RELEASABLE
DOC-CR-BT-88-003

A Study of Human Spatio-Temporal Visual Processing with Emphasis on Suppression of Visible Persistence and of Motion Smear

Being a research study performed under contract
27 ST. 36100-5-0084 on behalf of

The Department of Communications
Ottawa, Ontario

by

Dr. Vincent Di Lollo
Department of Psychology
University of Alberta
Edmonton
Alberta T6G 2E9
Tel: (403) 432-5260

Scientific Authority: Dr. Paul J. Hearty

31 March, 1986

A Study of Human Spatio-Temporal Visual Processing with Emphasis on Suppression of Visible Persistence and of Motion Smear

Being a research study performed under contract
27 ST. 36100-5-0084 on behalf of

The Department of Communications
Ottawa, Ontario

by

Dr. Vincent Di Lollo
Department of Psychology
University of Alberta
Edmonton
Alberta T6G 2E9
Tel: (403) 432-5260

Scientific Authority: Dr. Paul J. Hearty

31 March, 1986

Table of Contents

Page

Page

Abstract

All parts of a television picture appear to be simultaneously present on the screen at any given time. Physically, however, the television display consists of a single point of light displayed successively at every screen location, each of which continues to emit light for less than one millisecond. The fact that an entire scene appears to be present as a whole is, in fact, the final outcome of a series of complex sensory and perceptual events that take place within the viewer's visual system. Current television practice works because it is well matched to the spatio-temporal parameters of the human visual system. Traditionally, such parameters have been the object of study in the fields of perception, psychophysics, and sensory neurophysiology.

The present work reviews the psychophysical evidence pertaining to some of the fundamental sensory and perceptual processes that make possible the visual simulation that is television. The review begins with an examination of visible persistence, which is a process that enables the visual system to accept as input a very brief stimulus (in the order of microseconds), and to extend it in time so as to produce a perception whose duration is in the order of 100 milliseconds or longer. The methods employed to study visible persistence are critically examined, and the principal findings are systematically reviewed. Attention is paid both to stimulus parameters such as stimulus duration, intensity, and spatial frequency components, and to organismic parameters such as laterality effects. The theoretical accounts of visible persistence are then outlined, and the implications of visible persistence to television design

are examined.

If every brief stimulus impinging on the retina produced a perception lasting 100 ms or longer, normal visual functioning would be greatly impaired: every moving stimulus, or every small movement of the eyes or head, would produce an effect of "multiple vision" wherein a given object would be seen in its current spatial coordinates as well as in all spatial coordinates that it had occupied in the preceding 100 milliseconds or so. Clearly, the process of visible persistence also requires a corresponding process of suppression to sharpen the visual image and to prevent perception of smear of moving objects at velocities likely to be experienced in the natural environment.

A substantial body of evidence pertaining to suppression of visible persistence has accrued in a field of enquiry known as "Metacontrast suppression". Methods and findings in metacontrast suppression are evaluated and the factors affecting suppression are examined both in terms of attributes of the stimulus (e.g., stimulus intensity, chromaticity, orientation, and spatial frequency) and of attributes of the observer (e.g., effects of retinal eccentricity and of cognitive factors). Theories of metacontrast suppression are then reviewed, and the implications of findings and theories of metacontrast for television design are assessed, with particular reference to the spatio-temporal characteristics that might be found in new designs involving a higher spatial resolution and a broader dynamic range of intensity.

The review concludes with an examination of the empirical findings and of the theoretical accounts of suppression of smear of objects in motion. Again, implications for television design are pointed out.

A series of small empirical studies on the role of stimulus size on suppression of visible persistence is appended. Its major purpose was not to provide a definitive answer to the experimental question. Rather, its aim was to exemplify the type of design considerations and procedural problems that are typically encountered in this area of research.

1. SCOPE OF THE REVIEW

1.1 Visual psychophysics and television displays

Current television displays incorporate a picture tube coated with compounds that emit light (i.e., phosphoresce) when stimulated electrically. In black-and-white sets there is only one such compound; when stimulated, it emits light that corresponds to white. In colour sets, there are three such compounds; when stimulated, these emit lights corresponding to red, green, and blue. For purposes of the present analysis, the active display area can be regarded as a dense, two-dimensional matrix with each cell containing a "white" patch in black-and-white sets and discrete red, green, and blue patches in colour sets. It must be stressed that this is a largely intuitive description of the output of the display surface. In actuality, the single- or multiple-entry, two-dimensional appearance is the result of a combination of electronic, physical, and mechanical interventions. However, the intuitive description is adquate for the present purpose.

In North American television, a target scene is sampled 30 times per second. In effect, this sampling involves division of the camera's field-of-view into slightly more than 500 horizontal scan lines and continuous recording of light values along each line. However, prior to transmission, each sample (or frame) is divided into two display fields, one comprising the values of the even-numbered scan lines and one comprising the values of the odd-numbered scan lines. Thus, although only 30 frames are captured per second, 60 fields are displayed. As we shall see below, this tends to reduce the perceptibility of display flicker.

Effectively, these display and capture procedures result in rapid sequential activation of an array of spatially discrete white (or coloured) light sources distributed across the television screen. Moreover, because the phosphorescent compounds emit light for a very short time only (i.e., less than 1 ms), these light sources are intermittent temporally. That is, each light source is "on" for less than 1 ms every 33 ms (the period between successive frames).

Given this intermittent source of stimulation, how do we manage to see television images that appear to be continuous both spatially and temporally? That is, why do we not see alternating, interleaved arrays of spatially discrete, sequentially activated light sources which are "turned on" for 1 ms 30 times per second? If the human visual system perceived the physical reality accurately, a spatially and temporally discontinuous perception is precisely what one would expect. However, several sources of "inaccuracy" in human visual perception permit the artificial television affordances to simulate the real scene adequately.

First, the spatially discrete nature of the display tends to be missed due to imperfect <u>spatial</u> resolution in the human visual system. That is, discrete elements must be separated to some extent before they are seen as such. And, second, sequential activation within fields and the temporally discrete nature of frame - field display tend to be missed due to imperfect <u>temporal</u> resolution in the human visual system.

The spatial resolving capacity of the human visual system is beyond the scope of this review and will not be discussed further (the interested reader is invited to consult such sources as Kling & Riggs, 1971). Instead, we examine the question of temporal resolution and, in particular, the question of why frame-field display works as successfully as it does.

Consider again the individual light source in the display. It is "turned on" for less than 1 ms at the frame rate of 30 times per second. Why it is not seen as such?

It has been shown conclusively (e.g., Coltheart, 1980) that the effects of a brief light source persist in the human visual system well beyond the actual physical duration of the source itself. Called visible persistence, this phenomenon results in continued availability of brief or intermittent visual information. Thus, although light sources in the television display are activated very briefly, they appear to the human visual system to last much longer and, given appropriate display rates within fields, and appropriate frame and field rates, the light sources appear to co-exist temporally.

Visible persistence, however, does not last indefinitely. If this were the case, a scene would be exceedingly difficult to perceive whether directly or on television. Even if no change in the observer's body, head, or eye position were permitted, objects newly added to the scene would appear "multi-exposed" with (or superimposed on) objects that previously occupied that spatial position. By the same token, objects moving through the scene would appear at multiple locations, leaving a trail (or smear) of old images. This issue is discussed at length below.

Clearly, current television practice works because it is well matched to the pace and characteristics of the human visual system. However, there is now widespread interest in improving on the current generation of television technology. In the process, most of the significant parameters of current displays may be changed. As the impending changes in engineering and design draw closer, it is well to examine the likely implication of such changes for the human viewer. At this stage, the crucial question must be asked: How will the proposed changes affect the quality of the simulation provided by the television system?

To answer this question, we must re-examine and explore more fully the visual mechanisms that support the television simulation. In the present review, we explore the phenomenon of visible persistence. In so doing, we examine the methods by which it is demonstrated and explanations of how it is accomplished. Further, we explore the notions of how long it endures under different viewing conditions and, in particular, notions of how it is suppressed, and how "multiple exposure" and motion smear are avoided.

Of necessity, examination of other visual mechanisms just as important to the television simulation will have to be omitted from this work. These include mechanisms that underlie perception of brightness, contrast, contour and, most notably, the mechanisms that enable the human visual system to perceive smooth coherent motion when the physical display consists of discrete stimuli sampled intermittently as in television and cinematography. At present, there is no generally accepted theory of how the visual system reconstructs smooth coherent motion from sequential discrete stimuli. But there is much work currently underway in this field (e.g., Adelson & Bergen, 1984; Burt & Sperling, 1981; Fahle & Poggio, 1984; Van Senten & Sperling, 1985; Watson & Ahumada, 1985). The general approach is to translate the problem to the spatio-temporal frequency domain where appropriate Fourier analyses can be performed. In the Fourier domain, a series of discrete points displayed sequentially at closely spaced positions can be regarded as a time-sampled version of a corresponding point in real coherent motion. Application of the sampling theorem (e.g., Bracewell, 1965) shows that the two types of display (sampled and continuous) have identical fundamental Fourier components, but differ in that the sampled display has many harmonic components. This theory holds that sampled and continuous displays (i.e., apparent and real motion) become indistinguishable when the frequency of all harmonics in the spectrum of the sampled display exceeds the resolving power of the visual system. Although much psychophysical verification remains to be done, this approach has developed rapidly over the last few years, and offers strong prospects of providing a useful theory of real and apparent motion.

1.2 Visible persistence and its suppression

As mentioned above, it is well known that a brief display produces a visual sensation whose duration far exceeds that of the inducing stimulus. Suppose, for example, that a single point of light is displayed for one ms on the face of an oscilloscope equipped with fast-fading phosphor so that radiation of light from the screen terminates virtually as soon as the oscilloscope's beam is turned off. Under a reasonably wide range of viewing conditions, the image of the 1-ms dot will appear to last at least one hundred times longer. Such prolonged perceptual availability of brief visual stimuli is known as *visible persistence*.

Most estimates of the duration of visible persistence are in the range of 100-150 ms. Longer durations have been reported but, as is explained below, it is likely that these estimates may encompass a later stage of perceptual processing during which the internal representation of the stimulus is no longer strictly visible.

Visible persistence or, equivalently, the fact that the human visual system has a low temporal frequency response, has been utilized in a variety of technical applications such as AC lighting, video displays, and television. For example, a point plotted on a television screen equipped with P4 (a phosphor commonly used in black-and-white video monitors) decays to less than 1% of maximum relative brightness in less than 1 ms under typical operating conditions (Bell, 1970). At current raster-scan rates, a point on the screen would radiate visible light for less than 1 ms, and then remain totally dark for over 30 ms before being intensified again at the next scan. If our visual system had a high temporal response, perception of a whole scene on a video monitor would be impossible; instead, a single point would be seen, varying in intensity while moving rapidly across the screen.

