccadic response to the introduction of the prism-induced displacement of the visual image.

Summary. The results of several studies have been interpreted as indicating the presence of binocular disparity detection or binocular interaction in infants two months of age or less. In each of these studies alternative explanations of the observed behaviors are possible. Furthermore, lack of improved depth discrimination with binocular viewing, observed in infants less than three months old, would argue against the presence of mature mechanisms of stereopsis. Relatively mature disparity detection does not seem to appear prior to five months of age. On the other hand, binocular mechanisms related to binocular rivalry may be present at an earlier age; both the impairment of depth discriminations with binocular viewing and the crying of infants when presented virtual images are consistent with this interpretation; however, a convincing demonstration of binocular rivalry does not exist.

Conclusion

Investigations of adult binocular interaction using VEPs indicated three interocular suppression mechanisms, one related to the luminance of the continuously stimulated eye, one to the pattern element size of the continuously stimulated eye, and one to the similarity in size (or other feature) of the patterns presented to the flashed and continuously stimulated eyes. All three of the interocular

suppression effects require binocular cortical neurons, but only the size-specific suppression has been related to stereoacuity. Prior use of VEPs to study infant visual processes indicated the feasibility of using interocular suppression, as measured by VEPs to flashed patterns, to study the presence of binocular interaction in human infants. The lack of an unambiguous behavioral demonstration of binocularity in infants indicated the desirability and potential merit of a VEP investigation of infant binocular interaction.

Several considerations suggested the desirability of first conducting an experiment with adults. Preliminary consideration indicated that the use of infant subjects would require the use of different stimuli (dots instead of checks, grids, or gratings) and a different method of splitting the visual field (color separation instead of a haploscope; see Fox & Blake, 1971; Fox & Lehmkuhle, 1977; LeGrand, 1967). The primary purpose of the adult experiment was to determine if all three forms of binocular interaction obtained using other methods and stimuli could be obtained using the new method and stimuli (color separation). The use of the color separation method of splitting the visual field afforded the opportunity to determine the relationship, if any, of color and size channels in the visual system. The experiment presented below is the first to study all three interocular suppression effects concomitantly,

permitting a comparison of the relationship of the effects when all other variables are held constant.

In the available laboratory situation there would be no independent methods of testing infants' binocularity or of telling infants which aspects of the visual displays to attend to. It was decided, therefore, that a heterogeneous sample of largely naive, uninstructed subjects should be used in the adult study.

CHAPTER II

EXPERIMENT 1 (ADULT BINOCULAR INTERACTION): METHODS

The binocular interaction of eight adults, 22-37 years of age, was investigated using VEPs. Each subject participated in one experimental session consisting of two replications of the experimental procedure. Prior to the beginning of the session subjects' monocular acuities, binocular acuity, and stereoacuity were determined (see Appendix A). Further, they were asked about any history of visual problems. A child 5.5 years old was also tested. No behavioral measures were taken of the child's visual capacity.

VEPs were recorded monopolarly using a single gold-cup scalp electrode placed approximately 2.5 cm above the inion on the midline and held in place using a headband. The reference electrode was attached to the right earlobe. Cortical activity was amplified by a Grass polygraph with one-half amplitude high and low filters set at 35 and 1 Hz respectively. Cortical activity occurring during the 512 msec post-stimulus interval was recorded on an FM tape recorder, averaged on a Fabri-Tek signal averager and recorded on graph paper using a Hewlet-Packard X-Y plotter. Data were plotted after every four conditions. Subjects rested while the data were plotted (two to four minutes).

The stimuli were three 2" x 2" slides consisting of two patterned slides and one diffuse slide. The patterned slides consisted of dots subtending 20' and 80'. In the horizontal and vertical meridians the between dot distance was twice the dot size. In the diagonal, the between dot size and the dot size were equal. The diffuse slide was a neutral density filter (.50 log units) having the same luminance transmittance as the patterns (approximately 30 percent). The patterns were back projected onto a translucent screen that covered a window at one end of a large box. Two Kodak projectors, mounted at the other end of the box 179 cm from the screen, were on continuously. The projected patterns were located approximately 59 cm from the subject's eyes and their boundaries subtended a visual angle of 45 x 45 degrees of arc.

A revolving disc placed in front of one projector occluded the light from that projector except when a square hole cut into the disc passed before the projector's lens system. Passage of the hole in front of the projector created a flash with a total rise and fall time of approximately 40 msec. At the revolution rate used in this experiment, the time from the onset of one flash to the onset of the next flash was 1025 msec.

Before reaching the screen, the light from the projector with the revolving disc passed through a red filter (Kodak Wratten Filter No. 29) and the light from the projector which continuously illuminated the screen passed through a green filter (Kodak Wratten Filter No. 47). An opaque slide was used to terminate the continuous stimulus during the dark conditions. The intensity of the continuous stimulus was approximately 9.5 foot-candles and that of the flash approximately 2.5 log units above threshold with the continuous light on.

During the experimental session, the subject wore a set of specially-constructed glasses with one green filter (Kodak Wratten Filter No. 47) and one red filter (Kodak Wratten Filter No. 29). These two filters effectively split the visual field of adult viewers so that the eye with the green filter saw only the continuous green pattern and the eye with the red filter saw only the flashed red pattern. The red filter covered the left eye. Subjects' eyes were approximately 59 cm from the screen.

The experimenter monitored the subjects by means of a closed-circuit television. A television camera lens was inserted through the wall of the chamber at the level of the subject's right ear. A 28 volt dc lamp placed immediately above the camera illuminated the right side of the subject's face. The experimenter, by monitoring subjects' head and

eye movements on the television monitor, could determine if the subject was oriented toward the stimulus display. Subjects were given no instructions regarding which aspect of the stimuli to attend. They were merely told to try to remain alert and to keep their eyes open and directed toward the screen.

The experiment was conducted in an electrically-shielded, partially-soundproofed room. Stimulus presentation was remotely controlled by the experimenter. Stimuli were presented when the subject's eyes were open and oriented toward the stimulus display.

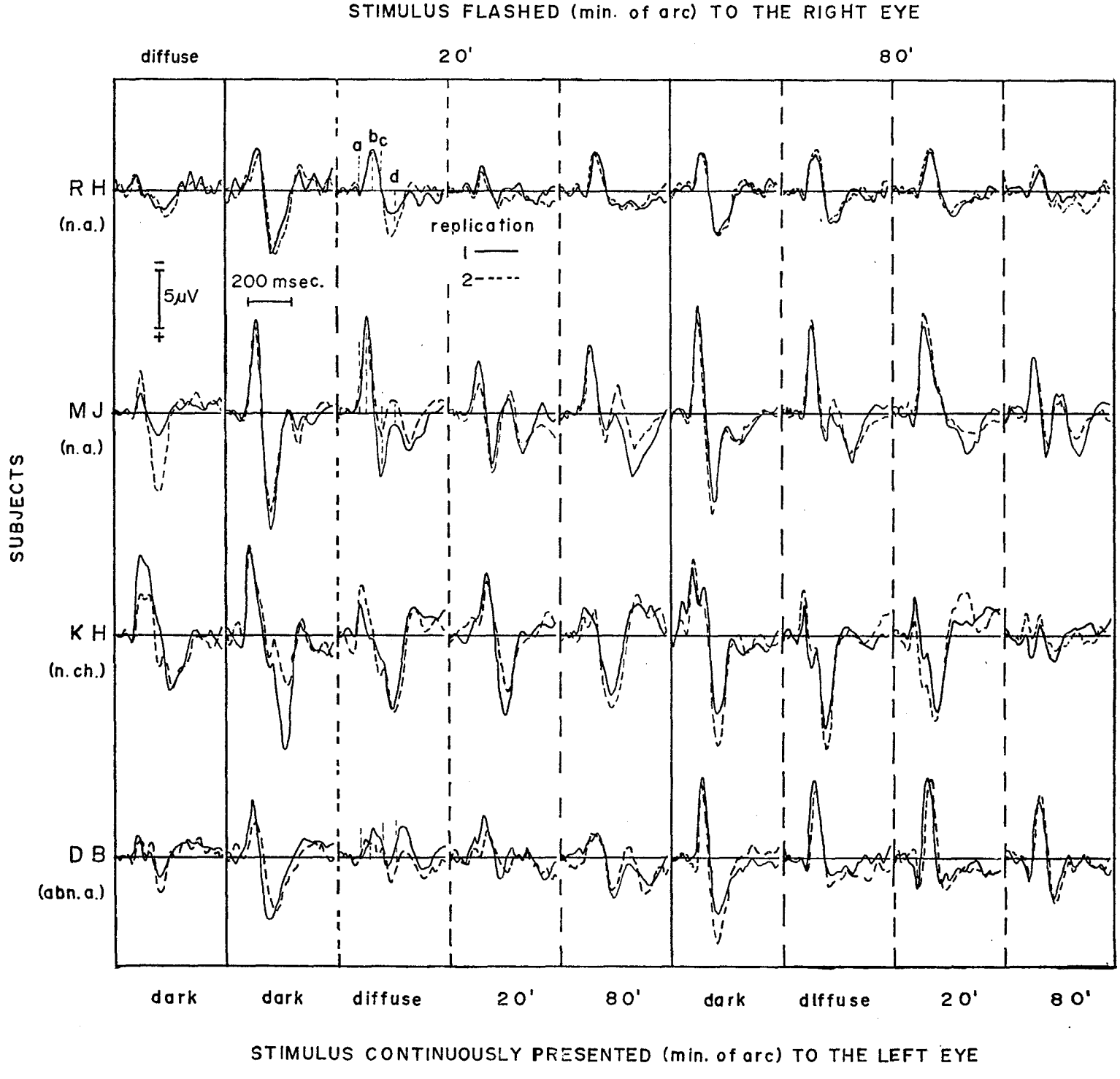
A recording session consisted of two blocks of thirty-two presentations of each of nine stimulus combinations. The flashed/continuous stimulus combinations were: diffuse/dark; 20'/dark; 20'/diffuse; 20'/20'; 20'/80'; 80'/80'; 80'/20'; 80'/diffuse; 80'/dark. Stimulus order was counterbalanced across subjects and replications. Counterbalancing was accomplished by reversing the order of stimulus presentation--ABCDEFGHI/IHGFEDCBA or IHGFEDCBA/ABCDEFGHI--with four subjects receiving each order.

CHAPTER III

EXPERIMENT 1 (ADULT BINOCULAR INTERACTION): RESULTS

Figure 1 shows the data from three of the eight adults who participated in Experiment 1. The data of a five and one-half year old child are also shown in the figure. Visual inspection of the raw VEPs indicated amplitudes at four latencies varied with the experimental conditions. They were 100, 150, 200, and 260 msec after trace onset (see Figure 1). There was a delay of 40 msec between trace onset and flash onset when flash onset was defined as the point where three-fourths of the rise in flash luminance had occurred; therefore, the actual latencies after the flash were 60, 110, 160, and 220 msec. These latencies were comparable to VEP measures measured in other experiments (Harter, Seiple, & Musso, 1974; Harter, Towle, & Musso, 1976; Harter, Towle, Zakzrewski, & Moyer, 1977; Harter, Conder, & Towle, Note 2; Towle, Note 4) which reflected interocular activity. Measurement of the amplitudes were made relative to a baseline, which was the average of the first 20 msec of the VEP following trace onset. When the flash was changed from diffuse to pattern, the 110 msec measure shifted negative and the 160 and 220 msec

FIGURE 1: VEPs of Adult Subjects


STIMULUS FLASHED (min. of arc) TO THE RIGHT EYE
diffuse
20'
80'
a
b
c
d
R H
(n.a.)
M J
(n.a.)
K H
(n. ch.)
D B
(abn. a.)
SUBJECTS
replication
1
2
200 msec.
5μV
dark
dark
diffuse
20'
80'
dark
diffuse
20'
80'
STIMULUS CONTINUOUSLY PRESENTED (min. of arc) TO THE LEFT EYE

measures shifted positive; thus, they were termed respectively $\overline{N110}$, P160, and P220. Measurements were made at the same latencies for all conditions and subjects, except for $\overline{N110}$ (the bar indicates that the latencies at which measures were taken varied with the subject). The peak of $\overline{N110}$ varied for subjects, but was in all cases between 100-120 msec after flash onset. The average latency of this surface-negative peak when the nonflashed eye viewed diffuse light and the flashed eye viewed 20' and 80' dots was determined for each subject and defined as $\overline{N110}$ for that subject.

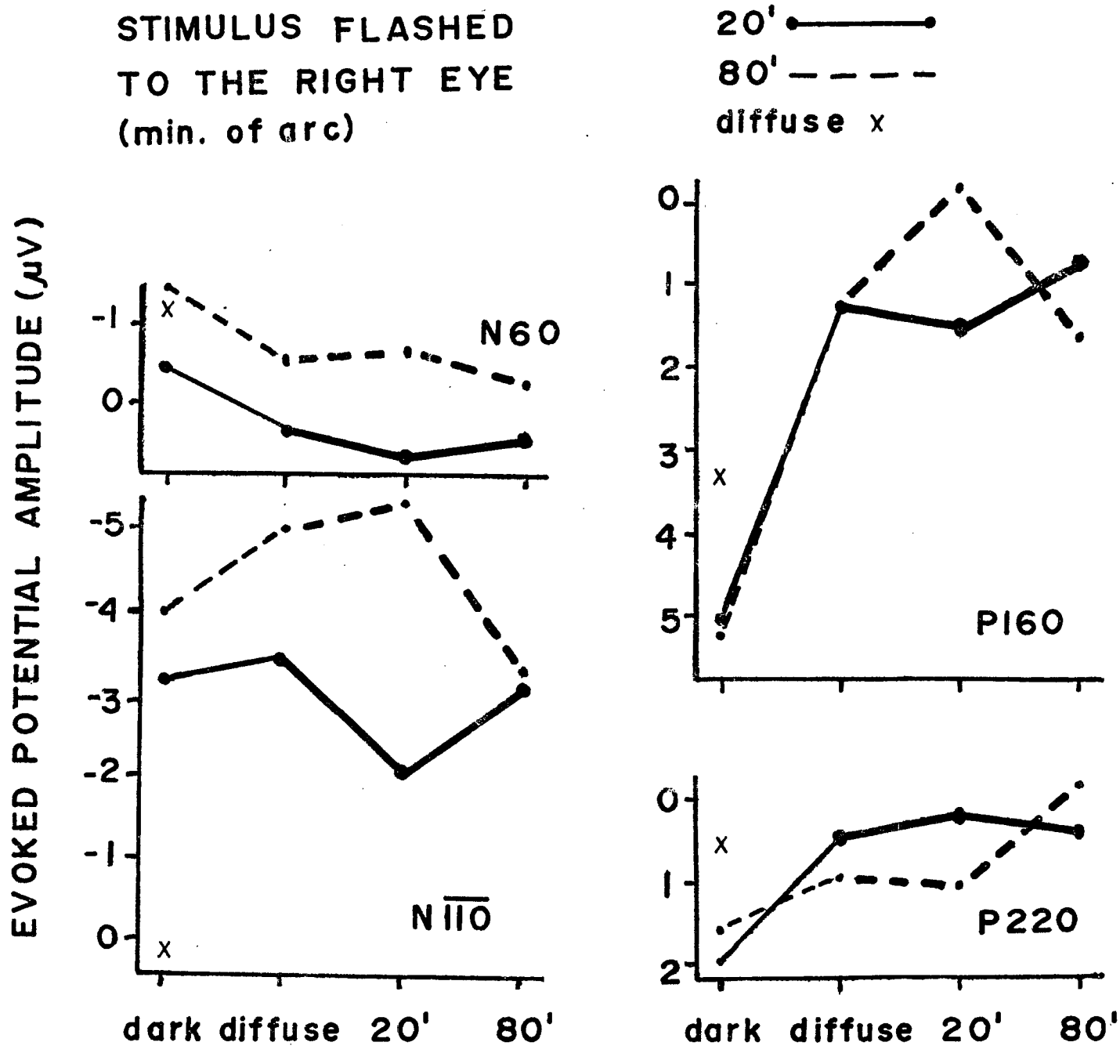
Data from four subjects are presented in Figure 1. Two subjects (RH and MJ) had good stereoacuity with no history of poor binocularity. Their data showed normal intraocular effects and interocular suppression due to luminance and pattern size. Visual inspection indicated VEP amplitude was generally smallest when a) the flashed stimulus was diffuse light and b) when the flashed and continuous patterns had the same size dots (20'/20' and 80'/80'). One subject (DB) had poor stereoacuity, had suffered from exotropia and diplopia as a child (corrected with lenses at seven years of age) and had been told by his doctor that he lacked good binocular vision. His data reflected a normal intraocular size effect; it did not reflect the interocular suppression due to shared pattern

size of the flashed and continuous stimulus. The fourth subject (KH) was a five and one-half year old child whose father (RH) had normal binocular vision. Although KH's data were not quantified or analyzed, they are included in Figure 1 as a comparison with adult subjects. Her data, like DB's, show normal intraocular effects, but the intraocular effects of pattern size are absent.

