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INDEPENDENT ON AND OFF PATHWAYS IN HUMANS UNDERLIE ASYMMETRIES IN BRIGHTNESS AND DARKNESS PERCEPTION

by

JANET S. WELCH

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York.

1987

This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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Abstract

INDEPENDENT ON AND OFF PATHWAYS IN HUMANS UNDERLIE ASYMMETRIES IN BRIGHTNESS AND DARKNESS PERCEPTION

by

Janet S. Welch

Advisors: Professors James Gordon

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ON and OFF pathways have been found in many vertebrate species, including man. ON cells respond to increments in light, OFF cells respond to decrements in light. ON and OFF pathways have been found to differ morphologically, physiologically, and pharmacologically. It has been hypothesized that ON and OFF pathways mediate the perception of brightness and darkness, respectively. There is some psychophysical evidence of differences in human perception of brightness and darkness, suggesting differences in the properties of the ON and OFF pathways.

Novel positive- and negative-contrast stimuli were designed in order to selectively emphasize responses from ON and OFF pathways. The responses to these stimuli were measured by recording visual evoked potentials (VEPs),

electrical responses from the visual cortex. The amplitudes and phases of the first four harmonic components of the VEP response were obtained by using Fourier analysis. The results revealed differences in the responses to positive- and negative-contrast stimuli, suggesting asymmetries in the ON and OFF pathways. The spatial tuning of the two pathways appears to be different; the spatial tuning of the OFF pathway may be finer than that of the ON pathway. At the higher spatial frequencies (check sizes of 5 to 9 minutes of arc), higher amplitude responses were reliably found for negative-contrast stimuli than for positive-contrast stimuli. The temporal tuning curves in response to positive- and negative-contrast stimuli are similar in shape but different in magnitude of response; negative contrasts elicited higher amplitude VEPs over the range of temporal frequencies tested. Contrast experiments also revealed higher amplitude responses to negative contrasts. Therefore, it appears that the OFF pathway has finer spatial tuning and greater contrast gain than the ON pathway. The techniques used in this research, as well as the results found, may be useful in delineating human perception of brightness and darkness.

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Table of Contents

page

Title page..... i

Copyright page..... ii

Approval page..... iii

Abstract..... iv

Acknowledgements..... vi

Table of Contents..... vii

List of Figures..... ix

INTRODUCTION..... 1

Retinal Processing..... 5

Differentiation of ON and OFF Pathways in the Retina..... 7

Pharmacological and Physiological Differentiation of ON and OFF Pathways in the Brain..... 16

Clinical Evidence of Independent ON and OFF Pathways in Humans..... 26

Psychophysical Evidence of Differences in Brightness and Darkness Perception in Humans..... 27

Electrophysiological Recording Techniques..... 32

Rationale for Proposed Research..... 40

METHODS..... 43

Subjects..... 43

Stimuli..... 43

METHODS (continued)

Stimulating Apparatus..... 44

Recordings..... 47

Analysis..... 48

Procedure..... 49

RESULTS..... 63

Experiment 1 - Spatial Tuning..... 63

Experiment 2 - Temporal Tuning..... 70

Experiment 3 - Contrast..... 78

a. Appearance-Disappearance Experiment..... 78

b. Constant Mean Contrast Experiment..... 100

c. Constant Depth of Modulation Experiment... 101

DISCUSSION..... 114

Contrast Sensitivity and Contrast Gain Models.... 130

Comparison of Data with Models..... 133

Contrast Gain and Phase Shift Effects..... 138

Independent Brightness and Darkness Processing... 140

Independent ON and OFF Pathways Model..... 142

Applications..... 148

Summary..... 152

REFERENCES..... 154

LIST OF FIGURES

page

Figure 1 - Examples of stimuli..... 45

Figure 2 - Luminance profiles of stimuli..... 51

Figure 3 - Schematic representation of appearance-disappearance stimuli..... 56

Figure 4 - Schematic representation of constant mean contrast stimuli..... 59

Figure 5 - Schematic representation of constant depth of modulation stimuli..... 61

Figure 6 - Spatial tuning plots for subject jw..... 64

Figure 7 - Spatial tuning plots for subject mc..... 66

Figure 8 - Temporal tuning plots for subject jw..... 71

Figure 9 - Temporal tuning plots for subject ep..... 73

Figure 10 - Measure of apparent latency..... 76

Figure 11 - Appearance-disappearance data plots for subject ep, plotted on linear coordinates..... 79

page

Figure 12 - Appearance-disappearance data plots for subject ep, plotted on semi-log coordinates..... 81

Figure 13 - Appearance-disappearance data plots for subject ep, plotted on log-log coordinates..... 83

Figure 14 - Appearance-disappearance data plots (second harmonic) for subject ep..... 87

Figure 15 - Appearance-disappearance data plots (using Michelson contrast) for subject ep..... 91

Figure 16 - Appearance-disappearance data plots (using optimally-sized checks) for subject jw.... 94

Figure 17 - Constant mean contrast data plots for subject ep..... 96

Figure 18 - Constant mean contrast data plots for subject mc..... 98

Figure 19 - Constant mean contrast data plots for subject mc, plotted on log-log coordinates..... 102

page

Figure 20 - Constant mean contrast data plots (second harmonic) for subject ep..... 104

Figure 21 - Constant depth of modulation data plots for subject lp..... 106

Figure 22 - Constant depth of modulation data plots for subject mc..... 108

Figure 23 - Constant depth of modulation data plots (second harmonic) for subject mc..... 111

Figure 24 - Full-field modulation data plots for subject mc..... 118

Figure 25 - Response asymmetry model for ON and OFF pathways..... 121

Figure 26 - Hypothetical response function..... 124

Figure 27 - Model of hypothetical responses to different contrast manipulations..... 128

Figure 28 - Hypothetical response curves with
a. different contrast sensitivity values
b. different contrast gain values..... 131

page

Figure 29 - Averaged appearance-disappearance data fit by Naka-Rushton equations..... 136

Figure 30 - Independent ON and OFF Pathways Model.... 143

INTRODUCTION

Most living creatures are sensitive to light. Plants utilize light as their energy source and animals utilize light to seek food, shelter, mates; in short, vision guides much of their behavior. The first simple eyes responded only to light intensity; perception of form and color developed as the eye and brain grew more complicated. Vision is the main sensory channel for information from the outside world for humans, as well as for many other species of animals. The main tasks of the human visual system are pattern recognition (including size, shape, color and brightness of objects) and spatial localization.

The visual system provides information about a three-dimensional world, but the only signal available to the brain is a two-dimensional pattern of light on the retina. This retinal image is sampled by a mosaic of photoreceptors, and the visual world becomes two small and slightly different, upside-down images on our retinas. Neural activity in the retina in turn signals other cells along the visual pathway. The brain is able to reconstruct the outside world based on information coded in patterns of neural activity. This pattern of

neural activity not only represents the object, but to the brain, it is the object. Although vision is considered a distal sensory modality, the stimulus is in reality a proximal one - the image of objects on the retina.

Perception can be thought of as the internal representation of the outside world based on sensations, and this representation changes at different levels of processing, it is not a point-by-point description. Certain features of the visual world are more salient than others in forming that representation; contrast between bright and dark areas is an extremely important aspect of the visual world. The overall level of luminance is not as important to the visual system as changes in luminance, whether changes are produced in time by successive increments and decrements in light (temporal contrast), or in space by patterns of light and dark areas (spatial contrast). Contrast between black and white has been of interest to vision scientists for many years, but it was recognized long before, and made use of by countless artists.

Early research on the human visual system in the nineteenth century was of a psychophysical nature, and

relied on subjective observations of the effects of different types of visual stimulation. Many principles of visual phenomena were discovered and analyzed psychophysically during this time, such as: simultaneous and successive contrast, binocular vision, and color vision. Purkinje, in his doctoral dissertation in 1819, (cited in Jung, 1973) asserted that sensory phenomena should have correlates in physiology. This remained largely an untested hypothesis for over 100 years until the first successful electrophysiological recordings were obtained. Adrian and Matthews recorded from the vertebrate optic nerve in 1927; Hartline and Graham recorded from single optic fibers in Limulus in 1932; and in 1935, Hartline recorded from single optic nerve fibers in the frog. The electrophysiological study of visual neurons progressed rapidly in the next few decades and now it is possible to provide neurophysiological correlates for many visual phenomena, such as brightness, contrast and color, on the basis of recordings of single neurons in the visual system. The increase in knowledge of neurophysiology in the last few decades has resulted mainly from intracellular and extracellular recordings of cells in the retino-geniculo-striate pathway, at all levels, in many different species. Knowledge of this pathway cannot be directly measured by these methods in man, and the applicability of results of animal studies

(especially in non-primate species) to man, is always questionable.

Electrophysiological research has revealed that visual information is processed in successive stages. The neural response to light starts at the receptors, and progresses through sequential layers of cells of the retina. Approximately 80% of the fibers from the human retina ascend to the lateral geniculate nucleus (LGN) of the thalamus. (The remaining retinal fibers ascend to the superior colliculus of the midbrain. In many phylogenetically lower animals the superior colliculus represents the major brain center for visual processing. In higher animals, the more newly-evolved visual cortex has replaced the superior colliculus as the major brain center for visual processing, however the superior colliculus does play a major role in these animals in visual orienting reflexes and eye movements.) The neurons of the LGN, in turn, relay information to the cortex where it continues through a series of cortical stages. A great deal of research attempting to examine the neural mechanisms underlying visual sensation and perception has been at the single-cell level, studying various stages in the process separately. Much progress has been made in determining how the activity of individual neurons in the

visual pathway is related to activity of the system as a whole.

Retinal Processing

In 1604, Kepler (cited in Gregory, 1966) discovered that an image created by the optical equipment of the eye (cornea and lens) is created on the retina. The retina (which means net or cobweb) is actually a piece of the central nervous system, an outgrowth of the brain which has budded out of the skull and become very sensitive to light. It retains typical brain cells between the receptors and the optic nerve which serve to modify the electrical signals from the receptors. In the human eye approximately one hundred million photoreceptors converge with one million optic nerve fibers. The converging messages must be integrated by the next cell in the pathway to produce a new message, thus some processing has occurred. The orderly, layered arrangement of cells within the retina and brain suggests that processing within it is carried out in these hierarchically arranged levels.

Some of the early work of the delineation of retinal functioning was performed by Werblin and Dowling (1969),

who measured the responses of the various cell types of the outer retina in the mudpuppy by stimulating the receptive fields of these cells with light. (A receptive field of a neuron is that area of the retina in which light stimulation can influence the response of that cell.) The light stimulation used by Werblin and Dowling consisted of either a small spot of light focussed on the center of a neuron, or a ring (or annulus) of light focussed on the surround area of a neuron.

The first level of processing occurs in the outer plexiform layer of the retina, which is made up of the synaptic connections between the receptors, horizontal cells and bipolar cells. In the dark the photoreceptors are depolarized and emit a neurotransmitter. When a small spot of light is present within the receptive field of a vertebrate photoreceptor it will respond by hyperpolarizing, as first demonstrated by Bortoff (1964) in the Necturus retina. (Hyperpolarization in the rods and cones of many other species was later demonstrated.) Thus, information that a stimulus is impinging on a receptor is signalled by a decrease in transmitter release. If the retina is illuminated for a long enough period of time the cone photoreceptors will adapt to this new level of light intensity and will start depolarizing

again. In general, horizontal cells also respond to stimulation by hyperpolarizing.

Differentiation of ON and OFF Pathways in the Retina

Physiological Differentiation

Within some types of cells in the retina (such as the photoreceptors and the horizontal cells) almost all cells respond to light with the same polarity of response; in the case of other types of retinal cells, different polarities of response to light are observed. Hartline (1938a) established that frog ganglion cells could be classified on the basis of their response to light increment or decrement. Hartline found three types of responses to changes in illumination in these ganglion cells. One group of cells responded to light increment, a second group to light decrement, the third group responded to both increment and decrement. These ganglion cells were named by Hartline as "on", "off" and "on-off", respectively.

The ganglion cells are the first cells in the visual pathway to fire action potentials; other retinal cells respond to stimulation with graded potentials. Most

mammalian ganglion cells exhibit a maintained discharge of firing in the absence of effective stimulation. The maintained discharge rate changes when the light level changes, but if the new level of illumination remains steady, the cells return to close to their former maintained discharge rate. This means that these cells are capable of signalling inhibition, as well as excitation, by a decrease or increase, respectively, in the maintained discharge rate.

Kuffler, 1953, recorded from the intact cat eye by piercing the sclera with tubing through which he inserted a microelectrode onto the retina. The microelectrode was used to record action potentials of ganglion cells while stimulating the cells with a small spot of light (which could be projected onto different parts of the receptive fields of the cells). Kuffler was able to demonstrate that each ganglion cell was most sensitive to stimuli positioned close to the center of its receptive field. He found one class of cells with a central region that responded to an increase in illumination by an increase in the rate of impulses firing, and an annular surrounding region which responded to an increase in illumination by a decrease in the rate of impulses firing. This type of cell was termed an "on-center" (ON)

cell. He also found cells, again with center-surround organization, but with the opposite polarity. The central region of these cells responded to decreased illumination with an increase in the firing rate, and the surround region responded with a decrease in the firing rate. This type of cell was termed an "off-center" (OFF) cell. An essential feature of the center and surround regions is that, within them, the type of response could not be changed by altering any of the stimulus parameters. In other words, an on-region always responded to increased illumination with an increase in firing rate, an off-region always responded in the opposite fashion. Kuffler found approximately half the ganglion cells he studied were ON cells and half were OFF cells. Other than the difference in polarity of response, the cells functioned in a similar manner. Furthermore, the center and surround regions were found to be antagonistic; stimulation of one region caused a suppression of the response of the other. Illumination of the entire receptive field resulted in either no response, or a much reduced response.

It was later found by Werblin and Dowling (1969) that the bipolar cells also possess center-surround organization, and can also be divided into two basic

groups. In one type of bipolars, stimulation of the center of the cell yields depolarization, stimulation of the surround results in hyperpolarization (these are named depolarizing, or ON bipolar cells). In the other type of bipolars, the response polarity is reversed; stimulation of the center of the cell results in hyperpolarization and stimulation of the surround results in depolarization (these are named hyperpolarizing, or OFF bipolar cells).

The origin of this differentiation was later found to reside in the type of synapse that cone bipolar cell dendrites form with cones, in the cat, by Boycott and Kolb (1973). Two types of synapses were found: flat and invaginating. In the turtle retina, Raviola and Gilula (1975) found in the postsynaptic membrane of flat and invaginating bipolar cells structures typical of excitatory and inhibitory membranes, respectively. Evidence from other species has demonstrated that the invaginating bipolars depolarize to illumination and flat bipolars hyperpolarize to illumination. This and other studies as reviewed by Kaneko, 1979, provide evidence that the morphological distinction between the two types of bipolars is the correlate of the fundamental difference in their functioning. The invaginating and

flat bipolar cells respectively mark the origin of the ON and OFF pathways. The spatially-antagonistic receptive fields of the bipolar cells make them the first cells in the visual pathway to detect not simply onset of light, but a particular spatial distribution of light, or spatial contrast. The response of the bipolar cells depends on the amount of light falling on the center relative to the amount falling on the surround of the cell.

Dowling, in a review of vertebrate retinal wiring (1979), has hypothesized a wiring scheme to explain the interaction and integration of excitation and inhibition in the retina. In his model there is present a direct pathway from receptor to bipolar which mediates the center response of both types of bipolar cells, and an indirect pathway from receptor to horizontal to bipolar which mediates the surround response of both types of bipolar cells. The surround antagonism is mediated by the laterally-spread processes of the horizontal cells. The antagonistic center-surround of the bipolar cells is then transferred to the ganglion cells.

Morphological Separation-Stratification in the IPL

It had long been recognized that the dendrites of the various types of ganglion cells branch on different levels of the IPL. Cajal (1893/1973) identified stratification of dendritic trees in the retinas of many different species; and in most species there appeared to be two major subdivisions of the IPL. It has been suggested that this layering may be correlated with physiological differences (Lettvin, Maturana, Pitts & McCulloch, 1959). Famiglietti and Kolb (1976) investigated the sublaminar organization of the IPL of the cat, and found that ganglion cells consist of two subclasses, based on the cell's pattern of dendritic branching. Ganglion cells of the outer portion of the IPL, generally have one primary dendrite. The hyperpolarizing, (OFF, or flat) bipolar cells terminate in the outer portion thus overlapping with OFF ganglion cells. The ganglion cells of the inner layer of the IPL tend to have many primary dendrites and they have a "bushy" appearance. The dendrites of these cells are found in the inner portion of the IPL. The depolarizing, (ON, or invaginating) bipolar cells terminate in the inner layer of the IPL and overlap with the dendrites of ON ganglion cells. Therefore, it appears that ON and OFF

bipolar cells each terminate in a different sublamina, and there they synapse separately with ON and OFF ganglion cells. The results of this study strongly suggest that the organization of the IPL provides a structural basis for the separation of ON and OFF responses in the retina. Additional evidence of differential stratification in the IPL of the cat of the dendritic trees of ganglion cells by using retrograde labelling with horseradish peroxidase has been reported by Wassle, Boycott and Illing (1981).

Famiglietti, Kaneko and Tachibana (1977), recorded intracellular responses of carp ganglion cells in order to separate them into ON and OFF cells, and then stained the cells to determine their distribution in the IPL. Dendrites of ON ganglion cells were found to terminate in the inner layer of the IPL, dendrites of OFF ganglion cells were found to terminate in the outer portion of the IPL. The bipolar cells which synapsed with the two different types of ganglion cells were also stratified, the depolarizing ON bipolar cells had synaptic terminals in the inner layer of the IPL, the hyperpolarizing OFF bipolar cells had synaptic terminals in the outer layer of the IPL. Again, as in the cat, the dendritic trees of the two types of bipolar cells differed morphologically.

Using the same experimental technique in the cat, Nelson, Famiglietti and Kolb, 1978, recorded intracellular responses from ganglion cells and then stained the cells. The dendrites of the ON ganglion cells were found to branch in the inner layer of the IPL where the ON bipolar cells terminated. The dendrites of OFF ganglion cells were found to branch in the outer layer of the IPL where the OFF bipolar cells terminated. In addition, Peichl and Wassle (1981) confirmed the stratification hypothesis; following extracellular recording, cat ganglion cells were stained with a silver stain dye. The dendritic trees of ON and OFF cells were found to lie in different strata of the IPL, ON cells in the inner portion, OFF cells in the outer portion. Thus, in cat and carp retinas ON and OFF center ganglion cells have different dendritic tree morphologies, these dendritic trees terminate on different levels of the IPL, and the morphological differences can be correlated with the functional differences.

The most impressive example of morphological segregation of retinal cells was found by Hartline (1938b) in the scallop. ON and OFF cells in the retina of each eye were organized in independent layers. The two layers differ morphologically and each gave rise to a

separate branch of the optic nerve, virtually creating two separate retinas.

Independent Mosaics of ON and OFF Ganglion Cells

More morphological evidence of differentiation of ON and OFF cells was found by examining the arrangement of ganglion cells in the cat retina. ON and OFF ganglion cells taken together were found to form an irregularly spaced mosaic in which the majority of cells were arranged in pairs. The ratio of ON to OFF cells was 48 to 52. However, when considered separately ON and OFF cells were found to each form a regularly spaced mosaic (Wassle, Boycott & Illing, 1981; Wassle, Peichl & Boycott, 1981).

The demonstration of independent and regularly-spaced mosaics of ON and OFF cells strengthens the argument that there exist two independent channels in the retina to signal light increment and decrement. One very important function of these cells is spatial resolution. French, Snyder and Stavenga (1977) have demonstrated that an irregular retinal mosaic results in the degradation of an image; and they further propose that a basic requirement for good spatial resolution is

the regular spacing of sampling points. If ON and OFF cells function together, they would form an irregular mosaic and resolution would be greatly reduced. If the ON and OFF cells function independently, each would possess regular sampling points and good resolution could be achieved. The grating resolution determined behaviorally (Campbell, Maffei & Piccolino, 1973) agrees well with the spatial resolution estimated by the inter-cell distances found in the independent mosaics.

Pharmacological and Physiological Differentiation of ON and OFF Pathways in the Brain

LGN

It is of interest to determine if the separation of ON and OFF pathways observed in the retina continues into the brain. The first synapse of central visual neurons of the retino-geniculo-striate tract is in the dorsal nucleus of the LGN. The receptive fields of LGN cells are very similar to those of the ganglion cells (So & Shapley, 1981). More than 90% of ganglion and LGN cells have been found to be ON or OFF cells with concentrically-organized center-surround organization (Cleland & Levick, 1974; Dreher & Sefton, 1979). Hubel

and Wiesel (1961) found that geniculate ON and OFF cells were approximately equal in number. When responses were recorded simultaneously from optic-tract fibers and their associated LGN cells, Hubel and Wiesel found that the receptive fields of both were concentric and of the same response polarity; ON and OFF ganglion cells were always associated with ON and OFF geniculate cells, respectively. This was also found by Cleland, Dubin and Levick (1971), who reported that ON and OFF ganglion cells provided excitatory input to ON and OFF LGN cells, respectively. Like ganglion cells, LGN cells exhibit a maintained discharge rate of firing that can be modulated up or down in response to increases or decreases of firing in ganglion cells providing input to them.

Investigation of central ON and OFF pathways has been accomplished by the use of a pharmacological approach developed by Slaughter and Miller (1981), who were able to inactivate the ON pathway using DL-2-amino-4-phosphonobutyric acid (APB). Slaughter and Miller recorded intracellularly following addition of APB to the bathing medium of the perfused retina-eyecup preparation of the mudpuppy. The found that a high concentration of APB blocked the responses of ON bipolar and ON ganglion cells; photoreceptors, horizontal, OFF

bipolar and OFF ganglion cells were not affected. It was hypothesized that the site of action of APB may be the synapse between the photoreceptor and the ON bipolar cell. Glutamate is thought to mediate neurotransmission at this synapse; APB, a structural analog of glutamic acid, may bind to the post-synaptic receptors on the ON bipolar cells, and block input to them. Consistent findings have been reported for other species as well. Application of APB abolished responses of ON ganglion cells in the rabbit retina (Neal, Cunningham, James, Joseph & Collins, 1981). Knapp and Mistler (1982) found that both center and surround responses of ON ganglion cells of the rabbit were blocked following APB application.

Schiller, 1982, used APB to examine the separation of ON and OFF pathways in the LGN and visual cortex of the monkey. Schiller perfused the eye and recorded simultaneously in the LGN and striate cortex of 10 rhesus monkeys. He found that APB quickly abolished the responses of ON cells in the LGN. OFF LGN cells were not affected significantly by APB. Schiller also attempted to determine whether the center-surround antagonism observed in LGN cells was produced by convergence of ON and OFF pathways. APB infusion inhibited both the center

and surround response of the ON cells; the surround of the ON cells was no longer stimulated by light offset. Infusion of APB did not affect either the center or surround of the OFF cells; both responded as they did before infusion. Thus, it appears that center-surround antagonism in the monkey LGN is not produced by convergence of retinal ON and OFF pathways.

In the cat, intraocular injection of APB abolished ON responses recorded from the LGN (Horton, 1981), and ON responses recorded simultaneously from ganglion cells and geniculate cells (Horton & Sherk, 1984). Center-surround organization was not affected for either ON or OFF cells. However, responding of OFF cells in the LGN was found to be reduced. This finding contrasts with results in other species where no effect was found on OFF cell responding. Whether this result represents a species-specific difference, or a variation in experimental procedure was not established. However, as the decrease in responding of OFF cells was considerably less than the decrease observed for ON cells, the conclusion drawn by these investigators is that APB primarily inactivates ON ganglion and LGN cells in the cat.

Physiological investigations of the sublaminar organization of the LGN have revealed stratification of ON and OFF cells in a number of species. In the tree shrew (Holdefer & Norton, 1986) geniculate laminae 1 and 2 were found to contain mostly ON cells which projected to cortical layer IVa; geniculate laminae 4 and 5 contained mostly OFF cells which projected to cortical layer IVb. Evidence of stratification of ON and OFF cells was also found in the cat (Bowling & Wieniawa-Narkiewicz, 1986). A gradient of distribution of ON and OFF cells was found in layer A of the cat LGN. In addition, the strength of the response of both ON and OFF cells was found to vary inversely with the local density of that cell type.

Cortex

Hubel and Wiesel pioneered the study of the functional properties of central neurons in visual pathways in cats and in monkeys (Hubel & Wiesel, 1962; 1977). The cells of the visual cortex exhibit some properties not observed in the retina or LGN; Hubel and Wiesel divided cortical cells into two main classes they termed simple and complex, the main basis for this distinction was the ability of a receptive field map of

ON and OFF areas to predict the pattern-selective properties of the cell. In the case of simple cells the relationship between the receptive field map and the behavior of the cell was relatively simple and predictable. Simple cells have discrete ON and OFF zones which are larger than those of the LGN cells and are elongated in shape. They may have a central ON region flanked by two OFF regions (or vice versa), or they may have only one ON region and one OFF region. Although a simple cell may respond to a small spot of light, a bar is a better stimulus if it is placed within the receptive field of the cell in a particular orientation. The simple cell is selective to a stimulus of a particular width, orientation and position. Simple cells can respond to both stationary or moving stimuli.

Many cells of the striate cortex respond to either a light moving edge or a dark moving edge, or to both types of edges (Hubel and Wiesel, 1962). Input from ON and OFF LGN cells is thought to produce cortical light- and dark-edge responses, respectively (Schiller, Finlay and Volman, 1976). Simple cells often demonstrate either a light-edge or a dark-edge response to stimulation.

Complex cells may respond to both light and dark moving edges. As they often do not have well-defined ON and OFF areas, they may give both ON and OFF responses throughout their receptive fields. Complex cells do, however, exhibit a preference for a stimulus of a particular orientation. Unlike simple cells, the position of the stimulus within the receptive field is not so important, they will respond to an appropriately-oriented stimulus falling anywhere within the boundaries of the receptive field. The relative unimportance of position to complex cells may account for their vigorous response to edges or bars moving through their receptive fields. Complex cells respond better to moving stimuli than to stationary stimuli, and they exhibit a directional selectivity; that is, they may respond preferentially to a stimulus moving in one direction rather than in another direction. Both simple and complex cortical cells, unlike ganglion or geniculate cells, are characterized by a low maintained discharge rate (Hochstein & Spitzer, 1985).