Although undeniably useful in bridging temporal gaps produced by intermittent sources of stimulation, visible persistence creates a problem for the perception of objects in motion. As the image of a moving object sweeps across the retina, it stimulates a series of successive locations. Were visible persistence to last 100-150 ms at each location, the moving object would be seen as trailing a wake of smear. For example, imagine a car travelling at 60 km/h, viewed at a distance of, say, 20 m. In 150 ms, the car will have travelled 2.5 m, a distance of over half its own length. Given these premises, a viewer should see a blurred image of the car with a trailing smear of 2.5 m. In actual fact, the viewer is likely to see a relatively sharp image with no trailing smear. An equivalent example would be to replace the observer's eye with a camera whose shutter is left open for 150 ms. The resulting photograph would reveal precisely the type of motion smear described above.

How does the human visual system avoid the smear that is unavoidable to the camera? Eye movements come immediately to mind, yet it cannot be that the eye avoids smear simply by tracking the moving object. Just imagine two cars travelling in opposite directions, crossing in the field of view: neither car is seen dragging a trail of smear, yet the eyes cannot track both cars simultaneously.

It is the purpose of the present review to examine the empirical work that has been done on the problem of suppression of visible persistence and to evaluate the theoretical explanations that have been proposed for the empirical findings. The major emphasis of the review is on the suppression of smear (or, equivalently, suppression of visible persistence) of objects in stroboscopic motion, as seen on an oscilloscopic screen or video monitor.

By far the richest source of evidence concerning suppression of visible persistence has been obtained with a paradigm, known as metacontrast, in which a sequence of only two stimuli is employed. In metacontrast, perception of a temporally leading stimulus is suppressed by a second stimulus displayed nearby and soon after. Clearly, metacontrast suppression is of direct relevance to the purpose of the present work, hence the principal findings and theories in the metacontrast literature are reviewed before examining suppression of smear in stroboscopic displays containing trains of multiple stimuli.

In broad outline, the review begins with a description of the salient empirical and conceptual work done on visible persistence, so as to provide an adequate background for approaching the work on suppression. Metacontrast is examined next, followed by suppression of smear under conditions of coherent stroboscopic motion. Recent developments are then examined in which suppression of smear is regarded as an outcome of spatio-temporal <u>summation</u> in sequential stroboscopic displays. Finally, a suggestion is made that the major theoretical approaches are not necessarily incompatible and could profitably be brought within an integrated conceptual framework.

Throughout the review, the major aim is not to present an exhaustive compendium of the work done in this area; rather, a deliberate attempt is made to abstract the major theoretical trends and to examine them in terms of empirical support and conceptual usefulness. In brief, the present work is aimed at describing and evaluating a set of ideas, rather than presenting a comprehensive annotated bibliography.

2. VISIBLE PERSISTENCE

2.1 Visible persistence as distinct from retinal afterimages

At the outset, it is necessary to draw a distinction between visible persistence and retinal afterimages. The latter typically last for substantial durations (measured in seconds or minutes), and require inducing stimuli of relatively high intensity. By contrast, visible persistence is brief (probably no longer than 200 ms, at most), and is most pronounced with stimuli of relatively low luminance; indeed, most studies of visible persistence have employed stimulus luminances no greater than 1000 Td, comparable to that of a moderately-to-dimly-lit room (Coltheart, 1980).

Two experimental operations distinguish most sharply visible persistence from retinal afterimages: variation in stimulus intensity, and variations in stimulus duration. If the intensity of the inducing stimulus is varied within a range below the level at which retinal afterimages are generated, the duration of visible persistence is _inversely_ related to the luminance of the stimulus (e.g., Allport, 1968; Bowen, Pola, & Matin, 1974; Pease & Sticht, 1965). This is known as the _inverse intensity effect_ (Coltheart, 1980). By contrast, the duration of retinal afterimages is _directly_ related to the intensity of the inducing stimulus (Brown, 1965). Variations in stimulus duration produce a similar dissociation: for stimulus durations up to about 100 ms, duration of visible persistence is _inversely_ related to duration of inducing stimulus (Allport, 1968; Bowen et al., 1974; Di Lollo, 1980; Efron, 1970a). This is known as the _inverse duration effect_. Duration of retinal afterimages, on the other hand, is directly related to stimulus duration (Brown, 1965).

The present review is concerned exclusively with visible persistence and its suppression. Retinal afterimages lie outside the scope of the present work.

2.2 Visible persistence: Methods and findings

Coltheart (1980) has examined methods and findings of visible persistence in a comprehensive review, to which the reader is referred for detailed treatment of specific topics. Here, methods and findings are presented in summary form, though in detail sufficient to provide an adequate background to the work on suppression.

Before discussing the methods that have been employed to study visible persistence, it is well to distinguish between two fundamental concepts pertaining to the temporal relationship between successive stimuli. The two concepts are inter-stimulus interval (ISI) and stimulus-onset asynchrony (SOA). It is often the case that duration of visible persistence is estimated by displaying two brief successive stimuli, separated by a variable temporal gap during which the display surface remains blank. The two stimuli are meaningless when seen separately, but form a meaningful configuration when seen simultaneously or when perceptually integrated with each other. Perceptual integration of the two stimuli across a temporal gap requires that sufficient visible persistence from the first stimulus be available to bridge the gap. In turn, duration of visible persistence can be estimated by varying the duration of the temporal gap and noting the duration at which the two portions of the display cease to be seen as a meaningful, temporally integrated unit and become a two-part sequence of meaningless stimuli.

The temporal separation between the two portions of the display can be expressed either in terms of ISI or SOA. When expressed in terms of ISI, the temporal interval refers to the time that elapses between the <u>termination</u> of the first stimulus and the <u>onset</u> of the second. In other words, the ISI refers to the actual duration of the temporal gap. On the other hand, when expressed in terms of SOA, the temporal interval refers to the time that elapses between the <u>onset</u> of the first stimulus and the <u>onset</u> of the second. Whether or not the temporal interval between the two onsets (i.e., the SOA) is filled by the continued presence of the first stimulus, or whether it includes a stimulus-free period, is not a matter of importance for this measure.

At very short durations of the first stimulus (e.g., 1 ms), the two measures are virtually equivalent; at longer stimulus durations (e.g., 100 ms), however, the two differ substantially. Whether one or the other measure is employed may have significant theoretical implications, as is discussed at greater length later in this review. To anticipate slightly, to employ ISI as a measure of visible persistence implies an underlying theoretical conviction that visible persistence begins at the <u>termination</u> of a stimulus, and continues for the duration of the critical ISI. On the contrary, by employing SOA as a measure, the assumption is made that the <u>onset</u> of a stimulus is a critical determinant of persistence, and that stimulus duration is a less prominent, or totally unimportant consideration. More specifically -- and as discussed in greater detail later in this review -- SOA measures are employed within conceptual frameworks that consider visible persistence to be a neural process that begins at the onset of a stimulus, and runs its natural course for a duration that is independent of the duration of the stimulus. In this context, visible persistence can exist even while the stimulus is on view; what is more, it can terminate before the stimulus itself terminates, thus giving rise to a condition wherein no persistence is available upon termination of the inducing stimulus. As we shall see later in this review, strong neurophysiological evidence of just this type of process, time-locked to the onset of a stimulus has been recently reported (Duysens, Orban, Cremieux, and Maes, 1985).

Five major methods, plus some variants, have been employed to study visible persistence and the factors that affect its duration. The five methods are surveyed below, in turn.

2.2.1 Phenomenal continuity

This method is probably the most obvious intuitively, and is best described by example. Suppose that an observer fixates a screen on which a small cross is projected for 10 ms every 100 ms (i.e., the screen contains the cross for 10 ms, and remains blank for the ensuing 90 ms; the cross is then shown again, and so on indefinitely). The observer is required to adjust the duration of the blank interval to a level at which the cross is just seen continuously on the screen. That is, if the blank interval were to be increased by even a small amount, the cross would be seen to disappear between successive projections.

What this method seeks to establish is not the critical fusion frequency (CFF), i.e., the duration of the blank interval at which the cross is seen steadily on the screen without any flicker. Rather, what is sought is the longest blank interval at which the cross can still be seen continuously, however dim, despite the obvious flicker in the display.

The duration of the blank interval, as set by the observer, is then taken to be an estimate of the duration of visible persistence under the given experimental conditions.

Studies of visible persistence have employed this method in a variety of situations (e.g., Adelson, 1978; Bowen, Pola, & Matin, 1974; Haber & Standing, 1969; Meyer, 1977; Meyer, Lawson & Cohen, 1975; Meyer & Maguire, 1977). The major outcomes of these studies have confirmed the inverse duration and the inverse intensity effects. In addition, the studies of Meyer and associates uncovered a strong relationship between duration of visible persistence and spatial-frequency composition of the inducing stimulus: visible persistence was briefest at the low spatial frequencies and longest at the high spatial frequencies.

Despite its intuitive appeal, this method suffers from two drawbacks:

a) Criterion effects. It is known that the onset of an inducing stimulus (in our case, the cross on the screen) produces a rapid increment in the level of activity within the visual system, followed by a much more gradual return to the baseline. The change in level of activity over time is known as the impulse response function (e.g., Roufs & Blommaert, 1981). Whether or not the impulse response function is at the basis of visible persistence, it can be employed as an analogy to illustrate the point being made here: as the visible persistence produced by a stimulus begins to fade, a stage will be reached at which an observer will decide that the image is no longer visible. However, the level of image visibility at which that decision is made will be strongly influenced by the observer's criterion: an observer with a "conservative" criterion will wait until there is absolute certainty that the image has totally vanished from the visual system before admitting as much. This would tend to yield long estimates of the duration of visible persistence. At the other extreme, an observer with a "liberal" criterion would declare an image to be totally faded much earlier in the decay process, thus yielding shorter estimates of persistence. The pervasiveness and significant consequences of criterion effects in psychophysical judgment have been considered at length in the work on Theory of Signal Detectability (e.g., Green & Swets, 1966).