Graphic presentation of the group means for the eight adult subjects for each condition and measure is made in Figure 2. The quantified raw data of these subjects are presented in Appendix A, and their visual characteristics are presented in Appendix B. No visual characteristics were taken from KH, nor were her data quantified or included in subsequent statistical analyses.

Analyses of variance (ANOVAs) for repeated measures were calculated for each measure to assess treatment effects statistically. Three analyses were performed, an analysis to assess the intraocular effects of pattern in the flashed stimuli when the nonflashed stimulus was darkness; an analysis to examine the interocular effects of changing the continuously viewed stimulus from darkness to diffuse light on VEPs to the dots; and an analysis to examine the interocular effects of changing the continuous stimuli (diffuse light, 20' or 80' dots) on VEPs to dot patterns. Following the ANOVAs, Newman-Keul tests were performed to compare the

FIGURE 2: Quantified Mean Adult Evoked Potential Amplitude


STIMULUS FLASHED
TO THE RIGHT EYE
(min. of arc)
20'
80'
diffuse x
EVOKED POTENTIAL AMPLITUDE (μV)
N60
N110
P160
P220
dark diffuse 20' 80'
dark diffuse 20' 80'
STIMULUS CONTINUOUSLY PRESENTED TO THE
LEFT EYE (min. of arc)

means. Correlation coefficients were also calculated between all variables as a test for linear trends in the data. These are presented in Appendices C, D, and E.

Intraocular Effects

VEP amplitude at 60, 110, 160, and 220 msec after the presentation of the flashed stimulus varied as a function of the nature of the monocularly presented evoking flash when the nonflashed eye viewed darkness continuously (N60, $F=6.74$, $df=2,30$, $p < .005$; $\overline{N110}$, $F=21.12$, $df=2,30$, $p < .0002$; P160, $F=6.19$, $df=2,30$, $p < .007$; P220, $F=7.17$, $df=2,30$, $p < .005$). The patterned flashes (20' and 80' dots) elicited larger amplitude $\overline{N110}$, P160, and P220 than did the diffuse flash ($p < .05$).

When the nonflashed eye viewed either darkness or diffuse light, N60 amplitude was less positive to the flashed pattern of 20' dots than to the 80' dots ($F=21.11$, $df=1,7$, $p < .01$). When the continuously presented stimulus was diffuse light, a pattern of 20' dots or of 80' dots, N60 and $\overline{N110}$ amplitude were more negative when the flash was 80' as compared to 20'. In general, VEP amplitude was greater to patterned than to diffuse flashes and greater to patterns of 80' dots than to patterns of 20' dots.

Interocular Luminance Effects

Changing luminance presented to the nonflashed eye from darkness to diffuse light generally reduced VEP amplitude. Amplitude at 60 msec shifted positive ($F=57.44$, $df=1,7$, $p < .001$); P160 shifted negative ($F=39.82$, $df=1,7$, $p < .001$); and P220 shifted negative ($F=20.50$, $df=1,7$, $p < .01$). Changing the level of luminance presented to the nonflashed eye did not significantly affect $\overline{N110}$ ($p > .08$).

Interocular Effects of Pattern

Presenting pattern to the nonflashed eye had two effects on the amplitude of VEPs to flashed patterns. First, as the size of the pattern elements increased, VEP amplitude grew smaller. Second, VEP amplitude was smallest when the flashed pattern and the continuously presented pattern were the same patterns. The nature of the continuous stimulus affected $\overline{N110}$ amplitude ($F=4.12$, $df=2,14$, $p < .05$) and P160 amplitude ($F=6.71$, $df=2,14$, $p < .01$). $\overline{N110}$ and P160 were reduced in amplitude as continuous stimulation was changed from diffuse light to dots. The effects of the continuous stimulus also depended on the nature of the flashed stimulus at $\overline{N110}$ ($F=24.72$, $df=2,54$, $p < .001$), P160 ($F=10.56$, $df=2,54$, $p < .001$), and P220 ($F=3.70$, $df=2,54$, $p < .05$). $\overline{N110}$ amplitude was reduced when the flashed and continuous patterns had the same sized dots ($p < .05$),

i.e., 20/20 and 80/80, indicating size-specific reduction in VEP amplitude. P220 amplitude elicited by the 80' dots was smallest when the 80' dots were viewed continuously ($p < .05$). The amplitude changes at P160 indicated that the smallest amplitude was elicited by 80' dots when 20' dots were continuously viewed ($p < .05$).

KH's Data

The data of the one five and one-half year old child tested under these conditions were not quantified. However, visual inspection of the VEPs (see Figure 1) indicated the presence of two of the three effects observed in adults. VEP amplitude was reduced as the continuous stimulus was changed from darkness to diffuse light. When the continuous stimulus was further changed to pattern, a further reduction of VEP amplitude was evident. Size-specific reduction was not evident, however.

Summary

When the nonflashed eye viewed darkness all latencies of the VEP indicated that VEPs elicited by pattern were of greater amplitude than those elicited by diffuse light. Introduction of light to the nonflashed eye reduced the amplitude of VEPs at 60, 160, and 220 msec (interocular luminance suppression). Interocular effects of presenting

pattern to the nonflashed eye were evidenced in two ways. $\overline{N110}$ and P160 amplitudes were smaller the larger the dot sizes of the continuously presented stimulus pattern (interocular pattern suppression). $\overline{N110}$ and P220 amplitudes were smallest when the flashed and continuous patterns had dots of the same sizes (interocular size-specific suppression).

CHAPTER IV

EXPERIMENT 1 (ADULT BINOCULAR INTERACTION): DISCUSSION

Relationship to Previous Research

The major purpose of this experiment was to assess whether size-specific interocular interaction as measured by VEPs could be obtained with the color separation method of splitting the visual field in adults. This relationship is prerequisite to assuming this method may be used to assess binocular vision in infants.

When the nonflashed eye was in darkness, the amplitudes of all four VEP measures varied as a function of the flash. The most pronounced effects, however, were at $\overline{N110}$, which has frequently been shown to vary with pattern element size or spatial frequency for binocularly elicited VEPs (Spekreijse, 1966; Rietveld, Tordoir, Hagenouw, Lubbers, & Spoor, 1967; Armington, Gaardner, & Schick, 1967; Harter & White, 1970; Harter, 1970, 1971; May, Forbes, & Piantanida, 1971; Lesevre & Remond, 1972). The spatial frequency or element size eliciting the largest amplitude VEP presumably reflects the modal receptive field size of the visual neurons stimulated, presumably 10-20' for human adults (Harter & White, 1970; Harter & Suitt, 1970; Harter, 1970, 1971; Harter, Deaton, & Odom, 1977a, 1977b; Armington,

Gaardner, & Schick, 1971). The fact that the amplitude elicited by 80' flashes was greater than the 20' flashes is somewhat puzzling in this context. The same phenomenon has been observed before, however (Harter, Towle, Zakzrewski, & Moyer, 1977). The effect is not attributable to acuity, for the poorest Snellen acuity found for a subject in this study was 20/29, nor could the nature of the stimuli (dots) cause the discrepancy (Towle & Harter, 1977); however, the large stimulus field size may (Harter, 1970).

The suppressing effects of presenting continuous diffuse light to the nonflashed eye were more apparent in the latter (160-220 msec) VEP amplitudes as has been reported previously (Harter, Conder, & Towle, Note 1). As in other experiments which have indicated interocular suppression of VEP amplitude due to pattern (Harter, Towle, & Musso, 1976; Harter, Towle, Zakzrewski, & Moyer, 1972; Towle, Note 4; Harter, Seiple, & Musso, 1974), $\overline{\text{N110}}$ and P220 are, generally, reduced in amplitude as the element sizes of the continuously presented patterns are increased up to about 60' (Harter, Seiple, & Musso, 1974; Harter, Towle, & Musso, 1976; Harter, Towle, Zakzrewski, & Moyer, 1977). $\overline{\text{N110}}$ and P220 also reflect a size-specific interocular suppression of VEP amplitude (Harter, Towle, & Musso, 1976; Harter, Towle, Zakzrewski, & Moyer, 1977; Towle,

Note 4) such that, for each patterned flash, the smallest amplitude VEP was elicited when the same sized pattern was continuously presented to the nonflashed eye.

In summary, the color separation technique for splitting the visual field was comparable to haploscopic techniques, reported previously. Three distinct interocular suppression effects were found. One effect, dependent on the luminance (either absolute or relative) presented to the nonflashed eye, does not appear to affect one flashed pattern more than another. A second effect, dependent on the size of the continuously presented stimulus, also affects all patterned flashes. A third effect, dependent on the sizes of both the flashed and the continuous pattern, was evidenced by size-specificity of suppression. These three effects can be seen to some degree in all of the measures; however, the relative magnitude of the effects varies with measures. An early measure at 60 msec shows only the interocular suppression effects of luminance. The nonspecific interocular effects of luminance are least readily observed in the measure which most clearly indicates size-specific suppression ($\overline{\text{N110}}$); P220, which indicates size-specific interocular suppression, fails to show the nonspecific suppressing effects of pattern. The separability of the three effects with respect to VEP

components suggests separable neural mechanisms of interocular suppression, one with respect to luminance, one to pattern which is nonselective, and a third mechanism which suppresses similar patterns.

Physiological Bases of the Effects

Binocularly activated cortical neurons (Hubel & Wiesel, 1962, 1968) as opposed to binocularly activated LGN neurons (Sanderson, Bishop, & Darian-Smith, 1971; Bishop, 1973) most likely account for the interocular effects of luminance, increasing element size, and size-specific VEP amplitude reduction (see Harter, 1977; Harter, Towle, & Musso, 1976; Harter, Musso, & Salmon, 1974; Harter, Conder, & Towle, Note 2). The mechanisms by which the receptive field properties of binocular cortical neurons create these effects cannot be stated with certainty. Investigations of single cortical neurons have not examined the size-specificity of interocular suppression, the effect of increasing element size, nor the interocular effects of luminance; rather, they have explored position disparity (Hubel & Wiesel, 1962; Barlow, Blakemore, & Pettigrew, 1967; Pettigrew, Nikara, & Bishop, 1968; Bishop, Henry, & Smith, 1971; Minke & Auerbach, 1977; Joshua & Bishop, 1970) and orientation disparity (Nelson, Kato, & Bishop, 1977; Blakemore, Fiorentini, & Maffei, 1972) and postulated their relationship to

stereopsis. Despite their speculative nature, it seems worthwhile to frame hypotheses about the neural basis of the binocular interactions observed in this experiment.

Interocular luminance suppression. Presentation of diffuse light to the nonflashed eye reduced the amplitude of VEPs elicited by a flash relative to the VEP amplitude elicited by that stimulus when the nonflashed eye viewed darkness. Investigations of the properties of single cells in the cat's visual cortex (area 17) suggest a means to account for interocular luminance suppression. The activity of cortical cells is influenced by regions beyond the bounds of the usual receptive fields (unresponsive regions). Stimulation of these regions by diffuse light inhibits the activity of cells (Maffei & Fiorentini, 1976). The unresponsive region, presumably, results from facilitory and inhibitory input to the cell from other cortical cells in a hypercolumn, composed of other cells which respond to stimulation in the same area of visual space (Maffei & Fiorentini, 1976, 1977; Hubel & Wiesel, 1974a, 1974b).

These luminance effects were studied monocularly. However, the majority of cortical cells are binocular with similar receptive fields in each eye (Hubel & Wiesel, 1962, 1968), suggesting that the above properties of cells may be binocular. In other words, diffuse light presented to one eye, presumably, reduces the responsivity of some

binocular cells to patterns presented not only in the one eye receiving diffuse light but from either eye.

Non-neural confounds exist which could account for interocular suppression due to luminance. In general, the accommodation and pupillary dilation of one eye influence that of the other. The luminance in the nonflashed eye provides cues for accommodation and reduced pupillary size. Reduced pupillary size of the flashed eye could reduce the luminance of the flash actually impinging on the retina. Reduced flash luminance decreases VEP amplitude and increases the latency of measures (Regan, 1972). Accommodation varies the refractive power of the eye; the eye's state of refraction alters VEPs to patterned stimuli (Harter & White, 1968). Although the influence of non-neural factors cannot be discounted totally, their impact in the present situation is probably minimal, given that luminance effects similar to those in the present study have been found when artificial pupils were used to control for pupillary size (Harter, Conder, & Towle, Note 2).

Interocular suppression by pattern. There are two interocular suppression effects resulting from the presentation of patterned stimuli to the nonflashed eye, suppression by increasing pattern size and size-specific suppression. It was noted above that the two effects are differentially reflected by VEP measures suggesting different neural bases.

Size-specific interocular suppression. Size-specific interocular suppression measured psychophysically is related to stereoacuity (Ware & Mitchell, 1974) and the interocular suppression of strabismic individuals is feature specific (Schor, 1977) suggesting that size-specific interocular interaction is related to stereopsis.

In the case of VEP measurements, the relationship of interocular size-specific suppression to stereopsis is less clear (see Harter, Towle, Zakzrewski, & Moyer, 1977). Size-specific interocular suppression as measured by the VEP appears to reflect binocular but not necessarily stereoscopic mechanisms. This might be expected from neural physiology.

Stereopsis, presumably, results from activation of binocular cortical cells which are responsive to disparities of horizontal position. In cats, these cells can be found in striate cortex (area 17; Barlow, Blakemore, & Pettigrew, 1967; Blakemore, 1970; Bishop, Henry, & Smith, 1971; Joshua & Bishop, 1970; Blakemore, Maffei, & Fiorentini, 1972; Nelson, Kato, & Bishop, 1977). Unlike cat, primate striate cortical cells do not appear to be disparity detectors. Seventy-seven to eighty percent of primate striate cortical cells (area 17) are binocular (Hubel & Wiesel, 1968; Baker, Grigg, & Von Noorden, 1974), with more complex cells binocular than simple cells--88 percent

and 49 percent, respectively (Schiller, Finlay, & Volman, 1976). Large differences in disparity of stimuli presented to the receptive fields of the two eyes do not lead to changes in the cell's activity (Hubel & Wiesel, 1970). Almost all of the cells in area 18 are binocular (Baker, Grigg, & Von Noorden, 1974; Hubel & Wiesel, 1970; Baizer, Robinson, & Dow, 1977). Most of the binocular cells of area 18 have properties similar to the complex cells of area 17. About 46 percent of the binocular cells are responsive only when stimulated through both eyes. These cells have predominately, though not exclusively, vertical orientations and alter their firing rates as a function of disparities between receptive fields of the two eyes (Hubel & Wiesel, 1970; see Baizer, Robinson, & Dow, 1977).

In summary, the vast majority of size-specific cortical cells are not disparity detectors and, therefore, are not involved in stereopsis; furthermore, the nondisparity detecting, size-specific neurons are closer to the electrode placement used in this and other similar studies, so they would be more clearly represented in the VEP.

Interocular pattern suppression. Suppression by increasing element size is greater in subjects with good stereoacuity; however, it is present in subjects with poor stereoacuity (Harter, Towle, Zakzrewski, & Moyer, 1977). It appears to be less influenced by luminance than is size-

specific suppression in that suppression by increasing pattern element size has been observed in dim light, but size-specific suppression has not (Harter, Towle, Zakzrewski, & Moyer, 1977). Binocular rivalry is a relatively non-selective suppression of input from one eye by disparate input to the other (Blake & Fox, 1974; Schor, 1977), suggesting that suppression by increasing element size may be related to the neural mechanism of rivalry suppression (Harter, Towle, & Musso, 1976). Interocular pattern suppression might result from the sensitivity of binocular unresponsive regions to spatial frequency; the greater the element sizes presented to the unresponsive regions the greater the suppression of a cell's activity to patterns presented in the same eye (Bisti, Clement, Maffei, & Mecacci, 1977; however, see Relationship to size channels below).

In summary, it has been suggested that the three interocular suppression effects observed in the present experiment have different physiological bases. Interocular luminance suppression may be attributable to the suppressing effects of uniform illumination of cells' unresponsive regions on their responsivity. Interocular pattern suppression due to increasing pattern element size may also be accounted for in terms of the characteristics of unresponsive regions. Interocular size-specific suppression is attributable

to the size selectivity of some binocular cells which inhibit their responsivity to stimuli presented in the receptive field of one eye if there is input by the same sized stimulus to the other eye.