Schiller (1982) also investigated the responses of simple and complex cells in the striate cortex of monkeys. Intraocular APB infusion resulted in elimination of the light-edge response in complex cells

that yielded both light- and dark-edge responses when the eye was untreated; this suggests some input from ON LGN cells. In other cortical cells, Schiller found more complicated responses. In simple cells exhibiting only light-edge responding, infusion of APB resulted in elimination of this response, as expected. Unexpectedly, however, the cell then exhibited a dark-edge response. Although it appears that ON and OFF ganglion cells provide input to ON and OFF cells separately in the LGN, in the brain there is evidence of both convergent excitation and inhibition between ON and OFF pathways.

Sherk and Horton (1984) injected APB into one eye and examined receptive field properties in the cat striate cortex to moving stimuli (as responding to stationary stimuli was greatly reduced in both ON and OFF cells). The major result of APB injection in the striate cortex was a severe reduction in overall cell responsiveness; this reduction was much greater than that observed in the LGN. In general, simple cells were less affected by APB than complex cells. In almost all of the cells tested, the light-edge response was greatly reduced; but only in 30 out of 149 cells was inhibition of response complete, as in the monkey (Schiller, 1982). The source of the remaining light-edge responding in the

cortex could not be geniculate ON cells (as their responding was abolished). The source of the light-edge responding, however, may be the surrounds of geniculate OFF cells. Although responding of cells of the LGN is typically dominated by the center mechanism, Horton and Sherk (1984) found that responding of the surrounds of APB-affected cells was 40% of the center responding. Dreher and Sanderson (1973) found that surrounds of LGN OFF cells can respond strongly to moving light edges, and may be able to drive cortical cells. This line of reasoning may help to explain the difference between simple and complex cells in the reduction of light-edge responding. The response of the simple cells may depend more on direct geniculate input (in this case from the surrounds of the geniculate cells) than the response of the complex cells. Complex cells may depend less on direct geniculate input and more on intracortical input. Monkey cells appear to have weaker surrounds than cat cells (Kaplan, 1986), perhaps explaining the difference in the effects of APB injection on light-edge responding between these two species.

The results of APB injection in the cat cortex are fundamentally similar to results obtained from monkey cortex; in both species convergence of separate

geniculate ON and OFF pathways is found in the cortex, and in both species this convergence appears to be both excitatory and inhibitory. In the cat the ON pathway is not essential for signalling light edges as the inactivation of the ON geniculate input did not abolish all cortical responding to light edges, although such responding was greatly reduced.

Zaha and Stryker, 1986, have examined whether the stratification of ON and OFF cells observed in separate sub-layers of laminae A in the ferret LGN is maintained in the projection of these cells to the striate cortex. In this investigation they made many vertical and tangential electrode penetrations of layer IV of area 17 of the cortex. Vertical penetrations resulted in responses of only one center type, therefore no evidence of layering of ON and OFF cells was found. When tangential penetrations were made, however, areas of ON and OFF cells in the striate cortex were found, separated by areas in which afferents of ON and OFF cells were mixed. These findings provide evidence that ON and OFF afferents from the ferret LGN segregate in vertically-arranged patches in the ferret striate cortex.

Clinical Evidence of Independent ON and OFF Pathways in Humans

Evidence of separation of ON and OFF pathways has been found in some human clinical studies of brain damage in which difficulties in visual perception or visuo-motor tasks are exhibited. Children with spastic cerebral palsy often perform poorly on these types of tasks in comparison to normal children. Stimulus patterns are usually organized into figure and ground, according to Gestalt psychologists. The figure is usually a dark object perceived against a light background. The ability of some brain-damaged individuals to do this may be impaired with traditional black-on-white materials (Wedell, 1960); Reversing the polarity of contrast to white-on-black often improves performance of such individuals (Uhlin & Dickson, 1970). Marozas and May, 1985, presented both black-on-white and white-on-black testing materials to spastic cerebral palsied and normal children. The performance of the normal children was not significantly affected by using white-on-black testing materials; the performance of the spastic cerebral palsied children, however, was found to improve in perceptual tasks (but not in visuo-motor tasks) when white-on-black testing materials were used.

Psychophysical Evidence of Differences in Brightness and Darkness Perception in Humans

Early evidence of differences in the human perception of brightness and darkness was provided by Helmholtz (1911/1962), who found that bright areas appeared larger than dark areas of the same size. If a grating with dark bars and intervals of equal lengths was held in front of a bright background, the intervals appeared to be wider than the bars. This phenomenon was reported with other shapes of bright and dark objects as well.

Comparisons of increment and decrement thresholds revealed some differences in brightness and darkness perception. Blackwell (1946) found that, when the surround luminance was low, the difference threshold for a black test-object was less than the difference threshold for a white test-object. When the surround luminance was increased the difference thresholds were the same. Herrick (1956) found a small difference in increment and decrement thresholds using a stimulus without a background. Using flash stimuli Boynton, Ikeda and Stiles (1964) observed that decremental thresholds were lower than the corresponding incremental thresholds.

Short (1966), and Patel and Jones (1968) compared increment and decrement thresholds, and also found that the decrement threshold was lower than the increment threshold when the surrounding luminance was low. In summary, most of the work comparing black and white test-objects, and incremental and decrmental flash stimuli have found that the threshold is lower for black test-objects or decremental flashes than for white test-objects or incremental flashes.

Another area of psychophysical investigation of asymmetries between brightness and darkness perception has involved the phenomena of brightness and darkness enhancement. Bartley (1938) observed that the subjective brightness of the light phase of a flickering light increased over the range of frequencies between 2- 20 Hz; this phenomenon was called brightness enhancement, or the Brucke-Bartley effect. Darkness enhancement was described by Glad and Magnussen (1972) who found the equivalent phenomenon for the dark phase of a flickering light. Several investigators have suggested that, in humans, brightness and darkness enhancement may reflect temporal frequency characteristics of ON and OFF pathways (Grind, Grusser & Lunkenheimer, 1973; Glad & Magnussen, 1972).

Magnussen and Glad (1975a) were interested in comparing the magnitude of brightness and darkness sensations over a range of temporal frequencies (as well, as across variations in mean luminance and depth of luminance modulation). Brightness and darkness matching judgments were made by human observers to the light and dark phases of suprathreshold square-wave flicker stimuli. The stimulus consisted of an inducing-field (6 degrees in diameter) which was steadily illuminated with a temporally modulating center test-field (1 degree x 42 minutes); this stimulus configuration was designed to preferentially stimulate center mechanisms rather than surround mechanisms.

Results indicated that brightness and darkness enhancement differed a great deal in magnitude; darkness enhancement far exceeded brightness enhancement. (The results also indicated many similarities between brightness and darkness enhancement. The temporal frequencies at which brightness and darkness enhancement reached their maxima were found to be the same, between 2-7 Hz. An increase in mean luminance had two effects both of which were observed for brightness and darkness enhancement: the magnitude of enhancement was increased, and the maximum was shifted to a higher temporal frequency. When the depth of modulation was increased

maxima remained the same but the magnitude of both brightness and darkness enhancement was increased.)

Magnussen and Glad (1975b), attempted to examine the surround mechanism by holding the test-field steady and modulating the inducing-field. Brightness and darkness enhancement were again measured over variations of temporal frequency, stimulus luminance and depth of modulation. Results indicated that, in general, the response functions were very similar to those obtained in the previous set of experiments (Magnussen & Glad, 1975a) in most aspects, except for gain. The large asymmetry in gain between brightness and darkness enhancement previously observed was not observed under these experimental conditions, brightness and darkness enhancement effects appeared to be equal.

De Valois (1977), in work investigating phase-sensitivity characteristics of spatial frequency-sensitive channels found that these channels were specific for contrast. Black-on-white and white-on-black patterns produced different results; in addition, channels responding to patterns of opposite contrast were found to be independent.

Following adaptation to a black/white rectangular-wave grating, a grating which (before adaptation) had appeared to have equal black and white bar widths no longer seemed to have equal bar widths. If the adaptation grating consisted of narrow white bars and wide black bars, a test pattern of equal white and black bars appeared to have wider white and narrower black bars. If the adaptation grating consisted of wide white bars and narrow black bars, a test pattern of equal white and black bars appeared to have wider black bars and narrower white bars. The apparent width of the white bars shifted away from the width of the white bars of the adaptation grating, and the apparent width of the black bars shifted away from the width of the black bars of the adaptation grating. The results indicated that spatial frequency channels are phase- or contrast-specific.

Repeating the experiment with single test and adaptation bars (as opposed to gratings) confirmed this contrast specific effect. Apparent change in width of test bars following adaptation to a white bar on a black background was different than the apparent change following adaptation to a black bar on a white background. Adaptation to a bar of one contrast should produce a change in the appearance of test bars of either

contrast if channels responding to these bars were not contrast-specific. But, adaptation to a white bar on a black background produced changes in the apparent width of white test bars and produced no significant change in the width of black test bars, demonstrating independence of mechanisms responsible for the change in the apparent width of test bars. These results suggest that information processing is specific to polarity of contrast.

Electrophysiological Recording Techniques

In order to investigate the neural responses underlying the human perception of brightness and darkness electrophysiologically, techniques less invasive than those used in animal studies had to be developed. These techniques involve recording the electrical activity of many neurons of the brain at the surface with scalp electrodes. One of these techniques (visually-evoked potentials) will be employed in the proposed research.

Electroencephalogram

The gross electrical activity of the brain was first recorded by Caton in 1875, using galvanometers which could detect large electrical potentials. The electrical activity of the human brain, however, was not recorded for many years until Berger (cited in Lindsley & Wicke, 1974) published his human electroencephalogram (EEG) studies in the 1920s and 1930s. The EEG records variable potential differences between two electrodes placed on the scalp; the electrodes are connected to an amplifier and the potential can be displayed on an oscilloscope. Oscillations in electrical potential differ in frequency and amplitude when the electrode placement is changed, in different states of awareness, and in pathological brain conditions.

Evoked Potentials

Monitoring the spontaneous electrical activity of the brain does not shed a lot of light on perception. However, this on-going activity can be influenced by direct or peripheral stimulation (electrical, optical, acoustical, etc.); the change in electrical activity thus induced is known as an evoked potential. They

differ from EEGs mainly in that they have a definite temporal relationship to the stimulus.

The visually-evoked potential (VEP) was discovered by Bartley, 1934, who observed an electrical response of the cortex following illumination of the retina in the rabbit. This technique was used to map the visual projections from the retina to the cortex in the cat by Talbot and Marshall (1941).

When a sufficient visual stimulus is presented to a subject, neurons in the cortex are activated and generate weak potentials that can be picked up by scalp electrodes. This measurement of the electrical activity of localized populations of neurons during specific perceptual tasks provides an objective indicator of sensory function. VEP recording techniques have improved dramatically over the last 20 years and can provide a bridge between human psychophysical measurements and data derived from single-unit recordings in experimental animals. The characteristics of the VEP depend on the stimulus employed, electrode placement (which groups of neurons are being measured), and the response properties of those neurons.

Creutzfeldt and Kuhnt (1973) have reviewed considerable electrophysiological evidence correlating VEPs elicited by flashes of light with simultaneously recorded intracellular responses of single cells of the visual cortex of anesthesized cats. These studies suggest that the source of the VEP is summed activity of postsynaptic changes (EPSPs and IPSPs) occurring on the apical dendrites of the pyramidal cells (the predominant neuronal structures located superficially in the cortical layers). If this is true VEPs are unlikely to be highly correlated with action potentials of cortical cells, as the action potential is the result of postsynaptic activity all over the cell, not just at the apical dendrites.

Following stimulation from the LGN, an initial positive wave, followed by a negative wave and a later positive wave, can be observed in the VEP recorded from the scalp. Zemon, Kaplan and Ratliff (1986) have determined that gamma-aminobutyric acid (GABA), the major inhibitory neurotransmitter in the cortex, is a very important contributor to the VEP. When a GABA blocker (bicuculline) was applied to the cortex the waveform of the VEP was changed. (GABA-mediated intracortical

inhibition is also the main contributor to the low maintained discharge rate found in the cortex.)

VEPs recorded from the cortical surface in humans are very similar to those recorded from the scalp surface, and are also very similar to those recorded from the cortical surface of the cat (Creutzfeldt & Kuhnt, 1973). But VEPs can vary a great deal, from one species to another, from one individual to another within the same species, and from day to day in one individual. Many of the factors affecting it are factors which also affect the EEG, such as; cortical arousal state, respiration rate, heart rate, pathological states, etc. The relative ease of data collection of VEPs contrasts with its complex form and the incomplete knowledge of the variables affecting the VEP. This makes interpretations of the VEP difficult. Technical advances and the growing amount of research in the field have contributed to greater understanding of VEPs. VEP recording has become an important tool in research on human perception. In general, results from VEP research have supported the hypothesis that the sensory pathways of the brain break down complex stimuli into a number of abstract features that are thought to be processed independently in different channels. This channel hypothesis has its

basis in much work in visual physiology and psychophysics. In pathological states it is possible that functioning in one channel is affected, but not in another (as may be the case in cerebral palsied children).

The main problem in recording VEPs is detecting them. They are extremely weak in comparison to the spontaneous activity of the brain; the amplitude of the VEP can range from 1 to 10 microvolts, while the amplitude of the EEG ranges from 50 to 100 microvolts. To the VEP investigator the EEG is an unwanted and overwhelming background noise, and must be minimized. There are two widely employed methods for enhancing the signal-to-noise ratio of VEPs, as reviewed by Regan (1972). The first method is signal-averaging of transient stimulation. A stimulus is presented repeatedly, separated by intervals long enough to allow the brain to attain its resting state between presentations. Each waveform of brain response is called a transient VEP. When a large number of these waveforms have been summed (by a computer), the amplitude of each point of the waveform is averaged and displayed as an averaged curve. Since the EEG activity is not correlated with the stimulus, and varies randomly, the summed

background noise builds up less rapidly than the summed evoked potential. As a result, although single responses in the transient evoked potential are buried in the noise, when many are summed the VEP emerges clearly.

The second method is narrow-band filtering of "steady-state" VEPs. If a stimulus repeats rapidly enough, successive VEPs will run into each other and become a series of identical waves of electrical activity that repeat at the same frequency as the sensory stimulus, thus creating a "steady-state" of stimulation. Steady-state VEPs must also be extracted from the background "noise" of the EEG. This can be accomplished by means of narrow-band filtering at selected frequencies.

A light flickering F times per second may elicit a steady-state VEP whose frequency would also be F cycles per second. This frequency at which the waveform repeats itself is equal to the frequency of the fundamental (or first harmonic) component. The response of a linear system driven by a sinusoidal input of frequency F Hz is a pure sinusoid of frequency F Hz. The amplitude of the response, as well as its phase may differ from that of the stimulus, but the frequency content always remains

unchanged. The visual system does not always respond in a linear manner. Its output often contains other frequency components, such as the second harmonic which has a frequency of twice the fundamental frequency, the third harmonic which has a frequency of three times the fundamental frequency, etc.

Any waveform, no matter how complex, can be described as a linear sum of its component sine waves. This was demonstrated by Fourier, a French mathematician, in 1807; and in his honor the elementary sinusoids making up a waveform are known as Fourier components. A precise description of the VEP waveform can be obtained in terms of amplitude and phase of its Fourier components. In practice only a few Fourier components may be required to obtain a good description of the waveform. An assumption used in the application of Fourier analysis to VEP recording is that in any particular experiment it is safe to neglect the VEP components which are not time-locked to the stimulus; it is only necessary to measure the VEP amplitudes and phases at the stimulus frequency and at its harmonics, all other frequencies are rejected. In effect, the rejected activity amounts to most of the unwanted noise. As there is no reason to expect much random noise at

precisely F Hz, 2F Hz, etc., it is possible to extract a steady-state VEP from the EEG by exploiting the prior knowledge that the bulk of the response will be at certain frequencies.

Rationale for Proposed Research

The studies so far presented provide substantial electrophysiological, morphological and pharmacological evidence that ON and OFF pathways (in many animal species) are separate from the level of the second-order neurons in the retina to the level of the LGN; the ON and OFF pathways most likely converge somewhat at the level of the cortex. There are no corresponding studies in humans, although clinical evidence in humans has suggested independence of the ON and OFF pathways. It is usually assumed that ON and OFF pathways do exist in humans, and that these pathways have properties similar to those observed in other species (especially primates). Psychophysical research has demonstrated differences in brightness and darkness perception in humans and animals. The independence of ON and OFF pathways, and the relationship of these pathways to the perception of brightness and darkness are two different issues. Barlow, Fitzhugh and Kuffler (1957) hypothesized that the

ON and OFF pathways mediate the perception of brightness and darkness, respectively. This idea was further developed by Baumgartner (1961), Magnussen & Glad (1975a), and Jung (1973). The leap of faith necessary to jump from physiological and pharmacological evidence of separate ON and OFF pathways to psychophysical evidence of differences in brightness and darkness perception is supported by the the results of Schiller, Sandell and Maunsell (1986). The ON pathway in monkeys was blocked by injecting APB intraocularly; the ability of these animals to detect light increment and decrement was then examined psychophysically. Light increment detection was found to be severely impaired; however, no significant effect was observed for light decrement detection. An examination of contrast sensitivity following APB injection revealed, as expected, a significant loss of sensitivity, especially at optimal spatial frequencies.

The proposed research will be an attempt to examine ON and OFF pathways in humans electrophysiologically by recording VEPs in response to light increment and light decrement. This approach has not been used to investigate these pathways, and will most probably provide yet another line of evidence of separability of

the ON and OFF pathways in humans, and evidence of asymmetries in their properties.

METHOD

Subjects

Nine healthy adult volunteers with normal (with correction, if necessary) visual acuity and no known neuro-ophthalmologic disease served as subjects in this study. (Four of these were tested on all VEP experimental conditions, and two of these subjects were tested on both psychophysical experimental conditions.)

Stimuli

Typical stimuli employed in VEP research are gratings or checkerboards whose luminance is modulated a manner such that part of the pattern increases in luminance as the other part decreases in luminance. Luminance modulation of this type would be expected to stimulate both ON and OFF pathways simultaneously, and therefore was not used in these experiments as the objective was to separate the responses of the ON and OFF pathways. Novel stimuli, designed to preferentially stimulate ON or OFF pathways, were employed in this study. The stimulus was a modified checkerboard pattern, consisting of checks which occupied one-quarter of the

stimulus screen (see figure 1). The luminance of the "isolated" checks was modulated sinusoidally in time, while the other three-quarters of the screen remained at the background level of luminance.

The luminance of the checks was modulated either above or below the constant background luminance. In the bright-check (or positive-contrast) condition, maximal contrast occurred when the luminance of the check was at a maximum (top half of figure 1). This type of stimulus was designed to preferentially elicit responses from the ON pathway. In the dark-check condition, the maximal contrast occurred when the luminance of the check was at a minimum (bottom half of figure 1). This type of stimulus was designed to preferentially elicit responses from the OFF pathway.

Stimulating Apparatus

Spatiotemporal stimuli were displayed on a Tektronix 608 oscilloscope monitor with a fast (P31) phosphor. Stimuli were generated by means a specially contructed waveform generator designed by the engineers and researchers of the Laboratory of Biophysics of The Rockefeller University (Milkman, Schick, Rosetto,

Figure 1

Examples of bright-check (top) and dark-check stimuli (bottom).

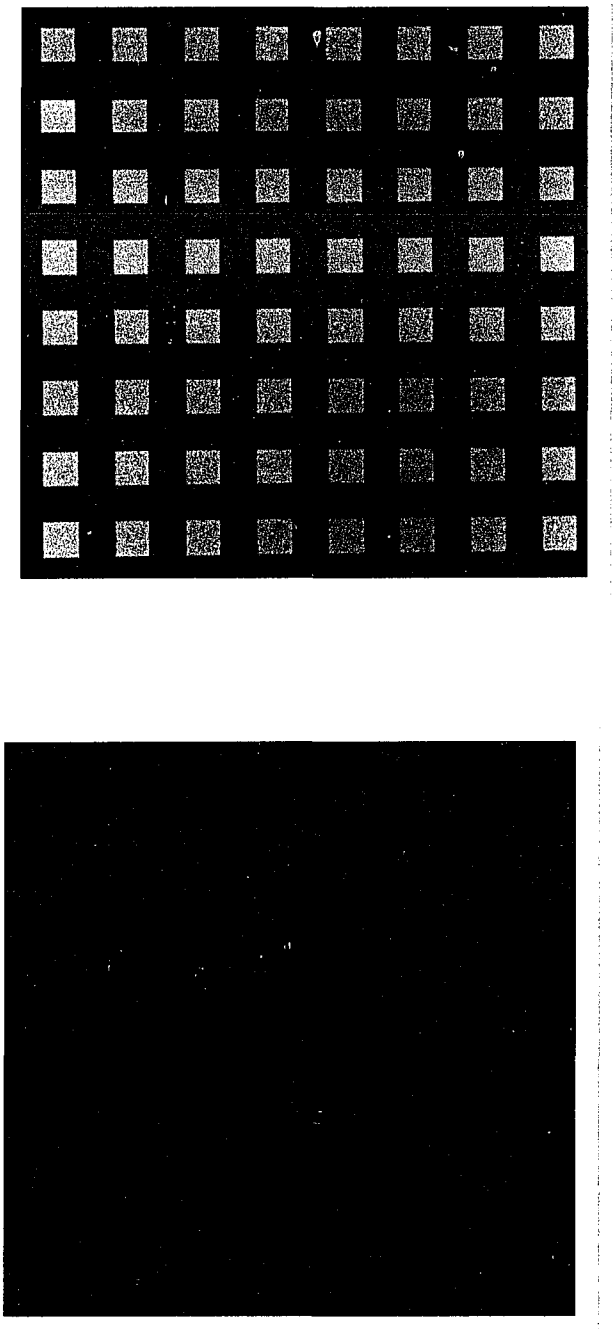


Figure 1

Ratliff, Shapley and Victor, 1980), which was interfaced to a LSI 11/23 computer. This apparatus provided for control of a 256 X 256-pixel raster display at a frame rate of 270.3 Hz. The mean luminance of the raster display was 154 cd/m2.

Recordings

Recordings were made in a darkened room (the stimulus display was at photopic levels), with the subject's head stabilized on a chinrest. Subjects were requested to fixate on a blackened point in the center of the display, which subtended a 10 X 10 degree region at a distance of 50 cm. Viewing for these experiments was binocular. A contiguous surround field (56 X 64 degrees) matched approximately in hue and luminance served to adapt the peripheral retina to the mean luminance of the stimulus display. The EEG was recorded using three gold cup electrodes placed on the midline of the head at sites Oz, Pz and Cz, according to the 10-20 electrode placement system (Jasper, 1958). The electrode at Oz ("active site"-located at the occipital pole of the head, over the striate cortex) was connected to the negative input of a specially-designed high-gain differential amplifier, and the electrode at Cz ("reference site") was connected to

the positive input. The electrode at Pz served as ground.

Analysis

After amplification (gain=10,000) and bandpass filtering (0.03-100 Hz), the EEG was fed into an analog/digital converter. The digitized EEG was then processed and stored by the LSI 11/23 computer. The EEG was sampled at a rate of 270 Hz, and two 30 second periods were averaged during each experimental run. The averaged EEG was Fourier analyzed and Fourier components of the responses (amplitudes and phases) were obtained at the first four harmonics frequencies. Noise estimates were obtained by Fourier analysis of the EEG at a frequency .03 Hz above the fundamental frequency, and .06 Hz above the second harmonic frequency. Amplitude was measured in microvolts, and phase was measured in degrees in relation to the stimulus phase. A phase of zero meant no lead or lag of the response phase in relation to the stimulus phase. At the end of each run, frequency components were printed as a hard copy, as well as stored on floppy disks.

Procedure

Experiment I-Spatial Tuning

In the first experiment, responses to bright- and dark-check stimuli of different sizes were measured in a series of descending check sizes. The largest size check to be tested was a 10 degree X 10 degree check (which occupied the entire stimulus display and was equivalent to full field modulation). All following check sizes in the series were one-half the size of the previous check. The smallest check that was tested was 5 minutes X 5 minutes. The VEP responses to the series of bright-check stimuli were compared to the responses to the dark-check stimuli. The luminance of the check was modulated sinusoidally in time at a temporal frequency of 6.3 Hz, a frequency at which optimal VEP responses have been found using a variety of stimuli. Contrast was defined using the Weber definition of contrast (C_w):

$$C_w = (L_0 - L_b) / L_b$$

where L_0 is the luminance of the check, and L_b is the luminance of the background. In the case of the bright checks, there was present a mean contrast of 15%, and a depth of luminance modulation of 15% around this mean

contrast. This resulted in a stimulus whose contrast was modulated from 0 to 30%. This stimulus "appeared" as contrast reached its maximum (30%), then "disappeared" as contrast decreased to its minimum (0%). In the case of the dark checks, there was present a mean contrast of -15%, and a depth of luminance modulation of 15% around that mean contrast. This resulted in a stimulus whose contrast was modulation from 0 to -30%. This stimulus "appeared" as contrast reached its maximum (30%), then "disappeared" as contrast decreased to its minimum (0%).

The luminance modulation of the bright-check stimuli was 180 degrees out-of-phase with respect to the luminance modulation of the dark-check stimuli. However, the absolute contrast of each type of stimulus was modulated in-phase (see figure 2). It is of interest to note if the phase of the VEP waveform is in-phase with luminance modulation or contrast modulation. VEP research has demonstrated that the contributions of spatial contrast and luminance are not equal when a spatial pattern (of optimal spatial frequency) is present; contrast is generally more relevant to the response than luminance (Spekreijse, Van Der Tweel & Zuidema, 1973). The phases of the VEP will differ in response to bright and dark checks if luminance is the

Figure 2

A profile of luminance modulation of the bright-check (left) and dark-check (right) stimuli in time. The dashed line represents the background luminance (B). Although the luminance signals for two types of stimuli are 180 degrees out-of-phase, both types of stimuli reach their peak in contrast at the same point in the cycle.