Estimates of duration of visible persistence obtained with the method of phenomenal continuity are subject to response criterion effects. Estimates obtained with this method tend to be relatively long: some are in excess of 400 ms (e.g., Haber & Standing, 1969), although others are much shorter. The problem with accepting the validity of any of these estimates is that we don't know to what extent they were due to different experimental conditions (an interesting and potentially useful finding) or to different response criteria induced by different instructions or task demands.

b) Basis of judgment. There is little doubt that a visible representation of a brief display (i.e., visible persistence) remains perceptually available for a short time after stimulus termination. There is also little doubt that some form of detailed yet nonvisible representation lingers for a brief interval thereafter. This is a form of literal, though not visible, short-term memory capable of maintaining moderately detailed spatial and figural characteristics of the display for a few hundred ms. It is usually referred to as "schematic persistence" (e.g., Di Lollo, 1983; Phillips, 1974; Turvey, 1978) although the term "iconic memory" has also been employed in a specialized sense (Coltheart, 1980). The clearest, albeit subjective, distinction between visible and schematic persistence can be given as follows: while visible persistence maintains a sensory representation of the display that is, in all respects, indistinguishable from that produced while the physical stimulus was present, schematic persistence maintains a mnemonic representation that is not phenomenologically visible but that still contains many more details of the display than would be contained in later types of memory representation such as short-term memory. Operationally, visible persistence can be distinguished from schematic persistence on the basis of whether or not fine spatial alignment can be performed between details of two successive displays: such alignment can be performed on the basis of visible, but not of schematic, persistence.

It has been cogently argued (e.g., Coltheart, 1980; Di Lollo, 1983; Turvey, 1978) that observers making judgments of phenomenal continuity cannot always separate visible from schematic persistence and may, in fact, base their judgments on the combined durations of the two processes. This suggestion is in line with the remarkably long estimates of almost a half second often obtained with this method. Although it is entirely likely that such estimates include nonvisible as well as visible components of stimulus representations, it is impossible to specify the point at which visible aftereffects terminate and nonvisible ones begin.

As is discussed below, the problems posed by response criterion and by basis of judgment (visible/non-visible) are not limited to the method of phenomenal continuity but, in at least some degree, apply to several other methods as well.

It is clear that these problems invalidate any absolute estimate of the duration of visible persistence; however, relative estimates may remain quite valid. Suppose, for example, that an observer is required to make phenomenal continuity judgments of targets varying in luminance (e.g., high or low luminance), and that it is found that, say, the low luminance targets yield longer persistence. Even though the actual estimates of persistence may be vitiated by criterion considerations, the finding of relatively longer persistence with dimmer stimuli may well remain credible. However, credibility would depend on the assumption that the response criterion and the basis of judgment (visible vs. schematic persistence) remained unchanged in all conditions of the experiment.

2.2.2 Subtractive reaction time.

As is implicit in its name, this technique employs reaction time (RT) as the basis for measurement. First, an observer is required to respond (say, to press a button) as quickly as possible after the onset of a visual stimulus (say, our cross on the screen). The RT is duly recorded. Next, the RT of the same observer is measured to the termination of the stimulus. Let us now subtract the onset RT from the termination RT. If the temporal responses of the observer were entirely veridical, and if onset and termination RTs consisted of identical components, it would stand to reason that the two RTs would be approximately the same. On the other hand, if the stimulus produced any amount of visible persistence, the observer would see it as terminating some time after its actual physical termination, and the termination RT would be correspondingly delayed. Thus, termination RT differences in excess of onset RTs may be taken as estimates of the duration of visible persistence.

Employing this method, Pease and Sticht (1965) confirmed the inverse duration effect. Other experiments that employed this technique to study visible persistence have been reported by Briggs and Kinsbourne (1972) and by Erwin (1976).

Obviously, the subtractive reaction time technique suffers from the same drawbacks as the method of phenomenal continuity, and is open to the same criticisms. In addition, it relies on the plausible but unsubstantiated assumption that RTs made to the onset or to the termination of a stimulus are, in every essential way, identical processes.

However, while clearly unsuitable for obtaining absolute values of visible persistence, subtractive reaction times may still be useful for measuring the relative duration of visible persistence, just as was the case with judgments of phenomenal continuity.

2.2.3 Judgment of synchrony.

Suppose that an observer views a brief display and hears a "click" at about the time the visual display terminates. The observer is given control over the temporal location of the click, and is required to adjust it so that it coincides precisely with the instant the visual stimulus appears to terminate. This is done over successive presentations until the observer is satisfied that he has adjusted the temporal location of the click so that it appears to occur in simultaneity with the instant of subjective termination of the visual stimulus. In this procedure, the click performs the function of a temporal probe. The difference between the time of physical termination of the visual stimulus and the temporal setting of the probe corresponds to the duration of visible persistence. Visual as well as auditory probes have been used.

This technique was first employed by Sperling (1967), and has been used extensively by Bowen, Pola, and Matin (1974), Efron (1970a, 1970b, 1970c) and by Haber and Standing (1970). The inverse duration as well as the inverse intensity effects have been demonstrated with this technique.

A moment's reflection will show that the "Judgment of synchrony" method is open to the same response-criterion effects as the methods described earlier. The basis of judgment on which these estimates are made is also indeterminate. Therefore, the wide range of estimates obtained with this method (from 120 ms to about half second) cannot be regarded as valid absolute estimates. The relative outcomes, however, are less likely to have been affected; thus the inverse duration and intensity effects are probably reliable.

2.2.4 Stroboscopic illumination.

This method has been employed in a variety of ways, and can best be illustrated with reference to a specific study. In a study of visible persistence, Efron and Lee (1971) employed a rotating disk containing a single radial line. The rotating display, located in an otherwise dark room, was illuminated by a stroboscopic flash whose duration was approximately one microsecond. The reasoning behind this method of estimating duration of visible persistence was as follows: Suppose that the rotating radius was illuminated once every 200 ms and that the total duration of visible persistence were only 100 ms (i.e., the visual activity produced by seeing one radial line subsided 100 ms after each stimulation). Under these conditions, the display would assume the form of a stationary single radius appearing briefly for about 100 ms every 200 ms. The radius would disappear between successive flashes and then reappear at the time of the next flash in a location whose angular distance from the previous location depended on the rate of rotation of the disk. Now, suppose that we illuminated the display more frequently, say, once every 20 ms. Because each appearance of the radius would still remain perceptually available for 100 ms before vanishing from view, we would see a group of five radial lines moving together around the disk.

By varying the rate of stroboscopic illumination and by asking the observers to report the number of lines that could be perceived simultaneously at any one time, Efron and Lee (1971) could estimate the duration of visible persistence. Variants of this method have been employed by Allport (1968, 1970), Dixon and Hammond (1972) and by Wade (1974). The sturdy findings of inverse duration and inverse intensity effects were confirmed with this technique.

In general, the estimates of duration of visible persistence obtained with stroboscopic illumination have been in the range of 100-150 ms. Although, in principle, the technique does not have a clearly determined basis of judgment and is still open to response criterion effects, the generally low and consistent estimates that have been reported suggest that the stroboscopic illumination technique is probably less affected than the techniques described earlier.

2.2.5 Integration of form.

Whereas the four methods described thus far depend, in varying degrees, on some form of subjective judgment or estimate on the part of the observer, the method of integration of form relies on performance of a task that can be done only while visible persistence remains perceptually available. No judgment or estimate of visible persistence is required with this method.

An illustrative example of this technique is provided by the work of Hogben and Di Lollo (1974). They employed an oscilloscopic display consisting of a square matrix of 25 dots arranged in five rows and columns. One of the 25 dots, chosen randomly on every trial, was not plotted. The observer's task was to name the coordinates of the missing dot within the matrix. To study visible persistence, the matrix was displayed in two portions of 12 dots each, separated by a temporal gap (inter-stimulus interval; ISI). The two sets of dots appeared to be unstructured when viewed separately but, when temporally integrated, they were seen as a 5x5 matrix with one missing element.

The task of identifying the location of the missing dot can be performed successfully only if all other elements of the matrix are visible simultaneously. Indeed, if the two portions of the display are not seen as simultaneous (or temporally overlapping), the display is perceived as two independent and successive aggregates of dots, each with 13 missing elements. Successful performance at this task requires the kind of fine spatial alignment that is possible only if all elements of the display are visible simultaneously (see Section 2.2.1.b). In turn, simultaneous visibility requires some form of visible persistence capable of bridging the temporal gap between the two successive portions of the display. Estimates of the duration of visible persistence can be obtained by increasing the ISI until temporal integration of the two successive displays is no longer possible. As may be expected, temporal integration is achieved easily at brief durations of ISI, but is virtually impossible at longer durations.

Estimates of duration of visible persistence obtained with this method are in the range of 100-150 ms (Di Lollo, 1977, 1980; Eriksen & Collins, 1967, 1968; Hogben & Di Lollo, 1974). Although the intensity effects have not been systematically investigated with this paradigm, a strong inverse duration effect has been reported (Di Lollo, 1980).

It must be stressed that, since no subjective judgments or estimates are required, the method of integration of form is free from response criterion effects. Also, since the task cannot be performed unless a visible representation of the temporally leading display is available, the technique can be regarded as yielding a valid measure of visible--as distinct from schematic (nonvisible)--persistence.

2.3 Principal empirical findings

Four main findings and some subsidiary findings have emerged from the empirical work on visible persistence.

2.3.1 The inverse duration effect

Regardless of the method employed, it has been found that duration of visible persistence is negatively related to the duration of the inducing stimulus. In addition, there are strong indications (e.g., Efron, 1970a; Di Lollo, 1980) that duration of inducing stimulus and duration of visible persistence stand in a reciprocal relationship such that the two always add up to a constant, estimated at about 100-150 ms. For example, adopting the longer estimate, a 10-ms stimulus will generate persistence lasting 140 ms; but a 130-ms stimulus will persist for only 20 ms.

Clearly, the reciprocal relationship applies to stimuli not exceeding the critical duration of 100-150 ms. What happens with stimuli exceeding the critical duration is not clearly understood. Some studies (e.g., Efron, 1970a; Haber & Standing, 1970) report an irreducible minimum of persistence (50-100 ms) regardless of stimulus duration; others (e.g., Di Lollo, 1980; Efron, 1970c) report that stimuli exceeding the critical duration produce no persistence at all. The crucial variables underlying these discrepant findings have not as yet been identified.

2.3.2 The inverse intensity effect

A second robust finding is a negative relationship between intensity of stimulation and duration of persistence. This appears to be true both in respect to intensity of the stimulus itself (e.g., Allport, 1970; Dixon & Hammond, 1972; Efron & Lee, 1971), and in respect to the background on which the stimulus is presented (e.g., Haber & Standing, 1970). This pattern of results seems to implicate level of contrast in the display as a salient variable. However the different methodologies and designs employed in these studies do not permit a direct assessment of the effect of contrast *per se*. This is obviously a promising area for further research.