Relationship to size channels. A number of investigators have proposed that the visual system may be composed of separate size (or spatial frequency) channels. The fact that intraocular and interocular adaptation to sinusoidal or square-wave gratings is spatial frequency specific supports the hypothesis of spatial frequency (or size) channels in the visual system with a half band width of one octave (Blakemore & Campbell, 1968, 1969; Blakemore & Sutton, 1969; Pantle & Sekuler, 1968). Square-wave stimuli are composed not only of their fundamental frequency but also of their harmonics. If stimuli are bars of equal white and black or checks, their odd harmonics (i.e., third, fifth, etc.) give the stimuli their square-wave appearance (Campbell, Howell, & Robson, 1971). Because any square-wave stimulus has not only the fundamental frequency but its harmonics contained within the pattern, adaptation to a square-wave pattern of one fundamental spatial frequency also adapts the system to the harmonics contained within it (Blakemore & Campbell, 1969; Tolhurst, 1972).

Size-specific interocular suppression may be presumed to result from the activation of binocular size (or spatial

frequency) channels. Interocular suppression by larger sized pattern elements may also have the same explanation, at least in the present experiment. If one assumes the fundamental frequency of the 20' dot pattern to be the fourth harmonic of the 80' dot pattern (1.5 and .375 cycles per degree respectively), then the suppression of the 20' dots may be a special case of the size-specific suppression, which may account for the fact that both types of pattern suppression are moderately related to stereopsis (Harter, Towle, Zakzrewski, & Moyer, 1977).

Interaction of Color and Size Channels

The primary purpose of Experiment 1 was to demonstrate the feasibility of using the color separation method to investigate size-specific binocular interaction. However, the fact that the color separation method yields size-specific interocular suppression of VEP amplitude gives information as to the organization of information processing channels for size and color in the human visual system. If size were binocularly coded within color channels so that for each color there were separate size channels, then presentation of green patterns to one eye would not necessarily cause reduced responsivity to patterns of the same size flashed in red to the other eye. The presence of size-specific interocular suppression in the present

experimental situation suggests that the binocular size channels influenced by the experimental conditions were either not spectrally selective or were activated by both the red and green channels. The most likely interpretation is that the size-specific binocular cells are not spectrally selective. Although several instances of interocular transfer of pattern specific color effects (Sharpe, 1974; Cosgrove, Kohl, Schmidt, & Brown, 1974) may best be explained by the presence of spectral and pattern specificity of individual cortical neurons, the difficulties in finding pattern contingent color after-effects (McCullough, 1965; Helper, 1968; Stromeyer & Mansfield, 1970; Murch, 1972; Stromeyer, 1972; Lovegrove & Over, 1973; Maudarbocus & Ruddock, 1973; but see Mikaelian, 1975; MacKay & MacKay, 1973) and the indications that color differences alone do not yield perceptions of depth (Julesz, 1971, pp. 264-267; Lu & Fender, 1972) suggest that such neurons are rare. In the monkey, some cells are both spectrally and spatially selective (Dow & Gouras, 1973). However, most of the pattern selective cortical cells are either spectrally non-selective (Hubel & Wiesel, 1968, 1974) or receive input from both red and green channels (Dow & Gouras, 1973).

CHAPTER V

EXPERIMENT 2 (INFANT BINOCULAR INTERACTION): METHODS

The binocular interaction of three full-term, normal infants was investigated using visually evoked potentials. Each infant completed at least five replications of the experimental procedure. Efforts to recruit a larger number of subjects were made. Additional mothers willing to participate for the required number of sessions were not located.

Mothers were informed of the purpose of the investigation and of the procedure and were asked to talk to their pediatricians before agreeing to participate in the experiment. Mothers' permissions were received before the infants began the experiment. Mothers served as experimenters so that they might have full knowledge of the experimental procedure and could monitor their own infant's welfare.

The procedure used was exactly the same as in Experiment 1, with the following exceptions:

1. Hypoallergenic tape was used to hold the active electrode approximately 1 cm above the inion.

2. The reference electrode was placed on the left ear.

3. Data were not plotted until the end of the session in order to reduce the length of the session.

4. Stereoacuity and other behavioral measures of visual capacity were not collected prior to the experiment.

5. The infant was placed in an infant seat or held in his mother's arms at approximately a 45-degree angle with the eyes approximately 59 cm from the stimulus display screen. Eye position and activity level were monitored using a closed-circuit television. VEPs were recorded only when the infant was in a quiet, alert state with eyes open and oriented toward the stimuli. When these conditions of eye fixation and alertness were not met, the experimenter pressed a switch which stopped the recording. Pressing the "not looking" button also caused a recycling timer to activate a counter each time it timed out, so that the number of seconds during which the infant did not look could be recorded for each stimulus condition.

6. An assistant and the mother were in the experimental chamber to monitor the infant's state, electrode placement, position of the glasses, and stimulus presentation.

7. A recording session consisted of one block of 32 presentations of each of nine stimulus combinations. The experimental conditions were replicated, counterbalancing for order across sessions. During some sessions control data were collected. If an infant fell asleep or became fussy during a session, recording stopped and began anew another day.

8. Responses were recorded from the right eye rather than the left.

Subjects. The three subjects were JB (male), KW (female), and MO (male). All three were first-borns, judged normal, and their gestational ages were 284, 285, and 285 days at birth. JB participated in five complete replications at 20, 69, 75, 78, and 93 days of age; KW participated in six at 99, 104 (two replications), 110, and 112 (two replications) days of age; MO in ten at 33, 53, 63, 69, 77, 84, 88, 95, 98, and 104 days of age. The average age for each infant was 65, 76, and 107 days respectively. Their average age at testing was 83 days.

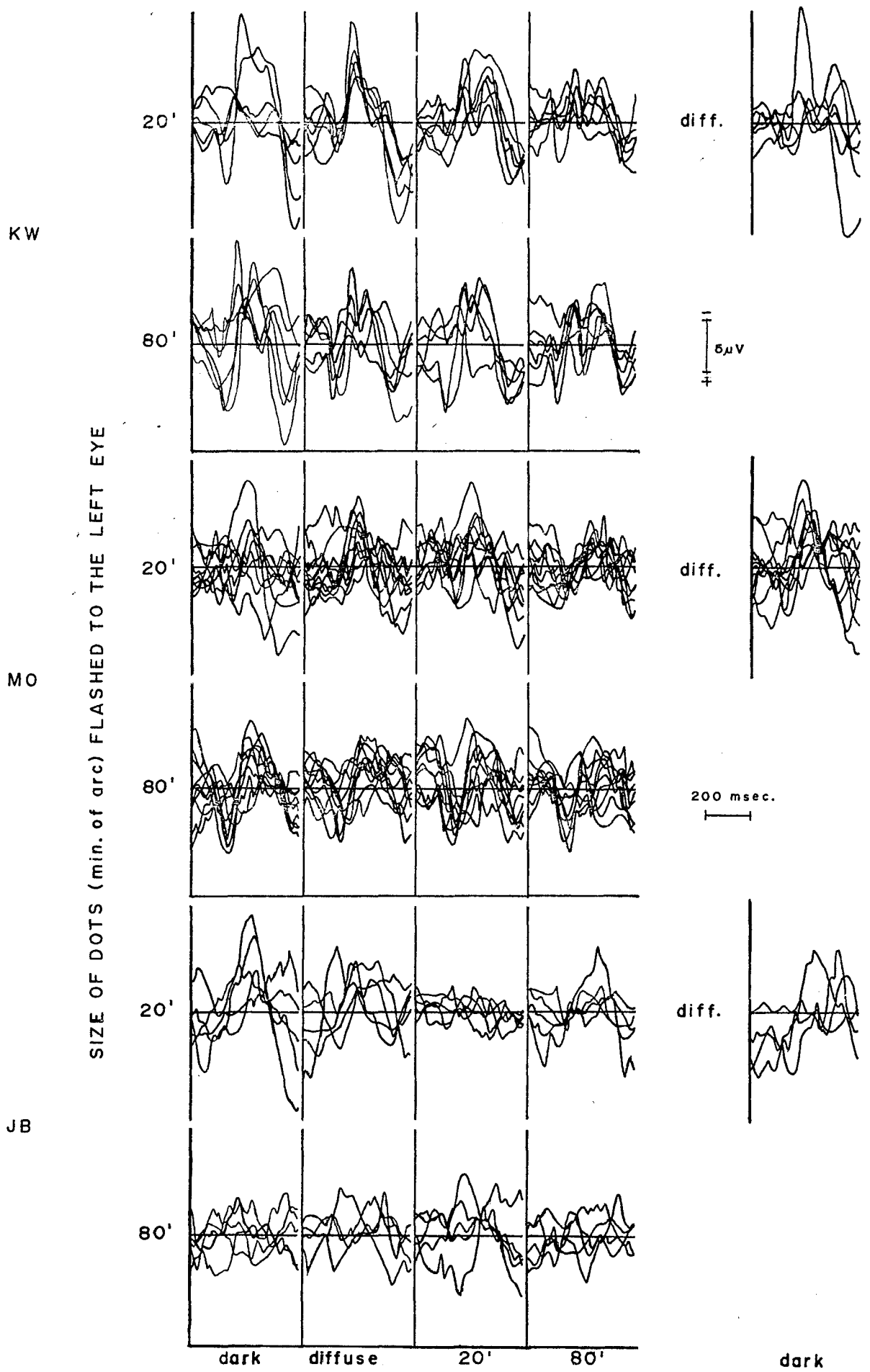
CHAPTER VI

EXPERIMENT 2 (INFANT BINOCULAR INTERACTION): RESULTS

Figure 3 shows the data from the three infants who participated in Experiment 2. Each tracing represents the average of 32 responses to the flashed stimulus. The waveform of the VEPs consisted of three prominent components which were respectively surface-positive, surface-negative, and surface-positive in polarity and had peak latencies at 200-100 msec, 350-200 msec, and 460-400 msec. These components were comparable in polarity and latency to those termed P2, N2-P3-N3 complex, and P4 (Harter & Suitt, 1970; Karmel, Hoffmann, & Fegy, 1974; Harter, Deaton, & Odom, 1977a, 1977b).

The data were quantified by measuring VEP amplitude, in reference to a baseline, at four latencies after trace onset, termed P2, N2, N3, P4 respectively. Baseline was the mean of the most surface-negative and surface-positive points in the entire VEP. Trace onset was approximately 40 msec prior to the flash onset (flash onset being defined as the point where three-fourths of the rise in flash luminance had occurred). Because latencies of P2, N2, N3, and P4 decrease with age (see Harter & Suitt, 1970), for

FIGURE 3: VEPs of Infant Subjects


VEPS OF INFANT SUBJECTS
KW
MO
JB
20'
80'
20'
80'
20'
80'
diff.
diff.
diff.
5μV
200 msec.
SIZE OF DOTS (min. of arc) FLASHED TO THE LEFT EYE
dark
diffuse
20'
80'
dark
STIMULUS PRESENTED CONTINUOUSLY TO THE RIGHT EYE

each of three age levels, an epoch was defined for each component and within the epoch the largest amplitude point was measured. Between 1-45 days the epochs were 120-160 msec (P2), 180-220 msec (N2), 280-320 (N3), and 380-420 (P4); between 46-84 days they were 100-140 msec (P2), 200-220 msec (N2), 300-320 msec (N3), and 380-420 msec (P4); and between 85-112 days they were 60-100 msec (P2), 160-200 msec (N2), 260-300 msec (N3), and 360-400 msec (P4). All latencies were time after flash onset. A fifth VEP measure was total amplitude (TA), which was the sum of the absolute values of the four components. A behavioral measure of looking preference was also calculated, percentage of time looking (PTL) at a stimulus condition. PTL was the amount of time looking (always 34 seconds) divided by the total time in a condition.

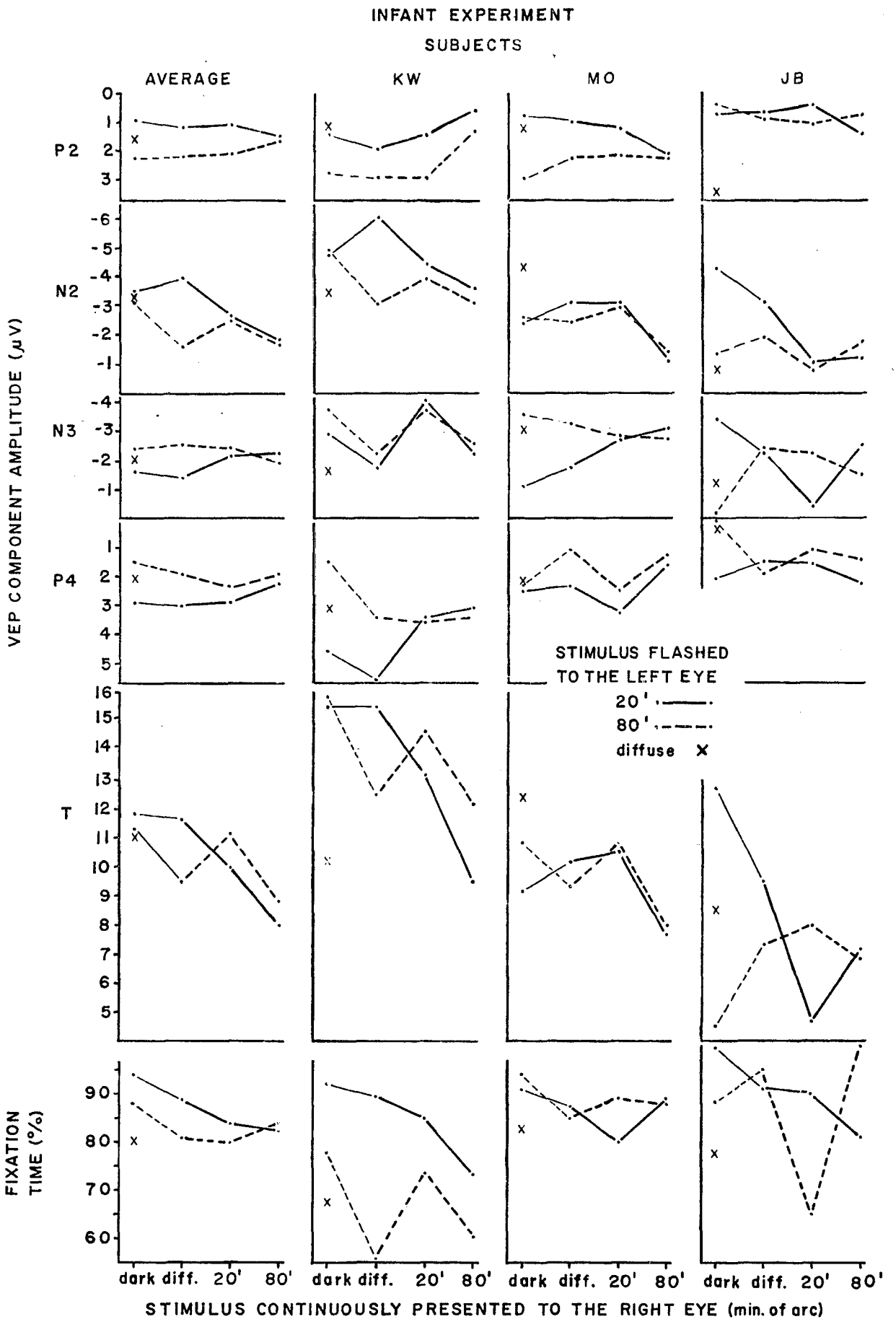
The VEPs presented for JB, MO, and KW in Figure 3 show that the data are variable both between and within subjects. Nonetheless, all three subjects appear to show some reduction of pattern VEPs as luminance is added to the nonflashed eye; also, the presentation of pattern to the nonflashed eye further reduces VEP amplitude to the pattern. Only one of the three subjects, JB, showed evidence of size-specific reduction of VEP amplitude. For JB, pattern VEP were smallest to 20' dots when 20' dots were viewed continuously, and to 80' dots when 80' dots were viewed continuously. JB's

size-specific reduction of VEP amplitude was evidenced during his first session at 20 days. Given that he was the youngest subject, age alone does not appear to account for his difference from the other two subjects.

Graphic presentation of the group mean and individual subject's means for each condition and measure is made in Figure 4. The quantified raw data of these subjects is presented in Appendix D.