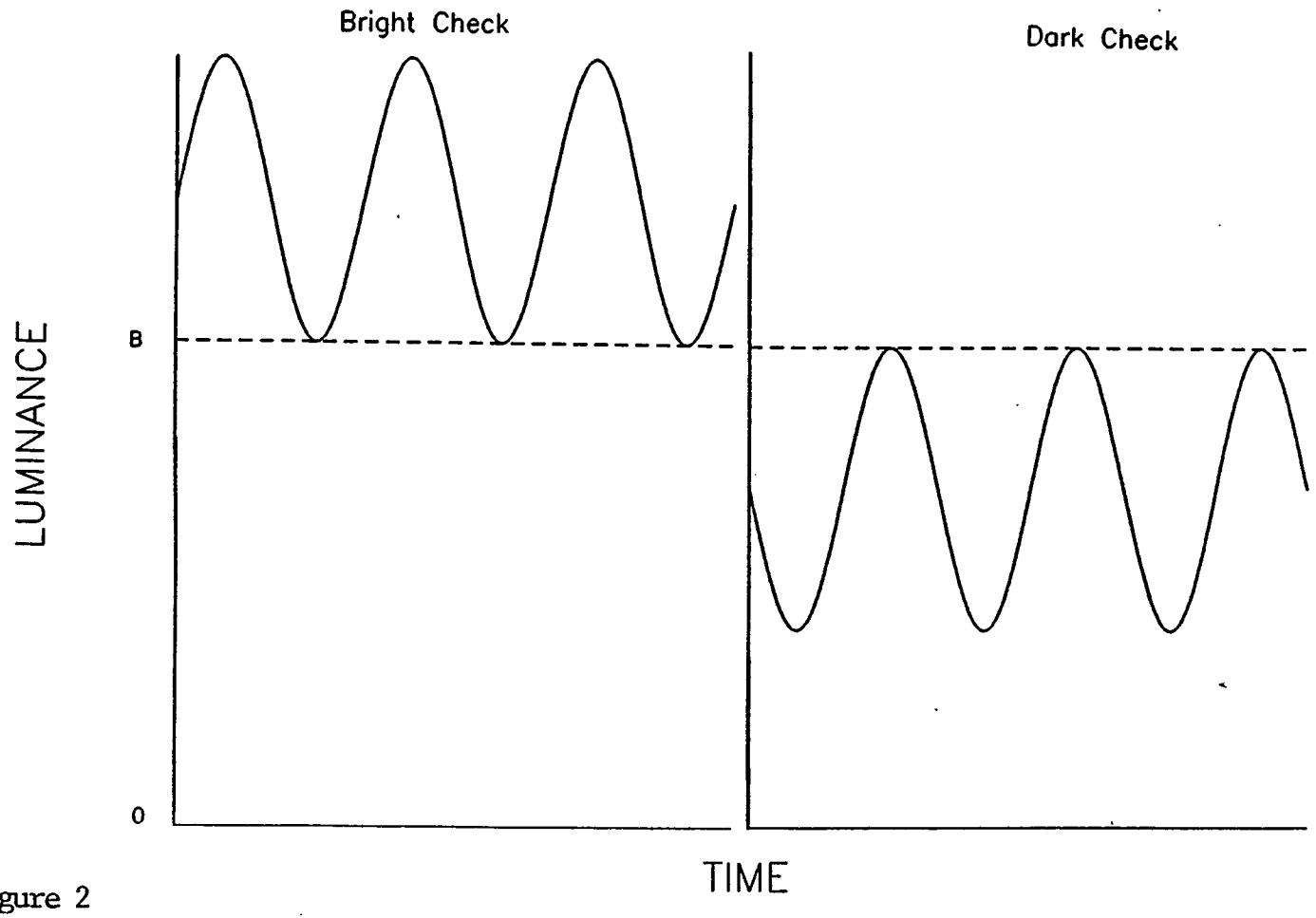


Figure 2

major contributing factor; the phases of the VEPs will be similar if contrast is the major contributing factor.

Experiment II-Temporal Tuning

In this experiment, the VEP to the bright- and dark-check stimuli was compared over a range of 10 temporal frequencies from 2 to 20 Hz. The size of check used in this experiment was the size which yielded high amplitude responses to both contrast conditions, and yielded large differences in amplitude between the two contrast conditions in the spatial tuning experiment. Contrast was modulated in the same manner as in the spatial tuning experiment. Contrast varied from 0 to 30% for the bright checks, from 0 to -30% for the dark checks, resulting in "appearing-disappearing" stimuli.

Experiment III-Contrast

In these experiments, responses to three different types of contrast manipulations for bright-check and dark-check stimuli were measured and compared. Stimuli used in all the contrast experiments were of optimal size (9') and temporal frequency (6.3 Hz), as determined in the spatial and temporal tuning experiments. In the

spatial and temporal tuning experiments the check patterns were presented in an "appearance-disappearance" manner. Mean contrast and depth of modulation were equal to each other (15% for positive-contrast stimuli, -15% for negative-contrast stimuli), and contrast varied from 0 to +30% or -30%. This type of stimulus presentation was again used in the first contrast experiment. Mean contrast and depth of modulation were covaried, but a range of values were used.

It is possible that the contributions of mean contrast and depth of modulation to the VEP waveform are not equal. In order to determine this, two other types of contrast manipulations were used in which mean contrast and depth of modulation were varied independently.

a. Appearance-Disappearance

Six bright-check and six dark-check stimuli of increasing contrast were used in this experiment (bright-check stimuli are schematically represented in figure 3). Mean contrast and depth of modulation were covaried, mean contrast was increased in each stimulus, and the depth of absolute luminance modulation around

that mean contrast was increased in the same manner. The mean contrasts and depth of modulations used for the bright-check stimuli were: 2, 4, 8, 16, 24, & 32%; this resulted in stimuli which were modulated in contrast from 0 to 4%, 0 to 8%, 0 to 16%, 0 to 32%, 0 to 48%, and 0 to 64%.

Similarily, mean contrast and depth of luminance modulation were covaried in the case of the dark-check stimuli. The mean contrasts and depth of modulations used for the dark-check stimuli were: -2, -4, -8, -16, -24, & -32%. This resulted in stimuli which were modulated in contrast from 0 to -4%, 0 to -8%, 0 to -16%, 0 to -32%, 0 to -48%, and 0 to -64%. These stimuli appeared and disappeared as contrast was modulated from a maximum to a minimum value.

b. Constant Mean Contrast

In this experiment the mean contrast was held constant and depth of modulation was increased, as shown for the bright-check stimuli in figure 4. The mean contrast used for all bright-check stimuli was 32%, and six depth of modulations used were used: 2, 4, 8, 16, 24, & 32%. For the dark-check stimuli the mean contrast

Figure 3

Schematic representation of bright-check stimuli in appearance-disappearance experiment. The minimum and maximum contrast of each stimulus is represented by the two open circles; the horizontal hatch-mark represents the mean contrast. The depth of modulation is equal to the distance from the mean contrast to either open circle. In each of these stimuli mean contrast is equal to the depth of modulation, and both increases from stimulus to stimulus. The contrast of each stimulus varies between 0% and some maximum value.

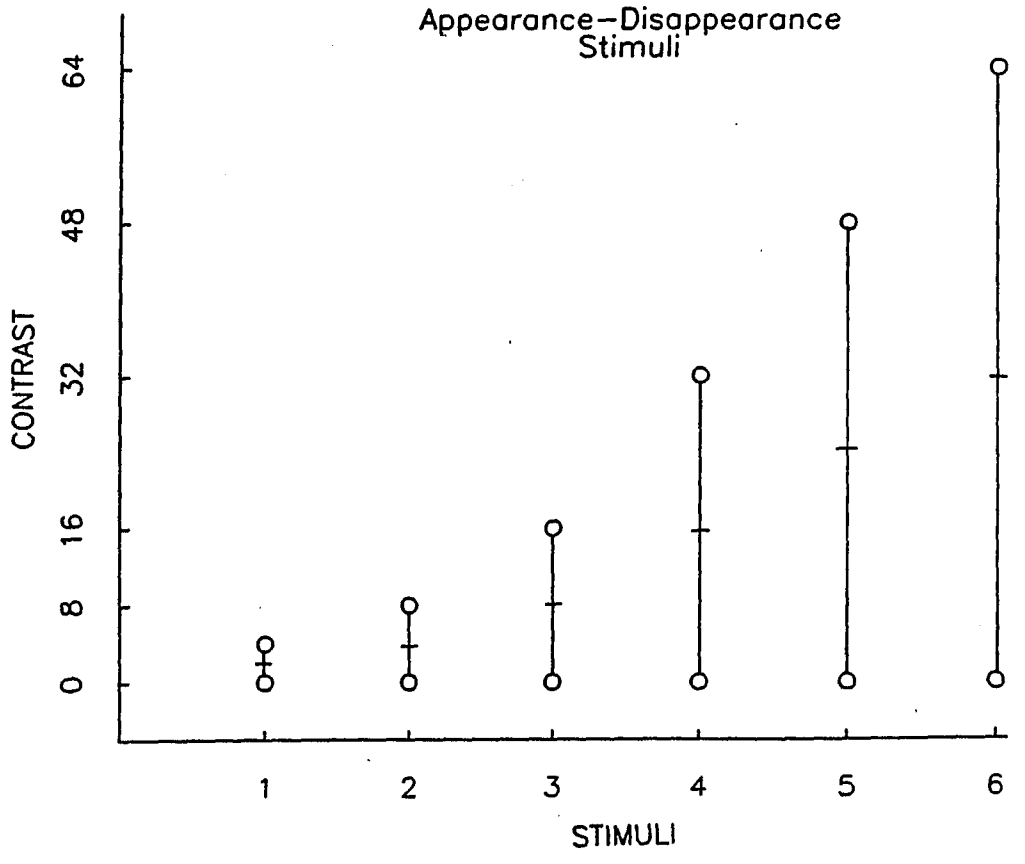

Appearance–Disappearance
Stimuli
CONTRAST
0
8
16
32
48
64
1
2
3
4
5
6
STIMULI

Figure 3

used was -32%, the six depth of modulations used were: -2, -4, -8, -16, -24 & -32%.

c. Constant Depth of Modulation

In this experiment the depth of modulation was held constant at 4%, and the mean contrast was increased, as shown for the bright-check stimuli in figure 5. Five levels of mean contrast were used for the bright-check stimuli: 4, 8, 16, 24 & 32%; the five levels of mean contrast to be used for the dark-check stimuli were: -4, -8, -16, -24 & -32%.

Figure 4

Schematic representation of bright-check stimuli in constant mean contrast experiment. Symbols and lines are used as in figure 3. In each of these stimuli the mean contrast is equal to 32%, and the depth of modulation is increased.

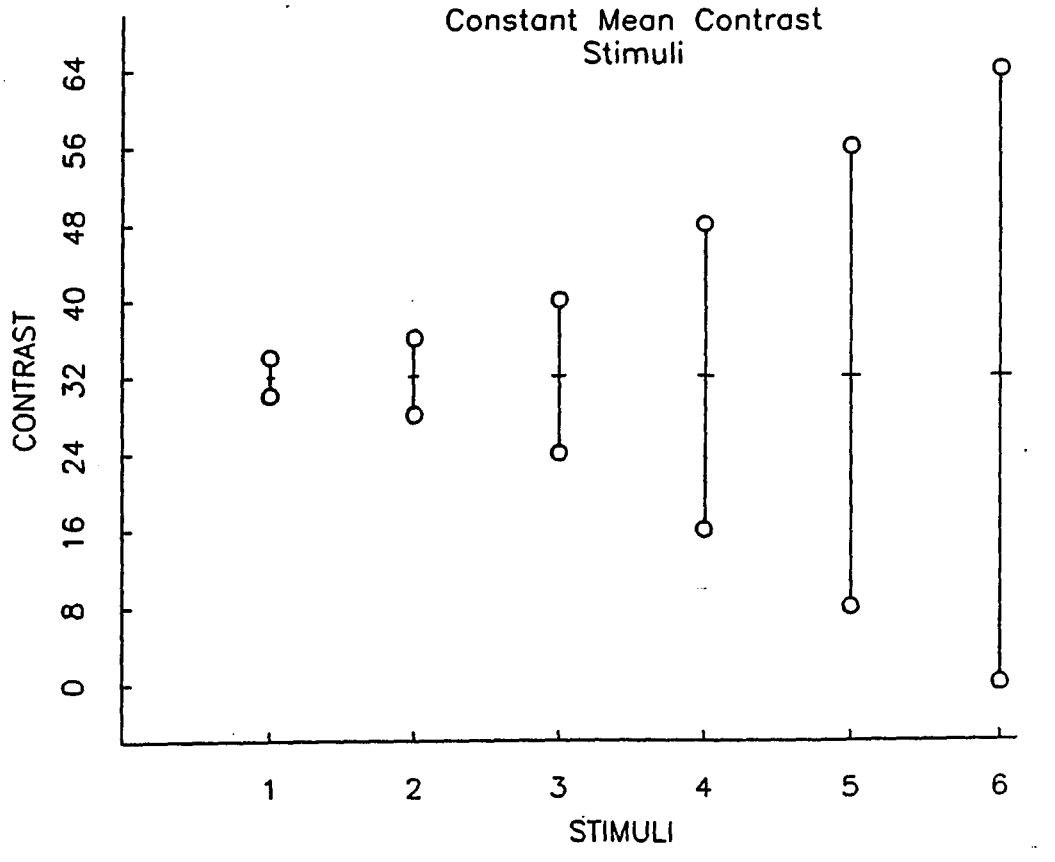

Constant Mean Contrast
Stimuli
CONTRAST
0
8
16
24
32
40
48
56
64
1
2
3
4
5
6
STIMULI

Figure 4

Figure 5

Schematic representation of bright-check stimuli in constant depth of modulation experiment. Symbols and lines are used as in figure 3. In each of these stimuli the depth of modulation is equal to 4%, and the mean contrast is increased.

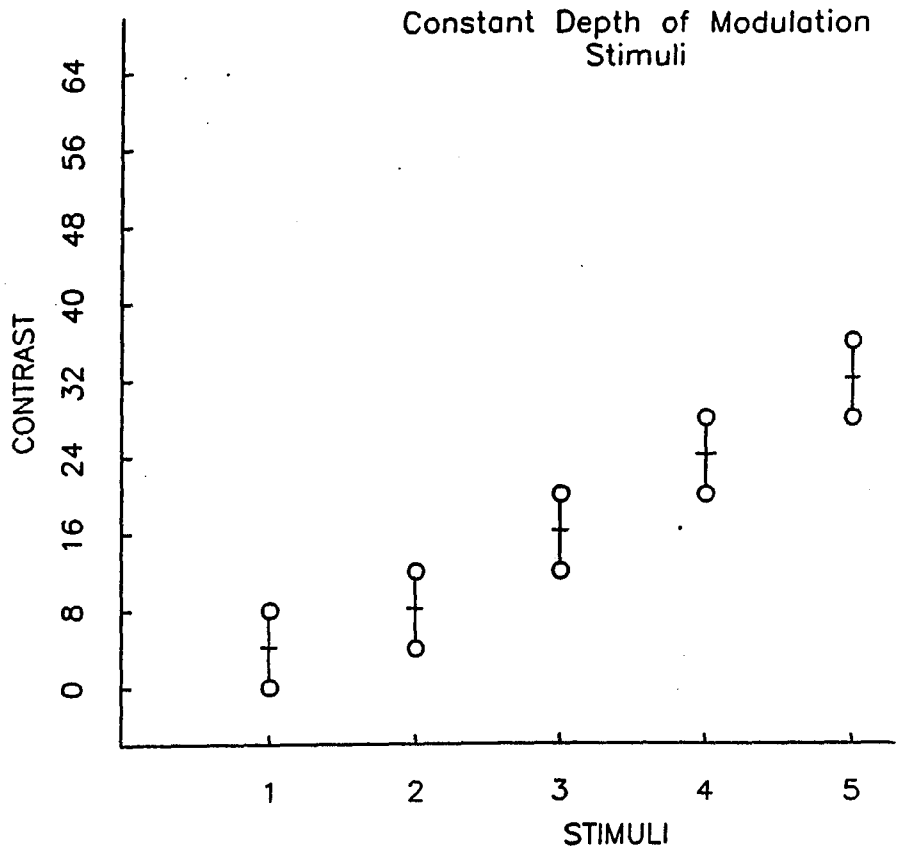

Constant Depth of Modulation
Stimuli
CONTRAST
0
8
16
24
32
40
48
56
64
1
2
3
4
5
STIMULI

Figure 5

RESULTS

Experiment I-Spatial Tuning

The human visual system responds selectively to stimuli of certain sizes; a range of optimally-sized stimuli will elicit high amplitude responses. As spatial tuning has been demonstrated previously in response to grating and checkerboard patterns in VEP experiments, it is reasonable to suspect that the human visual system will possess some spatial tuning in response to "isolated" check stimuli. High amplitude responses have been found by many investigators when stimulus elements were between 10 - 20 minutes in size (Spekreijse, H, Van Der Tweel, L. & Zuidema, T., 1973; Regan, D. & Richards, W., 1973; Sokol, S. 1976). Assuming that the bright-check stimuli preferentially stimulate the ON pathway, and dark-check stimuli preferentially stimulate the OFF pathway, the results of this experiment should provide information concerning the spatial tuning of these pathways.

In figures 6 and 7, the amplitudes and phases of the fundamental component are plotted as a function of check size for two subjects, jw and mc. The results of these

Figure 6

Plots of amplitude and phase of the fundamental component of the VEP versus check size for subject jw. Weber contrast was 30%, and the temporal frequency of modulation was 6.3 Hz. Open symbols represent data collected using bright check stimuli; filled symbols represent data collected using dark check stimuli. Circles and squares represent two replications; lines represent the averaged data. FF represents a "check" size of 600 minutes, which is equal to the entire stimulus field; therefore, it is equivalent to full-field modulation.

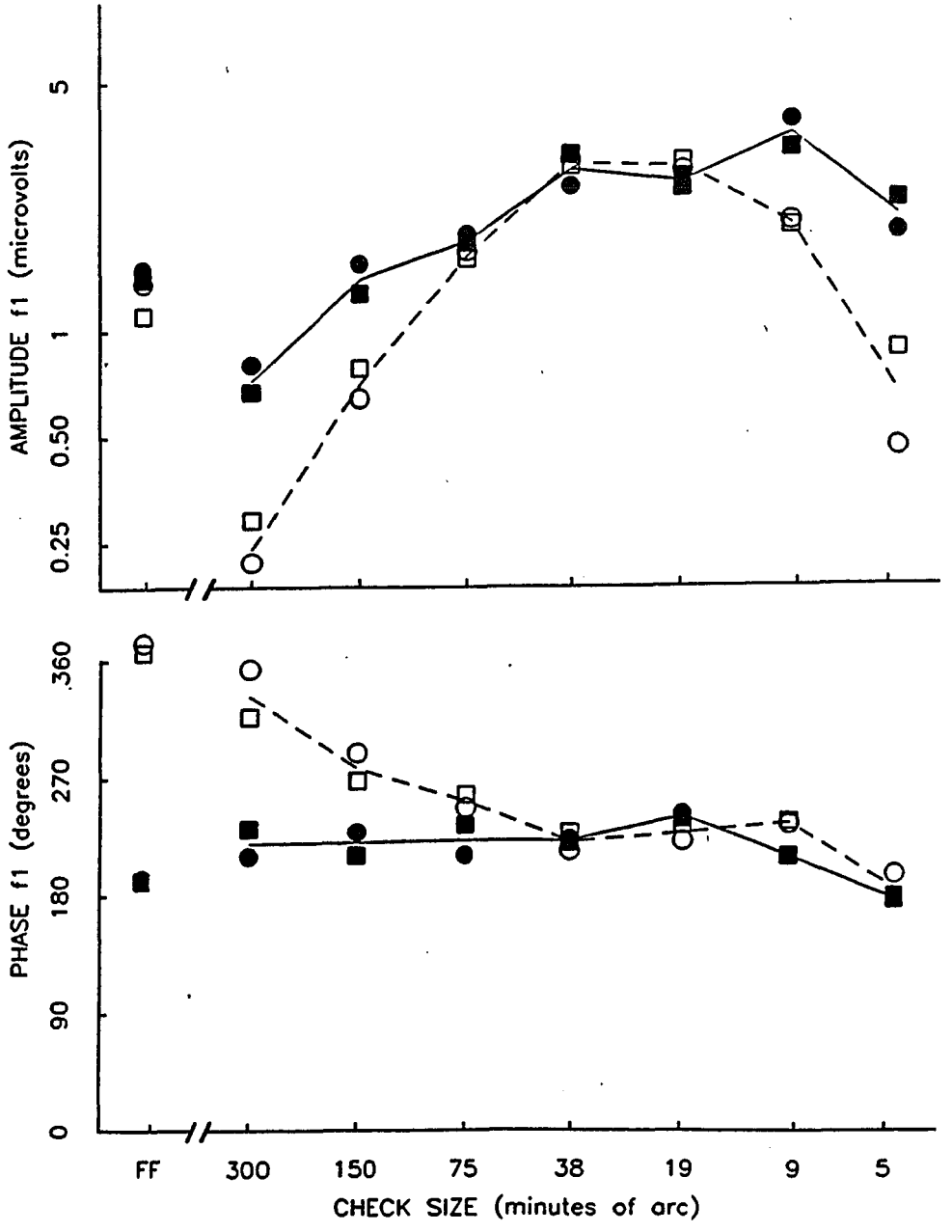

AMPLITUDE f1 (microvolts)
5
1
0.50
0.25
PHASE f1 (degrees)
360
270
180
90
0
FF
300
150
75
38
19
9
5
CHECK SIZE (minutes of arc)

Figure 6

Figure 7

Plots of amplitude and phase of the fundamental component of the VEP versus check size for subject mc. Weber contrast was 30%, and the temporal frequency of modulation was 6.3 Hz. Symbols and lines are used as in figure 6.

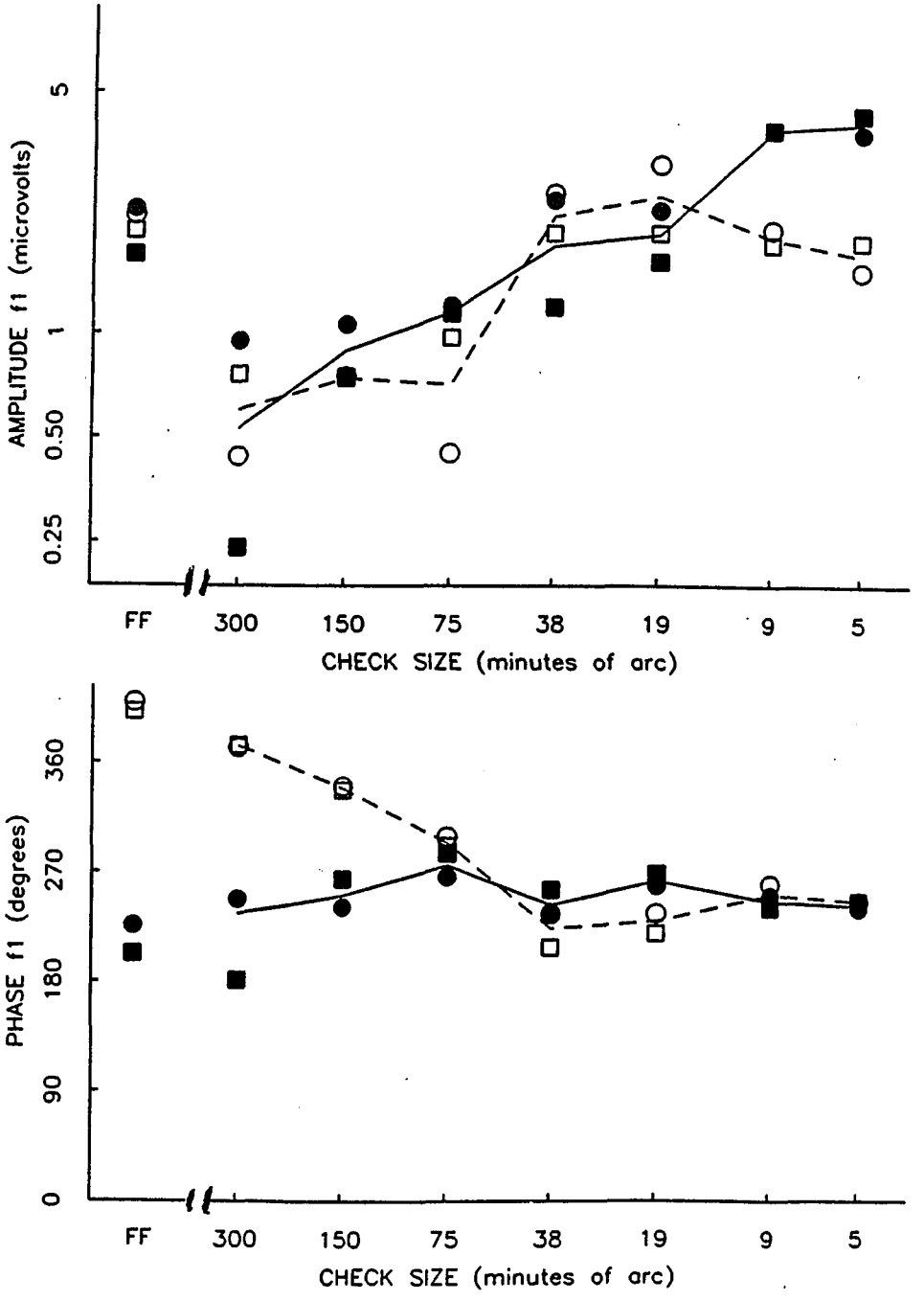

AMPLITUDE f1 (microvolts)
5
1
0.50
0.25
FF
300
150
75
38
19
9
5
CHECK SIZE (minutes of arc)
PHASE f1 (degrees)
360
270
180
90
0
FF
300
150
75
38
19
9
5
CHECK SIZE (minutes of arc)

Figure 7

experiments demonstrate that the visual system does exhibit spatial tuning in response to isolated check patterns of positive and negative contrasts, and that the spatial tuning of the ON and OFF pathway differ. There is not much difference in amplitude of response to luminance increment or luminance decrement under full-field and large check conditions (any differences in amplitude that do exist, however, appear magnified due to the use of logarithmic axes). In the small check conditions, particularly in the case of the 5 and 9 minute checks, reliable differences in amplitude to positive and negative contrasts can be observed. At these size checks, the amplitude of the VEP in response to dark checks was always higher than the amplitude of the VEP in response to bright checks. (Noise estimates, simultaneously recorded with the signals, were approximately .2 microvolts in these and all other experiments reported in the present study.)