It is important to note that the inverse effect is obtained only at intensity levels that are below that at which retinal afterimages are formed. At intensities higher than the critical level, the duration of the visual aftereffect is *directly* related to the intensity of the stimulus, as would be expected on the basis of what we know of retinal afterimages (e.g., Brown, 1965). Significantly, the only exceptions to the inverse intensity effect were obtained in studies that employed high-intensity stimuli and dark-adapted observers (e.g., Sakitt, 1976; Sakitt & Long, 1978). It is commonly agreed (e.g., Adelson & Jonides, 1980; Coltheart, 1980) that such studies estimated the duration, not of visible persistence, but of retinal afterimages.

2.3.3 Spatial frequency effects

Studies in which the spatial-frequency contents of the inducing stimulus were varied have shown that high spatial frequencies produce longer visible persistence than do low spatial frequencies. This finding was first reported by Meyer and Maguire (1977) who employed the method of phenomenal continuity, and has been confirmed in subsequent investigations in which other techniques were employed (Badcock & Lovegrove, 1981; Bowling, Lovegroove, & Mapperson, 1979; Di Lollo & Woods, 1981; Lovegrove & Meyer, 1984). In addition, evidence has been reported (e.g., Bowling & Lovegrove, 1981; Ueno, 1983) that duration of visible persistence is affected by the orientation of sine-wave gratings: persistence is longer for oblique than for vertical gratings.

Since stimulus attributes such as spatial frequency and orientation are not processed at levels more peripheral than the cortical projection areas (Hubel & Wiesel, 1977), the outcome of these studies strongly suggests a central component to visible persistence, perhaps in addition to more peripheral components.

2.3.4 Laterality effects

It seems well established that duration of visible persistence is the same in the two cerebral hemispheres. Using the integration-of-form technique, Hogben and Di Lollo (1974) showed that temporal integration of a matrix whose elements are displayed in rapid temporal sequence can be achieved easily, provided that all dots are plotted within a critical temporal interval. In a subsequent study on lateralization, Di Lollo (1981) showed that the duration of the critical interval is the same whether the stimuli are displayed in the left visual field or in the right visual field. These results suggest that duration of visible persistence is the same in both hemispheres. Evidence consistent with this conclusion has been reported by Erwin and Nebes (1976) and by Marzi, Di Stefano, Tassinari, and Crea (1979).

It must be stressed that the finding of hemispheric symmetry is limited to visible as distinct from nonvisible "schematic" persistence (see Section 2.2.1b). Indeed, strong laterality effects have been reported with respect to schematic persistence under experimental conditions that involved semantic and higher-order processes (Erwin & Nebes, 1976; Marzi, et al., 1979).

2.3.5 Subsidiary findings

The empirical findings reported above can be regarded as generally accepted, stable outcomes in the experimental literature. In addition to these, there are other findings that deserve mention even though the empirical support is not as broad, or the findings themselves are controversial.

2.3.5a Foveal vs. parafoveal persistence. In a study to be discussed in greater detail later in this review (Section 4.2), Di Lollo and Hogben (1985) found that duration of visible persistence increases significantly with increasing eccentricity of the display. As the eccentricity of the inducing stimulus was increased from 0.4° to 1.6° from the central fovea, duration of persistence increased from about 120 to about 150 ms. This result is consistent with Adelson's (1978) finding that stimulation of the rods (whose density increases rapidly with distance from the fovea) produces longer persistence than stimulation of the cones.

On the other hand, the opposite pattern of results has also been reported (e.g., Di Lollo, 1981).

At this point, little more can be done than to acknowledge the discrepancy in results. The studies differed in many respects, including types of stimuli employed, levels of light adaptation, and experimental paradigm. What is clearly needed is a broad approach in which observer variables as well as stimulus variables are systematically investigated.

2.3.5b Effect of chromatic stimuli. There is little doubt that coloured stimuli produce chromatic visible persistence of duration comparable to that of achromatic stimuli (Mollon, 1969, cited by Coltheart, 1980; Yund, Morgan, & Efron, 1983). Whether duration of persistence is actually the same at all wavelengths is less clear. For example, Mollon (1969, cited by Coltheart, 1980) found that a stroboscopically moving red light produced longer persistence than a blue light. This finding, however, cannot be taken as evidence for a differential effect of wavelength because the chromatic stimuli had not been matched for intensity. Hence, on the assumption that the red light might have been dimmer, the experimental outcome could be interpreted in terms of the inverse intensity effect (see Section 2.3.2).

2.4 Theoretical speculations

Accounts of visible persistence can be subsumed under two major rubrics: the storage hypothesis (e.g., Sakitt, 1975, 1976; Sperling, 1960) and the processing hypothesis (e.g., Di Lollo, 1980).

2.4.1 The storage hypothesis

First proposed by Sperling (1960), the storage hypothesis identifies visible persistence with the contents of a short-lived sensory store. A brief visual stimulus is said to charge a sensory store which then discharges rapidly following the termination of the external stimulus. The strength of the visible representation of the display is said to depend on the state of charge of the store: a vivid representation is available immediately after stimulus termination (when the store is full), but the representation fades rapidly as the store discharges over time. In essence, the sensory store resembles a simple resistance - capacitance circuit to which it has been explicitly compared (Sperling, 1970). Upon application of a voltage (i.e., upon stimulus presentation) the capacitor is charged. When the voltage source is turned off (i.e., when the stimulus is terminated) the capacitor releases its charge, thus maintaining a short-lived period of electrical activity in the circuit after the charging agent has been turned off.

In a more recent version of the storage hypothesis, Sakitt (1975, 1976) identified the locus of storage with the retinal photoreceptors, particularly the rod photoreceptors. It is known that the output of the rods increases with retinal illumination up to about 3 log Td. At that point, rod output is at its maximum, and further increments in retinal illumination result in rod hypersaturation. When that happens, the phenomenon of rod afterdischarge is obtained. Namely, the rods continue discharging for some time after the external stimulus has been turned off, duration of afterdischarge being directly related to the intensity of the inducing stimulus. Visible persistence is thus identified with photoreceptor (mainly rod) afterdischarge.

Despite its intuitive appeal, the storage hypothesis fares poorly in accounting for the empirical findings. Indeed, all versions of this hypothesis are flatly contradicted by the inverse intensity and inverse duration effects. It is difficult to conceive of a store whose contents diminish as we lengthen the duration of charge. And it is similarly difficult to conceive of a store whose contents diminish as we increase the strength of the charging agent. Sakitt's hypothesis is further weakened by the fact that virtually all studies of visible persistence were performed at levels of retinal illuminance well below 3 log Td, levels at which no rod afterdischarge takes place (e.g., Aguilar & Styles, 1954). In addition, the finding that duration of visible persistence depends upon the spatial-frequency contents and the orientation of the display (see Section 2.3.3) all but rules out the retina as the sole locus of visible persistence.

2.4.2 The processing hypothesis

First proposed by Di Lollo (1977, 1980; Di Lollo & Bourassa, 1983), the processing hypothesis regards visible persistence as an outcome of activity at early stages of visual information processing. Persistence begins at the same time as the early processing activity, and continues until activity at that processing phase terminates. According to this hypothesis, duration of persistence is time-locked to the onset of the inducing stimulus and is unaffected by either stimulus duration or termination. Rather, once started by the onset of a new stimulus, visible persistence endures to the end of the critical interval whether or not the inducing stimulus remains on view.

This hypothesis accounts well for the inverse duration effect because, as noted above, persistence is time-locked to stimulus onset. Thus, brief stimuli will appear to generate long persistence because the processing activity on which persistence is based will far outlast the termination of the stimulus. By contrast, stimuli of long duration will appear to generate no persistence at all because all activity in the early processing phase (and hence persistence) will have subsided before stimulus termination. This interpretation of the inverse duration effect received strong confirmation in a recent neurophysiological study by Duysens, Orban, Cremieux, and Maes (1985). Single-cell recordings of activity in the visual cortex of the cat revealed precisely the onset-dependent pattern of activity described above as a function of stimulus duration.

The inverse intensity effect is handled less directly but not inconsistently. It is known that more intense stimuli produce shorter system response latencies (e.g., Fehmi, Adkin, & Lindsley, 1969) and are processed more rapidly (e.g., Schiller, 1965, 1968) than dimmer stimuli. In terms of the processing hypothesis, this would correspond to shorter persistence for the brighter stimuli.

Finally, since the processing hypothesis is not limited to retinal events, it has no difficulty in encompassing such evidence of cortical involvement as the finding that duration of visible persistence is influenced by configurational aspects of the display (Section 2.3.3).

2.5 Concluding remarks

Having reviewed the salient empirical and conceptual work on visible persistence, the question asked at the beginning of the present review must be asked again: if visible persistence lasts 100 ms, why is the world not blurred?

Although smear is undeniably present under some conditions of viewing (e.g., with high-velocity stimuli), it is notably absent or much reduced under a wide variety of viewing conditions in which persistence-based smear should be expected. The remainder of the present review is devoted to examining the psychophysical, neurophysiological, and cognitive correlates of suppression of smear (or, equivalently, suppression of visible persistence), and to evaluating and integrating the theoretical accounts that have been proposed for such suppression.

We begin with an examination of metacontrast suppression, a well-studied phenomenon that involves suppression of the visibility of a temporally leading stimulus by a trailing stimulus displayed in close spatio-temporal contiguity.

2.6 Implications for television design

This review began with a suggestion that current television simulations work because they are well matched to the characteristics of the human visual system. The review has concentrated upon the low temporal resolution of the visual system and, in particular, upon one mechanism associated with low temporal resolving power, visible persistence. To pursue possible implications of visible persistence for future television designs, however, it is first necessary to consider some of the dimensions on which future systems may differ from their predecessors.

Many of the parameters of current television are now being considered for change (see, for example, Fujio, 1982). The changes proposed include: raising upper limits to display intensity, raising spatial resolution in image capture and display, increasing the size of the display screen, and changing the temporal characteristics of frame and field presentations.

It is well established that the duration of visible persistence decreases with display intensity (the inverse intensity effect, Section 2.3.1). Thus, persistence for the more intense displays possible if display upper intensity limits were raised would be shorter than that for dimmer displays. The result, then, of raising display limits would be not only to permit short persistence displays but also to increase the range of persistence durations experienced by viewers. Whether such effects would be disruptive to television viewing, of course, is an empirical question and worthy of study. If such disruption were observed, it might be necessary to provide a compensatory increase in frame rate.