Preliminary analyses failed to show an interaction of age with the experimental conditions; therefore, the effects of age on VEP were not examined further statistically. Analyses of variance (ANOVAs) for repeated measures were calculated for each measure to assess treatment effects statistically. Three analyses were performed, an analysis to assess the intraocular effects of pattern in the flashed stimuli when the nonflashed stimulus was darkness; an analysis to examine the interocular effects of changing the continuously viewed stimulus from darkness to diffuse light on VEPs to the dots; and an analysis to examine the interocular effects of changing the continuous stimuli (diffuse light, 20' or 80' dots) on VEPs to dot-patterns. Pooled error terms were used in group analysis if separate error terms estimated the same variance (p of $F > .25$). In addition to the ANOVAs of group data, ANOVAs were also performed on the data of individual subjects using replication x treatment

FIGURE 4: Quantified Means of Infant Subjects


INFANT EXPERIMENT
SUBJECTS
AVERAGE
KW
MO
JB
P2
N2
N3
P4
T
VEP COMPONENT AMPLITUDE (μV)
STIMULUS FLASHED
TO THE LEFT EYE
20'
80'
diffuse
FIXATION
TIME (%)
dark diff. 20' 80'
STIMULUS CONTINUOUSLY PRESENTED TO THE RIGHT EYE (min. of arc)

interactions as the error term. Following ANOVAs, Newman-Keul tests were performed to compare the means. Correlation coefficients were also calculated between all variables as a test for linear trends in the data. These tables are presented in Appendix E.

Intraocular Effects

Group analyses of VEP data failed to detect an effect of flashed stimuli when the nonflashed eye viewed darkness. The behavioral measure, PTL, however, indicated that as a group the infants spent more time looking at the 20' dot pattern (93 percent), then the 80' dots (88 percent), and then the diffuse flash (80 percent; $F=4.26$, $df=2,55$, $p < .03$). Individual subject analyses indicated that N3 amplitude varied with the flashed stimulus for JB ($F=8.9$, $df=2,7$, $p=.01$) and for MO ($F=4.49$, $df=2,17$, $p=.025$). The pattern giving the largest amplitude N3 differed for the two subjects. The 20' dots elicited the greatest N3 amplitude for JB ($p < .05$) and the 80' dots elicited the greatest N3 amplitude for MO ($p < .05$).

Group analyses indicated that the 20' dots elicited a larger amplitude N2 ($F=4.92$, $df=1,73$, $p < .05$) and P4 ($F=3.91$, $df=1,73$, $p < .05$) than elicited by the 80' dots when the continuously viewed stimulus was darkness or diffuse light. Correlation of N2 and P4 amplitude indicated

that each of the three subjects showed the same trend of larger amplitude VEP in response to the smaller dots (N2: Group, r=.20; JB, r=.46, $p < .05$; KW, r=.26; MO, r=.06; P4: Group, r=-.21; KW, r=-.37; JB, r=-.15; MO, r=-.14). MO and KW indicated the opposite trend (i.e., 80' dots elicited the larger amplitude), respectively, for N3 ($F=9.74$, $df=1,9$, $p < .01$) and P2 ($F=6.79$, $df=1,5$, $p < .05$).

Interocular Luminance Effects

Neither group nor individual analyses yielded a statistically significant relationship between VEP amplitude and whether subjects viewed darkness or diffuse light in the nonflashed eye.

Interocular Effects of Pattern

Group analyses indicated that N2 amplitude varied as a function of the main effect of the continuously presented stimulus ($F=4.66$, $df=2,113$, $p < .05$). N2 amplitude correlated positively (i.e., became less negative) with the dot size of the continuous stimulus ($r=.28$, $p < .05$) indicating that N2 decreased in amplitude as dot size increased. All subjects showed the same trend (MO, r=.31, $p < .01$; KW, r=.34; JB, r=.22).

Analysis of group data indicated that P2 amplitude elicited by 20' and 80' flashes interacted with the stimulus

presented continuously to the nonflashed eye ($F=10.62$, $df=2,4$, $p=.025$). Post hoc comparisons of the means were not statistically significant.

CHAPTER VII

EXPERIMENT 2 (INFANT BINOCULAR INTERACTION): DISCUSSION

The present results provide objective electrophysiological evidence of binocular interaction in young infants. Binocular interaction was evidenced by the size-specific interocular suppression and interocular pattern suppression; the P2 amplitude evoked by a particular dot pattern was in general smallest when a pattern composed of the same sized dots was viewed by the other eye, and N2 amplitude evoked by either dot pattern was reduced as the dots of the pattern viewed by the other eye increased in size. In addition, the present results corroborate the findings that infants spend a greater percentage of time fixating flashing patterns than diffuse flashes; that, as predicted, infants of an average age of 2.5 months spend a greater percentage of time looking at patterned flashes comprised of smaller elements (20') than at patterned flashes comprised of larger elements (80'); and that greater amplitude N2 and P4 are evoked by patterns with smaller elements than by patterns with larger elements (Harter, Deaton, & Odom, 1977a, 1977b; see Karmel, Hoffmann, & Negy, 1975). The interocular effects will be discussed separately and in relationship to the development

of binocularity and the intraocular effects will be discussed in relationship to previous investigations of infant pattern VEPs.

Interocular Luminance Suppression

Although the raw data suggest the presence of interocular suppression by luminance, the variability of VEPS in the dark conditions resulted in no statistically significant effect. In discussing the interocular suppressing effects of luminance for adults, both non-neural and neural factors were proposed to account for the data, the non-neural factors being changes in pupillary size and accommodative refractive error and the neural factors being the increased sensitivity of one eye to higher spatial frequencies as a result of increased luminance and the reduction of cellular response rates when unresponsive regions were stimulated by diffuse light. In the case of adults, the neural effects seemed more important. In the infant case, this may not be true. When infants viewed stimuli in darkness, the effects of the flash varied considerably from replication to replication (see Figure 3). Neither effects of age nor attention, as measured by PTF, appear to account for the variability; the inability of infants to maintain consistent accommodation might (see Haynes, White, & Held, 1965). The variability in the dark condition may have obscured an interocular effect of luminance.

Size-Specific Interocular Suppression

Size-specific suppression was presumed, in adults, to derive from binocular neurons, primarily in area 17, having similar receptive fields for each eye. A flashed continuous stimulus interaction was found in infants 20-112 days of age. Visual inspection of JB's data suggest size-specificity, suggesting that the binocular cells in area 17 are present early in postnatal life, perhaps as early as birth, in at least some infants. The presence of binocular neurons in area 17 of one-day-old macaques (Wiesel & Hubel, 1974) lends support to the interpretation of early development of binocular cells. It should be noted, however, that the apparent size-specific suppression was not statistically significant. Neither size-specific suppression of VEPs (Harter, Towle, Zakzrewski, & Moyer, 1976) nor the binocularity of area 17 cells (Hubel & Wiesel, 1970) appears directly related to stereopsis, especially as measured by stereoacuity. Therefore, the presence of these cells would not provide direct evidence of the presence of stereopsis in young infants.

Interocular Pattern Suppression

N2 decreased in amplitude as dot size presented to the nonflashed eye increased. The trend was present in all three subjects.

The interocular suppression due to increased pattern element size in the nonflashed eye was presumed in adults to result from the activity of inhibitory unresponsive regions. The unresponsive regions are present in both simple and complex cells in adult cats (Bisti, Clement, Maffei, & Mecacci, 1977).

An alternative explanation, which could not be entirely excluded in the present experiment, was that suppression by increasing pattern element size is an artifact of the use of square-wave patterns, in which case suppression of patterns with smaller elements by patterns with larger elements is a special case of size-specific suppression. The harmonics contained within the larger elements suppress the patterns with smaller elements which are within their spatial frequency channel.

A number of non-neural factors might account for the interocular effect of pattern size, namely intraocular suppression effects, poor contrast sensitivity, differential attention to continuous patterns of larger element size, and differential accommodation. Intraocular suppression might affect the results by means of the leakage of light or the visibility of patterns flashed to one eye, but, as a result of head position, is visible around the green lens to the nonflashed eye. The leakage of light is almost certain to have occurred but, especially in conditions where continuous

stimulation was present, the magnitude of light leakage seems unlikely to have created the effects. The leakage of flashed pattern stimulation is less likely. Cotton was placed over the bridge of the nose to prevent the infants peeking at the flashed or continuous stimuli with the inappropriate eye. In any case, to observe the flashed stimuli with the nonflashed eye or the continuous stimulus with the flashed eye would have required a major alteration in the infants' head positions, a change which the experimenter, the observer, or the mother would have noted, resulting in a cessation of the experiment. Therefore, intraocular effects are an unlikely explanation of the observed effects, although they cannot be totally excluded.

It is known that the contrast sensitivity of infants is less than that of adults (Atkinson & Braddick, 1976) and that smaller stimuli compared to larger stimuli of the same contrast have less subjective contrast as evidenced by their reduced detectability; they appear less sharp. Infants in the age range of this study frequently prefer to look at stimuli larger than 20' (Karmel & Maisel, 1975).

If infants attended more to patterns of increasing size, their response to the flashed stimuli might have been reduced. Infant PTF, the behavioral index of attention, was not related to the pattern size of the continuous stimulus ($r=-.04$, $p > .05$), although it was significantly related to N2 magnitude ($r=-.19$, $p < .05$), indicating that the infants

looked less at the stimulus combinations which elicited reduced N2 amplitude. Attention to the continuous pattern does not seem to account for the data, rather conditions yielding VEP suppression were less preferred by the infants.

Conclusion

Neural factors appear to account for the pattern size suppression evidenced by the VEP data. Non-neural factors may account for the absence of interocular luminance suppression. Size-specific suppression appears to reflect the early development of binocular cells in area 17.

Relationship to a Critical Period for the Development of Binocularity

In cats (Wiesel & Hubel, 1965b), monkeys (Baker, Grigg, & Von Noorden, 1974), and humans (Hickey, 1977; Banks, Aslin, & Letson, 1975; Hohman & Creutzfeldt, 1975) there is a proposed critical period for the development of binocularity. Estimation of the critical period is based on susceptibility to loss of binocularity and ability to recover from the effects of trauma which otherwise would result in the loss of binocularity. In the case of animals, the most frequently studied preparation is a monocular deprivation (MD) resulting from suturing the lids of one eye together. In the LGN, Y-cells are more affected by MD in the cat (Sherman, Hoffman, & Stone, 1972; Sherman, Wilson, & Guillery, 1975; Garey &

Blakemore, 1977b), tree shrews (Norton, Casagrande, & Sherman, 1977) and monkeys (see Von Noorden & Middleditch, 1975) than are other cell types, perhaps because they are less mature (Norman, Pettigrew, & Daniels, 1977; Rusoff & Dubin, 1977; Hickey, 1977). Y-cell loss in MD occurs concurrently with the loss of binocularity in cortical cells (Hubel & Wiesel, 1965; Wiesel & Hubel, 1965a, 1965b) and complex cells appear more affected by MD than simple cells (Wilson & Sherman, 1977). Experiments proposing a parallel processing model of the visual system suggest that complex cells receive input from Y-cells (Hoffmann & Stone, 1971; Stone & Dreher, 1973).

In cats, the most studied species, the onset of the critical period coincides with a) the clearing of the ocular media, so that the optics of the eye are relatively good (Thorn, Collender & Erickson, 1976); b) the emergence of relatively mature LGN cells, especially X-cells, whose extent of excitatory input corresponds with that of the adult (Ruskoff & Dubin, 1977); and c) the termination of a period of maximal LGN cell growth (Garey, Fisken, & Powell, 1973) and synapse formation in the LGN and cortex (Cragg, 1975). In cats, the end of the critical period a) coincides with the attainment of adult visual acuity (Marg & Freeman, 1975; Mitchell, Giffin, Wilkinson, Anderson, & Smith, 1976); b) coincides with the cessation of LGN cellular growth (Garey, Fisken, & Powell, 1973), and c) follows the emergence of "normal" interocular alignment (Sherman, 1972).

Human infants are born with clear ocular media. The most rapid growth of the LGN ceases at six months and twelve months for the parvocellular (X-cell) and magnocellular (Y-cell) layers, respectively (Hickey, 1977). A divergent strabismus is present at birth (Maurer, 1975; see Bower, 1975; Slater & Findlay, 1975). The fact that the eyes must shift position dramatically during development suggests that either the usual mechanisms of fusion would be inoperative or that cells' receptive field characteristics would have to be loosely tuned (see Bower, 1975), which is true in kittens (Barlow & Pettigrew, 1971; Imbert & Buisseret, 1975). Cellular growth continues in the human LGN until approximately 24 months of age (Hickey, 1977).

Based on these anatomical considerations and comparisons with the cat's critical period for the development of binocularity, one would propose that the beginning of the human critical period begins at around six months of age and continues until the end of the second year. This estimation agrees well with estimates of the critical period based on records of the onset of and recovery from strabismus (Banks, Aslin, & Letson, 1975; Hohman & Creutzfeldt, 1975). It does not agree well with an estimate of the critical period based on VEP studies of visual acuity development in infants (Marg, Freeman, Peltzman, & Goldstein, 1976). However, in estimating visual acuity, one attempts to find the

minimal resolvable pattern size. Simple cells have smaller receptive field sizes and resolve higher spatial frequencies than complex cells (Schiller, Finlay, & Volman, 1976), suggesting that they are important in estimates of acuity. LGN X-cell development appears to coincide well with the development of infant acuity; both mature at about six months of age. In infants, attaining adult visual acuity may indicate the beginning of the critical period, not its end.

The results of the present experiment provide no direct evidence regarding the beginning or ending of the critical period because no developmental trends were observable in the data. This absence of change is more understandable, however, if one assumes that the critical period begins only at the end of the first half-year of life.

Relationship to Previous Research

Intraocular effects. When infants viewed the flashed stimuli in darkness, they preferred to look at flashes in the order of 20' dots, 80' dots, and diffuse light, indicating that infants could discriminate the stimuli from one another. Visual preference was not significantly correlated with VEP amplitude, possibly because VEPs were very variable when the nonflashed eye viewed darkness. When the nonflashed eye viewed either darkness or diffuse light, 20' flashes elicited greater N2 and P4 amplitude than 80' flashes.

Other investigations using flashed stimuli have found that pattern affected the amplitude of P2, N2, and P4. P2 and N2 amplitudes in infants 45 days or less were evoked by small stimuli (11' or 22'; Harter, Deaton, & Odom, 1977b; but see Hoffmann, 1978). In infants older than 45 days, P2 and N2 amplitudes have been to larger stimuli, the size of the stimulus evoking the greatest amplitude decreasing with age (Karmel, Hoffmann, & Fegy, 1975; Hoffmann, 1978; Harter & Suitt, 1970). P4 amplitude, while not affected by pattern during the first month, is affected by patterns greater than 1^{o} during the second month (Harter, Deaton, & Odom, 1977b; also see Hoffmann, 1978). Presumably, smaller sizes evoke maximal P4 amplitude with age (see Harter, Deaton, & Odom, 1977b). The greater amplitude of P4 and N2 to the 20' dot patterns, when VEPs are combined across light and dark conditions, is consistent with the findings of the others cited above.

When the nonflashed eye viewed darkness, the flashed stimuli did not consistently differentially affect VEP amplitude. Infant VEPs vary from replication to replication, especially in the dark condition (see Figure 3). The variability could derive from three sources: accommodation, attention, or lack of binocular stimulation. 1) In the dark condition, infants may have had a difficult time maintaining accommodation; consequently,

both within and between trials infants' refractive error and the stimulus clarity would vary. 2) Without a constant stimulus to fixate, infants may have had a difficult time attending to the flash. The behavioral data suggest that this would be particularly true of the diffuse flash. Infants are not particularly attentive to unpatterned visual stimuli (see Fantz, Fagan, & Miranda, 1975; Salapatek, 1975; Harter, Deaton, & Odom, 1977a, 1977b). 3) Lastly, in adult cats the neural response to monocular stimulation is more variable than binocular stimulation (Crawford & Cool, 1970) which could cause a more variable VEP. Variability in infants' individual VEPs is correlated with reduced amplitude of average VEPs (Harter & Suitt, 1970).

Relationship to cortical and subcortical development. Prior investigations of VEPs elicited by patterned light have had one of two purposes, the measurement of basic sensory capacities or studying the relationship of VEP amplitude and pattern preferences. The nature of infant pattern preferences changes dramatically during the second postnatal month (see Fantz, Fagan, & Miranda, 1975; Salapatek, 1975) prompting several authors to propose that during the second month the infant's primary visual system (geniculostriate system or cortical system) becomes functional in controlling visual preferences (Bronson, 1973; see Salapatek, 1975). Changes in the relationship of VEP components to visual

preferences have led to proposals that prior to the second month control of visual behavior is controlled by subcortical structures; subsequently, control is cortical (Harter, Deaton, & Odom, 1977a, 1977b; Karmel & Maisel, 1975; Hoffmann, Note 3, 1978).