For most subjects, the positive-contrast curve was found to peak at a larger check size, and the slope of the curve was steeper at the smaller check sizes than the negative-contrast curve, as shown in figures 6 and 7. (In subjects not demonstrating this difference in the

peak of the spatial tuning curves, the peak of both curves was found at the same check size, 9 minutes.)

Under the full field condition, as observed in figures 6 and 7, phases of the response to the two contrast conditions were approximately 180^{o} apart. As luminance was modulated 180^{o} out-of-phase under the positive- and negative-contrast conditions, it would be expected that the phases of the response would also be 180^{o} out-of-phase. The large check condition is similar to the full field condition, and the resulting phases were also approximately 180^{o} out-of-phase. The phases of the response gradually come together as the check size is decreased, and remain in-phase thereafter. The luminance modulation is 180^{o} out-of-phase in all conditions, but response phases are 180^{o} out-of-phase in only the full field and large check conditions. In the midrange and smallest check sizes the response phases are in-phase, as is the modulation of absolute contrast.

As large amplitude fundamental responses and large differences between bright and dark checks occurred at the 9 minute check size, this size was used in all following experiments measuring temporal tuning and contrast responses.

Experiment II-Temporal Tuning

The human visual system also selectively responds to stimuli of certain temporal frequencies; this has been demonstrated previously for many different types of stimuli (Sokol, 1976; Regan, 1977). It is, therefore, highly likely that these stimuli elicited higher amplitude VEPs at some optimal temporal frequencies, and lower amplitudes at non-optimal frequencies. This temporal tuning may or may not be the same for the bright-check and dark-check stimuli, depending on the dynamic properties of the ON and OFF pathways.

Weber contrast in this experiment was 30%, check size was 9 minutes, and temporal frequency was varied from 2 to 20 Hz. In figures 8 and 9 the amplitudes and phases of the fundamental component are plotted versus temporal frequency for two subjects, jw and ep.

The amplitude of the fundamental VEP response to dark checks is higher than the response to bright checks over most of the range of temporal frequencies tested. The phase of the VEPs is similar for both contrast conditions. The similarity in shape of the two temporal

Figure 8

Plots of amplitude and phase of the fundamental component of the VEP versus temporal frequency for subject jw. Weber contrast was 30%, check size was 9'. Symbols and lines are used as in figure 6.

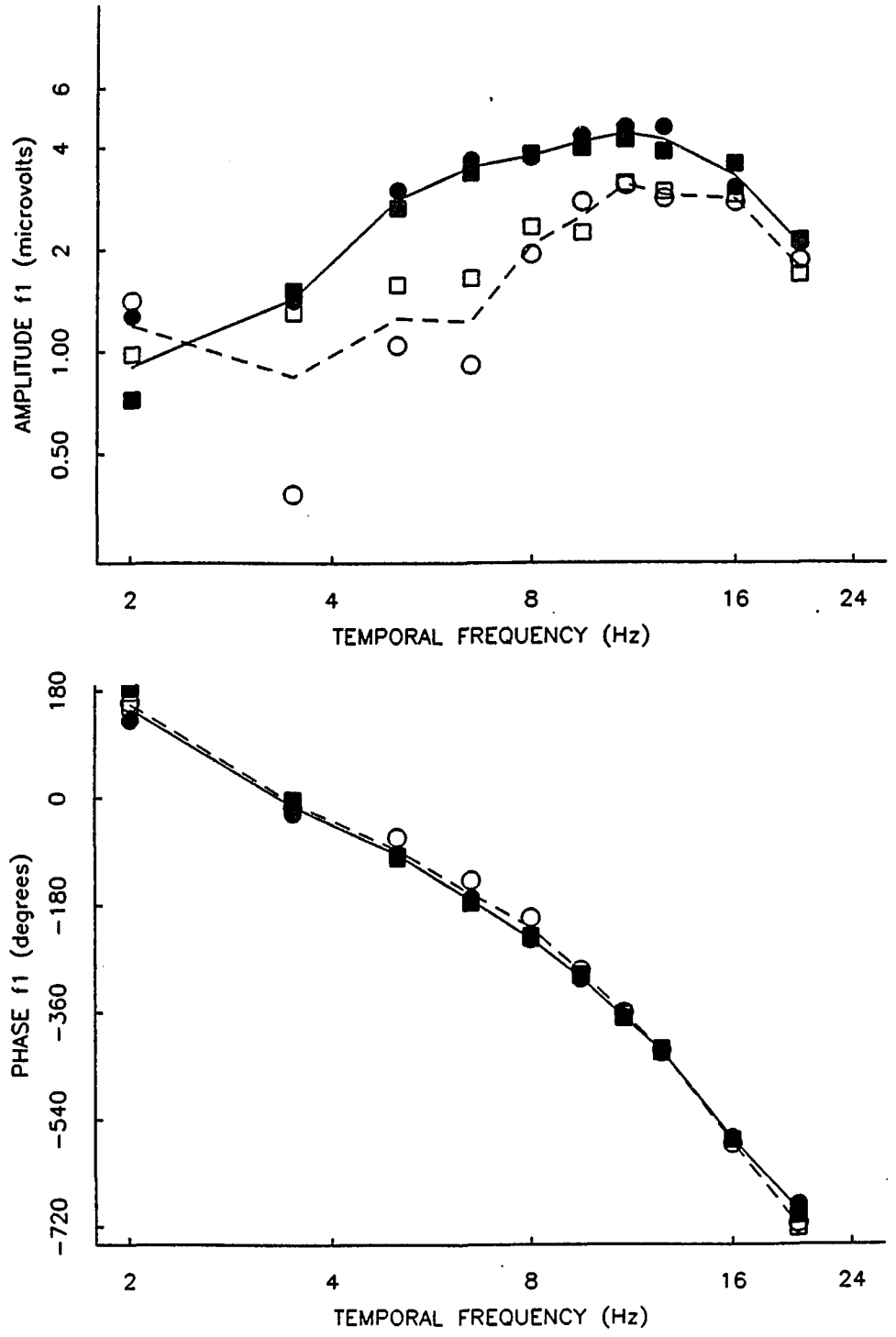

AMPLITUDE f1 (microvolts)
0.50
1.00
2
4
6
2
4
8
16
24
TEMPORAL FREQUENCY (Hz)
PHASE f1 (degrees)
180
0
-180
-360
-540
-720
2
4
8
16
24
TEMPORAL FREQUENCY (Hz)

Figure 8

Figure 9

Plots of amplitude and phase of the fundamental component of the VEP versus temporal frequency for subject ep. Weber contrast was 30%, check size was 9'. Symbols and lines are used as in figure 6.

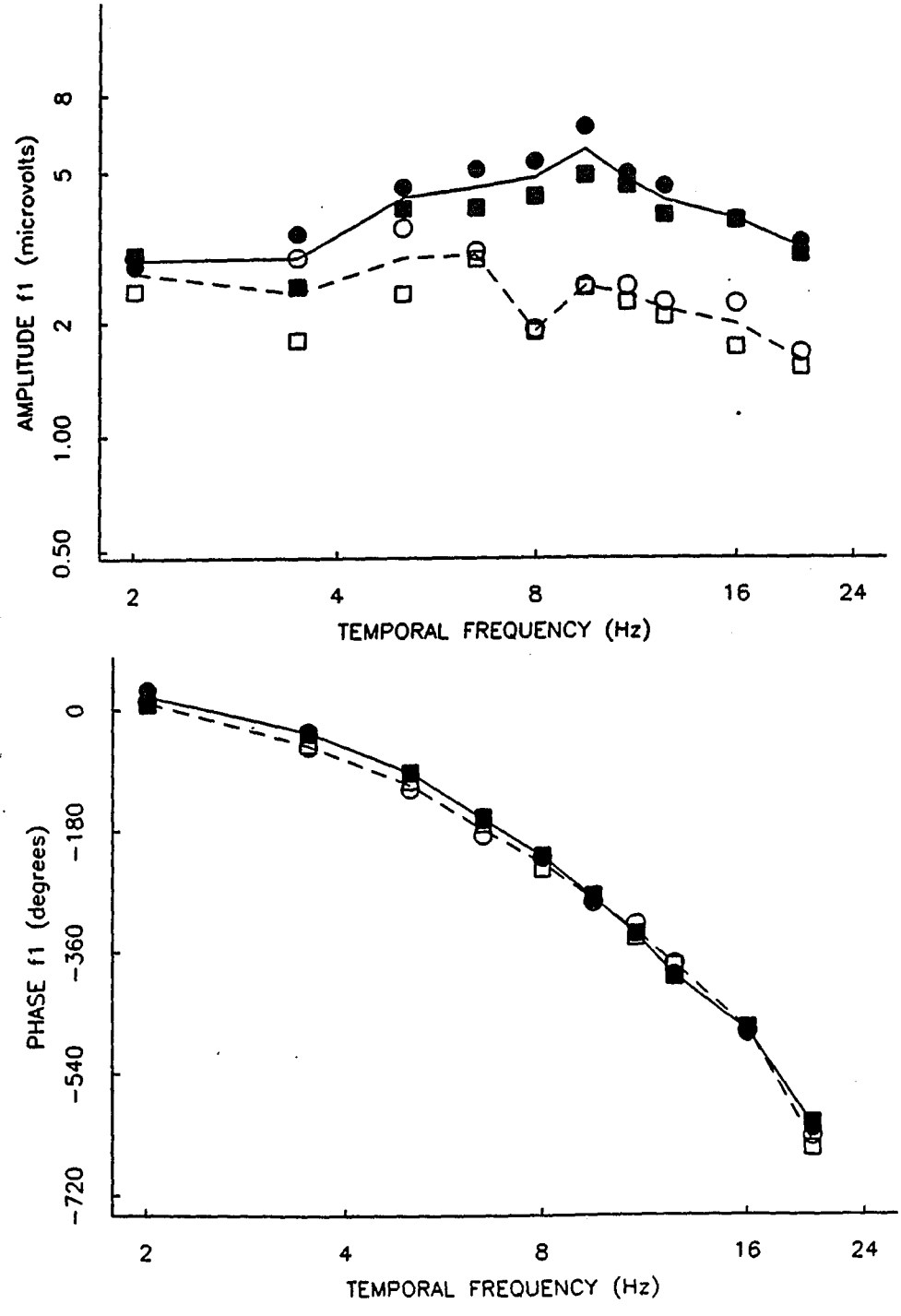

AMPLITUDE f1 (microvolts)
0.50
1.00
2
5
8
2
4
8
16
24
TEMPORAL FREQUENCY (Hz)
PHASE f1 (degrees)
0
-180
-360
-540
-720
2
4
8
16
24
TEMPORAL FREQUENCY (Hz)

Figure 9

tuning curves may indicate that the ON and OFF pathways have similar dynamic properties.

As in the spatial tuning experiment, the luminance modulation of the bright-check stimuli is 180° out-of-phase with the luminance modulation of the dark-check stimuli. The modulation of contrast is in-phase for both contrast conditions. As the responses are in-phase, it appears that these responses depend more on contrast modulation than on luminance modulation.

The phase of the fundamental component of the VEP to a range of temporal frequencies can be used to derive information regarding the latency of the visual system; a measure of the apparent latency can be derived from a linear plot of phase (in degrees) as a function of temporal frequency (Hz). In figure 10, the phase data of figure 8 have been replotted on linear coordinates. In addition, the line of best fit is depicted in this figure by the dashed line. A simple delay between stimulus and response of a certain amount will cause a phase lag that will increase linearly as stimulus frequency increases. If the delay is constant, the phase shift can be plotted as a linear function of stimulus frequency, and the slope of this function will be a measure of latency of the

Figure 10

Plot of phase of the fundamental component of the VEP versus temporal frequency for subject jw replotted on linear coordinates. The dotted line represents the line of best fit through the data points. The slope of this line is a measure of the apparent latency of the system in response to these stimuli.

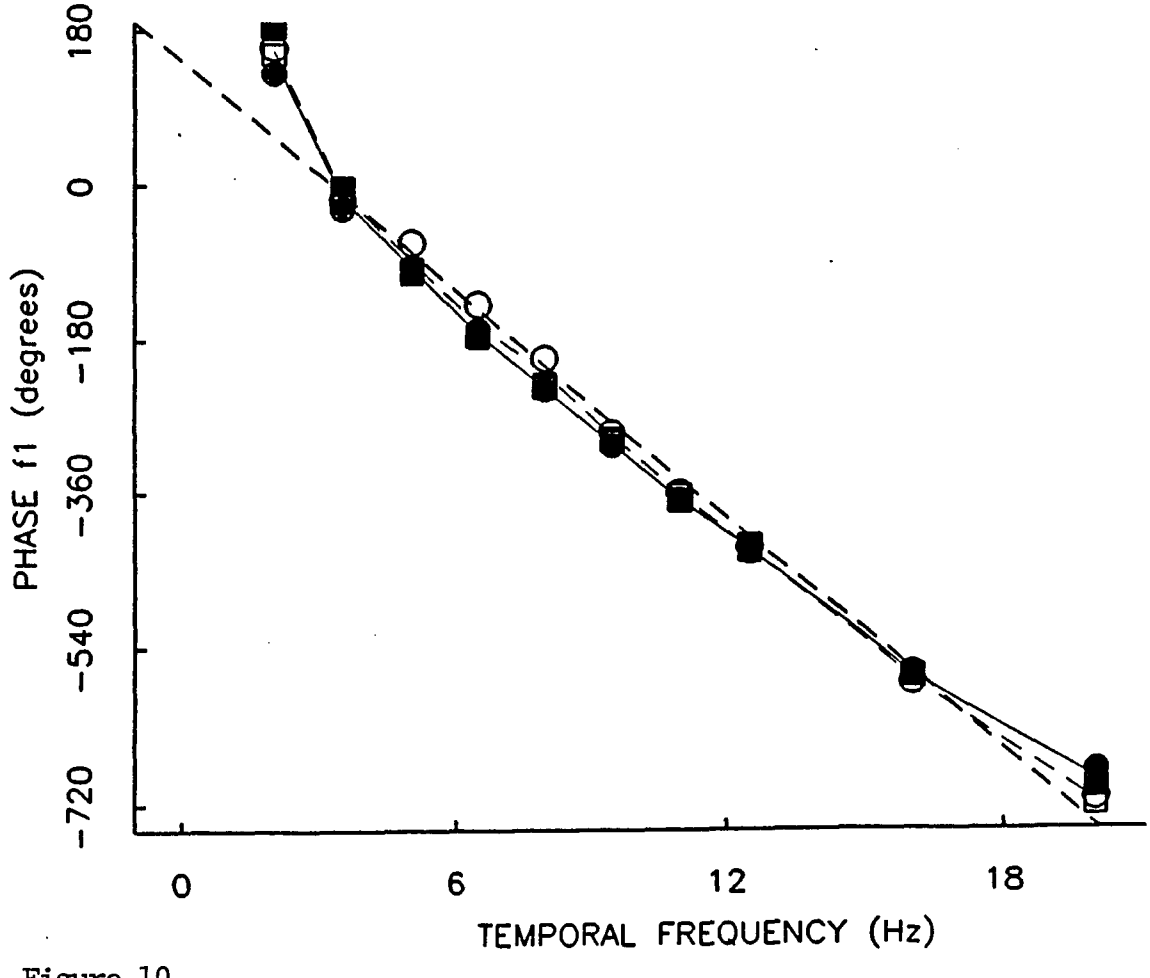

PHASE f1 (degrees)
180
0
-180
-360
-540
-720
0
6
12
18
TEMPORAL FREQUENCY (Hz)

Figure 10

system. A measure of the apparent latency (L_a) can be derived using the following formula:

$$L_a = \frac{\text{phase difference in degrees}}{\text{frequency interval in Hz}} \times \frac{1000}{360} \text{ msec}$$

(Duwaer & Spekreijse, 1978). The regression coefficient, or the slope of the line of best fit, is -44.6 for this data, and is equal to the left half of this formula. This results in an apparent latency of approximately 124 msec, for both the ON and OFF pathways.

Experiment III-Contrast

a. Appearance-Disappearance

In figures 11, 12 and 13, amplitudes and phases of the fundamental component are plotted versus Weber contrast on three different sets of coordinates for one representative subject, ep. The results were plotted on different sets of coordinates in order to examine different aspects of them. The amplitude of the positive-contrast function is lower than that of the

Figure 11

Plots of amplitude and phase of the fundamental component of the VEP versus Weber contrast for subject ep, plotted on linear coordinates. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

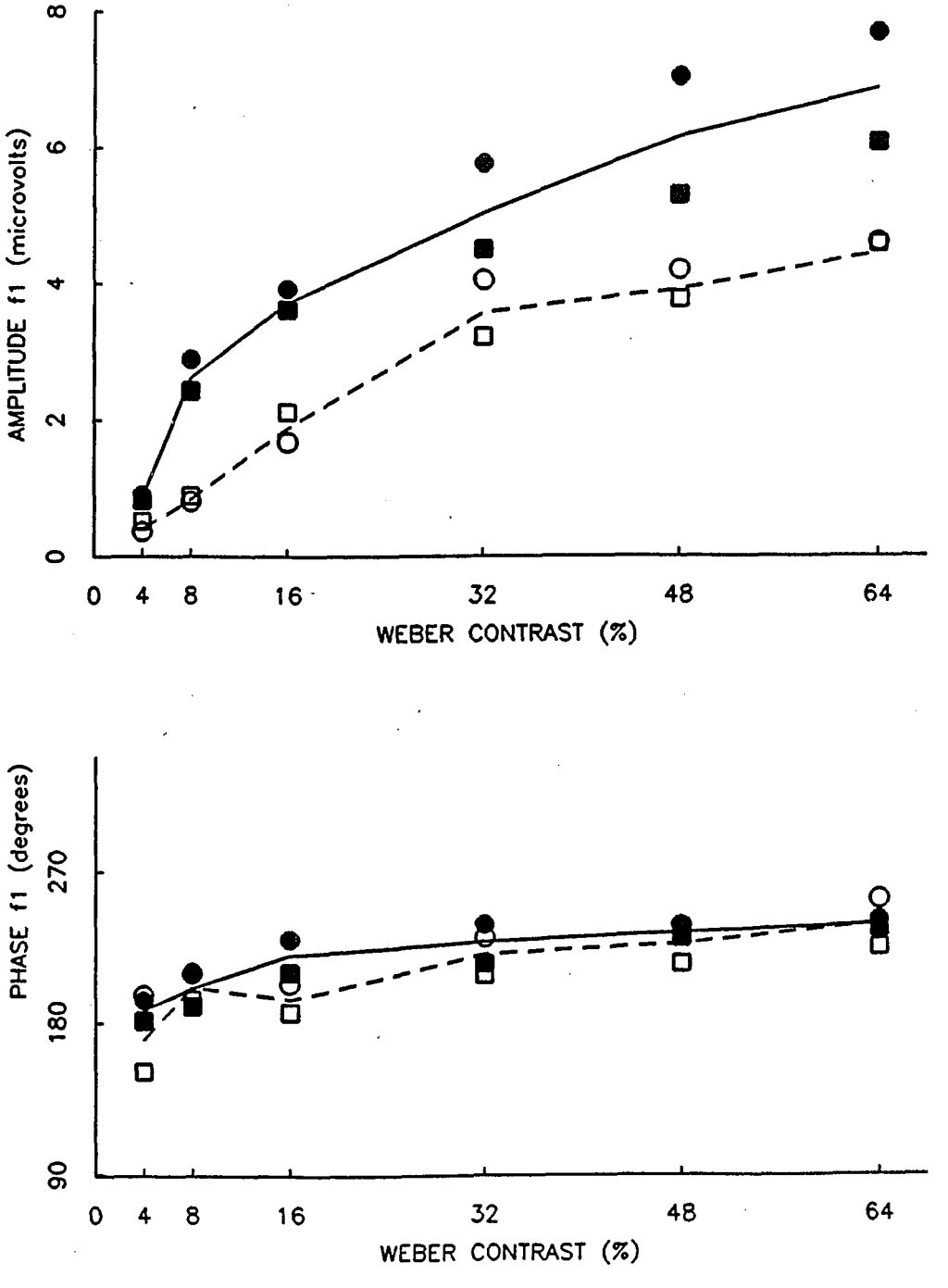

AMPLITUDE f1 (microvolts)
0
2
4
6
8
0 4 8 16 32 48 64
WEBER CONTRAST (%)
PHASE f1 (degrees)
90
180
270
0 4 8 16 32 48 64
WEBER CONTRAST (%)

Figure 11

Figure 12

Same data as Figure 11, plotted on semi-log coordinates.

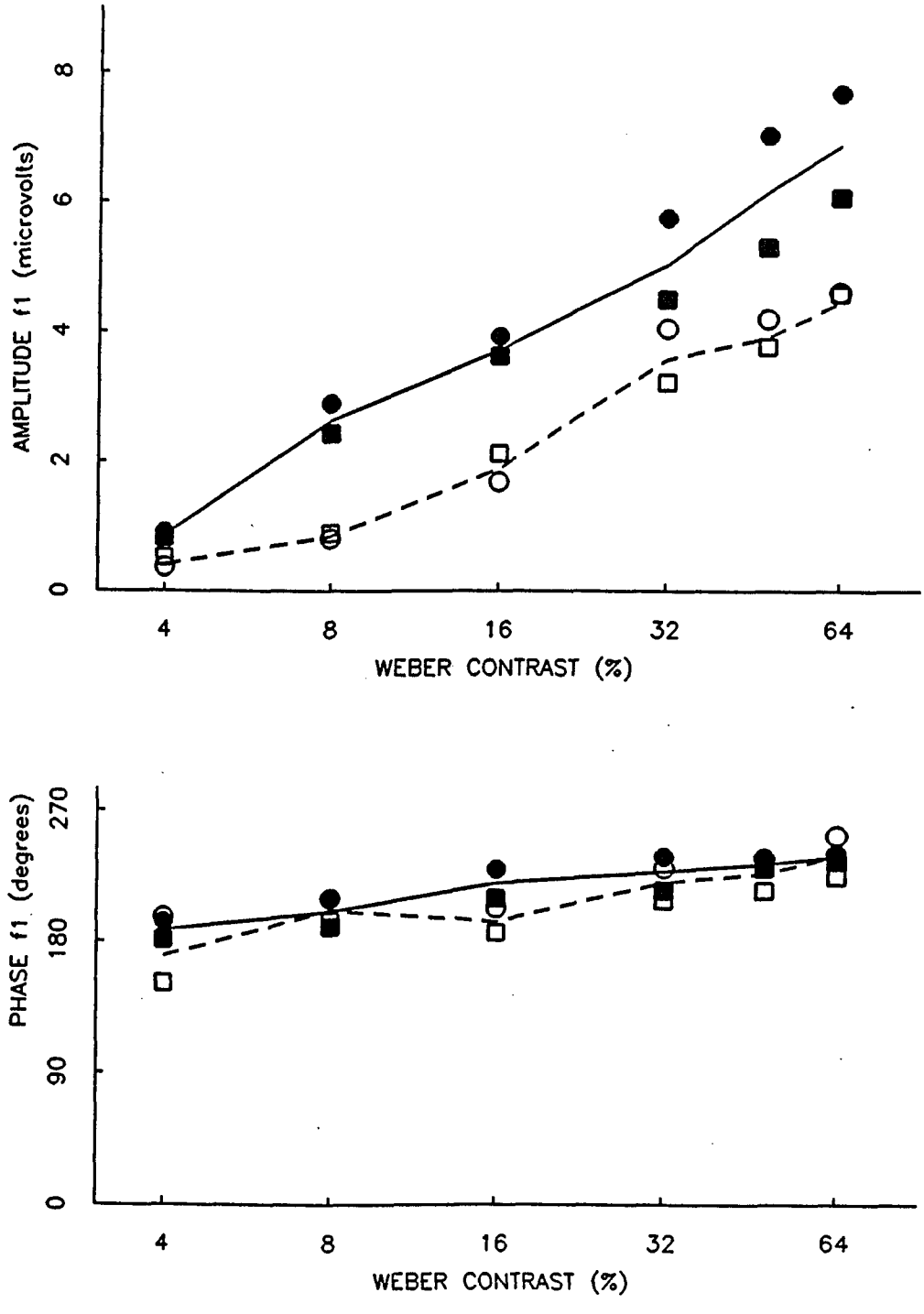

AMPLITUDE f1 (microvolts)
0
2
4
6
8
4
8
16
32
64
WEBER CONTRAST (%)
PHASE f1 (degrees)
0
90
180
270
4
8
16
32
64
WEBER CONTRAST (%)

Figure 12

Figure 13

Same data as Figure 11, plotted on log-log coordinates.