It is also well established that persistence duration increases with spatial frequency (Section 2.3.3). Thus, persistence for the higher frequency components permitted by increased spatial resolution in image capture and display would be longer than that for lower frequency components. In consequence, increased spatial resolution would permit not only longer persistence display components but also a greater range to the persistence of display components.

It has been suggested that persistence duration increases with increasing retinal eccentricity of the display (Section 2.3.5a). Thus, substantial increases in the size of the display not only would introduce long persistence regions to the display but also would increase the range of regional persistence durations.

Finally, because visible persistence is a temporally defined phenomenon, any change in the temporal parameters of television would have implications for persistence-based predictions of viewing performance. Thus, very low display rates within fields (i.e., clock rates), between fields, and between frames would stress, and perhaps exceed, the integrative capacity permitted by persistence. However, as these rates are increased, integrative advantage will accrue only to the point at which displays to be integrated fall within the temporal constant of the persistence mechanism. Beyond this point, advantage might accrue in better representation of rapid movement but not in better opportunity for integration of information. It should also be noted that, at very high frame rates, it is possible that inter-frame stimulus energies would summate resulting in greater levels of integrated stimulus energy and, under the inverse intensity effect (Section 2.3.2), reduction in persistence duration. The latter possibility, although speculative, raises the question of whether very high frame rates would, in turn, require still higher rates, resulting in a bandwidth consuming feedback loop.

The foregoing comments outline some of the implications of persistence findings for television design parameters. Although these discussions are speculative, they at least establish that persistence (as defined and measured) is affected by parameters associated with television design factors. It remains to be seen, however, whether proposed design changes do affect the duration of visible persistence and whether such effects have important implications for television viewing.

The discussion thus far has concentrated upon the influence of various aspects of the inducing display upon the estimated duration of visible persistence. It might appear, then, that visible persistence will run a course determined by a constellation of inducing stimulus properties (intensity, duration, etc.). However, it is already well known that persistence to one display will be affected by the properties of subsequent displays. The forthcoming chapter will consider such interactive influences. Clearly, the suggestions for television design proposed here may require amendment in light of the information to which we now turn.

3. METACONTRAST SUPPRESSION

3.1 Introductory remarks

Imagine three short vertical lines displayed briefly on the face of an oscilloscope. For the sake of this example, assume that the height of the lines is 1 deg. of visual angle, their thickness is 5 min, and the inter-line separation is also 5 min. Were the lines to be displayed simultaneously for, say, 1 ms, a normal observer would have no difficulty in seeing them clearly and distinctly.

Let us now display the lines in two successive frames separated by a temporal interval of, say, 50 ms during which the screen remains blank. The sequence is as follows: frame 1, which contains only the central line is shown for 1 ms; the screen then remains blank for 50 ms; finally, frame 2, which contains only the two flanking lines is displayed for 1 ms.

Assuming that each frame generates visible persistence lasting about 150 ms (see Section 2), it would be reasonable to expect that an observer should see a display that begins with a single line for 50 ms, continues with a composite of all three lines for 100 ms, and terminates with the two flanking lines for 50 ms. Instead, what is seen is a single display consisting of *only* the two flanking lines: the central line is not seen. The perceptual suppression of the temporally leading stimulus (the central line, in this case) is known as *metacontrast suppression*. It is the purpose of Section 3 to review methods, findings, and theories of metacontrast suppression.

In the terminology of metacontrast, the temporally leading stimulus is known as the *test stimulus*, and the trailing stimulus as the *masking* stimulus or mask. All metacontrast experiments share two essential features: first, there is no spatial overlay between the contours of test and masking stimuli (overlapping contours bring about masking by pattern, a topic beyond the scope of the present review) and, second, there is always some temporal asynchrony between the onsets of test and masking stimuli; this is known as stimulus-onset asynchrony (SOA).

It must be stressed that the crucial temporal variable in metacontrast suppression is not the duration of the blank period, if any, that elapses between the termination of the test stimulus and the onset of the mask. (The blank period is known as the inter-stimulus interval -- ISI.) Rather, the crucial variable is the SOA, namely the period of time that elapses between the onset of the test stimulus and the onset of the mask, whether or not the test stimulus continues to be on display during that interval. The onset-onset rule has been clearly demonstrated by Kahneman (1967) in a study in which the effects of ISI and SOA were compared directly.

Stimulus-onset asynchrony is also the principal determinant of the time-course of metacontrast. At an SOA of zero (i.e., at simultaneity of onsets), both test and masking stimuli are seen clearly and distinctly (an exception is "Type A" metacontrast, as noted below). As SOA is increased, suppression of the test stimulus increases and reaches a maximum at a value of SOA that varies with experimental conditions and is known as the optimal SOA. Thereafter, as SOA is increased further, degree of suppression decreases until both test and masking stimuli are seen again clearly and distinctly but, of course, in temporal sequence. When plotted as a graph with SOA on the abscissa and some measure of the availability of the test stimulus on the ordinate, the time-course of metacontrast suppression produces a typical "U"-shaped curve peaking at the optimal SOA. This is known as "Type B" metacontrast (Kahneman, 1968) and is by far the most common time-course of suppression.

Occasionally, a different time-course is encountered in which suppression is maximal at an SOA of zero (i.e., at simultaneity of onsets of test and masking stimuli) and decreases rapidly as SOA is increased. This is known as "Type A" metacontrast and is obtained under some conditions, particularly when the energy of the mask far exceeds (e.g., by a factor of ten) that of the test stimulus (e.g., Breitmeyer, 1978; Weisstein, 1972).

In many respects, Type-A metacontrast is akin to, and has a similar temporal course as, masking by light. This is a phenomenon in which perception of a test stimulus of relatively low energy is suppressed by a temporally-trailing field of light of much higher energy (e.g., Schiller, 1965; Turvey, 1973). Masking by light is not a prominent factor in suppression of visible persistence, and lies beyond the scope of the present review. Similarly, only occasional reference will be made to Type-A metacontrast. Unless qualified, the term "metacontrast" will refer to Type-B metacontrast having the "U"-shaped temporal course described above.

The range of values of SOA over which metacontrast suppression is obtained depends upon several stimulus and display parameters discussed below. Similarly, the value of the optimal SOA varies, depending on experimental conditions. Typically, peak metacontrast suppression is obtained at SOAs between 50 and 100 ms, and most of the suppressive effects have abated at SOAs beyond about 150 ms. However, there are cases in which some suppression is still evident at an SOA of 200 ms (e.g., Stoper & Banffy, 1977; Williams & Weisstein, 1984).

A wide variety of stimulus configurations have been employed in metacontrast. Perhaps the most common is a disk-annulus configuration in which the test stimulus consists of a small disk, and the mask is an annulus (a ring) that fits tightly around it. Other configurations have consisted of three adjacent rectangles (much as the three vertical lines in our earlier example), or adjacent alphabetic characters. Although, as noted below (Section 3.4), figural properties of the stimuli can play a role in metacontrast suppression, the crucial variables remain spatial contiguity and rapid succession.

Extensive and relatively recent reviews of the work on metacontrast are available (Breitmeyer & Ganz, 1976; Fox, 1978; Kahneman, 1968; Lefton, 1973; Weisstein, 1972). The present work does not attempt to duplicate them. Rather, an attempt is made at integrating the earlier reviews with the outcomes of more recent experiments, and at evaluating the conceptual schemas that have been proposed to account for metacontrast suppression.

3.2 What is and what is not suppressed in metacontrast

Having said that metacontrast involves perceptual suppression of the test stimulus, we must now qualify that definition. Although it is true that, under some viewing conditions, suppression is total, other viewing conditions may interfere with the perception of some, but not all, stimulus dimensions. For example, the test stimulus may appear dimmer, yet its contours may remain easily detectable. Empirical evidence has been obtained on metacontrast suppression of the following three stimulus dimensions:

3.2.1 Stimulus brightness (e.g., Alpern, 1953; Hogben & Di Lollo, 1984; Growney & Weisstein, 1972; Weisstein, 1972). The brightness of the test stimulus first decreases and then returns to normal as a function of SOA. Note that the term "brightness" refers not to the physical intensity of the stimulus but to the observer's subjective perception of the luminance of the light that is reflected, transmitted or emitted by the test stimulus.

3.2.2 Stimulus contour (e.g., Breitmeyer, Love, & Wepman, 1974; Hogben & Di Lollo, 1984; Westheimer & Hauske, 1975). Resolution of fine details of the contours of the test stimulus follows the typical time-course of metacontrast suppression as a function of SOA. Most suppression of fine detail occurs at the optimal SOA.

3.2.3 Stimulus identity. The prototypical example is a study by Averbach and Coriell (1961) who displayed an array of alphabetic characters one of which was followed in time by a tightly-fitting annulus. The probability of identifying that character followed the time-course of metacontrast: identification was most impaired at the optimal SOA. Congruent results were obtained by Weisstein, Jurkens, and Onderisin (1970).

An important detail, not mentioned so far, must now be highlighted: the display sequences employed in metacontrast are characterized not only by perceptual suppression of the test stimulus but also by a vivid perception of motion between test and masking stimuli. For example, returning to our hypothetical three-line display, metacontrast suppression of the test stimulus (the central line) is invariably accompanied by a strong sensation of motion from the centre outward. The phenomenological appearance of the total display consists of the two flanking lines plus a sensation that the lines had been in motion from a central region and had come to rest in their present location.

Despite severe, or even total, suppression of the brightness, contours, or identity of the test stimulus, the impression of motion remains unaffected. This was first demonstrated by Fehrer and Raab (1962) in a reaction-time experiment in which observers were required to respond to the onset of a test stimulus that was displayed at varying SOAs before the mask. The results showed that RT was unaffected by SOA. Put differently, despite severe suppression of the test stimulus, the impression of motion remained unaffected. What is more, the observers were able to employ the time of onset of apparent motion as a signal for initiating the response on which RT was based. This is a stable result, confirmed in later investigations (e.g., Bernstein, Amundson, & Schurman, 1973; Proctor, Nunn, & Pallos, 1983), and obtained under diverse conditions. The only necessary condition, it seems, is that test and masking stimuli be of approximately equal energies: if the energy of the test stimulus is progressively reduced, the impression of motion diminishes correspondingly until it is lost completely (e.g., Schiller & Smith, 1966). What these results show is that motion may be perceived even though the identity of the moving object may be suppressed. In turn, this points to at least some degree of independent processing of contour and motion information within the visual system. Examples of just such independence have recently been provided by studies in which motion perception was examined in combination with metacontrast suppression of the object in apparent motion (e.g., Stoper & Banffy, 1977; von Grunau, 1981).