The nature of hypotheses about the relationship of VEP components to cortical and subcortical structures and the nature of those structures differs, however. Karmel and his colleagues have proposed that in infants 55-107 days of age, P2 reflects the activity of the visual cortex and that P4 represents the activity of subcortical structures, possibly the pulvinar or cortical activity elicited by that structure. The mathematical estimates of younger infants' (second month) pattern preference in behavioral studies coincide with mathematical estimates relating P4 amplitude to stimulus size for infants having longer P2 latency (neurally younger infants); mathematical estimates relating P2 amplitude to pattern size for infants having longer P2 latency were similar to estimates of older infants' (fourth month) visual preferences. P4 amplitude was greatest to 40' and 5° checks for the neurally younger and older groups respectively. P2 was quantified in two ways, by means of fixed latency determined from group VEPs and by means of visual identification of components. P2 amplitude was greatest to 5° patterns for the younger group and 40' for the neurally

older group, as identified by fixed latency. The visual inspection procedure indicated that the greatest P2 amplitude for both groups was elicited to 80' patterns (Hoffmann, Note 3, 1978).

Harter, Deaton, and Odom (1977a) based on data from infants 6-45 days of age proposed that P2 amplitude reflected the activity of neurons tuned to higher spatial frequencies and that P4 reflected the activity of neurons tuned to lower spatial frequencies. P2 was unrelated to infants' visual preferences in the experiment, while P4 was related to the visual preferences of infants in the older (21-45 days) group. Because of their relationship to visual behavior, it was proposed that P2 reflected subcortical activity and P4 reflected cortical activity. Hoffmann's failure to find a relationship between P2 amplitude and pattern was attributed to his failure to use smaller check sizes (11' or 22').

The present study used a smaller dot size (20') and a larger dot size (80'). Infants were approximately the same age as in Hoffmann's study (20-112 days in the present study). ANOVAs indicated that P4 amplitude was larger to 20' than to 80' dot flashes. Correlations indicated the same trend for P4 ($r=-.21$, $p < .01$) and that P2 amplitude was correlated with large dot sizes ($r=.27$, $p < .01$). The two older infants showed the same relationship of P2 to dot size, while the

younger showed no relationship (MO, r=39, $p < .01$; KW, r=.26; JB, r=-.02). The pattern size eliciting the greatest P2 amplitude is exactly the same in the present study and in Hoffmann's when comparable methods of data quantification were used.

In the present study, P2 and P4 appear to reflect the activity of two separate populations of neurons, tuned to large and small dot sizes respectively. The concept of two separate neuronal populations is supported by the divergent relationships of N2 and N3 amplitudes to dot size and the relationship of the four components to one another. N2 amplitude is greater to the small dot flashes and N3 amplitude to the larger. P2 and N3, N2 and P4, and N2 and N3 are correlated (r=-.49; r=-.79; r=.37, respectively), indicating that N2 and P4 amplitudes are very much influenced by the same process and that N3 is influenced by two processes, one reflected by P2 and the other by N2.

The concept of separate neural populations in the cortex may be a more fruitful approach in explaining the relationships of P2 and P4, than a cortical subcortical dichotomy. In either case, the fact that at less than 45 days of age P2 gives a peak response to patterns of 22.5' and at greater ages to patterns of about 80' is puzzling.

Another approach to the question of cortical versus subcortical origin of P2 might be the presence of binocular

interaction. The fact that P2 may reflect binocular interaction would argue for its probable cortical origin. However, recent evidence that the superior colliculus of primates has binocular cells in the superficial layers which do not depend on the cortex for their binocularity (Schiller, Stryker, Cynander, & Berman, 1974) and that the ocular dominance columns of the colliculus reach maturity prior to those of the cortex in monkeys (Rakic, 1976, 1977) indicates the possibility that P2 reflects the activity of the superior colliculus.

In summary, the results of the present study are consistent with those of previous infant VEP research. The data of the present study do not conclusively indicate the origin of P2 and P4.

BIBLIOGRAPHY

REFERENCE NOTES

1. Crawford, M. L. J., & Blake, R. Striate neuron profile of the infant macaque. Unpublished manuscript, 1975. Available from Department of Psychology, University of Texas at Houston.

2. Harter, M. R., Conder, E. S., & Towle, V. L. Orientation-specific interocular suppression of visual evoked potentials in man. Manuscript submitted for publication, 1978.

3. Hoffmann, R. F. Developmental changes in human infant VEPs to patterned stimuli at different scalp locations and their relationship to visual attention. Unpublished doctoral dissertation. University of Connecticut. Storrs, Conn., 1973.

4. Towle, V. L. The binocular interaction of size and orientation channels: Evoked potentials and observer sensitivity. Unpublished doctoral dissertation. University of North Carolina. Greensboro, N. C., 1978.

REFERENCES

Abadi, R. V. Induction masking: A study of some inhibitory interactions during dichoptic viewing. Vision Research, 1976, 16, 269-275.

Appel, M. A., & Campos, J. J. Binocular disparity as a discrete stimulus parameter for young infants. Journal of Experimental Child Psychology, 1976, 23, 47-56.

Armington, J. C., Corwin, T. R., & Marsetta, R. Simultaneously recorded retinal and cortical responses to patterned stimuli. Journal of the Optical Society of America, 1971, 61, 1514-1521.

Armington, J. C., Gaardner, K., & Schick, A. M. L. Variation of spontaneous ocular and occipital responses with stimulus patterns. Journal of the Optical Society of America, 1967, 57, 1534-1539.

Aslin, R. N. Development of binocular fixation in human infants. Journal of Experimental Child Psychology, 1977, 23, 133-150.

Atkinson, J., & Braddick, O. J. Stereoscopic discrimination in infants. Perception, 1976, 5, 29-38.

Atkinson, J., Braddick, O., & Moar, K. Development of contrast sensitivity over the first three months of life in the human infant. Vision Research, 1977, 17, 1037-1044. (a)

Atkinson, J., Braddick, O., & Moar, K. Contrast sensitivity of the human infant for moving and static patterns. Vision Research, 1977, 17, 1045-1047. (b)

Baizer, J. S., Robinson, D. L., & Dow, B. M. Visual responses of area 18 neurons in awake, behaving monkey. Journal of Neurophysiology, 1977, 40, 1024-1037.

Baker, F. H., Grigg, P., & Von Noorden, G. K. Effects of visual deprivation and strabismus on the response of neurons in the visual cortex of the monkey, including studies on the striate and prestriate cortex in the normal animal. Brain Research, 1974, 66, 185-208.

Banks, M. S. Visual acuity development in human infants: A re-evaluation. Investigative Ophthalmology, 1977, 16, 191-192.

Banks, M. S., Aslin, R. N., & Letson, R. D. Sensitive period for the development of human binocular vision. Science, 1975, 190, 675-677.

Banks, M. S., & Salapatek, P. Contrast sensitivity function of the infant visual system. Vision Research, 1976, 16, 867-869.

Barlow, H. B., Blakemore, C., & Pettigrew, J. D. The neural mechanism of depth discrimination. Journal of Physiology, 1967, 193, 327-342.

Barlow, H. B., & Pettigrew, J. D. Lack of specificity of neurons in the visual cortex in the cat. Journal of Physiology, 1971, 218, 98 pp.

Bishop, P. O. Neurophysiology of binocular single vision and stereopsis. In R. Jung (Ed.), Handbook of sensory physiology. 3A: Central processing of vision information. New York: Springer-Verlaz, 1973.

Bishop, P. O., Henry, G. H., & Smith, C. J. Binocular interaction fields of single units in the cat striate cortex. Journal of Physiology, 1971, 216, 39-68.

Bisti, S., Clement, R., Maffei, L., & Mecacci, L. Spatial frequency and orientation tuning curves of visual neurons in the cat: Effects of mean luminance. Experimental Brain Research, 1977, 27, 335-345.

Bisti, S., & Sireteanu, R. C. Sensitivity to spatial frequency and contrast of visual cells in the cat superior colliculus. Vision Research, 1976, 16, 247-251.

Blake, R., & Fox, R. Interocular transfer of adaptation to spatial frequency during retinal ischaemia. Nature, 1972, 240, 76-77.

Blake, R., & Fox, R. Binocular rivalry suppression: Insensitive to spatial frequency and orientation change. Vision Research, 1974, 14, 687-692.

Blake, R., & Hirsch, H. V. B. Deficits in binocular depth perception in cats after alternating monocular deprivation. Science, 1975. 190, 1114-1116.

Blake, R., & Levinson, E. Spatial properties of binocular neurons in the human visual system. Experimental Brain Research, 1977, 27, 221-232.

Blakemore, C. The representation of three-dimensional visual space in the cat's striate cortex. Journal of Physiology, 1970, 209, 155-178.

Blakemore, C. Developmental factors in the formation of feature extracting neurons. In F. O. Schmitt and F. G. Warden (Eds.), The neurosciences: Third study program. Cambridge: The MIT Press, 1974.

Blakemore, C. The conditions required for the maintenance of binocularity in the kitten's visual cortex. Journal of Physiology, 1976, 261, 423-444.

Blakemore, C. Genetic instructions and developmental plasticity in the kitten's visual cortex. Philosophical Transactions of the Royal Society of London. B. 1977, 278, 425-434.

Blakemore, C., & Campbell, F. W. Adaptation to spatial stimuli. Journal of Physiology, 1968, 200, 11.

Blakemore, C., & Campbell, F. W. On the existence of neurons in the human visual system selectively sensitive to the orientation and size of retinal images. Journal of Physiology, 1969, 203, 237-260.

Blakemore, C., Fiorentini, A., & Maffei, L. A. A second neural mechanism of binocular depth discrimination. Journal of Physiology, 1972, 226, 725-740.

Blakemore, C., & Sutton, P. Size adaptation: A new aftereffect. Science, 1969, 166, 245-247.

Blakemore, C., & Van Sluythers, R. C. Innate and environmental factors in the development of the kitten's visual cortex. Journal of Physiology, 1975, 248, 663-716.

Boring, E. G. Sensation and perception in the history of experimental science. New York: Appleton Century, 1942.

Bough, E. W. Stereoscopic vision in the macaque monkey: A behavioural demonstration. Nature, 1970, 225, 42-440.

Bower, T. G. R. Stimulus variables determining space perception in infants. Science, 1965, 149, 88-89.

Bower, T. G. R. Morphogenetic problems in space perception. In D. A. Hamburg, K. Pribram, & A. J. Stunkard (Eds.), Perception and its disorders. Research Publications Association for Research in Nervous and Mental Disease. Vol. 48. Baltimore, Maryland: Williams and Wilkins, 1970.

Bower, T. G. R. The object in the world of the infant. Scientific American, 1971, 225(4), 30-38.

Bower, T. G. R. Infant perception of the third dimension and object concept development. In L. Cohen and P. Salapatek (Eds.), Infant perception: From sensation to cognition. II. Perception of space, speech, and sound. New York: Academic Press, 1975.

Bower, T. G. R., Broughton, J. M., & Moore, M. K. The coordination of visual and tactual input in infants. Perception and Psychophysics, 1970, 8, 51-53. (a)

Bower, T. G. R., Broughton, J. M., & Moore, M. K. Demonstration of intention in the reaching behaviour of neonate humans. Nature, 1970, 228, 679-681. (b)

Bronson, G. The postnatal development of visual capacity. Child Development, 1974, 45, 873-890.

Buisseret, P., & Imbert, M. Visual cortical cells: Their developmental properties in normal and dark reared kittens. Journal of Physiology, 1976, 255, 511-525.

Campbell, F. W., & Green, D. G. Monocular versus binocular visual acuity. Nature, 1965, 208, 191-192.

Campbell, F. W., Howell, E. R., & Robson, J. G. The appearance of gratings with and without the fundamental Fourier component. Journal of Physiology, 1971, 217, 17.

Conel, J. L. The postnatal development of the human cerebral cortex. Vol. I-III. Cambridge: Harvard University Press, 1939-1947.

Cosgrove, M. P., Kohl, G. A., Schmidt, M. J., & Brown, D. R. Chromatic substitution with stabilized images: Evidence for chromatic-specific pattern processing in the human visual system. Vision Research, 1974, 14, 23-30.

Cragg, B. C. The development of synapses in the visual system of the cat. Journal of Comparative Neurology, 1975, 160, 147-166.

Crawford, M. I. J., Blake, R., Cool, S. J., & Von Noorden, G. K. Physiological consequences of unilateral and bilateral eye closure in macaque monkeys: Some further observations. Brain Research, 1975, 84, 150-154.

Crawford, M. L. J., & Cool, S. J. Binocular stimulation and response variability of striate cortex units in the cat. Vision Research, 1970, 10, 1145-1153.

Daitch, J. M., & Green, D. G. Contrast sensitivity of the human peripheral retina. Vision Research, 1969, 9, 947-952.

Dow, B. M., & Gouras, P. Color and spatial specificity of single units in rhesus monkey striate cortex. Journal of Neurophysiology, 1973, 36, 79-100.

Ellingson, R. J. The study of brain electrical activity in infants. In L. P. Lipsitt and C. C. Spiker (Eds.), Advances in child development and behavior. Vol. 3. New York: Academic Press, 1967.

Erickson, R. P. Stimulus coding in topographic and non-topographic afferent modalities. Psychological Review, 1968, 75, 447-465.

Erickson, R. P. Parallel "population" neural coding in feature extraction. In F. O. Schmitt and F. G. Worden (Eds.), The neurosciences: Third study program. Cambridge: The MIT Press, 1974.

Fantz, R. L. A method for studying depth perception in infants under six months of age. Psychological Record, 1961, 11, 27-32.

Fantz, R. L. Visual perception from birth as shown by pattern selectivity. Annals of the New York Academy of Sciences, 1965, 118, 793-814.

Fantz, R. L. Pattern discrimination and selective attention as determinants of perceptual development from birth. In A. H. Kidd and J. L. Riviore (Eds.), Perceptual development in children. New York: International Universities Press, 1966.

Fantz, R. L., Fagan, J. F., III, & Miranda, S. B. Early visual selectivity. In L. B. Cohen and P. Salapatek (Eds.), Infant perception: From sensation to cognition. Vol. 1. Basic visual processes. New York: Academic Press, 1975.

Fiorentini, A., & Maffei, L. Contrast in night vision. Vision Research, 1973, 13, 73-80.

Fox, R., & Blake, R. R. Stereoscopic vision in the cat. Nature, 1971, 233, 55-56.

Fox, R., Lehmkuhle, S. W., & Bush, R. C. Stereopsis in the falcon. Science, 1977, 197, 79-80.

Freeman, D. N., & Marg, E. Visual acuity development coincides with the sensitive period in kittens. Nature, 1975, 254, 614-615.

Garey, L. J., & Blakemore, C. Monocular deprivation: Morphological effects on different classes of neurons in the lateral geniculate nucleus. Science, 1977, 195, 414-416. (a)

Garey, L. J., & Blakemore, C. The effects of monocular deprivation on different neuronal classes in the lateral geniculate nucleus of the cat. Experimental Brain Research, 1977, 28, 259-278. (b)

Garey, L. J., Fisken, R. A., & Powell, T. P. S. Observations on the growth of the cells in the lateral geniculate nucleus of the cat. Brain Research, 1973, 52, 359-362.

Gordon, F. R., & Yonas, A. Sensitivity to binocular depth information in infants. Journal of Experimental Child Psychology, 1976, 22, 413-422.

Graham, N. Spatial frequency channels in the human visual system: Effects of luminance and pattern drift rate. Vision Research, 1972, 12, 53-68.

Gstalder, R. J., & Green, D. G. Laser interferometric acuity in amblyopia. Journal of Pediatric Ophthalmology, 1971, 8, 251-265.

Harter, M. R. Evoked cortical responses to checkerboard patterns: Effects of check size as a function of retinal eccentricity. Vision Research, 1970, 10, 1365-1376.

Harter, M. R. Visually evoked cortical responses to the on- and off-set of patterned light in humans. Vision Research, 1971, 11, 685-695.

Harter, M. R. Binocular interaction: Evoked potentials to dichoptic stimulation. In J. E. Desmedt (Eds.), Visual evoked potentials in man: New developments. Oxford: Oxford University Press, 1977.

Harter, M. R., Deaton, F. K., & Odom, J. V. 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, 1977, 42, 595-607. (a)

Harter, M. R., Deaton, F. K., & Odom, J. V. Pattern visual evoked potentials in infants. In J. E. Desmedt (Ed.), Visual evoked potentials in man: New developments. Oxford: Clarendon Press, 1977. (b)

Harter, M. R., Seiple, W. H., & Musso, M. Binocular summation and suppression: Visually evoked cortical responses to dichoptically presented patterns of different spatial frequencies. Vision Research, 1974, 14, 1169-1180.

Harter, M. R., & Suitt, C. D. Visually evoked cortical responses and pattern vision in the infant: A longitudinal study. Psychonomic Science, 1970, 18, 235-237.

Harter, M. R., Towle, V. L., & Musso, M. F. Size specificity and interocular suppression: Monocular evoked potentials and reaction times. Vision Research, 1976, 16, 1111-1117.