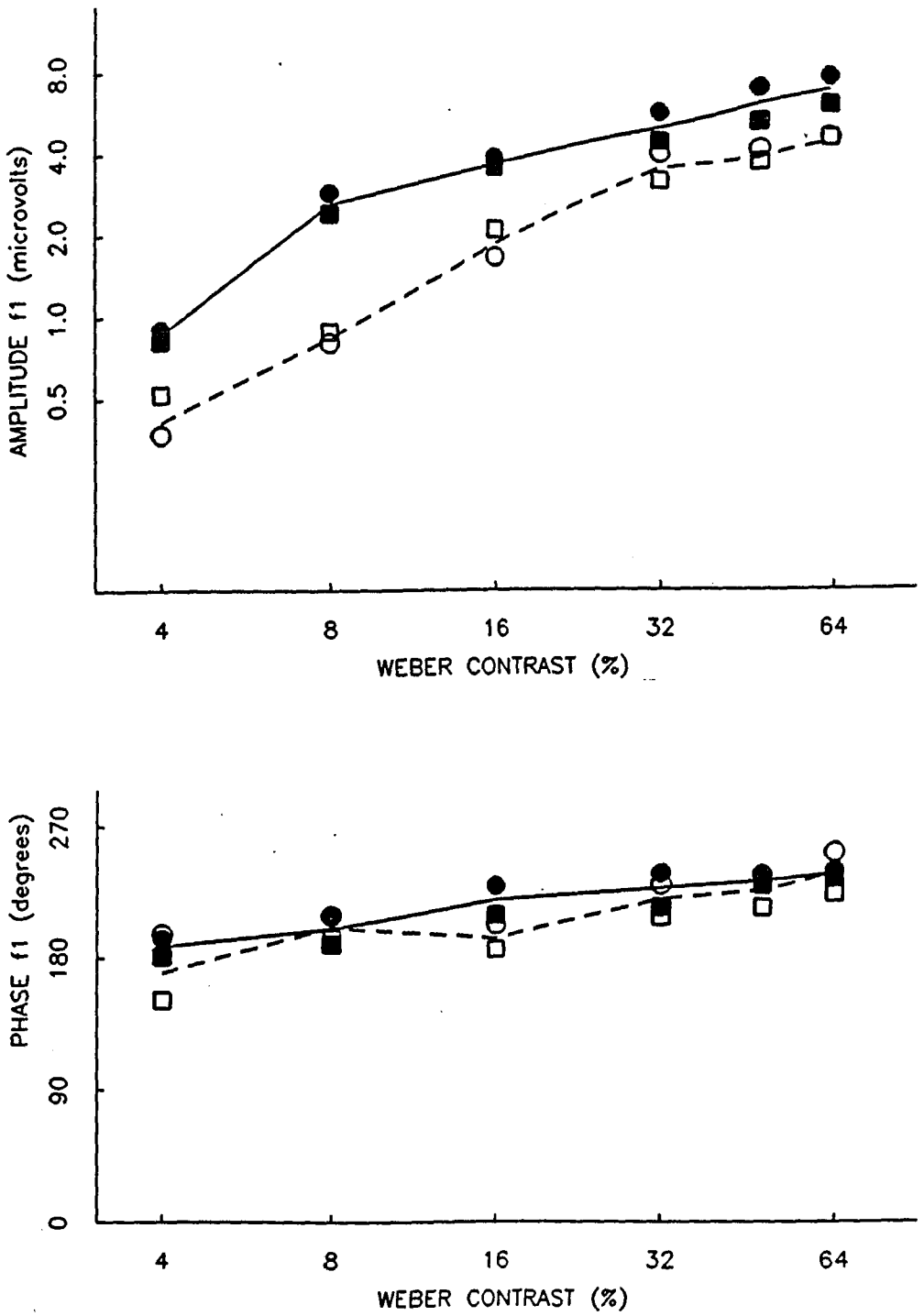

AMPLITUDE f1 (microvolts)
0.5
1.0
2.0
4.0
8.0
4
8
16
32
64
WEBER CONTRAST (%)
PHASE f1 (degrees)
0
90
180
270
4
8
16
32
64
WEBER CONTRAST (%)

Figure 13

negative-contrast function. The data plotted on linear coordinates are obviously not linear. When the data are plotted on linear-log coordinates (as shown in figure 12) an approximately linear relation between contrast and response amplitude can be observed, indicating a logarithmic response function. When the data are plotted on the log-log coordinates (as shown in figure 13), it can be observed that the positive- and negative-contrast functions differ mainly by a scaling factor as the negative-contrast function is shifted above the positive-contrast function.

The phases of the fundamental VEP component for positive and negative contrasts are very similar. The phase of the response changes as contrast changes; there is an increasing phase lead as contrast increases. This phase lead is similar for both positive and negative contrasts, suggesting that the dynamical properties of the ON and OFF systems are similar.

It would be reasonable to expect second harmonic responses to these types of stimuli since contrast in each stimulus originates at zero. Modulations of contrast which include the nonlinear regions (at low and high contrasts) would be expected to elicit nonlinear

responses. In figure 14, amplitude and phase of the second harmonic component of the VEP are plotted as a function of contrast, for subject ep. Second harmonic responses were similar to fundamental responses in that responses elicited by negative contrasts rose out of the noise at lower levels than responses elicited by positive contrasts, and negative contrasts elicited larger responses than positive contrasts. However, second harmonic responses were smaller than fundamental responses throughout the range of contrasts tested.

Effect of Contrast Definition on Results

As mentioned previously, the contrast of the check patterns in these experiments has been defined using the Weber definition of contrast (C_w):

$$C_w = (L_0 - L_b) / L_b$$

where L_0 is the luminance of the check, and L_b is the luminance of the background. The contrast of a pattern is therefore proportional to the luminance change associated with the pattern, thus positive and negative Weber contrasts represent equal luminance changes. There exists an inherent asymmetry in the measurement of

Figure 14

Plots of amplitude and phase of the second harmonic component of the VEP versus Weber contrast for subject ep. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

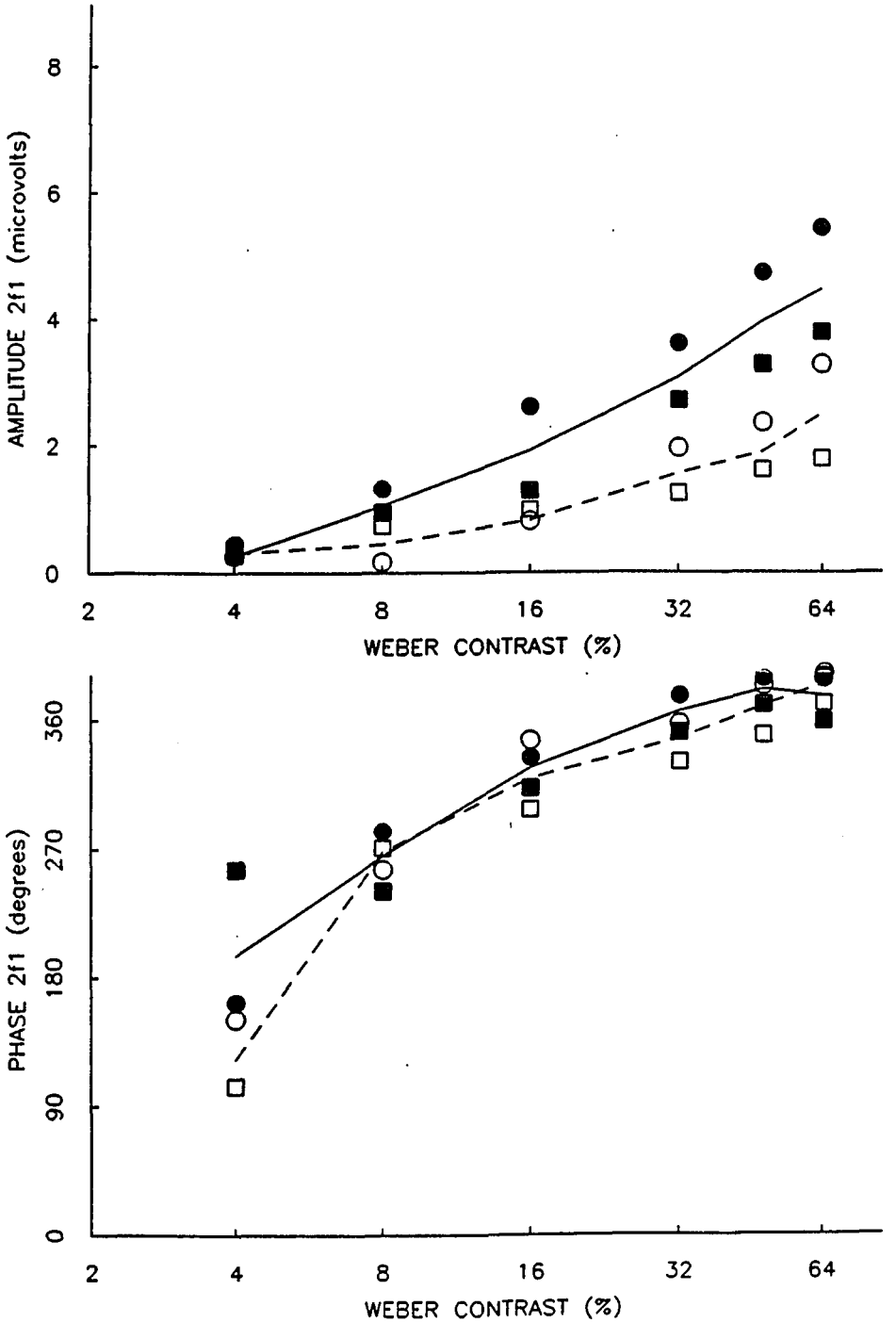

AMPLITUDE 2f1 (microvolts)
0
2
4
6
8
2
4
8
16
32
64
WEBER CONTRAST (%)
PHASE 2f1 (degrees)
0
90
180
270
360
2
4
8
16
32
64
WEBER CONTRAST (%)

Figure 14

positive and negative Weber contrasts. In the case of negative contrast, for a given background luminance L_b, the luminance of dark checks can range from 0 to $-L_b$. This results in a contrast ranging from 0 to -100%. By comparison, in the case of positive contrast, the luminance of bright checks can range from 0 to infinity, resulting in a contrast ranging 0 to infinity. The visual system, therefore, codes luminance decrements over a limited range and luminance increments over a much larger range.

Another definition of contrast, Michelson (or Rayleigh), is symmetrical for positive and negative contrasts. Michelson contrast, C_m is defined as follows:

$$C_m = (L_{max} - L_{min}) / (L_{max} + L_{min})$$

where L_{max} is the maximum luminance, and L_{min} is the minimum luminance in the pattern.

It is difficult to state with assurance if the visual system measures contrast using the Weber or the Michelson definition. For stimuli of the same size and duration, the Weber contrast is proportional to the change in the mean number of photons affecting vision.

Thus, the Weber definition seems to be related to the physical situation in a fundamental manner. In some psychophysical studies in which bright contrast was matched to dark contrast asymmetries were found when the Weber definition was used. Transforming the data using the Michelson contrast definintion eliminated the asymmetries (Burkhardt, Gottesman, Kersten & Legge, 1982; Legge & Gersten, 1983). It is possible that the asymmetries observed in the positive- and negative-contrast functions in these experiments may be due in part to the way in which contrast has been defined.

When the data from figure 12 are plotted as a function of Michelson contrast (see figure 15) there is still a difference in amplitude between the positive- and negative-contrast functions, although the difference appears smaller. This suggests that the difference in the response functions is not due to the inherent asymmetry between positive and negative contrasts present in the Weber definition of contrast, but rather a real difference in the responses to positive and negative contrasts.

Figure 15

Plots of amplitude and phase of the fundamental component of the VEP versus Michelson contrast for subject ep, plotted on semi-log coordinates. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

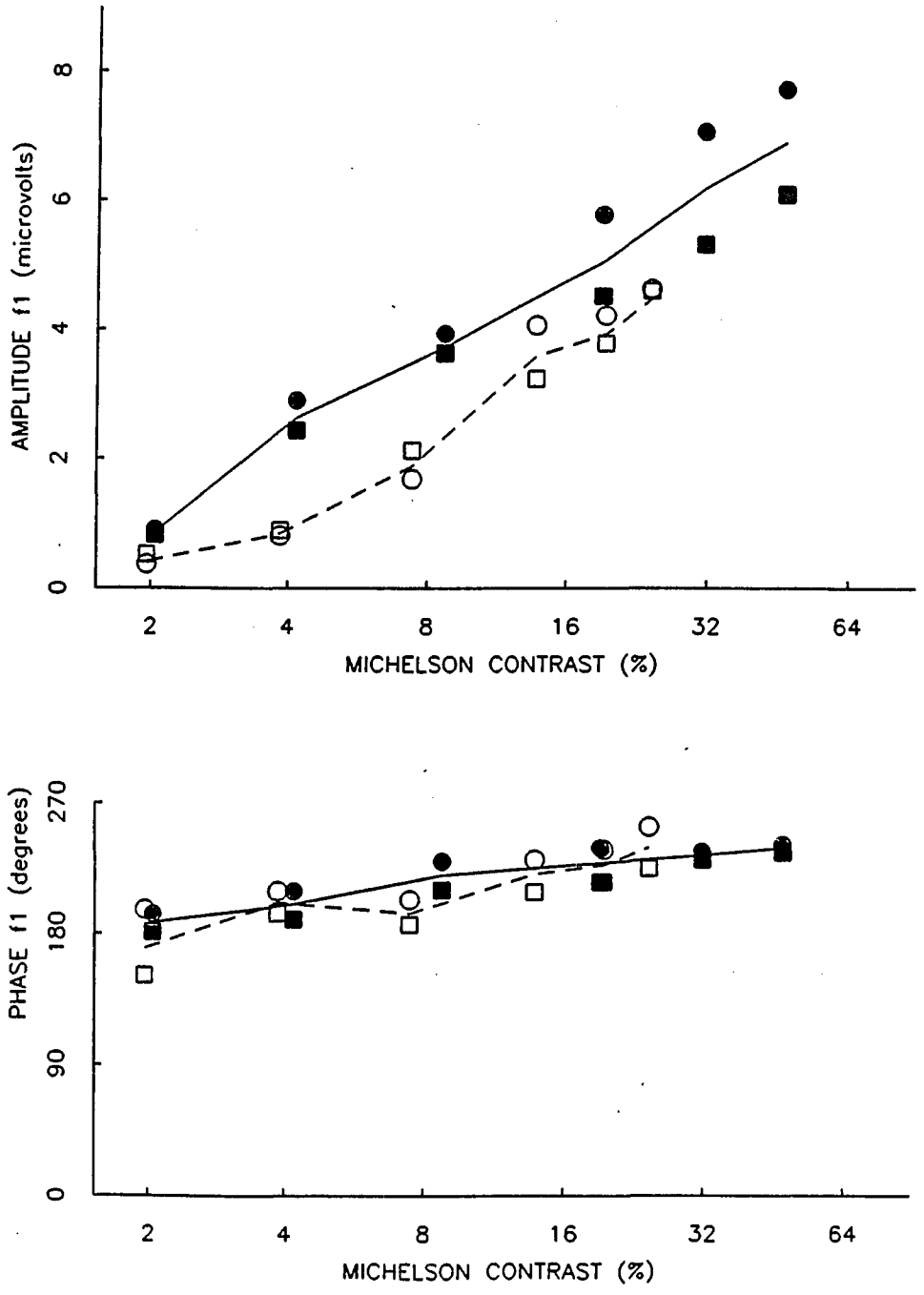

AMPLITUDE f1 (microvolts)
0
2
4
6
8
2
4
8
16
32
64
MICHELSON CONTRAST (%)
PHASE f1 (degrees)
0
90
180
270
2
4
8
16
32
64
MICHELSON CONTRAST (%)

Figure 15

Effect of Spatial Tuning Differences Between ON and OFF Pathways on Results

The spatial tuning experiments determined that at the check size of 9 minutes high amplitude responses for both positive and negative contrasts were elicited, and a large difference in amplitude between the two functions was observed. For these reasons, this size was chosen for the remaining experiments. It was also noted that the peak of the positive- and negative-contrast functions differed for most subjects. It is possible that the results of the contrast experiments would be different if the optimal check size was used for each contrast condition, rather than using the 9 minute size for both contrast conditions. In order to investigate this possibility, the appearance-disappearance experiment was repeated using optimally-sized checks: 19' for the positive-contrast stimuli and 9' for the negative-contrast stimuli. The results of this experiment are shown in figure 16, for subject, jw. It can easily be observed that the results do not differ much from those observed when the 9' size check was used for both contrast conditions. Negative contrasts elicited higher amplitude responses than did positive contrasts. And the phase data are also similar, a slight

Figure 16

Plots of amplitude and phase of the fundamental component of the VEP versus Weber contrast for subject jw, using two different check sizes. Bright check size was 19', dark check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

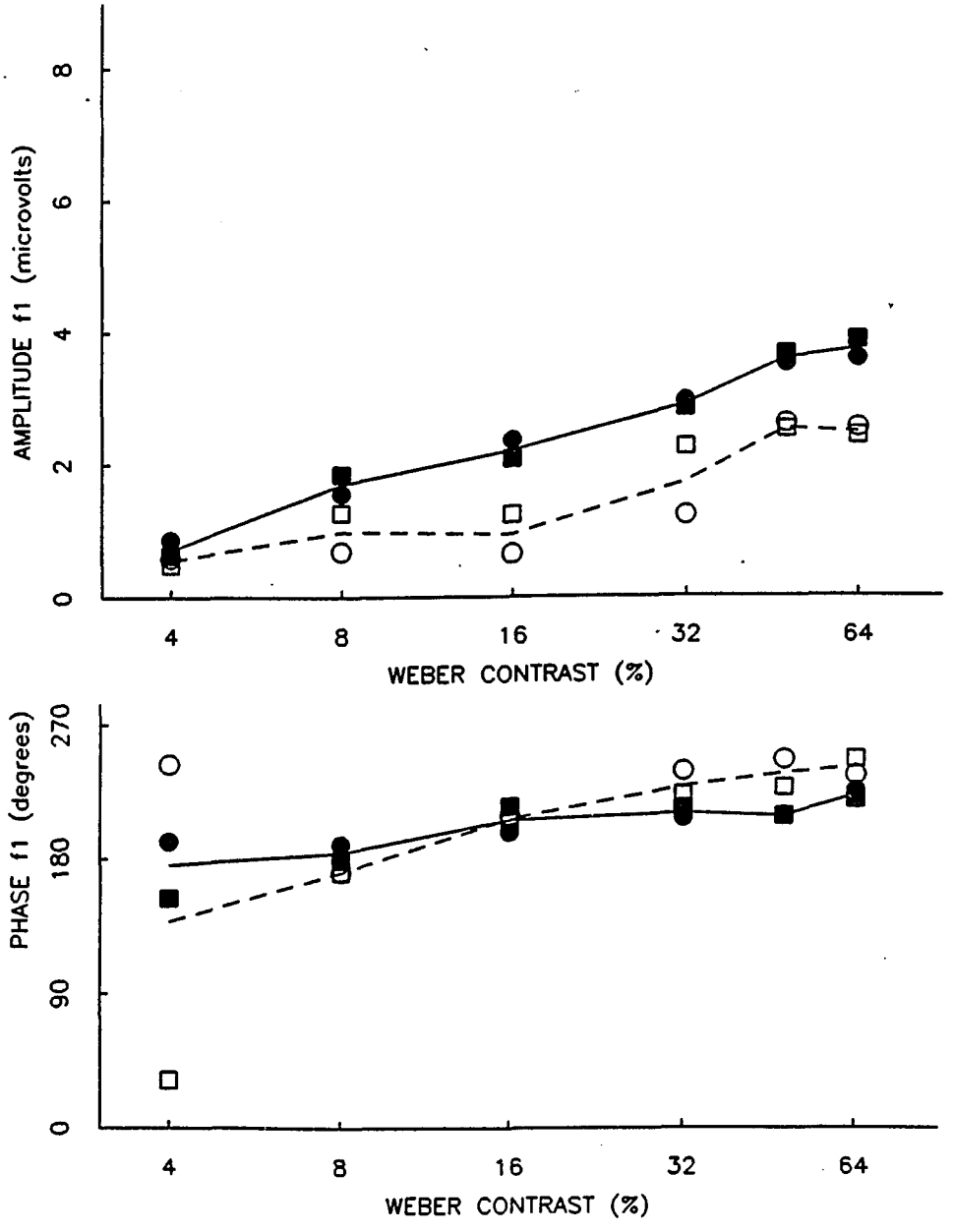

AMPLITUDE f1 (microvolts)
0
2
4
6
8
4
8
16
32
64
WEBER CONTRAST (%)
PHASE f1 (degrees)
0
90
180
270
4
8
16
32
64
WEBER CONTRAST (%)

Figure 16

Figure 17

Plots of amplitude and phase of the fundamental component of the VEP versus depth of modulation for subject ep, plotted on linear coordinates. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

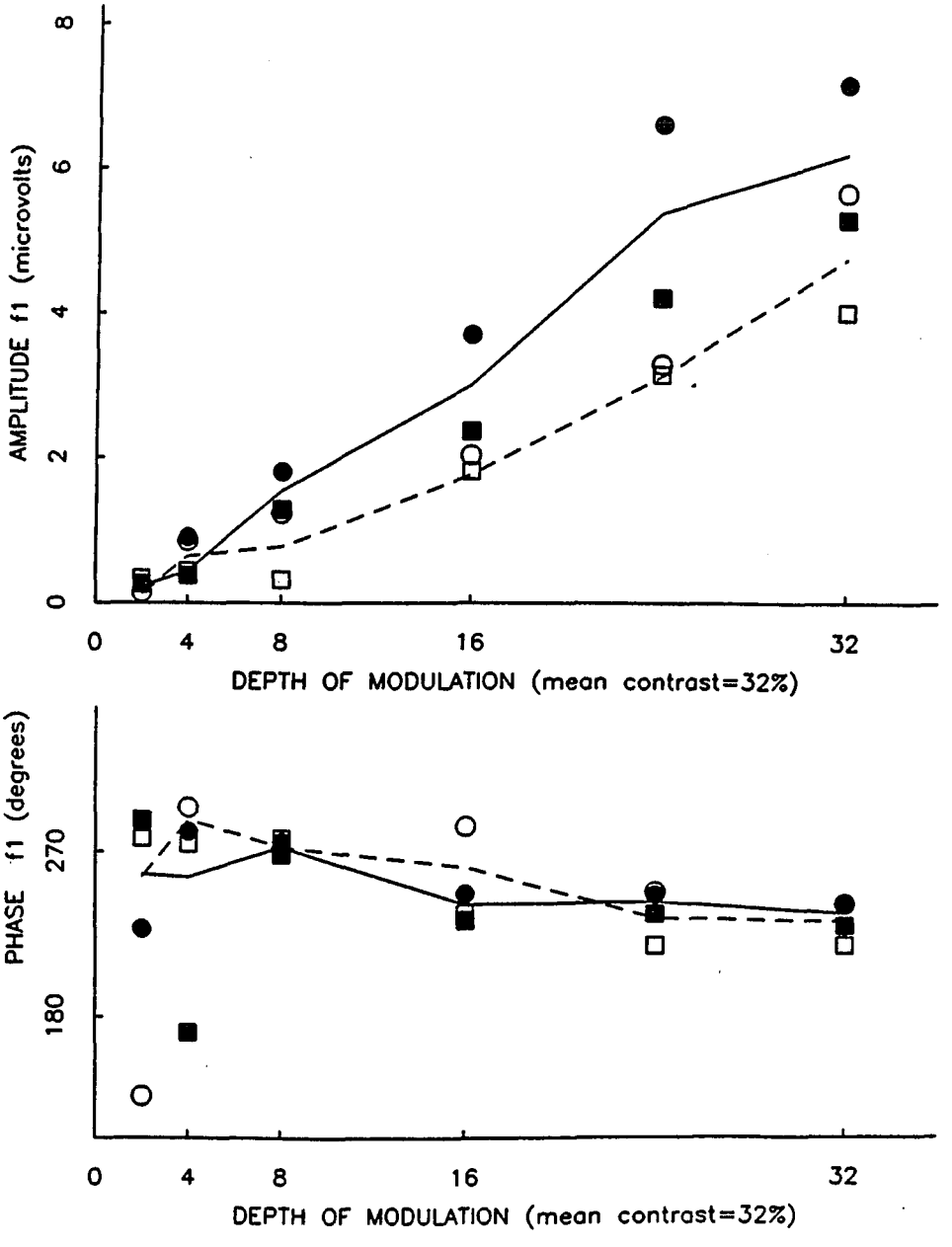

AMPLITUDE f1 (microvolts)
0
2
4
6
8
0
4
8
16
32
DEPTH OF MODULATION (mean contrast=32%)
PHASE f1 (degrees)
180
270
0
4
8
16
32
DEPTH OF MODULATION (mean contrast=32%)

Figure 17

Figure 18

Plots of amplitude and phase of the fundamental component of the VEP versus depth of modulation for subject mc, plotted on linear coordinates. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

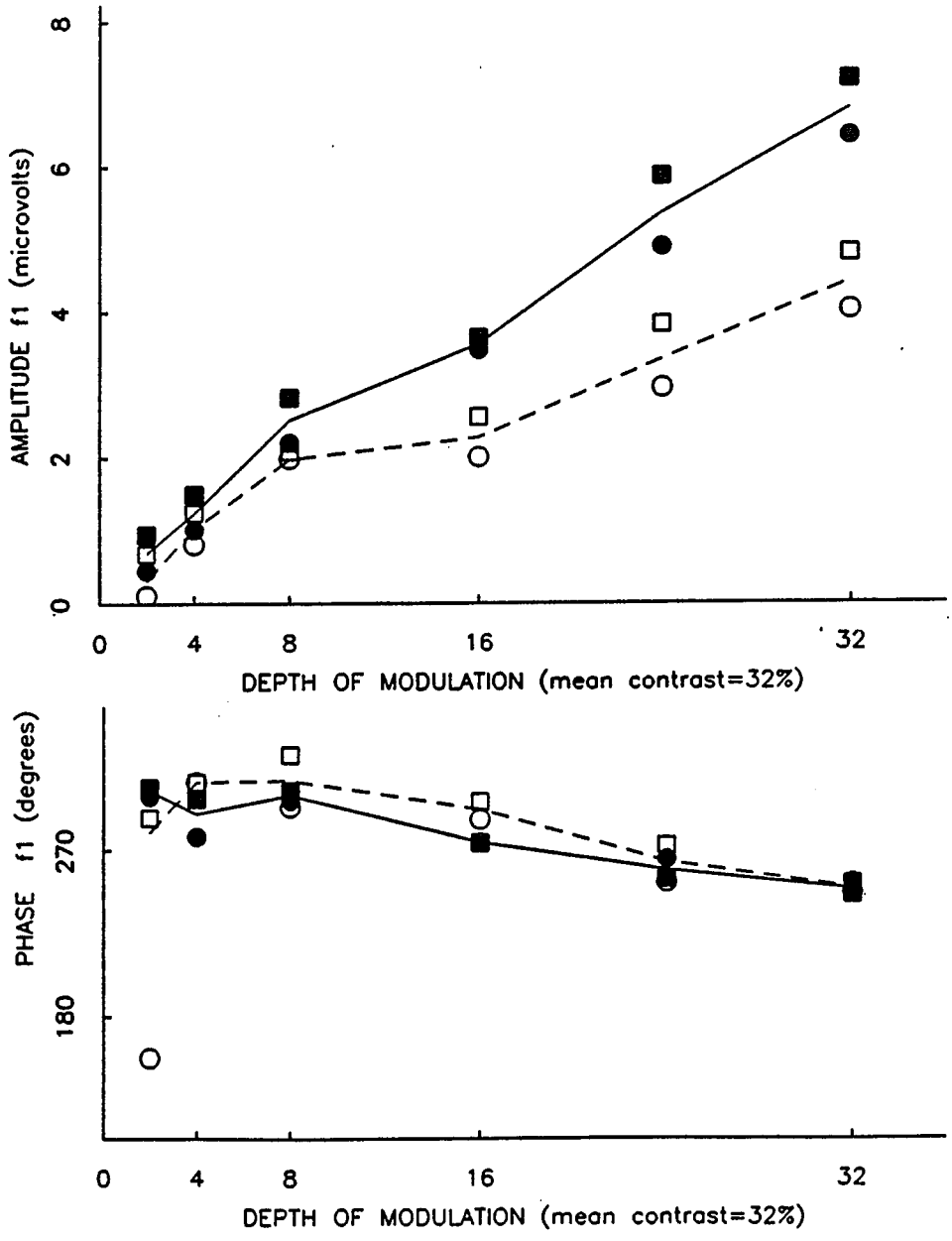

AMPLITUDE f1 (microvolts)
0
2
4
6
8
0
4
8
16
32
DEPTH OF MODULATION (mean contrast=32%)
PHASE f1 (degrees)
180
270
0
4
8
16
32
DEPTH OF MODULATION (mean contrast=32%)

Figure 18

increase in phase lead is observed as contrast is increased.

b. Constant Mean Contrast

In the appearance-disappearance experiments mean contrast and depth of modulation were covaried. In this experiment mean contrast was held constant at + or -32%, and depth of modulation was varied from 4% to 32%. In figures 17 and 18, the amplitude and phase of the fundamental response are plotted as a function of depth of modulation for two subjects, ep and mc. When mean contrast is held constant at this value, the amplitude of the response appears to be an approximately linear function of the depth of modulation. Negative contrasts elicited larger responses than positive contrasts at all contrasts greater than 16%; at the lower contrasts responses are similar. (This is in contrast to the results of the appearance-disappearance experiments in which the amplitude of the responses to the two types of contrast conditions differed at all contrast levels.) The slope of the negative contrast function is steeper than that of the positive contrast function, possibly due to a higher contrast gain of the OFF subsystem.