3.3 Metacontrast suppression: Allied paradigms

In the examples considered thus far, the test stimulus was either flanked (e.g., three vertical lines) or surrounded (e.g., disk-annulus) by the masking stimulus. However, perceptual suppression of the temporally leading stimulus is not limited to these display configurations. Entirely homologous suppression is obtained when the test stimulus is followed by only one flanking stimulus (an arrangement known as stroboscopic-motion paradigm), or when it is part of a stream of sequential stimuli (a paradigm known as sequential blanking). The two paradigms are outlined below, in turn.

3.3.1 Stroboscopic motion

If a visual stimulus, say a short vertical line, is plotted briefly on the face of an oscilloscope and, after a brief interval (e.g., 50 ms) is re-plotted in an adjacent location (either to the right or to the left), perception of the temporally leading line is suppressed, and the display is seen as a single line in motion. This phenomenon is known as stroboscopic motion.

A correlative classification of suppression in stroboscopic motion and in metacontrast was first proposed by Kahneman (1967). He employed a metacontrast paradigm (test stimulus followed by a mask on both sides) and a stroboscopic paradigm (test stimulus followed by mask on one side only) within a single study. The time-course of suppression as a function of SOA was found to be virtually identical in the two paradigms. This result has been replicated and well documented (e.g., Breitmeyer, Battaglia, &

Weber, 1976; Didner & Sperling, 1980; Hogben & Di Lollo, 1984).

It would be a mistake, however, to regard stroboscopic motion as a causative factor in perceptual suppression (as was suggested by Kahneman, 1967). The main reason is that strong stroboscopic motion can be perceived under conditions in which suppression is totally absent. To wit, if the temporal interval (SOA) or the spatial separation between test stimulus and mask are progressively increased, a point will be reached at which stroboscopic motion between the two stimuli is still clearly perceived, but perception of the test stimulus is totally unimpaired. For example, Breitmeyer and Horman (1981) varied systematically the spatial separation between test and masking stimuli, and found that suppression subsided at much smaller separations than did perception of motion. Indeed, at a separation of 3 deg, at which no suppression was obtained, motion was still clearly perceivable. Similar findings had been obtained in earlier investigations (e.g., Weisstein & Growney, 1969). A causative relationship between motion perception and metacontrast suppression is discredited further by the finding that strong suppression can occur without any perception of motion (e.g., Stoper & Banffy, 1977).

It must be concluded that the mechanisms underlying metacontrast suppression and stroboscopic motion are at least partly independent, although communality may be found under conditions of close spatio-temporal contiguity.

3.3.2 Sequential blanking

This paradigm was first employed by Mayzner and colleagues (e.g., Mayzner & Tresselt, 1970; Newark & Mayzner, 1973). In a typical demonstration, the word CHAIR is flashed on an oscilloscopic screen. The five letters, however, are not displayed simultaneously but sequentially; moreover, each letter is displayed for 20 ms, and there is a 20-ms blank interval before the next letter is displayed. If the order of presentation is from left to right (i.e. if the order is 1 2 3 4 5), or from right to left (i.e. 5 4 3 2 1), the word can be read with ease. However, if the letters in the even positions are displayed first, followed by the letters in the odd positions (i.e. if the order is 3 1 4 2 5), the two letters that are presented first in the sequence are suppressed or blanked, and the display appears to be composed of only three letters: C __ A __ R.

Mayzner and Tresselt (1970) noted that sequential blanking is obtained when the item to be blanked is followed by an adjacent item at an interval of about 100 ms. This temporal contingency places sequential blanking well within the range of optimal SOAs obtained in metacontrast suppression. Although Mayzner and Tresselt's (1970) 100-ms adjacency rule, as well as other rules, have been severely questioned by Mewhort, Hearty, and Powell (1978) on a variety of grounds, the conclusion ultimately reached by Mewhort, Hearty and Powell (1978) was that sequential blanking was nevertheless a metacontrast-type phenomenon.

In view of the very similar spatio-temporal parameters governing suppression in metacontrast as well as in stroboscopic motion and in sequential blanking, it is plausible to adopt the working hypothesis that all three belong to the same class of events.

3.4 Factors affecting metacontrast suppression

As a result of extensive empirical work, a variety of stimulus attributes and display conditions that influence strength of metacontrast suppression have been identified. The major findings are described below.

3.4.1 Intensity of stimuli and background

In general, the greater the intensity of the test and masking stimuli, the greater is the range of SOAs over which suppression takes place, and the longer is the SOA at which peak suppression occurs. This was one of the earliest findings reported by Alpern (1953) in a series of pioneering studies. The magnitude of the effect reported by Alpern was notable: the value of the optimal SOA almost doubled from 75 ms to 125 ms as the luminance of both test and masking stimuli was increased from 0.1 to 3000 ft-L.

The effects of relative intensity of test and masking stimuli have been examined in earlier reviews (e.g., Weisstein, 1972). The compelling conclusion from the available evidence is that if the intensity of the test stimulus is equal to or greater than the intensity of the mask, the temporal course of suppression is a "U"-shaped, Type-B function. That is, suppression is absent at an SOA of zero, peaks at SOAs of 50-100 ms, and is absent again at SOAs beyond about 150 ms. On the other hand, if the intensity of the mask is greater than that of the test stimulus by a factor of two or more, a Type-A function is obtained in which peak masking occurs at an SOA of zero, and suppression decreases monotonically until it subsides at SOAs longer than about 150 ms. Relevant evidence reported since the time of the earlier reviews is entirely consonant with these conclusions (e.g., Breitmeyer, 1978).

It may be noted that this pattern of results supports the suggestion, made in Section 3.1, that Type-A metacontrast is akin to, and perhaps indistinguishable from, backward masking by light. To wit, it is conceivable that, even when the mask has significantly greater energy than the test stimulus, suppression is a "U"-shaped Type-B function of SOA, with the additional effect of masking by light superimposed on the Type-B function at the short SOAs. Indeed, for SOAs longer than the critical SOA, the suppression curves are the same over a broad range of intensities, regardless of whether the test or the masking stimulus has the higher level. However, at SOAs between zero and the optimal SOA, greater suppression is obtained when the mask is more intense, as would be expected if masking by light (which is most severe at an SOA of zero) were to overlay and combine with the underlying Type-B function to yield the observed Type-A curve.

Intensity of the background on which the stimuli are displayed also exerts a powerful influence on the course of suppression. The effect is similar to that of varying the luminance of the stimuli: as the luminance of the background is increased, both the range of SOAs over which suppression occurs and the value of the optimal SOA increase. The effect was first reported by Alpern (1953), and was confirmed in later investigations (e.g., Purcell, Stewart, & Brunner, 1974; Stewart & Purcell, 1974).

Varying the intensities of the stimuli and of the background necessarily produced concomitant changes in the level of contrast in the displays. The methodologies and experimental designs employed in these studies, however, do not permit an unambiguous assessment of the effect of contrast *per se* on the magnitude and course of metacontrast suppression. The critical studies in this area remain to be done.

3.4.2 Chromatic stimuli

Although a considerable amount of work has been done to study the role of stimulus wavelength in metacontrast suppression, and despite the relatively high precision and stability of the psychophysical measurement techniques, a definitive solution to the problem is yet to be achieved.

Initially, it was believed that no inhibitory interactions took place between chromatic and achromatic test and masking stimuli (Alpern, 1965; Alpern & Rushton, 1965). In a similar vein, further research reported no inhibitory interactions amongst blue, green, and red stimuli, corresponding to Stiles' (1939, 1949, 1959) pi1, pi4, and pi5 mechanisms (Alpern, Rushton, & Torii, 1970a, b, c, d).

Beyond their direct implications for the role of wavelength in suppression, these studies have less direct but far more fundamental implications for understanding the inhibitory interactions between rod (achromatic) and cone (chromatic) mechanisms, and between different types of cones (corresponding to Stiles' mechanisms beyond pi-zero). As we shall see in Section 3.5.2, such inter-channel inhibitory interactions are fundamental to one of the most recent and prominent theories of metacontrast suppression (Breitmeyer, 1984; Breitmeyer & Ganz, 1976).

It is not the purpose of the present section to explicate in detail the complex developments that followed Alpern's early work. Suffice it to say that, while not contradicting Alpern's data, more recent work has arrived at a diametrically opposite conclusion regarding inhibitory interactions amongst stimuli of different wavelengths. This was done by expanding the sampling range of salient stimulus parameters (e.g., stimulus size), and by expanding the range of SOAs over which the effects were explored. For example, one of the surprising findings reported by

Foster (1976) was that the optimal SOA with chromatic stimuli could be as high as 300 ms, with notable levels of suppression being recorded at even longer SOAs.

Indeed, with appropriate stimulus parameters, not only has metacontrast suppression been obtained between chromatic and achromatic stimuli (implying rod-cone inhibitory interactions), but suppression was obtained with dichoptic stimuli (test and masking stimuli shown one to each eye, separately) thus suggesting some possible cortical involvement (Foster & Mason, 1977).

Cortical as well as retinal involvement in metacontrast suppression with chromatic stimuli has also been suggested by Yellott and Wandell (1976). In addition, Yellott and Wandell's (1976) results seemed to reconfirm the earlier position (e.g., Alpern, 1965) that no suppression occurs with test and masking stimuli of different wavelengths. However, in their experimental design, Yellott and Wandell confounded the effects of chromatic transients (when switching between colours) and luminance transients (both test and masking stimuli had higher luminance than the background). Unconfounding the two types of transients seems to confirm that suppression is not obtained with test and masking stimuli of different wavelengths unless the display is accompanied by luminance transients (Bowen, Pokorny, & Cacciato, 1977).

The most recent chapter in the saga of chromatic stimulation has been provided in a recent set of two experiments performed by Reeves (1981). The conclusion was that substantial metacontrast suppression can indeed be obtained (optimal SOAs ranged between 80 and 120 ms) with displays differing in chromaticity, even in the absence of luminance transients, provided that the difference in wavelength between test and masking stimuli is sufficiently large. In Reeves' study, the dominant wavelengths of the stimuli were 630, 535, and 470 nm.

If an overall conclusion is to be reached on the basis of this empirical evidence, it must be that metacontrast suppression can probably occur with stimuli of different chromaticity. However, the variables underlying this effect have not as yet been completely identified. A corollary of this conclusion is that rod-cone inhibitory interactions are not ruled out as a basis for metacontrast suppression.