Harter, M. R., Towle, V. L., Zakzrewski, M., & Moyer, S. M. An objective indicant of binocular vision in humans: Size-specific interocular suppression of visual evoked potentials. Electroencephalography and Clinical Neurophysiology, 1977, 43, 825-836.

Harter, M. R., & White, C. T. Effects of contour, sharpness and check-size on visually evoked cortical patterns. Vision Research, 1968, 8, 701-711.

Harter, M. R., & White, C. T. Evoked cortical responses to checkerboard patterns: Effect of check-size as a function of visual acuity. Electroencephalography and Clinical Neurophysiology, 1970, 28, 48-54.

Haynes, H., White, B. L., & Held, R. Visual accommodation in human infants. Science, 1965, 148, 528-530.

Helper, N. Color: A motion-contingent aftereffect. Science, 1968, 162, 376-377.

Hess, R. F., & Howell, E. R. The threshold contrast sensitivity function in strabismic amblyopia: Evidence for a two type classification. Vision Research, 1977, 17, 1049-1055.

Hickey, T. L. Postnatal development of the human lateral geniculate nucleus: Relationship to a critical period for the visual system. Science, 1977, 198, 836-838.

Hochberg, J. Nativism and empiricism in perception. In L. Postman (Ed.), Psychology in the making. New York: Knopf, 1962.

Hoffmann, K. P. Receptive fields in the cat's superior colliculus after early monocular deprivation. Brain Research, 1974, 66, 360.

Hoffmann, K. P., & Sherman, S. M. Effects of early monocular deprivation on visual input to cat superior colliculus. Journal of Neurophysiology, 1974, 37, 1276-1286.

Hoffmann, K. P., & Stone, J. Conduction velocity of afferents to cat visual cortex: A correlation with cortical receptive field properties. Brain Research, 1971, 32, 460-466.

Hoffmann, R. F. Developmental changes in human infant visual-evoked potentials to patterned stimuli recorded at different scalp locations. Child Development, 1978, 49, 110-118.

van Hof-van Duin, J. Pattern discrimination and visuomotor behaviour after monocular visual deprivation in cats. Brain Research, 1974, 66, 359.

Hohman, A., & Creutzfeldt, O. D. Squint and the development of binocularity in humans. Nature, 1975, 254, 613-614.

Hubel, D. H., & Wiesel, T. N. Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. Journal of Physiology, 1962, 160, 106-154.

Hubel, D. H., & Wiesel, T. N. Binocular interaction in striate cortex of kittens reared with artificial squint. Journal of Neurophysiology, 1965, 28, 1041-1059.

Hubel, D. H., & Wiesel, T. N. Receptive fields and functional architecture of monkey striate cortex. Journal of Physiology, 1968, 195, 215-243.

Hubel, D. H., & Wiesel, T. N. The period of susceptability to the physiological effects of unilateral eye closure in kittens. Journal of Physiology, 1970, 206, 419-436.

Hubel, D. H., & Wiesel, T. N. Sequence regularity and geometry of orientation columns in the monkey striate cortex. Journal of Comparative Neurology, 1974, 158, 267-294. (a)

Hubel, D. H., & Wiesel, T. N. Uniformity of monkey cortex: A parallel relationship between field size, scatter and magnification factor. Journal of Comparative Neurology, 1974, 158, 295-305. (b)

Hubel, D. H., Wiesel, T. N., & LeVay, S. Plasticity of ocular dominance columns in monkey striate cortex. Philosophical Transactions of the Royal Society of London. B. 1977, 278, 377-409.

Imbert, M., & Buisseret, P. Receptive field characteristics and plastic properties of visual cortical cells in kittens reared with and without visual experience. Experimental Brain Research, 1975, 22, 25-36.

Joshua, D. E., & Bishop, P. O. Binocular single vision and depth discrimination. Receptive field disparities for central and peripheral vision and binocular interaction on peripheral single units in cat striate cortex. Experimental Brain Research, 1970, 10, 389-416.

Julesz, B. Foundations of cyclopean perception. Chicago: University of Chicago Press, 1971.

Karmel, B. Z., Hoffmann, R. F., & Fegy, M. J. Processing of contour information by human infants evidenced by pattern-dependent evoked potentials. Child Development, 1974, 45, 39-48.

Karmel, B. Z., & Maisel, E. B. A neuronal activity model for infant visual attention. In L. B. Cohen and P. Salapatek (Eds.), Infant perception: From sensation to cognition. I. Basic visual processes. New York: Academic Press, 1975.

Kelly, D. H. Adaptation effects on spatio-temporal sine-wave thresholds. Vision Research, 1972, 12, 89-102.

Larsen, J. S. The sagittal growth of the eye. IV. Ultrasonic measurement of the axial length of the eye from birth to puberty. Acta Ophthalmologica, 1971, 49, 873-886.

Lee, D. N. Theory of the stereoscopic shadow-caster: An instrument for the study of binocular kinetic space perception. Vision Research, 1969, 9, 145-156.

Le Grand, Y. [Form and space vision] (M. Millodot and G. C. Heath, Trans.). Bloomington, Indiana: Indiana University Press, 1967.

Lehmann, D., Beeler, G. W., & Fender, D. H. EEG responses to light flashes during the observation of stabilized and normal retinal images. Electroencephalography and Clinical Neurophysiology, 1967, 22, 136-142.

Lehmann, D., & Fender, D. Monocularly evoked electroencephalogram potentials: Influence of target structure presented to the other eye. Nature, 1967, 215, 204-205.

Lehmann, D., & Fender, D. H. Component analysis of human averaged evoked potentials dichoptic stimuli using different target structure. Electroencephalography and Clinical Neurophysiology, 1968, 24, 542-553.

Lehmann, D., & Fender, D. H. Averaged visual evoked potentials in humans: Mechanism of dichoptic interaction studies in a subject with a split chiasma. Electroencephalography and Clinical Neurophysiology, 1969, 27, 142-145.

Lehmann, D., Koukkou, M., & Dittrich, A. Pattern evoked average EEG potentials and dichoptic visual percepts. Perception, 1977, 6, 77-84.

Lema, S. A., & Blake, R. Binocular summation in normal and stereoblind humans. Vision Research, 1977, 17, 691-695.

Lesevre, N., & Remond, A. Potentials evoquées par l'apparition de patterns: Effects de la dimension du pattern et de la densité des contrastes. Electroencephalography and Clinical Neurophysiology, 1972, 32, 593-604.

Lovegrove, W. J., & Over, R. Color adaptation of spatial frequency detectors in the human visual system. Science, 1972, 176, 541-543.

Lovegrove, W. J., & Over, R. Colour selectivity in orientation masking and aftereffect. Vision Research, 1973, 13, 895-902.

Lu, C., & Fender, D. H. The interaction of color and luminance in stereoscopic vision. Investigative Ophthalmology, 1972, 11, 482-490.

MacKay, D. M. Evoked potentials reflecting interocular and monocular suppression. Nature, 1968, 217, 81-83.

MacKay, D., & MacKay, V. Orientation-sensitive aftereffects of dichoptically presented colour and form. Nature, 1973, 242, 477.

Maffei, L., & Fiorentini, A. The unresponsive regions of visual cortical receptive fields. Vision Research, 1976, 16, 1131-1139.

Maffei, L., & Fiorentini, A. Spatial frequency rows in the striate visual cortex. Vision Research, 1977, 17, 257-264.

Marg, E., Freeman, D. N., Peltzmann, P., & Goldstein, P. J. Visual acuity development in human infants: Evoked potential measurements. Investigative Ophthalmology, 1976, 15, 150-153.

Maudarbocus, A. Y., & Ruddock, K. H. The influence of wavelength on visual adaptation to spatially periodic stimuli. Vision Research, 1973, 13, 993-998.

Maurer, D. Infant visual perception: Methods of study. In L. B. Cohen and P. Salapatek (Eds.), Infant perception: From sensation to perception. Vol. 1. Basic visual processes. New York: Academic Press, 1975.

May, J. G. Chromatic adaptation of orientation and size-specific visual processes in man. Vision Research, 1972, 12, 1509-1517.

May, J. G., Forbes, W. B., & Piantanida, T. P. The visual evoked response obtained with an alternating barred pattern: Rate, spatial frequency, and wavelength. Electroencephalography and Clinical Neurophysiology, 1971, 30, 222-228.

McCullough, C. Color adaptation of edge-detectors in the human visual system. Science, 1965, 149, 1115-1116.

McIlwain, J. T. Large receptive fields and spatial transformations in the visual system. In R. Porter (Ed.), International review of physiology. Neurophysiology II. Vol. 10. Baltimore: University Park Press, 1976.

Mikaelian, H. H. Interocular generalizations of orientation specific aftereffects. Vision Research, 1975, 15, 661-663.

Minke, B., & Auerbach, E. Latencies and correlation in single units and visual evoked potentials in the cat striate cortex following monocular and binocular stimulation. Experimental Brain Research, 1972, 14, 409-422.

Mitchell, D. E., Giffin, F., Wilkinson, F., Anderson, P., & Smith, P. Visual resolution in young kittens. Vision Research, 1976, 16, 363-366.

Monahan, J. S., & Sterenko, R. J. Stimulus luminance and dichoptic pattern masking. Vision Research, 1977, 17, 385-390.

Murch, G. M. Binocular relationships in a size and color orientation specific aftereffect. Journal of Experimental Psychology, 1972, 93, 30-34.

Nelson, J. I., Kato, H., & Bishop, P. O. Discrimination of orientation and position disparities by binocularly activated neurons in cat striate cortex. Journal of Neurophysiology, 1977, 40, 260-283.

Noda, H., Creutzfeldt, O. D., & Freeman, R. B., Jr. Binocular interaction in the visual cortex of awake cats. Experimental Brain Research, 1971, 12, 406-421.

Norman, J. L., Pettigrew, J. D., & Daniels, J. D. Early development of X-cells in kitten lateral geniculate nucleus. Science, 1977, 198, 202-204.

Norton, T. T., Casagrande, V. A., & Sherman, S. M. Loss of Y-cells in the lateral geniculate nucleus of monocularly deprived tree shrews. Science, 1977, 197, 784-786.

Packwood, J., & Gordon, B. Stereopsis in normal domestic cat, siamese cat, and cat raised with alternating monocular occlusion. Journal of Neurophysiology, 1975, 38, 1485-1500.

Pantle, A., & Sekuler, R. Size-detecting mechanisms in human vision. Science, 1968, 162, 1146-1148.

Paris, J., & Prestrude, A. M. On the mechanisms of the interocular light adaptation effect. Vision Research, 1975, 15, 595-603.

Parker, D. M., & Salzen, E. A. The spatial selectivity of early and late waves within the human visual response. Perception, 1977, 6, 85-95.

Pettigrew, J. D., Nikara, T., & Bishop, P. O. Binocular interaction on single units in cat striate cortex: Simultaneous stimulation with single moving slits with receptive fields in correspondence. Experimental Brain Research, 1968, 6, 391-410.

Rakic, P. Prenatal genesis of connections subserving ocular dominance in the rhesus monkey. Nature, 1976, 261, 467-471.

Rakic, P. Prenatal development of the visual system in rhesus monkey. Philosophical Transactions of the Royal Society of London. B. 1977, 278, 245-260.

Regan, D. Evoked potentials in psychology, sensory physiology, and clinical medicine. London: Chapman and Hall, 1972.

Richards, W. Stereopsis with and without monocular contours. Vision Research, 1977, 17, 967-969.

Rietveld, W. J., Tordoir, W. E. M., Hagenouw, J. R. B., Lubbers, J. A., & Spoor, T. A. C. Visual evoked responses to blank and to checkerboard patterned flashes. Acta Physiologica et Pharmocologica Neerlander, 1967, 14, 259-285.

Rose, G. H., & Lindsley, D. B. Development of visually evoked potentials in kittens: Specific and nonspecific responses. Journal of Neurophysiology, 1968, 31, 607-623.

Rusoff, A. C., & Dubin, M. W. Development of receptive-field properties of retinal ganglion cells in kittens. Journal of Neurophysiology, 1977, 40, 1188-1198.

Salapatek, P. Pattern perception in early infancy. In L. B. Cohen and P. Salapatek (Eds.), Infant perception: From sensation to cognition. Vol. 1. Basic visual processes. New York: Academic Press, 1975.

Sanderson, K. J., Bishop, P. O., & Darian-Smith, J. The properties of the binocular receptive fields of lateral geniculate neurons. Experimental Brain Research, 1971, 13, 178-207.

Schiller, P. H., Finlay, B. L., & Volman, S. F. Quantitative studies of single-cell properties in monkey striate cortex. II. Orientation specificity and ocular dominance. Journal of Neurophysiology, 1976, 39, 1320-1333.

Schiller, P. H., Finlay, B. L., & Volman, S. F. Quantitative studies of single-cell properties in monkey striate cortex. V. Multivariate statistical analyses and models. Journal of Neurophysiology, 1976, 39, 1362.

Schiller, P. H., Stryker, M., Cynander, M., & Berman, N. Response characteristics of single cells in the monkey superior colliculus following ablation or cooling of visual cortex. Journal of Neurophysiology, 1974, 37, 181-194.

Schor, C. M. Visual stimuli for strabismic suppression. Perception, 1977, 6, 583-593.

Sharpe, C. R. The colour specificity of spatial adaptations: Red-blue interactions. Vision Research, 1974, 14, 41-51.

Sherk, H., & Stryter, M. P. Quantitative study of cortical orientation selectivity in visually inexperienced kitten. Journal of Neurophysiology, 1976, 39, 63-70.

Sherman, S. M. Development of interocular alignment in cats. Brain Research, 1972, 37, 187-203.

Sherman, S. M., Hoffmann, K. P., & Stone, J. Loss of a specific cell type from the dorsal lateral geniculate nucleus in visually deprived cats. Journal of Neurophysiology, 1972, 35, 532-541.

Sherman, S. M., Wilson, J. R., & Guillery, R. W. Evidence that binocular competition affects the postnatal development of Y-cells in the cat's lateral geniculate nucleus. Brain Research, 1975, 100, 441-444.

Slater, A. M., & Findlay, J. M. Binocular fixation in the newborn baby. Journal of Experimental Child Psychology, 1975, 20, 248-273.

Sokol, S., & Dobson, V. Pattern reversal visually evoked potentials in infants. Investigative Ophthalmology, 1976, 15, 58-62.

Spekreijse, H. Analysis of EEG responses in man evoked by sine wave modulated light. Junk: The Hague, 1966.

Spekreijse, H., van der Tweel, L. H., & Regan, D. Interocular sustained suppression: Correlations with evoked potential amplitude and distribution. Vision Research, 1972, 12, 521-526.

Stone, J., & Dreher, B. Projection of X- and Y-cells of the cat's lateral geniculate nucleus to areas 17 and 18 of visual cortex. Journal of Neurophysiology, 1973, 36, 551-567.

Stromeyer, C. F. Edge-contingent color aftereffects: Spatial frequency specificity. Vision Research, 1972, 12, 969-978.

Stromeyer, C., & Mansfield, R. Coloured aftereffects produced with moving edges. Perception & Psychophysics, 1970, 7, 108-114.

Thorn, F., Collender, M., & Erickson, P. The development of the kitten's visual optics. Vision Research, 1976, 16, 1145-1149.

Tolhurst, D. J. Adaptation to square-wave gratings: Inhibition between spatial frequency channels in the human visual system. Journal of Physiology, 1972, 226, 231-248.

Towle, V. L., & Harter, M. H. Objective determination of human visual acuity: Pattern evoked potentials. Investigative Ophthalmology, 1977, 16, 1073-1076.

Van Meeteren, A., & Vos, J. J. Resolution and contrast sensitivities at low luminances. Vision Research, 1972, 12, 825-833.

Van Nes, F. L., & Bourman, M. A. Spatial modulation transfer in the human eye. Journal of the Optical Society of America, 1967, 57, 401-406.

Von Noorden, G. K. Histological studies of the visual system in monkeys with experimental amblyopia. Investigative Ophthalmology, 1973, 12, 727-738.

Von Noorden, G. K., Crawford, M. L. J., & Middleditch, P. R. The effects of monocular visual deprivation: Disuse or binocular interaction? Brain Research, 1976, 111, 277-285.

Von Noorden, G. K., & Middleditch, P. R. Histological observations in the normal monkey lateral geniculate nucleus. Investigative Ophthalmology, 1975, 14, 55-58.

Von Noorden, G. K., & Middleditch, P. R. Histology of the monkey lateral geniculate nucleus after unilateral lid closure and experimental strabismus: Further observations. Investigative Ophthalmology, 1975, 14, 674-683.