When the same data (for subject mc) are plotted on log-log coordinates, as shown in figure 19, it can be observed that the two functions differ by a scaling factor, suggesting higher contrast gain of the OFF subsystem. In the phase plots the fundamental component of the VEP exhibits a slightly phase lag as the depth of modulation increases.

In figure 20, the amplitude and phase of the second harmonic component of the VEP are plotted versus depth of modulation for subject, ep. The amplitudes of the second harmonic of both the positive- and negative-contrast functions are very low and close to the level of the noise at depth of modulations below 16%. Above this depth of modulation, amplitude increases rapidly, suggesting that it is at this point that the response becomes nonlinear.

c. Constant Depth of Modulation

In this experiment the depth of modulation was held constant (at 4%), and the mean contrast was varied from 4 to 32%. In figures 21 and 22, the amplitude and phase of the fundamental component of the VEP are plotted as a function of mean contrast for two subjects, lp and mc.

Figure 19

Plots of amplitude and phase of the fundamental component of the VEP versus depth of modulation for subject mc, plotted on log-log coordinates. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

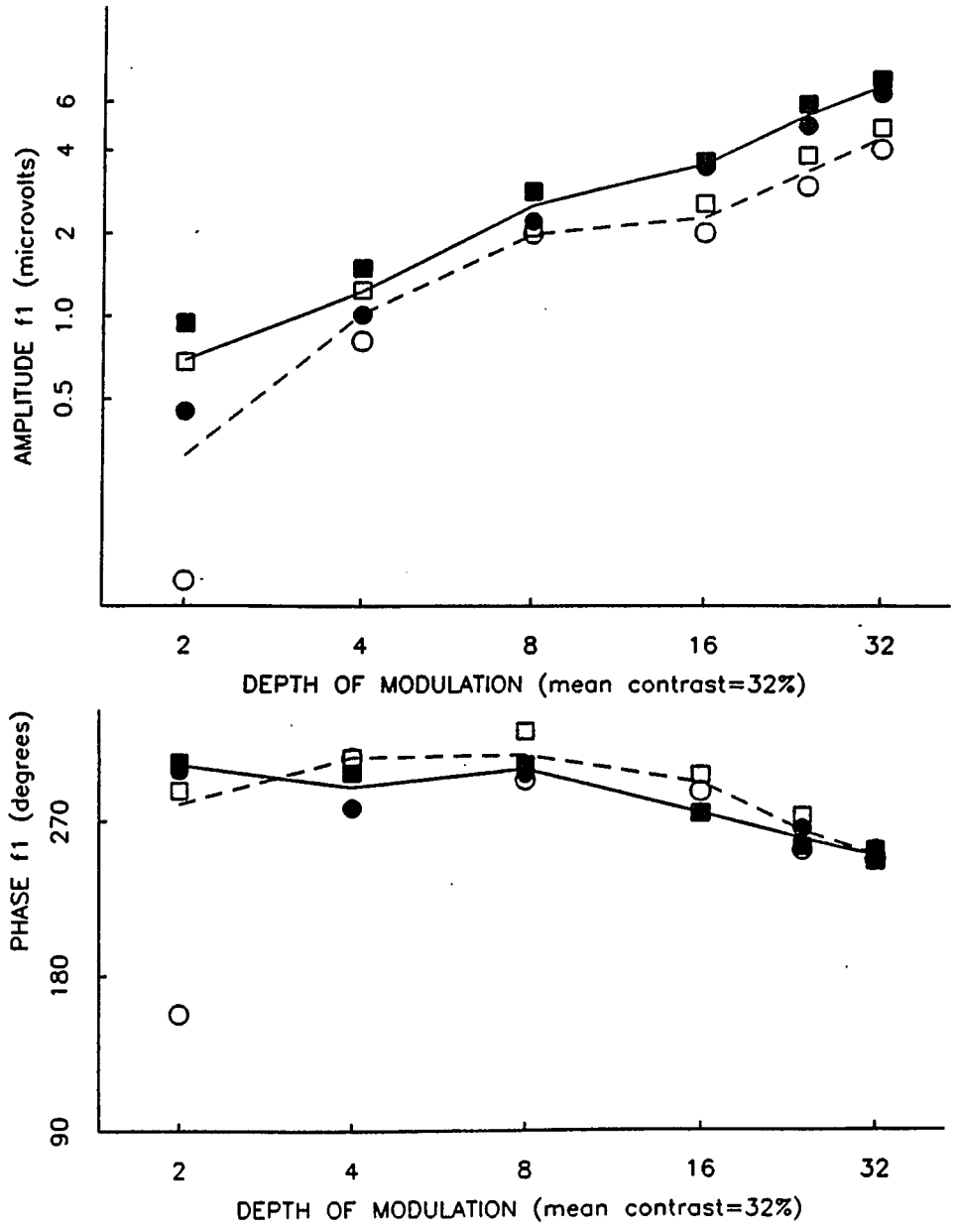

AMPLITUDE f1 (microvolts)
0.5
1.0
2
4
6
2
4
8
16
32
DEPTH OF MODULATION (mean contrast=32%)
PHASE f1 (degrees)
90
180
270
2
4
8
16
32
DEPTH OF MODULATION (mean contrast=32%)

Figure 19

Figure 20

Plots of amplitude and phase of the second harmonic component of the VEP versus depth of modulation for subject ep, plotted on linear coordinates. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

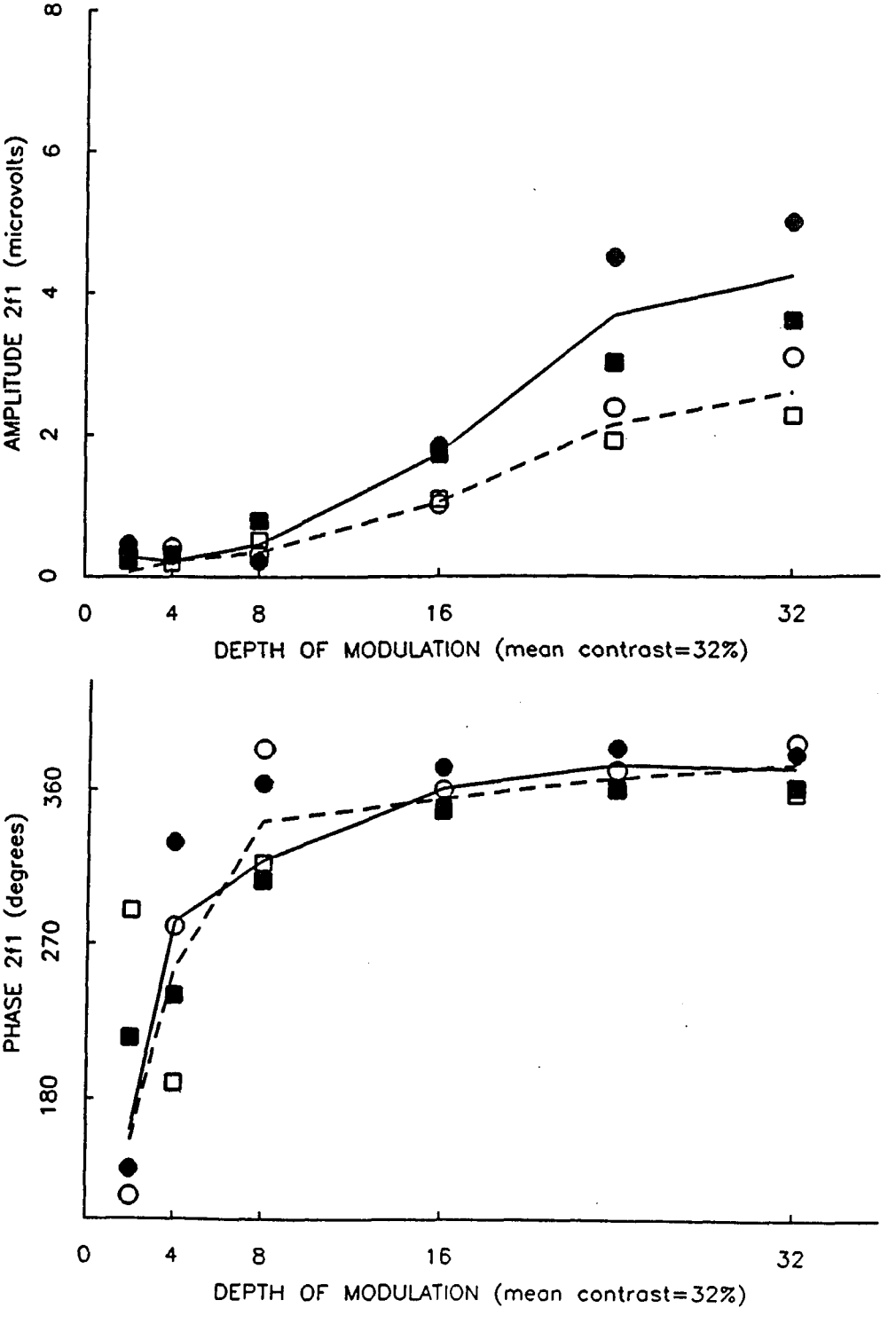

AMPLITUDE 2f1 (microvolts)
0
2
4
6
8
0
4
8
16
32
DEPTH OF MODULATION (mean contrast=32%)
PHASE 2f1 (degrees)
180
270
360
0
4
8
16
32
DEPTH OF MODULATION (mean contrast=32%)

Figure 20

Figure 21

Plots of amplitude and phase of the fundamental component of the VEP versus mean contrast (depth of modulation=4%) for subject lp, plotted on linear coordinates. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

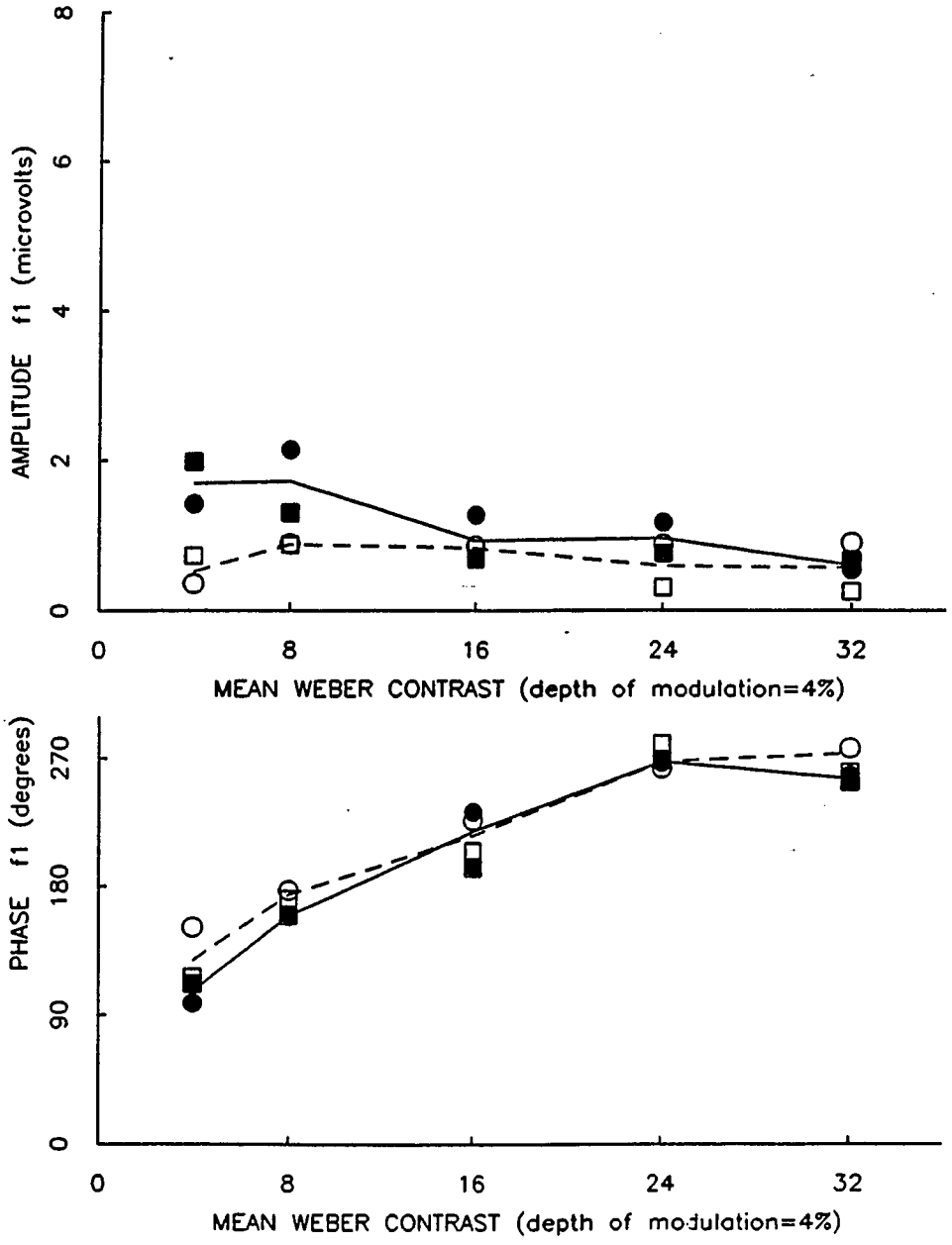

AMPLITUDE f1 (microvolts)
0
2
4
6
8
0
8
16
24
32
MEAN WEBER CONTRAST (depth of modulation=4%)
PHASE f1 (degrees)
0
90
180
270
0
8
16
24
32
MEAN WEBER CONTRAST (depth of modulation=4%)

Figure 21

Figure 22

Plots of amplitude and phase of the fundamental component of the VEP versus mean contrast (depth of modulation=4%) for subject mc, plotted on linear coordinates. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

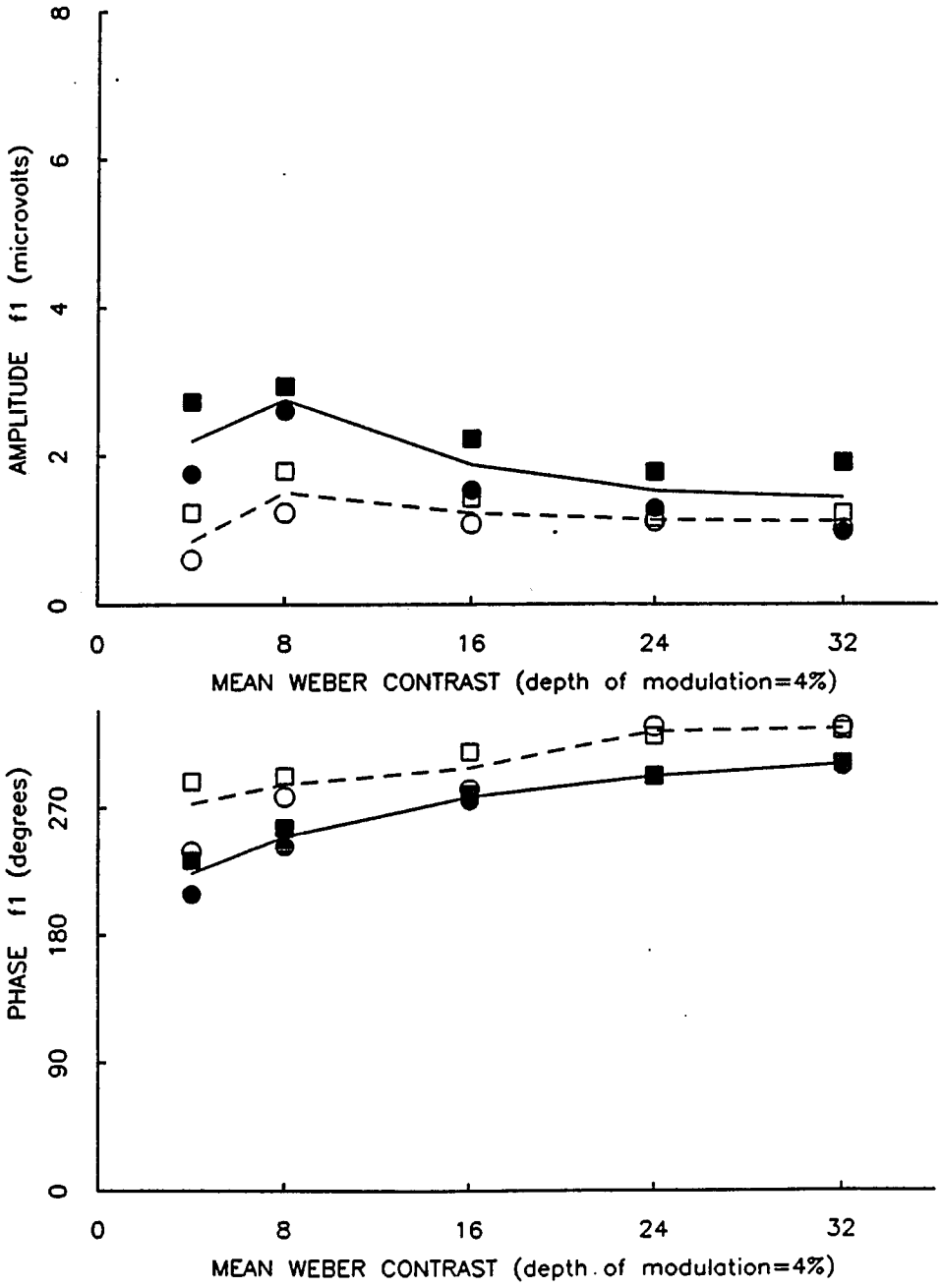

AMPLITUDE f1 (microvolts)
0
2
4
6
8
0
8
16
24
32
MEAN WEBER CONTRAST (depth of modulation=4%)
PHASE f1 (degrees)
0
90
180
270
0
8
16
24
32
MEAN WEBER CONTRAST (depth of modulation=4%)

Figure 22

In this experiment, the luminance modulation (or the percent contrast change) is the same for each stimulus. Therefore, the change in amplitude is a measure of contrast gain (the response magnitude per unit contrast) which changes as the point around which the contrast modulation increases (the mean contrast level). The amplitude of the negative-contrast function is higher than the amplitude of the positive-contrast function over this range of mean contrast levels; however, the difference between the curves is greatest at low mean contrast levels. In other words, the contrast gain is highest when the mean contrast is low (4 to 8%) and decreases at mean contrast levels above 16%. The phase data indicate an increasing phase lead as mean contrast was increased, as previously observed in the appearance-disappearance data.

The amplitude and phase of the second harmonic component of the VEP are plotted in figure 23 as a function of mean contrast for one subject, mc. As expected, this small depth of modulation can produce second harmonic responses at the low mean contrast levels where the response is driven into the nonlinear region near threshold. At higher mean contrast levels, this

Figure 23

Plots of amplitude and phase of the second harmonic component of the VEP versus mean contrast (depth of modulation=4%) for subject mc, plotted on linear coordinates. Check size was 9', temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

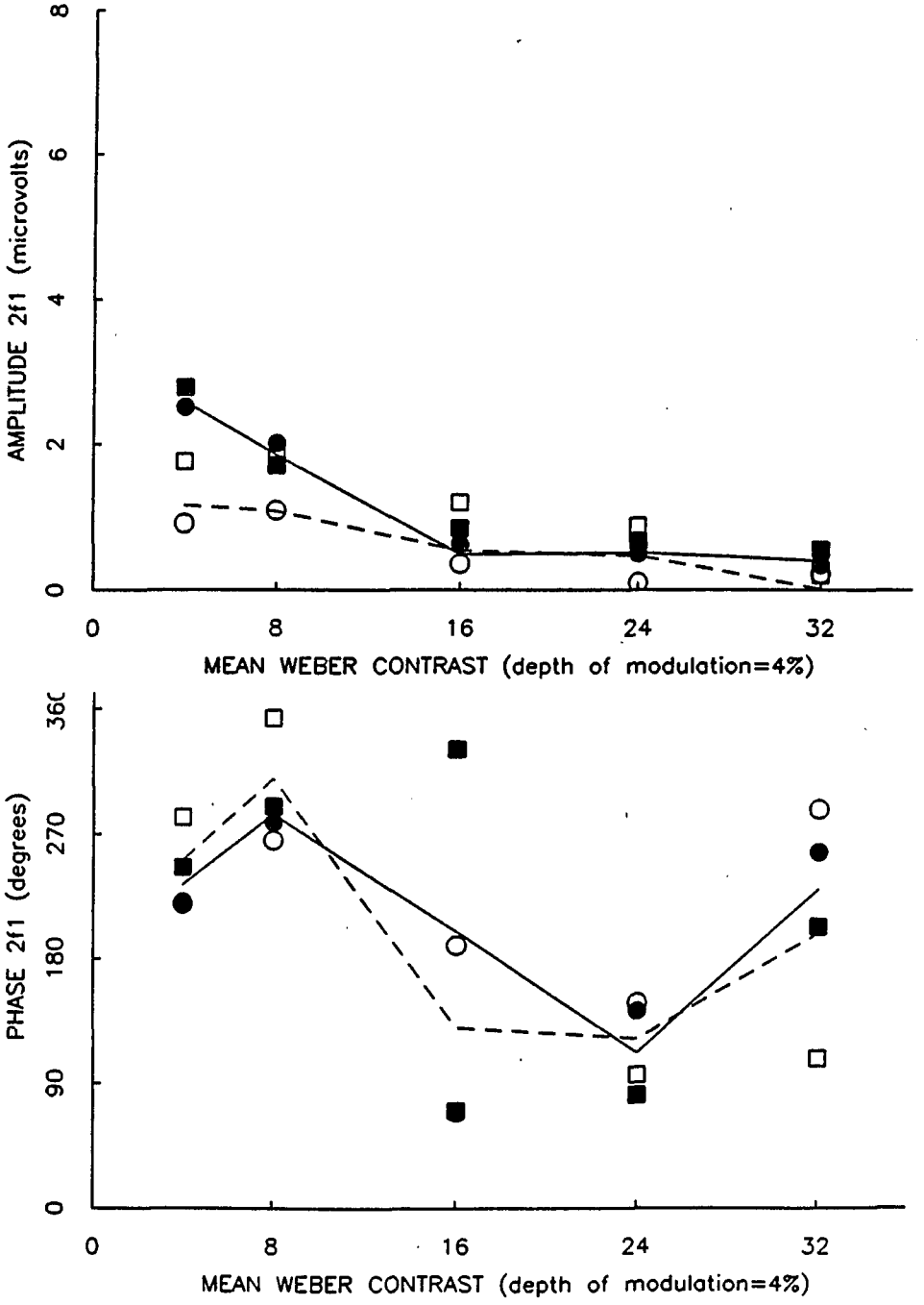

AMPLITUDE 2f1 (microvolts)
0
2
4
6
8
0
8
16
24
32
MEAN WEBER CONTRAST (depth of modulation=4%)
PHASE 2f1 (degrees)
0
90
180
270
360
0
8
16
24
32
MEAN WEBER CONTRAST (depth of modulation=4%)

Figure 23

depth of modulation does not produce second harmonic responses as stimulation is above the threshold region.