3.4.3 Stimulus orientation and spatial frequency

Until recently, only one, very early experiment had been conducted on the effect of orientation (Werner, 1935). The results, however, were clear-cut: in order for optimal metacontrast suppression to occur, test and masking stimuli must have the same orientation. In Werner's experiment, the test stimulus was a square-wave grating oriented either vertically or horizontally; the mask consisted of a pair of vertical bars displayed at various SOAs on both sides of the test stimulus. While typical metacontrast suppression was obtained with the vertical grating (test and masking stimuli in the same orientation), perception of the horizontal grating was totally unimpaired. This effect is probably related to the more general finding that the level of metacontrast suppression is directly related to the degree of similarity between test and masking stimuli (Fehrer, 1966; Toch, 1956; Uttal, 1970).

Werner's (1935) findings have been confirmed in a recent investigation by Ishizuka and Ichihara (1984) who employed a disk-annulus configuration, each made up of square-wave gratings of either 6.6 or 13.2

cycle/deg. They found that suppression was highest when test and masking stimuli were displayed in the same orientation and diminished considerably when orientations were different.

Ishizuka and Ichihara (1984) also investigated the effects of spatial frequency on suppression and found maximum masking when test stimulus and mask shared the same spatial frequency. This confirmed an earlier report (Rogowitz, 1983) that spatial frequency affected the value of the optimal SOA as well as the severity of suppression, with maximum suppression occurring when the spatial frequencies of test and masking stimuli were the same. It must be noted, however, that the evidence is not in complete agreement on this issue. For example, Growney (1978) found that similarity of spatial frequencies between test and masking stimuli had no effect on metacontrast suppression.

It must be noted that while similarity of orientation of stimuli appears to be crucial to metacontrast suppression, it seems to be of far less consequence to perception of motion. For example, von Grunau (1981) reported clear stroboscopic motion between a vertical and a horizontal line when displayed at the appropriate spatio-temporal relationship. In turn, this speaks to at least some degree of separation between the metacontrast suppression and the stroboscopic motion systems (see Section 3.2).

3.4.4 Spatial separation between test and masking stimuli

Perhaps because it is such a fundamental variable in metacontrast, inter-stimulus separation has been studied extensively (Alpern, 1953; Kolers, 1962). The common finding is that severity of metacontrast suppression diminishes and the value of optimal SOA increases as separation between test and masking stimuli is increased (e.g., Alpern, 1953; Growney, Weisstein, & Cox, 1977; Ishizuka & Ichihara, 1984). However, the magnitude of the effects interacts with retinal eccentricity. At the fovea, suppression is significantly reduced by inter-stimulus separations of just a few minutes of arc, and is virtually eliminated at separations of about half degree (Kolers & Rosner, 1960). By contrast, at eccentricities of only three or four degrees, vigorous suppression is still obtained at inter-stimulus separations as large as 2 deg (Alpern, 1953; Breitmeyer, Rudd, & Dunn, 1981). The effect of eccentricity is discussed further in Section 3.4.6.

3.4.5 Size of stimuli

Investigations of the effect of size of masking stimulus on degree of suppression present a discordant picture. Some studies have reported a direct relationship: as width of the mask is increased, magnitude of suppression increases (e.g., Kao & Dember, 1973; Matteson, 1969). Other studies have reported the opposite relationship: less suppression with masks of greater width (e.g., Schiller & Greenfield, 1969; Sturr & Frumkes, 1968). Although the salient variables have clearly not been identified as yet, there is a possibility, suggested in a study by Growney and Weisstein (1972), that degree of suppression may be a "U"-shaped function of the width of the mask. Growney and Weisstein's results show a rapid increment in degree of suppression as the width of the mask was increased from 1 to 10 min of arc, followed by a gradual decrement as width of mask was increased further. More work is clearly required before this issue can be resolved.

The effect of size of test stimulus on degree of suppression was studied by Bridgeman and Leff (1979). As was the case for inter-stimulus separation (Section 3.4.4), the effect of test-stimulus size varies with retinal eccentricity: at the fovea, increments in stimulus size result in marked decrement in strength of suppression; outside the fovea, variations in stimulus size have far less notable effects. This issue is discussed further in Section 3.4.6, below.

3.4.6 Effect of retinal eccentricity

For some time following Alpern's (1953) seminal work, it was believed that metacontrast suppression occurred in parafoveal but not in foveal locations of the retina (e.g., Kolers & Rosner, 1960). More recently, however, strong suppression of stimuli presented entirely within the fovea has been reported (Lyon, Matteson, & Marx, 1981). The results of Lyon et al. (1981) are consonant with similar findings by Bridgeman and Leff (1979; see Section 3.4.5) and can be explained in terms of an interaction between retinal eccentricity and optimal size of test stimuli for metacontrast suppression. As noted in Section 3.4.5, the optimal stimulus size is much smaller in the fovea than in the periphery. That is to say, stimuli that exceed an angular size of 20-25 min of arc are unlikely to be suppressed in the fovea, but are easily suppressed in the periphery. The early failures to obtain foveal metacontrast suppression can be explained in terms of this effect if it is realized that relatively large test stimuli were employed in these investigations. For example, the diameter of the smallest test stimulus employed by Kolers and Rosner (1960) was over 25 minutes of arc, as compared to Lyon et al.'s (1981) stimuli of 10 min. It stands to reason that, had smaller test stimuli been employed, foveal suppression would have been obtained in the early investigations just as it was in the more recent studies.

Retinal eccentricity is a powerful determinant of suppression not only in respect to stimulus size but also, as noted in Section 3.4.4, in respect to spatial separation between test and masking stimuli. As a rule of thumb, it could be said that large things (i.e., large stimulus sizes; large inter-stimulus separations) in the periphery are functionally equivalent to smaller things in the fovea. How can this effect be explained?

I suggest that at least a partial account may be given in terms of the cortical magnification factor (CMF). The CMF describes the quantitative neuroanatomical relationship that exists between any given place on the retina and the corresponding part of the visual cortex to which it projects. It is known that the amount of area of visual cortex corresponding to any given area of retina decreases as retinal eccentricity increases. In other words, given a retinal patch of constant size, the corresponding area of visual cortex is much larger if the retinal patch happens to be in the fovea than if it is in the periphery. The CMF provides a quantitative index of this relationship. One outcome of the CMF is that two stimuli that are equidistant at various places on the retina do not produce equidistant representations at the corresponding places in the visual cortex. Rather, as mapped on the cortex, they are much further apart when displayed on the fovea than when displayed in the retinal periphery.

The CMF has been employed as a correction factor to account for differences in spatial resolution and in spatial summation that occur as a function of retinal eccentricity (e.g., Johnson & Massof, 1983; Rovamo & Raninen, 1984; Tyler & Silverman, 1983). It can similarly be employed to account for the above-mentioned findings that the suppressive effects of stimulus size and inter-stimulus separation are tied to retinal eccentricity. Take, for example, the case of inter-stimulus separation. As noted in Section 3.4.4, it is known that, under the conditions employed by Kolers & Rosner (1960), an inter-stimulus separation of about half a degree of visual angle yields no suppression at the fovea but strong suppression at the periphery. Now let us consider the inter-stimulus separations as represented in the visual cortex. Owing to the systematic changes introduced by the CMF, a pair of stimuli separated by half deg. on the fovea produces a cortical separation many times greater than that produced by a similarly spaced pair of stimuli displayed in the retinal periphery. Thus, even though the retinal separations are the same, the effective cortical separation is far greater in the case of the foveal stimuli and the degree of suppression is correspondingly smaller.

On the basis of this hypothesis, the suppressive potential of inter-stimulus separation depends on extent of separation not on the retina but on the visual cortex. A similar argument can be made in respect to stimulus size. It must be noted, however, that this hypothesis applies only to spatial variables: in its present form, it has no bearing on the temporal aspects of metacontrast, notably on the fact that optimal SOA is longer in the periphery. It is unlikely that an account of the temporal events can be given in terms of the CMF alone.

A clear prediction made by this hypothesis is that, to the extent to which CMF is a salient factor, the effect of inter-stimulus separation should be the same throughout the retina, provided that the separations at different eccentricities are scaled in terms of the CMF. For example, scaled in terms of the CMF, two stimuli would have far greater separation on the retinal periphery than on the fovea. The cortical separation, however, would be the same and, according to the hypothesis, so should be the degree of metacontrast suppression.

The available data (outlined in this and in the preceding two sections) is generally confirmatory. But a formal test of the hypothesis must await a systematic empirical investigation designed in light of current knowledge of the CMF.

3.4.7 Cognitive factors

The vast majority of studies concerned with metacontrast suppression have examined the effects of variables that may be regarded as "low level". These are variables that are processed early in the chain of information-processing events, and that require little or no attention (e.g., stimulus intensity, orientation, size, wavelength, inter-stimulus separation). One of the consequences of this approach is that the theoretical accounts of metacontrast suppression have been limited to pre-cognitive stages of information processing (see Section 3.5).

Recent investigations, however, have shown that both the strength and the time-course of metacontrast suppression are affected by higher-level variables that must be regarded as requiring at least some degree of cognitive involvement (e.g., Jacobson & Rhinelander, 1978; Merikle, 1977). A series of most telling studies in this field have been reported by Weisstein and her collaborators (e.g., Weisstein, Williams, & Williams, 1979; Williams & Weisstein, 1984). The foundation for this work is the "object superiority effect" which refers to the finding that a line briefly displayed in the context of other lines is identified more accurately if the contextual lines form a meaningful object (of which the test-line is part) than if they form a meaningless aggregate (e.g., Weisstein, Williams, & Harris, 1982). From this finding, Weisstein and her collaborators went on to investigate metacontrast suppression as a function of the object superiority effect. This was done by presenting test line and contextual lines in two successive displays over a range of SOAs. Before the experiment proper, observers were required to rate the composite displays (test plus contextual lines) in terms of how well various spatial configurations conveyed an impression of depth and, separately, in terms of connectedness (i.e., the extent to which the elements in the display tended to coalesce into whole figures instead of being perceived as independent segments).

From these studies (Weisstein, Williams, & Williams, 1979; Williams & Weisstein, 1984) it was found that as the rating of depth increased, strength of metacontrast decreased and optimal suppression occurred later (optimal SOA shifted from about 40 ms to about 140 ms as the depth rating changed from minimum to maximum). Degree of connectedness, on the other hand, affected only the level (not the optimal SOA) of suppression. Suppression was at a maximum when connectedness was least, and at a minimum when connectedness was high.

The powerful effects of such organizational and figural attributes of the display on strength and time-course of suppression clearly implicate some form of cognitive mechanism. This does not mean, however, that metacontrast suppression does not occur at earlier stages of processing. Rather, the overall pattern of results invites the hypothesis that metacontrast suppression probably occurs at several stages in the chain of information-processing. In turn, to be regarded as comprehensive, any theory of metacontrast suppression must be capable of accounting for central (cognitive) as well as for peripheral (sensory) events.