Walk, R. D. Monocular compared to binocular depth perception in human infants. Science, 1968, 162, 473-475.

Ware, C., & Mitchell, D. E. On interocular transfer of various visual aftereffects in normal and stereoblind observers. Vision Research, 1974, 14, 731-734.

Westendorf, D. H., & Fox, R. Binocular detection of disparate light flashes. Vision Research, 1977, 17, 697-702.

Wickelgren, L. W. Development of convergence. Journal of Experimental Child Psychology, 1967, 5, 74-85.

Wickelgren, L. W. The ocular response of human newborns to intermittent visual movement. Journal of Experimental Child Psychology, 1969, 8, 469-482.

Wiesel, T. N., & Hubel, D. H. Comparison of the effects of unilateral and bilateral eye closure on cortical unit responses in kittens. Journal of Neurophysiology, 1965, 28, 1029-1040. (a)

Wiesel, T. N., & Hubel, D. H. Extent of recovery from the effects of visual deprivation in kittens. Journal of Neurophysiology, 1965, 28, 1060-1072. (b)

Wiesel, T. N., & Hubel, D. H. Ordered arrangement of orientation columns in monkeys lacking visual experience. The Journal of Comparative Neurology, 1974, 158, 307-317.

Wilson, J. R., & Sherman, S. M. Differential effects of early monocular deprivation on binocular and monocular segments of cat striate cortex. Journal of Neurophysiology, 1977, 40, 891-903.

Yonas, A., & Pick, H. L., Jr. An approach to the study of infant space perception. In L. B. Cohen and P. Salapatek (Eds.), Infant perception: From sensation to cognition. Vol. II. New York: Academic Press, 1975.

APPENDIX A

Quantified Data: Adults

Subject	Replication	Measure	Flashed Stimulus / Continuous Stimulus: diffuse dark	20' dark	20' diffuse	20' 20'	20' 80'	80' dark	80' diffuse	80' 20'	80' 80'
JB	1	60	-8	10	6	-1	0	10	23	-10	13
	1	110	-35	-47	-40	-40	-41	-30	-26	-51	-32
	1	160	16	39	5	22	14	25	24	0	16
	1	220	21	19	-8	11	-6	20	43	20	12
	2	60	7	-28	6	5	4	18	18	-11	-6
	2	110	0	-57	-41	-31	-39	-36	-38	-53	-19
	2	160	28	24	30	32	11	41	18	-14	6
	2	220	22	22	22	24	-12	40	27	3	0
DB	1	60	-21	-65	0	-21	-7	-2	13	42	23
	1	110	-7	21	-36	-55	-28	-65	-103	-107	-73
	1	160	28	83	-16	-14	-5	70	-2	7	12
	1	220	-8	32	-13	0	50	40	20	30	26
	2	60	-16	-24	-14	-12	5	20	15	23	24
	2	110	-15	-25	-18	-26	-31	-21	-80	-102	-82
	2	160	47	56	-12	-15	-6	116	30	-12	15
	2	220	-5	45	18	17	36	38	28	25	27
JM	1	60	-9	-13	-1	-4	-9	8	7	14	14
	1	110	18	-18	-63	3	-36	-27	-54	-60	-31
	1	160	54	66	0	21	16	65	-2	-3	4
	1	220	36	44	28	24	8	10	11	16	-8
	2	60	-19	-12	0	-3	14	7	20	19	22
	2	110	24	2	-31	-38	-33	-25	-53	-52	-38
	2	160	54	62	16	6	6	60	21	-24	6
	2	220	26	46	24	23	5	15	13	2	-12

Quantified Data: Adults (continued)

Subject	Replication	Flashed Stimulus / Continuous Stimulus Measure	diffuse dark	20' dark	20' diffuse	20' 20'	20' 80'	80' dark	80' diffuse	80' 20'	80' 80'
MH	1	60	-10	-14	21	-9	-19	-2	26	17	0
	1	110	36	-16	-10	-14	-47	-32	-77	-112	-83
	1	160	77	48	18	2	11	93	37	28	30
	1	220	-8	0	-20	-11	8	9	13	29	-31
	2	60	-20	3	-13	-3	-7	-6	23	10	15
	2	110	43	-7	-15	0	-30	-78	-89	-70	-66
	2	160	62	28	9	27	19	65	5	-15	50
	2	220	5	-9	-7	10	20	30	5	29	2
MRH	1	60	-18	-14	8	-4	7	-1	10	5	9
	1	110	8	-40	-54	-32	-52	-38	-45	-53	-29
	1	160	23	78	0	3	-5	51	30	-2	12
	1	220	12	40	29	-5	17	36	30	35	14
	2	60	-18	-18	0	2	2	-9	5	6	8
	2	110	5	-39	-55	-19	-50	-32	-53	-54	-27
	2	160	22	66	-3	6	-18	47	9	-15	14
	2	220	26	61	58	9	9	47	27	29	25
MJ	1	60	-12	-29	-15	-4	-15	-35	-3	9	-6
	1	110	-13	-126	-130	-56	-89	-144	-122	-100	-77
	1	160	30	158	86	67	19	116	31	-27	45
	1	220	-13	11	14	-14	9	18	16	17	-27
	2	60	-23	-5	-25	-2	-11	-18	-6	-5	5
	2	110	-31	-108	-95	-28	-85	-116	-124	-121	-70
	2	160	107	125	23	65	35	126	21	-34	41
	2	220	3	31	-12	-17	-36	25	-1	10	-13

Quantified Data: Adults (continued)

Subject	Replication	Measure	Flashed Stimulus: diffuse dark / Continuous Stimulus: dark	Flashed Stimulus: 20' dark / Continuous Stimulus: diffuse	Flashed Stimulus: 20' diffuse / Continuous Stimulus: 20'	Flashed Stimulus: 20' 20' / Continuous Stimulus: 80'	Flashed Stimulus: 20' 80' / Continuous Stimulus: dark	Flashed Stimulus: 80' dark / Continuous Stimulus: diffuse	Flashed Stimulus: 80' diffuse / Continuous Stimulus: 20'	Flashed Stimulus: 80' 20' / Continuous Stimulus: 80'
LS	1	60	-42	-22	6	-18	-12	2	1	24	28
	1	110	7	-101	-32	-29	-3	-108	-69	-66	-11
	1	160	45	58	26	33	25	58	-8	7	37
	1	220	-17	14	-3	4	11	2	-46	-34	-27
	2	60	5	-6	-17	-13	0	6	3	28	0
	2	110	-13	-109	-72	-22	-58	-91	-77	-61	-39
	2	160	75	117	55	56	54	70	34	29	18
	2	220	-27	55	-28	-9	-22	-7	12	4	17
PM	1	60	-17	-15	-15	-7	-9	-19	-16	6	-6
	1	110	-1	-4	40	-27	-28	-18	-48	-46	-23
	1	160	45	68	21	7	5	63	7	4	25
	1	220	19	22	0	-15	-7	9	4	8	-7
	2	60	-11	-36	-10	-12	-5	-14	0	4	10
	2	110	-5	-27	-24	-25	-23	-24	-53	-58	-20
	2	160	42	48	18	4	10	86	31	10	36
	2	220	19	11	1	1	-5	16	7	7	2

APPENDIX B

Adult Subjects' Visual Characteristics

Subject	Binocular		Left		Right		Left-Right		Stereoacuity	
	1	2	1	2	1	2	1	2	1	3
RH	.83	1.2	.83	1.2	.83	1.2	.00	.00	19.0	6
MJ	.91	1.1	.91	1.1	.83	1.2	-.08	-.10	9.7	9
LS	1.11	.9	1.11	.9	.91	1.1	.20	-.20	32.0	4
MH	.91	1.1	.91	1.1	.91	1.1	.00	.00	13.0	7
PM	1.43	.7	1.43	.2	1.25	.8	18.00	-.10	362.0	0
JB	1.11	.9	1.00	1.0	.91	1.1	.09	-.10	362.0	7
DB*	1.25	.8	1.25	.8	1.11	.9	.13	-.10	83.0	2
JM*	1.25	.8	1.11	.9	1.11	.9	.00	.00	362.0	0

1 acuity in minutes of arc

2 decimal acuity

3 score (0-9), an increasing score indicates better stereoacuity

* diagnosed by private ophthalmologist or optometrist as lacking binocularity; no manifest phoria

Interrelationship of Measures of

Visual Acuity of Adult Subjects

(N=8)

	Binocular		Left		Right		Left-Right		Stereoacuity
	1	2	1	2	1	2	1	2	1
Binocular	-98								
Left 1	96	-93							
Left 2	-97	97	-99						
Right 1	94	-89	92	-90					
Right 2	-94	91	-92	91	-1.00				
Left-Right 1	57	-58	69	-70	36	-35			
Left-Right 2	-31	37	-40	45	-03^{+}	03^{+}	-92		
Stereoacuity 1	72	-72	53	-55	64	-64	10^{+}	06	
Stereoacuity 3	87	88	-74	77	-77	81	-30	.10^{+}	-86

$^{+}$ $p > .05$

1 acuity measured in minutes of arc

2 decimal acuity

3 score on orthorater test (0-9)

APPENDIX C

Adult Correlation Matrices:

Intraocular Effects of Pattern

(N=48)

	60	110	160	220
Experimental Conditions				
Flashed Stimulus (diffuse, 20', or 80')	33	-53^{xxx}	32^{x}	31
VEP Measures				
110	-10			
160	-04	-53^{xxx}		
220	20	-16	16	
Visual Measures				
Minutes of Arc (Acuity)				
Both Eyes	08	24	-13	01
Left Eye	-02	19	-05	-06
Right Eye	-02	38^{xx}	-11	05
Difference (L-R)	-01	-26	10	-26
Stereoacuity	23	30^{x}	-36^{xx}	18
Decimal Acuity				
Both Eyes	-12	-21	13	01
Left Eye	-03	-17	04	08
Right Eye	-01	-39^{xx}	13	-05
Difference (L-R)	-05	43^{xx}	-16	29^{x}
Other (score 0-9)				
Stereoacuity	26	-37^{xx}	42^{xx}	19
Post hoc Subject Classification				
Good vs. Poor Stereoacuity	17	-35^{xx}	31^{x}	23
Good vs. Poor Binocularity	11	28^{x}	05	23

---

^{x} = $p < .05$
^{xx} = $p < .01$
^{xxx} = $p < .001$

Adult Correlation Matrices:

Interocular Effects of Luminance

(N=64)

	60	110	160	220
Experimental Conditions				
Flashed Stimulus (20' or 80')	43^{xxx}	-23	02	01
Continuous Stimulus (dark or diffuse)	41^{xx}	-12	-71^{xxx}	37
VEP Measures				
110	01			
160	-39^{xx}	-26^{x}		
220	11	09	30^{x}	
Visual Measures				
Minutes of Arc (Acuity)				
Both Eyes	05	36^{xx}	-11	-11
Left Eye	-05	29^{x}	-06	-16
Right Eye	-02	-46^{xxx}	-13	-06
Difference (L-R)	10	-16	10	-30^{x}
Stereoacuity	-21	44^{xxx}	-21	07
Decimal Acuity				
Both Eyes	-09	-33^{xx}	11	13
Left Eye	00	-27^{x}	06	18
Right Eye	-01	-47^{xxx}	14	06
Difference (L-R)	-16	36^{xx}	-16	31^{xx}
Other (score 0-9)				
Stereoacuity	28^{x}	-55^{xxx}	28^{x}	-09
Post hoc Subject Classification				
Good vs. Poor Stereoacuity	20	49^{xxx}	-21	15
Good vs. Poor Binocularity	23	26^{x}	-09	22

---

^{x} = $p < .05$
^{xx} = $p < .01$
^{xxx} = $p < .001$

Adult Correlation Matrices:

Interocular Effects of Pattern

(N=96)

	60	110	160	220
Experimental Conditions				
Flashed Stimulus (20' or 80')	54^{xxx}	-40^{xxx}	-08	09
Continuous Stimulus (diffuse, 20', or 80')	08	21^{x}	-00	-17
VEP Measures				
110	-03			
160	-20^{x}	-04		
220	19	-06	-29	
Visual Measures				
Minutes of Arc (Acuity)				
Both Eyes	06	25^{xx}	-13	-04
Left Eye	-01	19	-10	-08
Right Eye	-03	24^{x}	-22^{x}	05
Difference (L-R)	-10	03	20^{x}	-32^{xx}
Stereoacuity	10	35^{xxx}	-13	06
Decimal Acuity				
Both Eyes	-07	-24^{x}	10	06
Left Eye	-01	19	08	10
Right Eye	-05	24^{x}	23^{x}	-06
Difference (L-R)	07	07	30^{xx}	-37^{xxx}
Other (score 0-9)				
Stereoacuity	-21	-42^{xxx}	25^{xx}	-13
Post hoc Subject Classification				
Good vs. Poor Stereoacuity	14	24^{x}	-29^{xx}	22^{x}
Good vs. Poor Binocularity	27^{xx}	-01	-35^{xx}	29^{xx}

---

^{x} = $p < .05$
^{xx} = $p < .01$
^{xxx} = $p < .001$

APPENDIX D

Quantified Data: KW

Experimental Condition: Flashed/Continuous (min. of arc)

	Flashed Stimulus		diffuse	20'	20'	20'	20'	80'	80'	80'	80'
	Continuous Stimulus		dark	dark	diffuse	20'	80'	dark	diffuse	20'	80'
Measure	Replication	Age									
P2	1	99	14	-23	24	18	-2	25	5	5	-10
N2	1		-11	-13	-25	-19	-7	-26	-8	-12	-20
N3	1		-5	-5	-9	-15	5	-18	-14	-23	11
P4	1		15	18	22	12	13	-6	17	9	21
Time	1		1	5	3	--	40	--	--	35	--
P2	2	104	1	36	12	4	6	33	23	39	34
N2	2		-66	-62	-58	-37	-30	-18	-18	-33	-21
N3	2		-16	-33	-20	-11	-26	-38	-22	-34	-36
P4	2		66	54	58	35	26	-11	6	24	28
Time	2		16	6	0	0	0	22	47	--	30
P2	3	104	9	13	6	7	-5	-8	32	35	6
N2	3		-13	-15	-35	-7	-20	-22	-44	-11	-24
N3	3		-1	-12	-6	-32	-15	-9	-20	-35	-16
P4	3		6	12	21	32	22	12	44	33	24
Time	3		0	0	0	0	0	0	0	0	0
P2	4	110	12	8	9	-8	-3	9	1	15	-15
N2	4		-6	-38	-42	-37	-19	-58	-28	-25	-25
N3	4		-9	-43	-15	-39	-11	-32	-15	-14	-20
P4	4		-11	41	41	5	18	58	27	9	25
Time	4		29	3	0	25	3	9	0	0	18

Quantified Data: KW (continued)

Measure	Replication	Age	Flashed Stimulus / Continuous Stimulus	diffuse dark	20' dark	20' diffuse	20' 20'	20' 80'	80' dark	80' diffuse	80' 20'	80' 80'
P2	5	112		-5	7	18	7	23	35	22	--	9
N2	5			-19	-15	-35	-22	-5	-17	-17	--	-4
N3	5			-3	6	-2	-25	-22	-28	-23	--	-18
P4	5			18	11	35	16	24	-33	25	--	8
Time	5			56	0	0	0	24	34	54	--	73
P2	6	112		11	--	1	25	3	4	11	-1	24
N2	6			-7	--	-25	-6	-20	-35	-5	-35	-19
N3	6			-23	--	-13	-27	-8	-9	10	-5	-7
P4	6			-18	--	25	25	9	34	12	34	15
Time	6			35	--	42	16	45	0	44	41	31

Quantified Data: JB

Experimental Condition: Flashed/Continuous (min. of arc)