DISCUSSION

Asymmetries in VEPs elicited by positive- and negative-contrast checks demonstrate some differences in the ON and OFF pathways in humans. Fundamental responses elicited by negative-contrast stimuli elicited higher amplitude responses than did positive-contrast stimuli over most of the range of spatial, temporal and contrast conditions tested. When present, second harmonic responses elicited by negative contrasts were also greater in amplitude than those elicited by positive contrasts.

The spatial tuning functions of the two pathways are different. In the small check conditions, where reliable differences can be observed in these pathways, the OFF pathway response is always higher in amplitude than the ON pathway response. The differences observed in the peak and slope of the positive- and negative-contrast spatial tuning curves may reflect differences in the receptive field organization of the cells of the ON and OFF pathways; specifically, in the size of the center mechanism. As the negative-contrast curve was generally found to peak at a smaller check size, it would be reasonable to suspect that cells of the OFF pathway have

smaller center mechanisms than the cells of the ON pathway. (It is possible that the difference in the peak and slope of the curves may be due to differences in the surround mechanisms rather than differences in the center mechanisms, as postulated. However, preliminary computer modeling of these responses, using different center and surround strengths and sizes, indicates that the differences observed in these experiments are most probably due to different center mechanisms.)

The spatial tuning phase data yield some interesting information about the relative contributions of luminance and contrast modulation. When the stimulus is a full field (or very large checks which approximate a full field), the phase of the response to bright checks is 180^{o} out-of-phase with respect to the phase of the response to dark checks, revealing that luminance modulation is a major contributing factor. As the check sizes get smaller, the response phases begin to merge, and by the 38-75 minute sizes, the responses are in-phase. This would indicate that the modulation of absolute contrast, rather than the modulation of luminance, is the major contributing factor for small checks. The amount of luminance modulation is the same in all check conditions, from the largest check to the

smallest. If responding were due to luminance modulation alone, there should be equal amplitude of response at all check sizes. The phase of response should be similar within a set of bright- and dark-check data, and differ by 180° between the two sets of data. This is not the case, thus eliminating luminance modulation as a sufficient explanation of the results.

The similarity in the temporal functions strongly suggests that the ON and OFF pathways have similar dynamic properties. There is a difference in the magnitude of response, the negative-contrast function is higher in amplitude over most of the range of temporal frequencies tested. The phase of the VEP to positive- and negative-contrast in the spatial and temporal tuning functions clearly indicate that luminance modulation is not a major factor in the response asymmetries observed in these experiments. When a spatial pattern is present, the phase of the bright- and dark-check responses were always in-phase with respect to each other, rather than 180° out-of-phase as predicted by the luminance modulation hypothesis. Responses to full-field, or large check patterns, were 180° out-of-phase in accordance with the luminance modulation hypothesis.

A further demonstration that luminance modulation does not provide a sufficient explanation of the results was demonstrated by full-field modulation of luminance at values ranging from 4 to 64% above or below the initial luminance level. The results of this experiment are shown in figure 24, for subject mc. It can readily be observed that the results of the full field experiment differ a great deal from the results of the contrast appearance-disappearance experiment. There is very little, if any, difference in the amplitude of response to positive and negative luminance changes; the response functions are very similar. In addition, the amplitude of response changes very little as luminance changes from 4% to 64%. Another major difference between the full field and contrast appearance-disappearance experiments can be observed by comparing the phase data. The phase of the positive-contrast function is 180^{o} out-of-phase relative to the phase of the negative-contrast function.

In the case of the check stimuli, three-quarters of the display remain at the background luminance level. Luminance either modulates above that background luminance level (for bright checks), or below it (for dark checks). Obviously, in the case of full-field modulation there is no static background present; when

Figure 24

Plots of amplitude and phase of the fundamental component of the VEP versus temporal Weber contrast for subject mc, plotted on log-log coordinates. The stimulus field subtended 10^{o}, temporal frequency was 6.3 Hz. Symbols and lines are used as in figure 6.

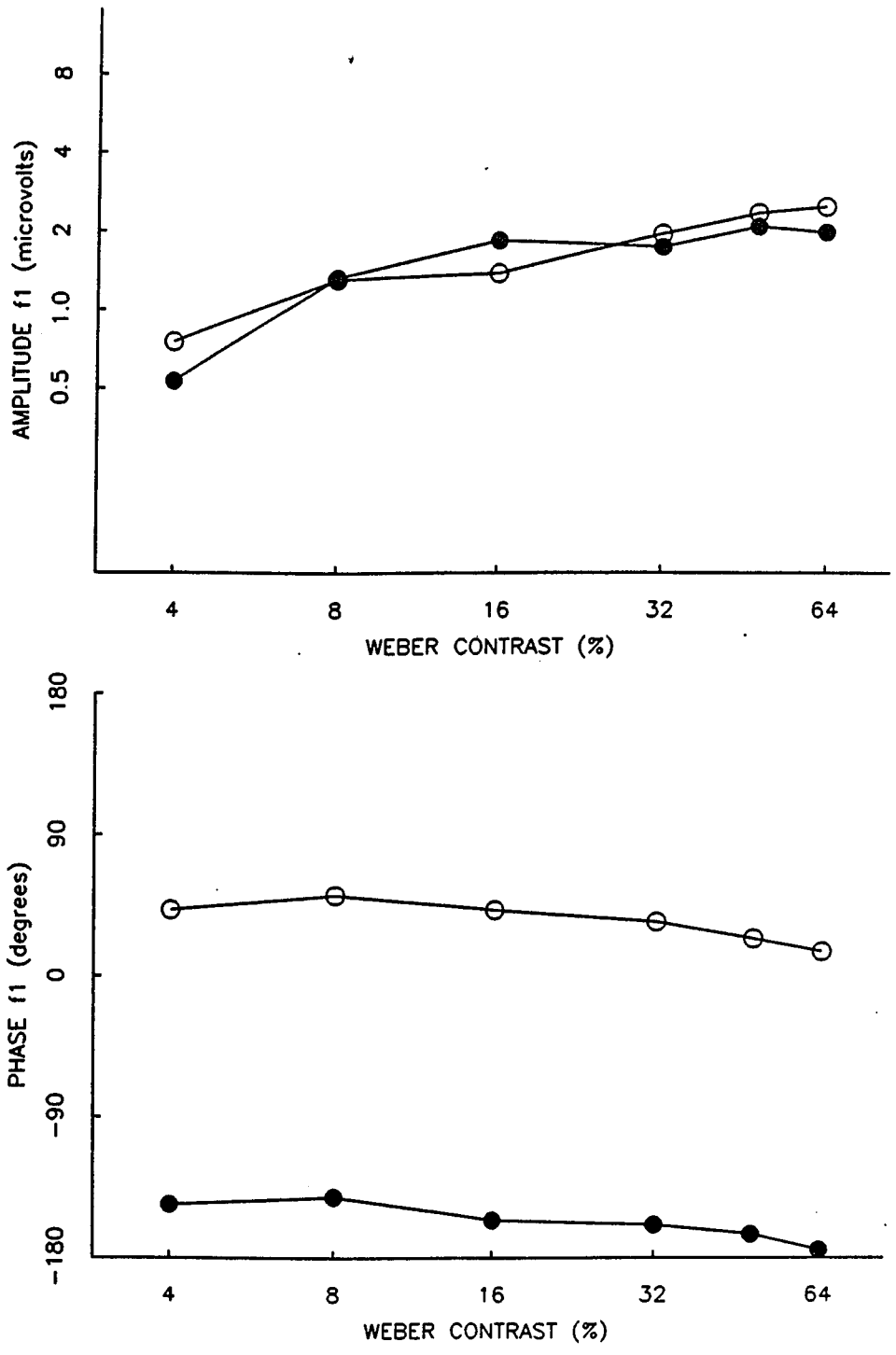

AMPLITUDE f1 (microvolts)
0.5
1.0
2
4
8
4
8
16
32
64
WEBER CONTRAST (%)
PHASE f1 (degrees)
180
90
0
-90
-180
4
8
16
32
64
WEBER CONTRAST (%)

Figure 24

the luminance of the entire field is modulated, both ON and OFF cells would be stimulated, as luminance modulates around a mean level. Therefore, full-field modulation would not be expected to elicit fundamental components of the VEP unless some asymmetry exists between ON and OFF pathways. The presence of a fundamental suggests that some asymmetry does exist; for example, unequal numbers of ON and OFF cells, different dynamics of the two pathways, or unequal response strength. Physiological work has demonstrated that ON and OFF cells are generally found in approximately equal numbers in the retina and LGN (Wassle, Boycott & Illing, 1981; Hubel & Wiesel, 1961). If human ON and OFF cells are also approximately equal in number, the asymmetry is due to another factor. The results of the temporal tuning experiment would seem to eliminate the hypothesis that the dynamics are different. It seems more likely that the response magnitude of the two pathways differ. If the response amplitude of the OFF pathway is greater than that of the ON pathway, as shown in figure 25, a fundamental response would result from full-field modulation.

Figure 25

Response Asymmetry Model. Full-field modulation should elicit a response from both the ON and OFF pathways. If the responses are equal and 180° out-of-phase, they will cancel. If the responses are not equal and similar dynamics for the ON and OFF pathways is assumed, a larger fundamental for the OFF pathway than for the ON pathway could result in a small fundamental response.

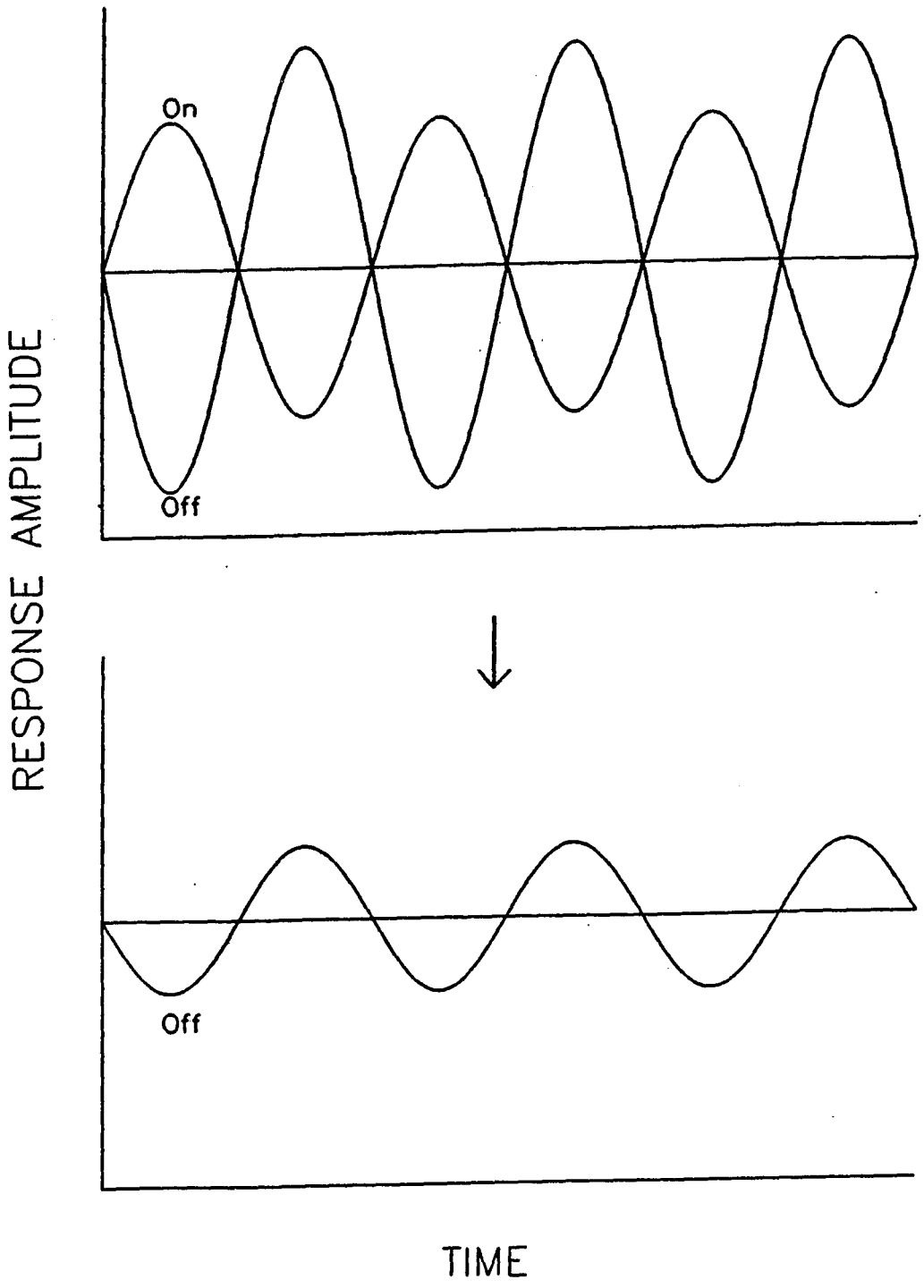


Figure 25

Contrast Response Model

The magnitude of the VEP response is related to the magnitude of stimulation to the visual system. The mathematical form of that relationship can be derived from experimental data, and can be explained in terms of a model. Neurophysiological models have been used to describe a variety of sensory phenomena. Naka and Rushton (1966, 1967) found an equation to express the stimulus intensity-response magnitude relationship in fish retinal neurons; this equation is:

$$R = I / (I + I_s)$$

where R is the response (in this case the change in membrane potential), I is the illumination of the stimulus, and I_s is the semi-saturation constant (equal to the illumination at which R reaches half of its maximal value). This equation has become known as the Naka-Rushton equation; when it is plotted on linear coordinates a nonlinear curve is produced (see figure 26). This relationship has been found to hold for many different sensory phenomena, in many different sensory systems, and in many different species (Lipetz, 1973). It is highly likely, therefore, that the data from the contrast experiments will fit this model.

Figure 26

A hypothetical response function relating stimulus strength and magnitude of response. It is based on the Naka-Rushton equation (see text).

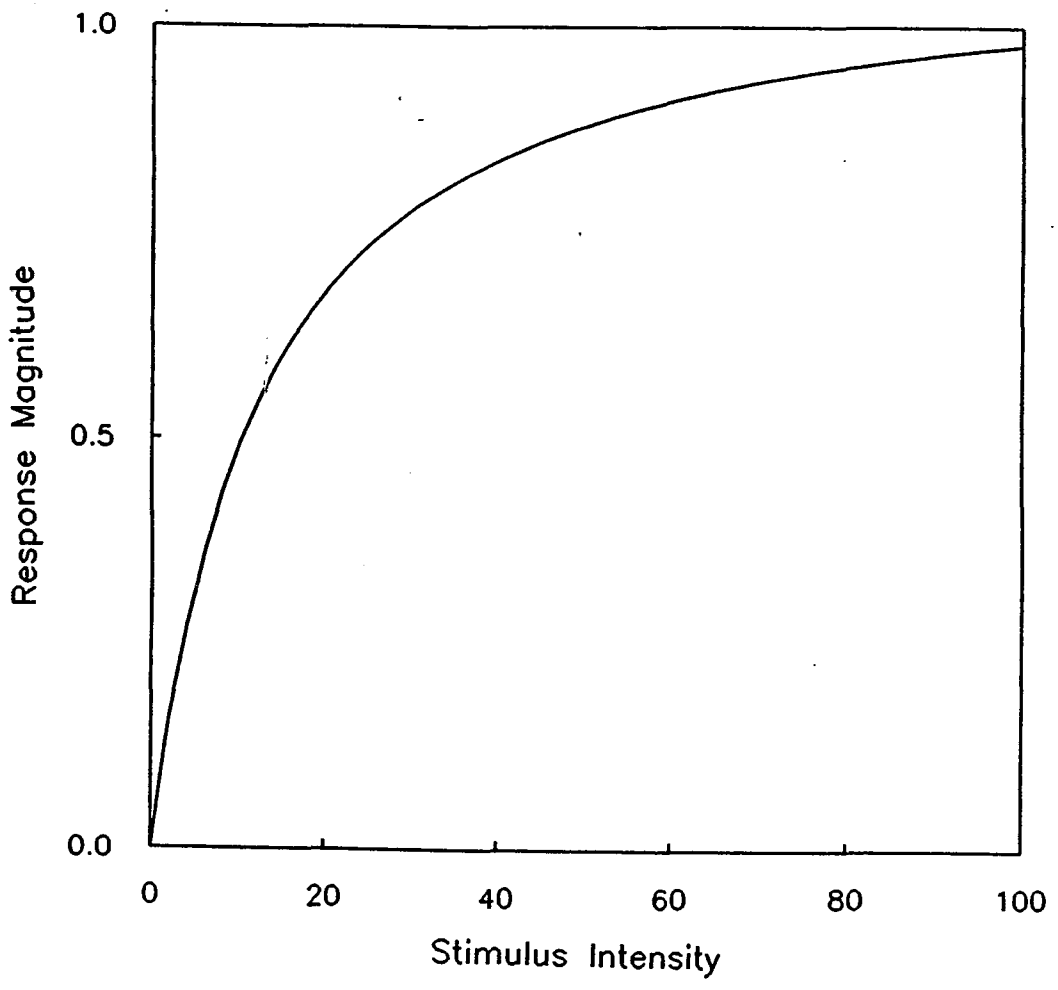

1.0
0.5
0.0
Response Magnitude
0
20
40
60
80
100
Stimulus Intensity

Figure 26

As the slope of the response curve is greatest at the lowest contrast levels, stimuli whose contrast reach zero, or low contrast levels, generally elicit higher amplitude fundamental responses than stimuli whose contrast do not reach these levels. In addition, rectification occurs at low contrast levels and second harmonic responses are expected. In the appearance-disappearance experiment, contrast always increases from 0% to some peak value, therefore fundamental response amplitudes should be high and second harmonic responses should be found.

Contrasts in the two contrast modulation experiments do not reach the 0% level (with one exception). In the constant mean contrast experiment, the mean contrast remains constant at 32%. The slope of the curve at this point is fairly low. Small depths of modulation (4 to 8%) around this value will yield relatively small fundamental responses, and negligible second harmonic responses. When the depth of modulation increases to 16% and higher, the slope of the response curve is greater; fundamental response amplitudes should increase, and some second harmonic responses should be observed. In the constant depth of modulation experiment, the depth of modulation remains constant at 4%. This low depth of

modulation is predicted to elicit rather small responses. The highest amplitude fundamental responses should be observed at low mean contrasts. When mean contrast is equal to 4 or 8%, high amplitude fundamental responses should be observed, as the slope of the response curve is highest at the low mean contrast levels. Second harmonic responses are also expected at low mean contrast levels. As the mean contrast level is increased, the slope of the response curve decreases and fundamental response amplitudes should decrease. Second harmonic responses should also decrease as responding is no longer driven to the threshold region where nonlinearities have been found.

In figure 27, the responses to the three types of contrast manipulations are compared. For example, in the appearance-disappearance experiment, a stimulus with a mean contrast of 16% and a depth of modulation of 16%, will yield response R_1. In the constant mean contrast experiment, a stimulus with a depth of modulation of 16% and a mean contrast of 32% will yield response R_2; this is a smaller response than the response in the appearance-disappearance experiment. In the constant depth of modulation experiment, a stimulus with a mean

Figure 27

A comparison of hypothetical responses to different contrast manipulations (R_1 represents the response in the appearance-disappearance experiment; R_2 represents the response in the constant mean contrast experiment; and R_3 represents the response in the constant depth of modulation experiment).

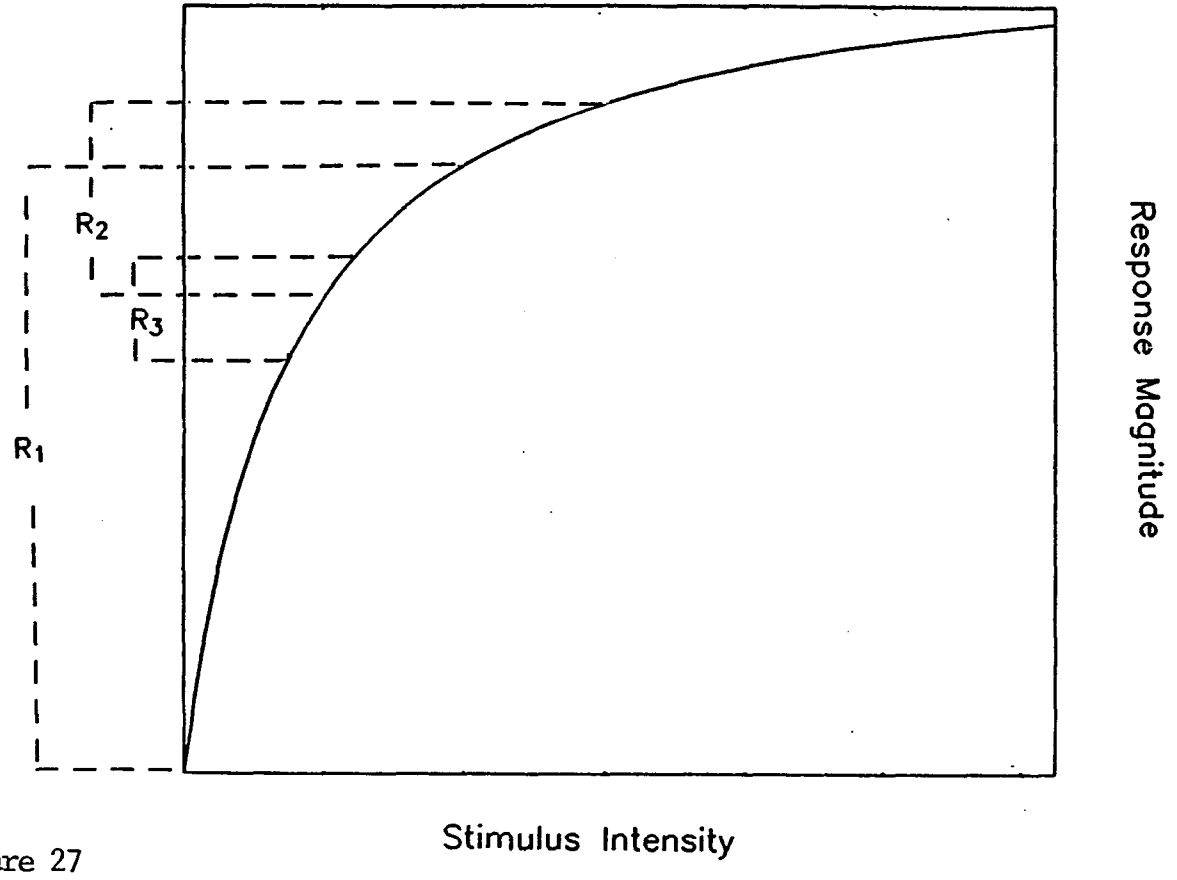


Figure 27

contrast of 16% and a depth of modulation of 4% will elicit response R_3, a still smaller response.

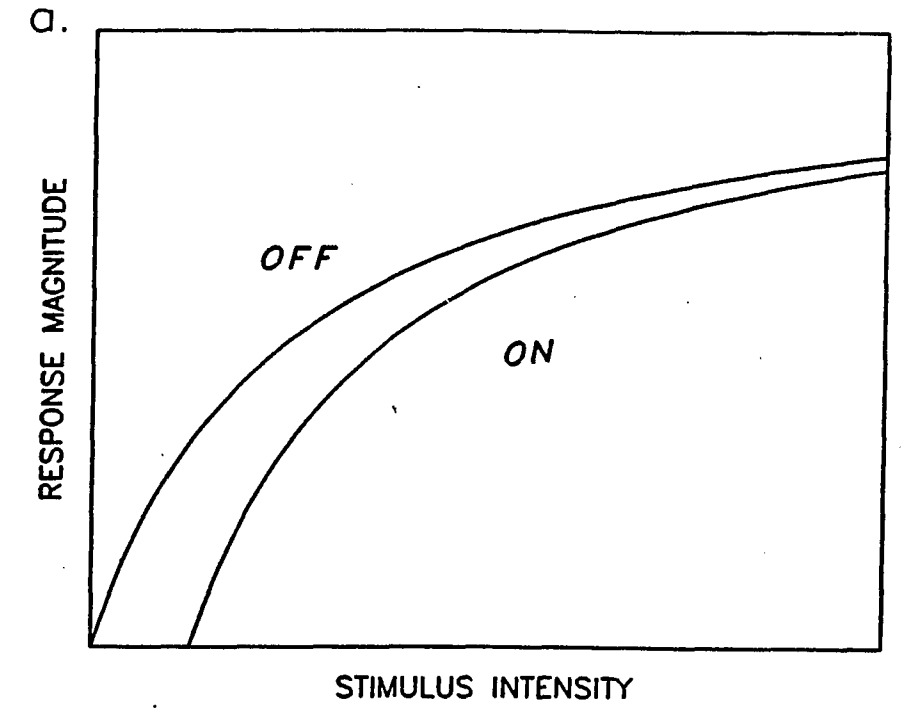
Contrast Sensitivity and Contrast Gain Models

Psychophysical work has demonstrated some differences in the response magnitude between the ON and OFF pathways (Magnussen & Glad, 1975a). The two pathways may differ in contrast sensitivity or contrast gain (or both). Contrast sensitivity may be defined as the reciprocal of the contrast necessary for a criterion response. Contrast gain may be defined as the response magnitude per unit contrast.

If the two pathways differ in their contrast sensitivity the response functions may be represented by those in figure 28a. The curves representing the ON and OFF pathways are equal in slope; the ON pathway curve is shifted laterally. This assumes that the contrast sensitivity of the ON pathway is lower than that of the OFF pathway. This model would predict lower responses from the ON pathways at all contrast levels until saturation occurs. The maximum response amplitude attained at saturation is predicted to be identical for

Figure 28

a. Two hypothetical response curves with different contrast sensitivity values. b. Two hypothetical response curves with different contrast gain values.


a.
RESPONSE MAGNITUDE
OFF
ON
STIMULUS INTENSITY

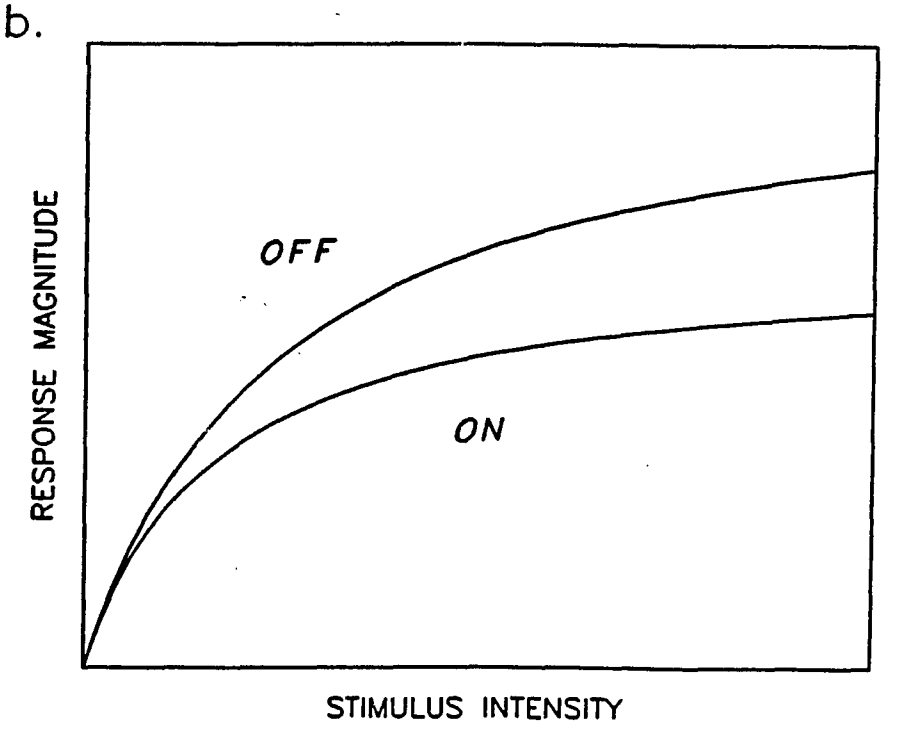

b.
RESPONSE MAGNITUDE
OFF
ON
STIMULUS INTENSITY

Figure 28

both pathways, but the ON pathway requires a higher contrast level than the OFF pathway to reach saturation.

If the ON and OFF pathways differ by a gain factor, the response functions may be represented by those of figure 28b. In this case, the slopes are not identical, they differ by a gain factor. This model, as the model described above, predicts lower amplitude responses for the ON pathway. However, this model predicts a difference in the maximum amplitude attained at saturation. The maximum amplitude attained by the ON pathway at saturation is predicted to be lower than that of the OFF pathway. Both models predict differences in the degree of asymmetry in the positive- and negative-contrast response functions. The largest asymmetries are expected in the appearance-disappearance experiment, next largest in the constant mean contrast experiment, and smallest in the constant depth of modulation experiment.

Comparison of Data with Models

The model comparing hypothetical responses to different types of contrast manipulations predicted that appearance-disappearance type of stimulation would result

in high amplitude fundamental responses, and large differences in response amplitude between the positive- and negative-contrast functions. A comparison of the results of the contrast experiments reveal this to be true. Responding to appearance-disappearance stimuli did yield the largest fundamental responses. Sizeable second harmonic responses were also found, even at low contrast levels, as all stimuli in this experiment drove the response into the nonlinear range.

As expected, responding in the constant mean contrast experiment was lower than responding in the appearance-disappearance experiment. At low depths of modulation around a mean contrast of 32%, the slope of the response curve is fairly shallow, and small responses would be expected. Response amplitudes were found to be low until a depth of modulation of 16% (the point at which the depth of modulation begins to approach the mean contrast). At this, and higher depths of modulation, the stimulus tapped the response curve at a region of greater slope, and the amplitude of responding was increased. The last stimulus was equivalent to an appearance-disappearance stimulus and the amplitude of response to it was high. Second harmonic responses are also neglible until the depth of modulation reaches 16%,

the point at which the response was driven to the nonlinear region.

As predicted, response amplitudes in the constant depth of modulation experiment were lower than those of the other two contrast experiments. In this experiment, the highest response amplitudes were expected at the low mean contrast levels, around points of the response curve where the slope is highest (4 to 8% mean contrast). Highest amplitude responses were found at these mean contrast levels. Second harmonic data in this experiment also behave according to expectations; they were found at mean contrast levels of 4 and 8%, but disappear into the noise above that point.

The results of the contrast experiments suggest that a difference in contrast sensitivity alone would not account for the data, as the model based on a difference in the pathways in contrast gain provides a better prediction of the results. The averaged data from figure 11 (represented by lines through the data points) are presented again in figure 29 (represented by symbols). The averaged positive-contrast and negative-contrast data can be fit by two Naka-Rushton equations which differ from each other simply by a gain factor. This strongly suggests that a difference in contrast gain could account

Figure 29

Plot of average amplitude of the fundamental component of the VEP versus Weber contrast for subject ep, plotted on linear coordinates, as repeated from figure 11. Stars represent the averaged response to dark checks, diamonds represent the averaged response to bright checks. The data for each type of stimulus could be well fit to a Naka-Rushton equation, which is:

$$R = g(I / (I + I_s))$$

where R is the response, I is the illumination of the stimulus, I_s is the semi-saturation constant, and g is a gain factor. These two Naka-Rushton curves were found to differ from each other by g, the gain factor.

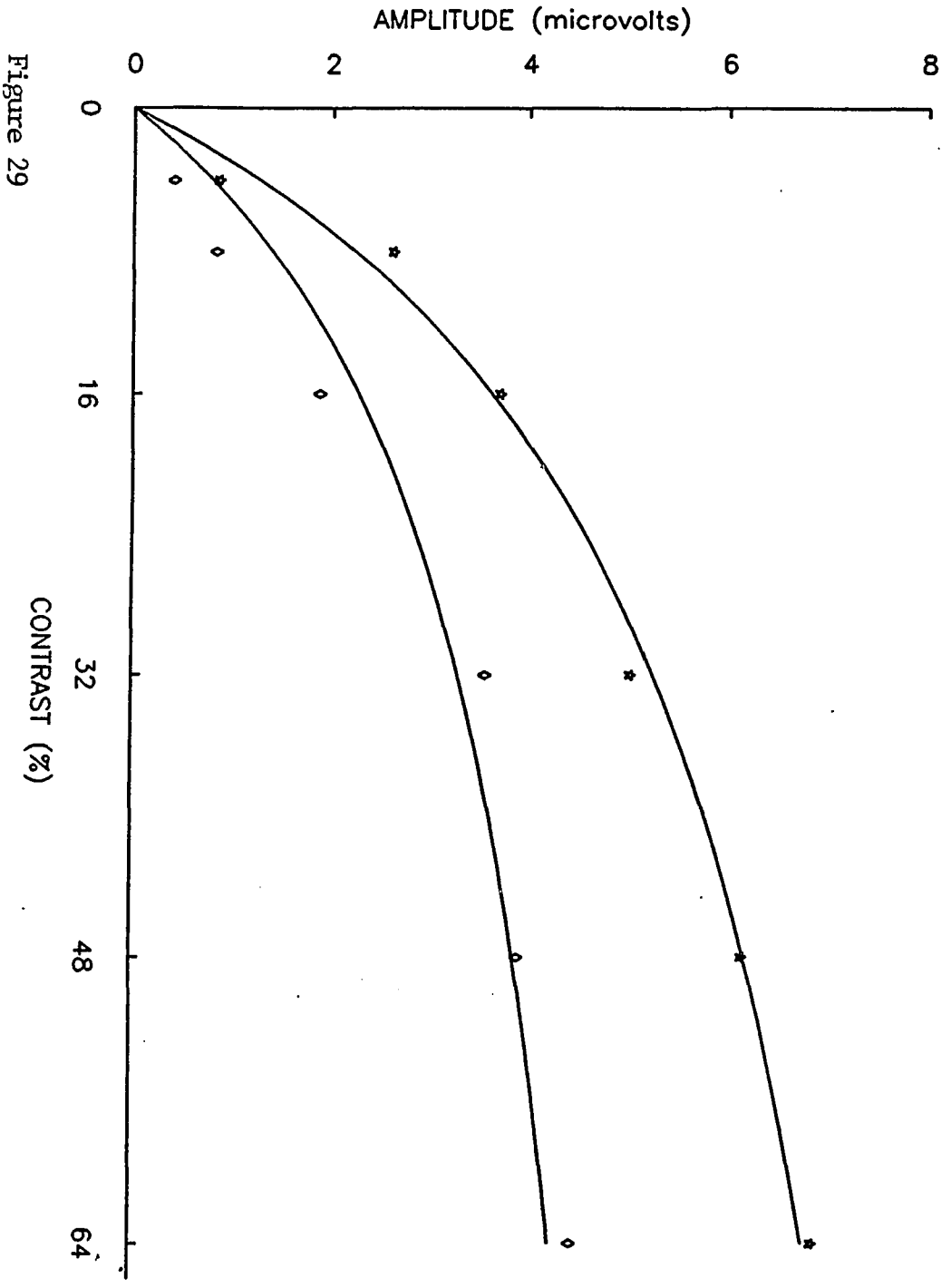


Figure 29

for the differences observed in response to positive- and negative-contrast stimuli.

Contrast Gain and Phase Shift Effects

The time course of the response of a cell was found to vary with adaptation level. As illumination was increased in incremental steps, the response of cat ganglion cells became increasingly transient in nature, and the response latency was decreased in both ON and OFF cells (Enroth-Cugell & Shapley, 1973; Jakiela, Enroth-Cugell & Shapley, 1976). In response to sinusoidally-modulated, contrast-reversing stimuli (gratings and bars) of moderate to high modulation frequencies, an increase in contrast resulted in a decrease in the gain of the first-order (or linear) responses of cat ganglion cells and an increase in the phase lead of these responses (Shapley & Victor, 1978). The contrast gain control mechanism is thought to average contrast over a wide expanse of the retina, approximately 10 degrees (Shapley & Enroth-Cugell, 1984). Thus, in the present experiments contrast gain should be regulated by the contrast present in the entire field.

The advance in phase lead as contrast increased, observed by Shapley and Victor (1978), was observed in the appearance-disappearance and constant depth of modulation experiment. In both of these experiments, mean contrast is increased from stimulus to stimulus, and the phase of the fundamental response exhibited an increasing phase shift. When mean contrast was held constant, the phase of the fundamental response exhibited a decreasing phase shift with increasing depth of modulation. In the two former experiments, mean contrast increased as contrast increased, resulting in a decrease in contrast gain, and an increase in phase shift. In the latter experiment, in which mean contrast remained constant as the depth of modulation increased, contrast gain was fairly constant (as evidenced by the close to linear slope) and the phase shift exhibited a small decrease.

The dependence of contrast gain on the mean contrast level has been demonstrated in cat cortical cells (Ohzawa, Sclar & Freeman, 1982). These investigators varied contrast around different mean contrast levels and found that the contrast response functions shifted laterally along a log-contrast axis as the mean contrast was increased. This lateral shift implies a change in the contrast gain of the cell based on the mean contrast.

The contrast gain of the cell decreased as mean contrast was increased.

Independent Brightness and Darkness Processing

There is physiological, morphological and pharmacological evidence that the ON and OFF pathways are independent in many animal species (Kuffler, 1953; Famiglietti & Kolb, 1976, Wassle, Boycott & Illing, 1981; Schiller, 1982; Sherk & Horton, 1984). There is also psychophysical evidence of asymmetries in the perception of brightness and darkness perception (Helmholtz, 1911/1962; Blackwell, 1946; Short, 1966; Magnussen & Glad, 1975a; De Valois, 1977). As it has been hypothesized that the ON and OFF pathways mediate brightness and darkness, respectively, the results of the present experiments suggest that human ON and OFF pathways have somewhat different properties, and are likely to be independent. (However, this parsimonious explanation involves comparing the results of single-cell recordings, psychophysical results, and VEP results. These techniques record responses at different levels of processing and may not be comparable. However, as the results from the three different techniques seem to be in

agreement they may be seen as converging lines of evidence.)

Information regarding brightness or darkness could be coded by a single system by increases or decreases in the maintained discharge of its cells. De Valois, Jacobs and Jones, 1962, found that monkey LGN cells respond to brief changes in luminance by proportional increases or decreases in the maintained firing rate of that cell. Both ON and OFF cells are capable of signalling information regarding increments and decrements in luminance.

Signalling large changes in both brightness and darkness would require a high maintained discharge rate so that light decrements could be signalled equal well in comparison to light increments, as there exists an asymmetry in the limit of modulation of the maintained discharge. Both light decrement stimulation and neuronal inhibition are limited at the zero level by complete absence of light, or complete cessation of firing. In general, the lower margin is therefore much more narrow than the upper margin for light increment stimulation, or increase in firing rate. In theory, it would be possible for a one-pathway system to signal both brightness and

darkness, as long as all cells in the pathway can signal information regarding an increment or decrement in stimulation. It is known that two parallel pathways do exist in most species, originating at the bipolar level, and although they might not be necessary at precortical levels, each may serve to enhance the information carried by the other, or serve as a "back-up system" for each other.

Independent ON and OFF Pathways Model

Although ganglion and geniculate cells exhibit a sizeable maintained discharge level, cortical cells do not (Hochstein & Spitzer, 1985), probably due to intracortical inhibition exerted by gamma-aminobutyric acid (GABA)-mediated interneurons (Krnjevic & Schwartz, 1967; Crawford & Curtis, 1964). Without a sizeable maintained discharge, rate decreases in firing cannot be coded; one pathway would therefore not be sufficient to provide both brightness and darkness information.

A model can be proposed to illustrate independent ON and OFF pathways (see figure 30). The assumptions implicit in the model include: 1) greater strength for center than surround mechanisms for both ON and OFF

Figure 30

Independent ON and OFF Pathways Model. A bright check is centered on a geniculate ON cell (L) and a geniculate OFF cell (L). In the luminance profile of the bright check, it can be observed that the luminance of the check is modulated sinusoidally at a level higher than the background luminance (B). (The ON cell is depicted as slightly larger in size than the OFF cell due to the difference in spatial tuning.) The firing rate of the ON cell is modulated above the maintained discharge level (MD) as the luminance of the check is modulated above the background level. In the case of the OFF cell, its firing rate is modulated below the maintained discharge level as luminance is modulated below the background level. The simple cell in the cortex (S) consists of linear (L) and nonlinear (N) processing. Intracortical inhibition (I) decreases the maintained discharge level to a very low level creating a nonlinearity (rectification). In the model the excitatory input from the ON geniculate cell is greater than the average excitatory input setting the intracortical inhibition, and the ON simple cell exhibits a response. The excitatory input from the OFF geniculate cell is much lower than the average excitatory input setting the intracortical inhibition, therefore, the OFF simple cell does not exhibit a response. A complex cell (C) receives input from both ON and OFF simple cells.

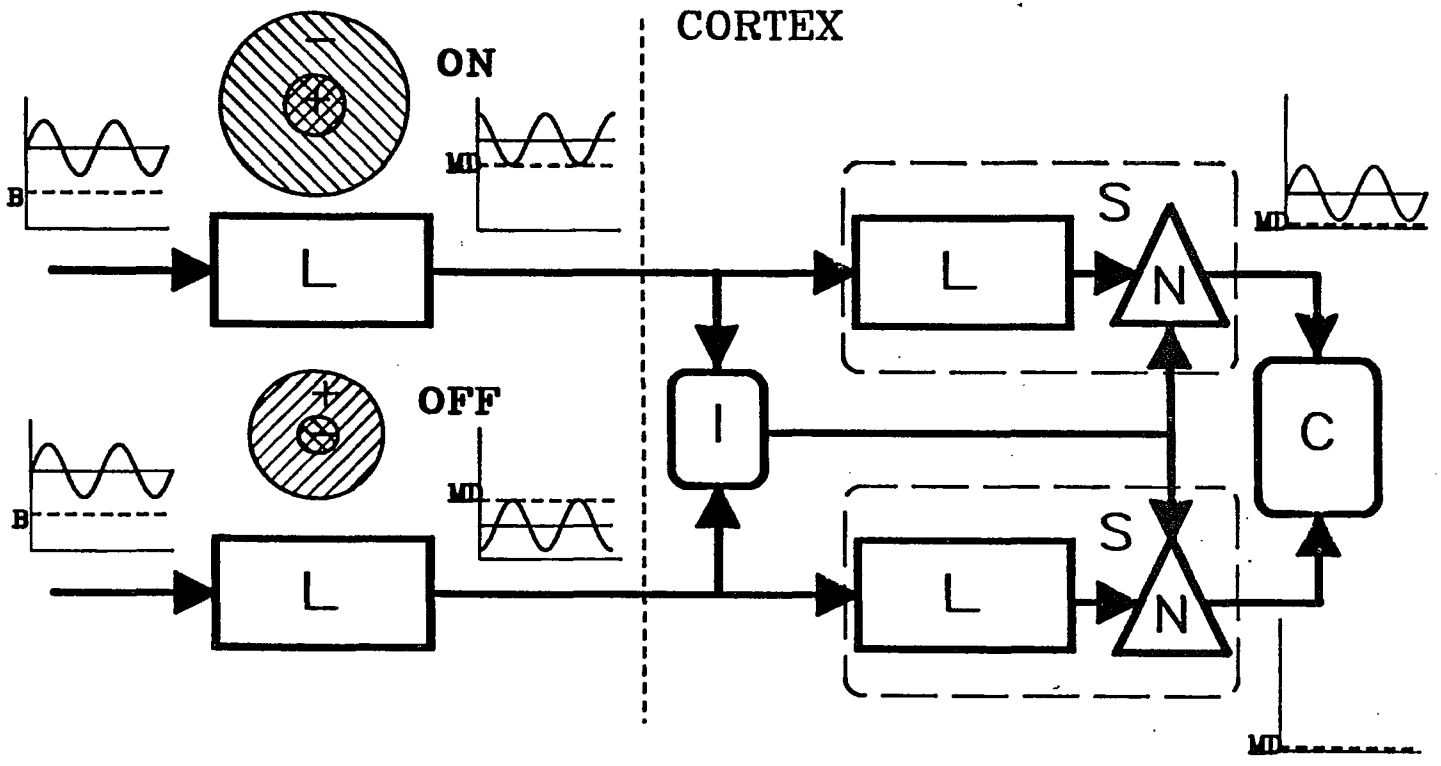


Figure 30

cells, and 2) higher mean firing rates for ON than OFF cells when bright checks are presented to the receptive field center, and the reverse situation when dark checks are presented.

ON and OFF pathways process information independently in approximately a linear manner up to the level of the visual cortex. In this example, the stimulus is a bright check centered over an ON cell and an OFF cell. Both ON and OFF ganglion and geniculate cells can signal an increment or a decrement in luminance by a modulation of their maintained discharge rate. The firing rate of the ON cell is modulated above the maintained discharge level (excitation), as the luminance of the check is modulated above the background level. In the case of the OFF cell, its firing rate is modulated below the maintained discharge level (inhibition), as luminance is modulated above the background level. In the cortex, intracortical inhibition decreases the maintained discharge level. The amount of intracortical inhibition depends on the amount of excitatory input to the cortex, and it is assumed that intracortical inhibition is set by some average of the afferent excitatory input. In the model, the excitatory input from the ON geniculate cell is greater than the average

excitatory input setting the intracortical inhibition, and the ON cortical cell exhibits a response. The excitatory input from the OFF geniculate cell is much lower than the average excitatory input setting the intracortical inhibition, therefore, the OFF cortical cell does not exhibit a response.

In this way cortical cells behave like half-wave rectifiers; firing above an certain level (the maintained discharge rate) can be signalled, firing below this level cannot. This rectification due to the low maintained discharge rate creates a situation in which cortical cells receiving input from ON center units respond almost exclusively to increments in luminance, and cortical cells receiving input from OFF units respond mostly to decrements in luminance. Therefore, at the level of the cortex, with its low maintained discharge rate, both brightness and darkness cannot be signalled by one system; only increases in firing rate above the low maintained discharge rate can provide information regarding stimulus conditions. However, two pathways, one resulting in an increase in firing rate when luminance increases, and the other resulting in an increase in firing rate when luminance decreases would be

able to provide the brain with both brightness and darkness information.

It should be mentioned that the ideal case (depicted in the independent pathways model), in which the bright-check stimuli elicit cortical responses from the ON pathway cells only, is highly unlikely. It is more likely that a bright-check stimulus would elicit responses from both types of cells, but a much greater response from the ON pathway cells than from the OFF pathway cells.

Alternate models could be postulated to explain the results of these experiments. One of the assumptions used in the independent pathways model was that the magnitude of response for the center mechanism was greater than the magnitude of response for the surround mechanism. If this is not true, the contributions of center and surround to the response may be approximately equal. (Although the response of the surround is lower than the response of the center, the area of the surround is greater.) If so, the bright- and dark-check stimuli could elicit responses from both ON and OFF pathway cells. Bright checks could stimulate the centers of ON-center cells, and the surrounds of OFF-center cells;

dark checks could stimulate the centers of OFF-center cells and the surrounds of ON-center cells. If responding to positive contrasts saturated at lower contrast levels than responding to negative contrasts, responding to negative contrasts would always be greater than to positive contrasts. Therefore, the results of these experiments might not point out differences in response properties of ON and OFF cells, but differences in response of both types of cells to positive and negative contrasts. However, evidence from single-cell work suggests that the center response is greater than the surround response, and provides the major contribution to the overall response of the cell. This factor makes the independent pathway model a more parsimonious explanation of the results.

Applications

If the ON and OFF pathways are independent, it is possible that pathological ophthalmologic or neurologic conditions may affect one pathway and another. Given this, VEPs elicited by positive and negative contrasts may aid in the diagnosis of such disorders. A form of cerebral palsy may be an example of a disorder in which the OFF pathway is affected, as the performance of

patients with this disease was improved in visuomotor tasks using white-on-black testing materials rather than the traditional black-on-white materials (Marozas & May, 1985).

Another application of the asymmetry in response to positive- and negative-contrast stimuli may be found in the study of visual tasks using video display terminals (VDTs) often used with computers. Typical VDT screens have light characters on a dark background, as opposed to traditional reading materials which are dark characters on a light background.

It has been oberved by Leermakers and Boschman (1984), in comparisons of letter-search time for positive and negative contrasts on VDT screens, that search time was lower for negative contrasts. Bauer and Cavonius (1980), found that reading speed was faster and accuracy improved on VDT screens when contrast polarity was negative. However, Cushman (1984), did not find significant differences in reading speed between negative- and positive-contrast VDT screens. Tinker (1963) found faster reading speed for negative contrasts than for positive contrasts (on paper); however, type size and font were found to have a large effect on this

difference. Gould and Grischkowsky, 1984, found that subjects read more slowly from a VDT screen (green characters on a dark background) than from paper (black characters on a white background). Gould (1986) tried to determine which of the many variables possible (experience with VDTs, display orientation, character size, font, polarity of contrast, etc.) could explain the observed difference. In examining polarity, Gould compared reading speed and accuracy between three conditions: a VDT screen with green characters on a dark background, a negative-contrast photograph of a VDT screen, and a positive-contrast photograph of a VDT screen; no significant differences in performance under any of these conditions were found. Gould concluded that no one variable studied could account for the slower reading speed on the VDT screen, but that it was due to some combination of the variables.

In general, it can be said that the results of experiments examining the effect of polarity on performance are somewhat inconsistent. A major problem in comparing positive and negative contrasts on a VDT screen involves the difference in critical fusion frequency (CFF) under different luminance conditions. As the temporal frequency of a stimulus increases, it is no

longer perceived as flickering, but appears to be a steady light; this point is known as the CFF. At low luminance levels, a light modulating with a temporal frequency of 30 Hz may appear steady, at higher luminance levels, a temporal modulation of 60 Hz may be necessary to reach the CFF (Granit & Harper, 1930). This factor was not taken into account in most of the above studies. In a study by Gyr, Nishiyama, Geierer, Laubli and Grandjean, 1984, on the effect of the temporal frequency of modulation of the VDT screen on eyestrain and other visually-related fatigue symptoms, it was found that symptoms were increased on a negative-contrast screen when temporal frequency was 60 Hz or below. Above that level, the incidence of symptoms were similar for positive- and negative-contrast screens. Isensee and Bennett (1983) found that subjects reported that they were more aware of flicker at 60 Hz on a negative-contrast screen than on a positive-contrast screen. It has been recommended that positive-contrast screens require at least 60 Hz temporal modulation to be flicker-free, and negative-contrast screens require at least 100 Hz temporal modulation to be flicker-free (Gyr, et al. 1984). If the same temporal frequency is used for both a positive- and negative-contrast display (below the CFF of the negative-contrast display), the positive-contrast display will have less apparent

flicker, and this will surely affect visual performance and visual comfort.

Summary

The stimuli used in these experiments were designed in order to separately stimulate the ON and OFF pathways. Asymmetries were found between positive and negative contrast data; responses to negative-contrast stimuli were higher in amplitude than responses to positive-contrast stimuli over a large range of spatial, temporal and contrast conditions.

The visual system demonstrates different spatial tuning in response to bright and dark checks; asymmetries in response amplitude are observed at small check sizes, but not at full field or large check sizes. Response phase at full field and large check sizes reflects luminance modulation, at the small check sizes, the response phase reflects contrast modulation.

The visual system also demonstrates differences in temporal tuning in response to bright and dark checks; higher amplitude response to dark checks were observed over a large range of temporal frequencies. The

similarity of the phase functions implies that the ON and OFF pathways have similar dynamic properties.

In the contrast experiments, asymmetries in responding were also found under most stimulus conditions. Negative-contrast stimuli elicited higher amplitude responses than did positive-contrast stimuli. Responding differed in the three types of contrast experiments. Some differences between VEPs to stimuli in which the depth of modulation is equal to the mean contrast and VEPs to stimuli in which the depth of modulation is lower than the mean contrast can be observed: 1) the asymmetries between the responses to positive- and negative-contrast stimuli are reduced or eliminated; 2) second harmonic responses are reduced or eliminated (when a depth of modulation is less than the mean contrast it avoids driving the response to the nonlinear regions of the response curve). This may be due to response functions which are similar in shape, although the ON response function is shifted to the right and may be lower in gain. The difference in the type of phase shift found in the contrast experiments implies that contrast gain is largely dependent on mean contrast.

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