Flashed Stimulus / Continuous Stimulus			diffuse dark	20' dark	20' diffuse	20' 20'	20' 80'	80' dark	80' diffuse	80' 20'	80' 80'	Control	
Measure	Replication	Age											
P2	1	20	36	13	-12	2	15	-4	15	35	6		
N2	1		14	-7	-30	-3	-20	-7	-6	19	9		
N3	1		-4	-22	2	9	-37	6	-25	-31	-8		
P4	1		0	-21	10	9	38	0	8	16	0		
Time	1		99	0	0	0	0	0	0	248	0		
												80'/diffuse	
P2	2	69	28	10	9	0	5	21	3	3	4	6	
N2	2		-30	-39	-11	-11	3	-4	-15	-8	-17	-12	
N3	2		-29	-22	-24	-6	-8	-12	-21	-9	-19	7	
P4	2		20	26	-11	6	8	-14	12	10	6	9	
Time	2		2	5	0	0	0	0	0	1	0		
												20'/diffuse	20'/dark
P2	3	75	15	-7	6	-7	9	4	4	-4	-4	0	0
N2	3		1	-24	-11	-3	-13	9	-1	-2	-35	-12	-9
N3	3		2	-13	5	5	-10	10	-13	-1	-6	4	-10
P4	3		-13	13	7	10	-2	-8	2	10	32	9	-4
Time	3		4	0	5	14	7	21	1	20	0		
												80'/20'	80'/dark
P2	4	78	2	3	1	7	8	-12	--	3	10	13	5
N2	4		-2	-8	-29	-8	-3	-17	--	-10	4	-11	-6
N3	4		3	-9	-31	-11	-5	-2	--	-17	-11	-17	6
P4	4		4	-6	26	6	10	16	--	15	-2	6	6
Time	4		0	0	0	2	2	15	--	15	0		
P2	5	93	--	3	16	9	6	3	0	-5	8		
N2	5		--	-50	-12	-5	-2	-21	-24	-21	-14		
N3	5		--	-35	-18	-9	-15	-6	0	-9	-1		
P4	5		--	50	13	15	15	10	25	13	7		
Time	5		--	0	30	10	27	0	13	13	2		

Quantified Data: MO

Experimental Condition: Flashed/Continuous (min. of arc)

Flashed Stimulus / Continuous Stimulus			diffuse dark	20' dark	20' diffuse	20' 20'	20' 80'	80' dark	80' diffuse	80' 20'	80' 80'	Control	
Measure	Replication	Age											
P2	1	33	7	-5	16	25	14	17	12	12	22		
N2	1		-15	-5	-6	-1	-10	3	-1	-14	2		
N3	1		-5	8	-17	-13	-6	-16	-1	-16	-22		
P4	1		3	-4	16	13	8	13	14	23	11		
Time	1		0	0	0	14	0	0	0	5	20		
												diffuse/dark	
P2	2	53	18	-10	9	-3	4	5	-2	6	0	-2	
N2	2		-11	2	-8	-13	-6	-19	-13	-3	-2	-5	
N3	2		-21	1	-13	-13	-15	-5	-7	-12	-2	0	
P4	2		14	3	14	15	4	4	2	2	-5	3	
Time	2		8	10	0	113	0	0	3	0	0	10	
P2	3	63	3	3	10	3	7	19	19	11	18		
N2	3		-14	-33	-5	-10	-3	3	5	3	-16		
N3	3		-21	-14	-13	-19	-1	-6	-17	-22	-18		
P4	3		-10	32	7	23	3	20	-13	-3	-7		
Time	3		9	9	18	22	10	0	0	5	0		
												80'/dark	diffuse/dark
P2	4	69	4	8	22	22	13	-5	-7	23	12	-8	-3
N2	4		-21	-15	-20	-23	-9	-23	-24	-22	-18	-15	-13
N3	4		-11	-7	-6	-14	-5	-16	-14	-10	5	-7	-2
P4	4		14	9	12	-6	0	11	19	22	17	11	9
Time	4		5	0	5	0	8	12	0	4	0		
												80'/20'	
P2	5	77	15	-3	12	-10	5	3	4	20	29	-2	
N2	5		-33	-14	-15	-9	-7	-8	-10	-15	8	-3	
N3	5		-8	-13	11	20	-8	-5	-11	7	-18	-8	
P4	5		0	3	-23	12	12	1	-1	22	4	-6	
Time	5		0	0	0	0	0	0	0	0	0		

Quantified Data: MO (continued)

Flashed Stimulus / Continuous Stimulus			diffuse dark	20' dark	20' diffuse	20' 20'	20' 80'	80' dark	80' diffuse	80' 20'	80' 80'	Control	
Measure	Replication	Age											
P2	6	84	26	29	13	10	25	18	30	21	4		
N2	6		-41	-29	-8	-7	-27	-16	-31	-5	-13		
N3	6		-23	-21	-4	-11	-31	-33	-29	-10	-21		
P4	6		38	16	14	17	29	8	30	2	23		
Time	6		5	3	0	13	7	8	13	13	40		
P2	7	88	-13	-3	-20	9	22	32	19	26	31		
N2	7		-11	-52	-22	-27	4	-22	-18	-24	-28		
N3	7		-23	15	11	-9	-15	-14	-14	-25	-26		
P4	7		13	41	17	21	-5	25	-10	0	12		
Time	7		23	0	30	28	18	0	0	2	0		
P2	8	95	-26	1	-21	7	13	40	31	-11	11		
N2	8		-40	15	-40	-49	-6	-25	-29	-41	2		
N3	8		-1	30	-3	-13	-16	-30	-14	-11	5		
P4	8		38	16	39	45	14	20	22	30	0		
Time	8		12	24	0	0	0	0	0	0	3		
												80'/diffuse	80'/diffuse
P2	9	98	13	11	16	14	23	19	19	26	10	-3	-10
N2	9		-51	-12	-30	-25	-14	-29	-12	-23	-9	-7	-11
N3	9		0	-7	-2	-23	-21	-16	-29	-35	-11	-19	1
P4	9		43	12	31	26	22	25	-2	24	1	18	4
Time	9		14	0	22	2	8	14	92	0	0		
P2	10	104	24	17	3	-4	-5	18	11	-4	0		
N2	10		-18	-4	-33	-21	-4	-21	-12	-26	8		
N3	10		-18	-8	-19	-19	-13	-25	-11	14	-9		
P4	10		-18	16	4	28	11	9	2	22	16		
Time	10		0	10	14	0	22	1	112	63	45		

APPENDIX E

Group Average: Correlation Matrices

: Luminance Effects - N = 80

	Rep	Age	Flash	Cont	P2	N2	N3	P4	T1	PT
P2	.13	.22^{x}	.27^{xx}	.01	--					
N2	-.12	-.43^{xx}	.20^{+}	-.01	-.08	--				
N3	.06	.17	-.19^{+}	.03	-.49^{xx}	.37^{xx}	--			
P4	.10	.35^{xx}	-.21^{+}	.05	-.03	-.72^{xx}	-.15	--		
T1	.13	.46^{xx}	-.09	-.06	.42^{xx}	-.81^{xx}	-.53^{xx}	.65^{xx}	--	
PT	-.21^{x}	-.35^{xx}	-.17	-.15	-.11	-.11	.05	.11	-.03	

: Interocular Pattern Effects - N = 125

P2	.00	-.01	.19^{x}	-.02	--					
N2	-.18^{x}	-.44^{xx}	.12	.28^{xx}	.09	--				
N3	.04	-.09	-.08	-.04	-.46^{xx}	.11	--			
P4	.08	.36^{xx}	-.15^{+}	-.08	-.04	-.65^{xx}	-.16^{+}	--		
T1	.13	.33^{xx}	.01	-.18^{x}	.39^{xx}	-.71^{xx}	-.53^{xx}	.66^{xx}	--	
PT	-.08	-.21^{x}	-.09	-.04	-.01	-.19^{x}	.06	.07	.05	

: Intraocular Pattern Effects - N = 63

P2	.08	.05	.12		--					
N2	-.16	-.39^{xx}	.05		-.03	--				
N3	.01	-.21	-.11		-.47^{xx}	.43^{xx}	--			
P4	.19	.32^{xx}	-.08		-.14	-.74^{xx}	-.17	--		
T1	.20	.40^{xx}	.02		.35^{xx}	-.81^{xx}	-.59^{xx}	.67^{xx}	--	
PT	.07	-.12	.20		-.07	-.13	.04	.06	-.11	

$^{+}$ = $p < .10$
^{x} = $p < .05$
^{xx} = $p < .01$

KW: Correlation Matrices

: Luminance Effects - N=24

	Rep	Age	Flash	Cont	P2	N2	N3	P4	T1	PT
P2	-.07	.02	.26	.08	--					
N2	.05	-.07	.27	.02	-.21	--				
N3	.23	.08	-.18	.30	$-.46^{x}$	$.43^{x}$	--			
P4	.05	.10	-.37	.24	-.17	$-.78^{xx}$	-.11	--		
T1	-.06	.09	.09	-.12	$.47^{x}$	$-.86^{xx}$	$-.71^{xx}$	$.57^{xx}$	--	
PT	-.27	-.27	$-.48^{x}$	-.20	-.27	$-.45^{x}$	.18	$.45^{x}$	.14	--

: Interocular Pattern Effects - N=34

P2	-.09	-.09	$.30^{+}$	-.22	--					
N2	.10	.01	.19	.34	.05	--				
N3	.08	-.04	-.02	-.04	$-.29^{+}$	.05	--			
P4	-.05	-.01	-.15	$-.30^{+}$	.20	$-.59^{xx}$	-.11	--		
T1	-.15	-.05	.04	$-.28^{+}$	$.50^{xx}$	$-.66^{xx}$	$-.54^{xx}$	$.75^{xx}$	--	
PT	$-.34^{+}$	-.27	$-.37^{x}$	-.14	.06	$-.47^{xx}$	-.12	$.52^{xx}$	$.45^{xx}$	--

: Intraocular Pattern Effects - N=17

P2	-.04	.03	.26	--	--					
N2	.14	.02	-.20	--	-.12	--				
N3	.03	-.08	-.39	--	$-.55^{x}$	$.46^{+}$	--			
P4	-.05	.00	-.15	--	-.29	$-.81^{xx}$	-.18	--		
T1	-.09	.04	.31	--	.38	$-.88^{xx}$	$-.76^{xx}$	$.59^{xx}$	--	
PT	-.30	-.39	.22	--	-.21	-.10	.26	.27	-.10	--

MO: Correlation Matrices

: Luminance Effects - N=40

	Rep	Age	Flash	Cont	P2	N2	N3	P4	T1	PT
P2	.20	.18	.39^{xx}	-.05	--					
N2	-.41^{xx}	-.43^{xx}	.06	-.05	.01	--				
N3	-.10	-.12	-.48	-.04	-.56^{xx}	.20	--			
P4	.20	.20	-.14	-.16	.01	-.53^{xx}	.01	--		
Total	.48^{xx}	.49^{xx}	.05	-.03	.39^{xx}	-.70^{xx}	-.25	.63^{xx}	--	
PT	-.32^{x}	-.32^{x}	.01	-.20	.08	-.03	.04	.03	.01	--

: Interocular Pattern Effects - N=60

P2	-.08	-.10	.21	.11	--					
N2	-.41^{xx}	-.41^{xx}	.10	.31^{xx}	.11	--				
N3	-.06	-.05	-.13	-.09	-.48^{xx}	.08	--			
P4	.26^{x}	.21^{+}	-.18	-.04	-.18	-.58^{xx}	-.09	--		
Total	.39^{xx}	.37^{xx}	-.01	-.18	.26^{x}	-.77^{xx}	-.39^{xx}	.60^{xx}	--	
PT	-.13	-.10	.05	.04	.14	-.11	.04	-.05	.10	--

: Intraocular Pattern Effects - N=30

P2	.24	.23	.31^{+}		--					
N2	-.32^{+}	-.35^{+}	.26		-.08	--				
N3	-.07	-.10	-.11		.50^{xx}	.16	--			
P4	.29	.31^{+}	.00		.02	-.57^{xx}	.14	--		
Total	.54^{xx}	.56^{xx}	-.11		.38^{x}	-.72^{xx}	-.23	.71^{xx}	--	
PT	-.03	-.11	.26		.38^{x}	-.06	-.06	-.20	-.08	--

JB: Correlation Matrices

: Luminance Effects - N=20

	Rep	Age	Flash	Cont	P2	N2	N3	P4	T1	PT
P2	-.11	.03	-.02	.07	--					
N2	-.31	-.24	.46^{x}	.05	.31	--				
N3	-.04	-.09	.38^{+}	-.13	-.42^{+}	.43^{+}	--			
P4	.52^{x}	.42^{+}	-.15	.11	-.32	-.84^{xx}	-.32	--		
T1	.20	.19	-.47^{x}	-.10	.12	-.80^{xx}	-.73^{xx}	.67^{xx}	--	
PT	-.37	-.36	-.16	.04	.03	-.23	-.42^{+}	-.06	.13	--

: Interocular Pattern Effects - N=30

P2	-.12	-.25	.04	.10	--					
N2	-.19	-.22	.08	.22	.54^{xx}	--				
N3	.08	.19	.03	.18	-.55^{xx}	.08	--			
P4	.12	-.04	.02	.04	-.03	-.46^{xx}	-.27	--		
T1	-.16	-.31^{+}	.03	-.15	.39^{x}	-.36^{x}	-.63^{xx}	.65^{xx}	--	
PT	-.08	-.02	-.04	-.04	.44^{x}	-.51^{xx}	.17	-.11	-.14	--

: Intraocular Pattern Effects - N=15

P2	-.52^{+}	-.36	-.54^{x}	--	--					
N2	-.37	-.46^{+}	-.05	--	.26	--				
N3	-.02	-.13	.23	--	-.26	.77^{xx}	--			
P4	.45^{+}	.45^{+}	-.06	--	-.22	-.84^{xx}	-.56^{x}	--		
T1	.04	.18	-.18	--	.26	-.78^{xx}	-.91^{xx}	.72^{xx}	--	
PT	.28	.33	.14	--	-.39	-.49^{+}	-.32	.09	.06	--

APPENDIX F

MODELS TESTED: INFANT DATA*

Group Analyses (Effects tested by Subject x Treatment)

Flash Effects:
Subjects (3) x Flashed Stimuli (3)
Subjects (3) x Flashed Stimuli (3) x Age (3)

Luminance Effects:
Subjects (3) x Flashed Patterns (2) x Continuous Stimuli (2)
Subjects (3) x Flashed Patterns (2) x Continuous Stimuli (2) x Age (3)

Pattern Effects:
Subjects (3) x Flashed Patterns (2) x Continuous Stimuli (3)
Subjects (3) x Flashed Patterns (2) x Continuous Stimuli (3) x Age (3)

Analyses of Individuals' Data (JB, KW, MO) (Effects tested by Replication x Treatment)

Flash Effects: Replications x Flashed Stimuli

Luminance Effects: Replications x Flashed Stimuli x Continuous Stimuli

Pattern Effects: Replications x Flashed Stimuli x Continuous Stimuli

---

*For each model each measure was tested, i.e., P2, N2, N3, P4, TA, and PT.

PT: Flash Effects

ANOVA Summary Table

Source	df	MS	F^1	F^2
Subject	2	.07	4.10	4.26
Flash	2	.115		
Subject x Flash$^+$	4	.028		
Residual$^+$	51	.027		
Pooled Error	55	.027		

$^+$ = included in pooled error

^{1} = calculated using appropriate error term

^{2} = calculated using pooled error term

N2: Luminance Effects

ANOVA Summary Table

Source	df	MS	F^1	F^2
Subject	2	1212.14		
Flash	1	1040.77	4.90	4.92*
Subject x Flash$^+$	2	212.53		
Continuous	1	6.41	<1	
Subject x Continuous	2	22.06		
Flash x Continuous	1	94.63	<1	<1
Subject x Flash x Continuous$^+$	2	274.83		
Residual$^+$	69	209.47		
Pooled Error	73	211.38		

$^+$ = included in pooled error

^{1} = calculated using appropriate error term

^{2} = calculated using pooled error term

* = $p < .05$, df = 1,73

P4: Luminance Effects

ANOVA Summary Table

Source	df	MS	F^1	F^2
Subject	2			
Flash	1	1138.40	4.29	3.91*
Subject x Flash+	2	265.30		
Continuous	1	149.45	< 1	< 1
Subject x Continuous+	2	338.49		
Flash x Continuous	1	94.40	< 1	< 1
Subject x Flash x Continuous	2	177.20		
Residual+	69	290.37		
Pooled Error	73	291.00		

+ = included in pooled error

1 = calculated using appropriate error term

2 = calculated using pooled error term

* = $p < .05$, df = 1,73

N2: Pattern Effects

ANOVA Summary Table

Source	df	MS	F^1	F^2
Subject	2	1402.91		
Flash	1	253.66	12.00	
Subject x Flash	2	21.15		
Continuous	2	659.92	3.46	4.66*
Subject x Continuous+	4	190.93		
Flash x Continuous	2	324.00	3.22	2.28
Subject x Flash x Continuous+	4	100.71		
Residual+	105	141.54		
Pooled Error	113	141.84		

+ = included in pooled error

1 = calculated using appropriate error term

2 = calculated using pooled error term

* = $p < .05$, df = 2,109

P2: Pattern Effects

ANOVA Summary Table

Source	df	MS	F
Subject	2	780.20	
Flash	1	490.75	5.98
Subject x Flash	2	82.10	
Continuous	2	19.20	
Subject x Continuous	4	180.67	
Flash x Continuous	2	90.26	10.62*
Subject x Flash x Continuous	4	8.50	
Residual	105	142.67	

---

* = $p < .05$, df = 2,4