3.5 Theories of metacontrast

3.5.1 Introductory remarks

The crucial phenomenon to be explained in Type-B ("U"-shaped) metacontrast is that maximum suppression occurs not when test and masking stimuli are displayed simultaneously, but when the onset of the mask *follows* the onset of the stimulus by 50-100 ms.

A dozen or more models and hypotheses, differing one from the other in varying degrees, have been proposed since Alpern's (1953) initial attempt. The purpose of the present section is not to provide an exhaustive historical review of all these theories; such pursuit would take us on a lengthy detour that would have only tangential relevance to the focus of the present work, namely suppression of visible persistence. With some exceptions (e.g., Burr, 1984; Kahneman, 1967; Stoper & Banffy, 1977), the theories that have been proposed are variations on a theme of inhibitory interactions between relatively slow excitatory processes and faster inhibitory processes initiated by the onsets of test and masking stimuli. Amongst these theories, one has emerged as being most capable of handling the psychophysical evidence on metacontrast suppression and as being most closely linked to the salient neuroanatomical and neurophysiological evidence. This theory, developed by Breitmeyer and his colleagues (Breitmeyer, 1984; Breitmeyer & Ganz, 1976) is the most recent and best developed exemplar of the inhibitory theories, and has gained wide acceptance amongst researchers in the field. In the present section, Breitmeyer's theory is described and evaluated. Attention is then devoted to a recent hypothesis that regards metacontrast suppression not as the result of inhibition but as the outcome of spatial summation within the visual system (Burr, 1984; Stoper & Banffy, 1977). This is done in anticipation of the discussion of recent views that emphasize the role of summation within spatial and temporal filters in the suppression of visible persistence. The interested reader wishing to pursue in detail the individual hypotheses that have been proposed to account for metacontrast masking is referred to the following: Alpern (1953), Bachmann (1984), Breitmeyer (1984), Breitmeyer and Ganz (1976), Bridgeman (1971), Burr (1984), Eriksen & Hoffman (1963), Ganz (1975), Kahneman (1967), Kolers (1968), Matin (1975), Navon & Purcell (1981), Reeves (1982), Stoper & Banffy (1977), and Weisstein (1968, 1972).

3.5.2 Breitmeyer's transient-sustained inhibitory model

Like other similar models (e.g., Weisstein, Ozog, & Szog, 1975), Breitmeyer's model is based on the general assumptions that visual stimulation produces both excitatory and inhibitory activity, and that inhibitory events have shorter latencies. But before describing the model itself, we should review briefly the neuroanatomical and neurophysiological findings on which it is based. These findings have been recently classified and evaluated by Lennie (1980) in a detailed and comprehensive review.

Of fundamental importance to Breitmeyer's model is Enroth-Cugell and Robson's (1966) first discovery of two classes of visual cells, termed X- and Y-cells. For reasons detailed below, the X-cells have come to be known as sustained cells, and the Y-cells as transient cells. More recently, several sub-classes of X- and Y-cells have been identified (e.g., De Monasterio, 1978a, b), but the overall classification of "sustained" and "transient" has been maintained. Transient and sustained pathways have been studied in infra-human species, including primates, and the outcomes of these studies have been generally confirmed for human vision with psychophysical techniques.

Transient and sustained pathways differ substantially in their spatio-temporal response properties. In the temporal domain, perhaps the most significant difference lies in the way in which the two types of cells respond to stimulation: transient cells respond only to the onset or to the termination of a stimulus. Thus, if a stimulus is on view for, say, two sec., a transient cell will show a burst of activity at the beginning or at the end of the period of stimulation, but activity will remain at baseline level at any other time. This is the principal reason for designating such cells as transient cells. By contrast, the activity of sustained cells departs from baseline at the onset of stimulation, and returns to baseline when the stimulus terminates, hence the designation sustained.

In general, transient pathways have high conduction velocities, short latencies, and are maximally sensitive to high temporal frequencies of stimulation as well as to fast-moving stimuli. By contrast, sustained pathways have low conduction velocities, long latencies, and are maximally sensitive to low temporal frequencies of stimulation as well as to stationary or slow-moving stimuli. The impulse-response functions (i.e., the amount of activity produced within the visual system by a very brief stimulus -- say, 10 ms) of the two channels mirror their different temporal response properties: the impulse response function of transient channels has short latency and brief duration; that of the sustained channels is characterized by longer latency and longer duration. The absolute values of latency and duration vary with other factors, notably background luminance and strength of stimulation (typically, everything is faster in the light), but the relative differences between transient and sustained channels are maintained, except under conditions of total dark adaptation.

Spatially, transient cells have relatively large receptive fields, and are maximally sensitive to low spatial frequencies. Transient channels have been compared to low-pass spatial filters within the visual system. Sustained cells, on the other hand, have smaller receptive fields and are maximally sensitive to higher spatial frequencies. There appear to be not one but several sustained channels, each attuned to different bands of spatial frequencies; in this sense, each sustained channel may be regarded as performing the functions of a band-pass filter within the visual system.

Functionally, a most important distinction between transient and sustained channels pertains to the type of information that is carried. While activity in the transient channels signals the occurrence of a new event and, to some extent, locates that event in space, activity in the sustained channels defines the figural properties, identity, and fine detail of the inducing stimulus. This distinction is consonant with the distinct spatial-frequency tuning of the two types of channels, as described above.

Both transient and sustained channels show strong orientation tuning at cortical levels.

Of greatest relevance to Breitmeyer's model are the inhibitory interactions that occur both within channels and between channels. Within-channel inhibition is the basis for masking when the contours of test-stimulus and mask are spatially overlapping. Inter-channel inhibition, on the other hand, is central to Breitmeyer's account of metacontrast suppression, and requires further elaboration.

It has been known for some time that a burst of activity in the transient channels inhibits or suppresses ongoing activity in the sustained channels, both at the level of the lateral geniculate nucleus (e.g., Singer & Bedworth, 1973) and at cortical levels (e.g., Singer, Tretter, & Cynader, 1975). More recently, the reverse has also been found under special circumstances, but it is transient-on-sustained inhibition that is crucial to an explanation of metacontrast suppression.

Given these premises, Breitmeyer's theory can account not only for metacontrast suppression but for other categories of masking as well (e.g., type-A metacontrast, masking by unpatterned visual noise or by overlapping contours). The account given for metacontrast suppression is almost compellingly simple. Suppose that a brief test stimulus is followed by a masking stimulus 50 ms later. The onset of the test stimulus activates both the transient and the sustained channels. However, while transient activity starts immediately and is over quickly, sustained activity starts later and lasts longer. This is so because of the temporal differences, noted above, between transient and sustained impulse response functions. The onset of the mask also activates both channels, with the transient response having the shorter latency.

Now let us examine the patterns of transient-on sustained inhibition. The transient activity produced by the temporally leading test stimulus is over well before any sustained activity is generated by either stimulus. Next, the sustained activity produced by the test stimulus gets on the way. However, the onset of the mask generates a burst of activity in neighbouring transient pathways, and if this happens while the sustained activity produced by the test stimulus is still ongoing (i.e., if the SOA is appropriate), the transient activity of the mask will inhibit or suppress the sustained activity of the test stimulus, and masking will follow. In this connection, it must be remembered that it is the sustained channels that carry information regarding the figural identity and fine detail of the test stimulus, and that these are the very attributes of the stimulus that are lost or impaired in metacontrast suppression. It must also be noted, however, that phenomenal dimming is the most pronounced consequence of metacontrast suppression; but it is totally unlikely that the dimming is produced by activity in the high spatial-frequency channels. Indeed, this effect could well be related to energy summation in the low frequency channels (see Section 3.5.3).

Transient-on-sustained inhibition can account for a wide range of findings in metacontrast suppression. Breitmeyer (1984) has provided a comprehensive coverage of this topic. For example, the reliable finding that strength of suppression decreases as inter-stimulus separation increases (Section 3.4.4) is explained in terms of the retinotopic organization of columnar structures in the visual cortex (e.g., Hubel & Wiesel, 1977). Inter-channel inhibition is far greater within a given column (which receives input from a small area of retina) than between separate columns. To the extent to which inter-stimulus separation exceeds the retinal area encompassed by a single column, inter-channel inhibition -- and hence metacontrast suppression -- will decrease.

Metacontrast suppression in stroboscopic motion (Section 3.3.1) is handled in precisely the same manner, and so is sequential blanking (Section 3.3.2). The finding that metacontrast suppression is orientation-specific (Section 3.4.3) is expected on the grounds that there are separate orientation-specific pathways within both the transient and the sustained channels (e.g., Stone & Dreher, 1973), and that inhibitory interactions amongst these pathways are also orientation-specific (e.g., Nelson & Frost, 1978). This effect fits nicely with the known columnar organization of the primate visual cortex (Hubel & Wiesel, 1977). Columns containing cells tuned to similar orientations are located close to each other in cortical space; as the orientation-tuning of two columns becomes more dissimilar, the cortical separation between them increases. Presumably, strength of inhibitory interactions also varies with cortical separation.

In a similar vein, the model can account easily for the findings that optical blurring of the masking stimulus (a procedure that removes the high - but not the low - spatial frequencies, and hence does not affect activation of the transient channels) has only minimal effect on strength of suppression (Growney, 1976).

In general, although the model cannot claim to be completely general (for example, it has difficulty in accounting for cognitive effects on suppression -- Section 3.4.7), it has been remarkably successful at encompassing the available empirical evidence within a single conceptual framework, and is currently employed extensively both as an explanatory and as a heuristic device in this area of work.

3.5.3 The spatial summation model

Contrary to the commonly accepted view that some form of inhibition is probably involved in metacontrast suppression, an alternative account has been proposed, couched exclusively in terms of spatio-temporal summation within the visual system. The most explicit statement of this account has been made by Burr (1984), but its roots can be traced back to the Gestalt theory of apparent motion (Koffka, 1935). According to Gestalt theory, there is an isomorphic relationship between the pattern of excitation produced by a stimulus on the retina and the corresponding excitation in the visual cortex. In turn, the pattern of cortical excitation is isomorphic with what is perceived. Two salient properties of cortical excitation are attraction and fusion; that is, the foci of cortical activity produced by two stimuli displayed in close spatio-temporal contiguity are held to attract each other and ultimately fuse into a single area of excitation.

Metacontrast suppression is explained within Gestalt theory in the same terms as apparent motion. That is, given two sequential stimuli displayed next to each other, the temporally leading one (the test stimulus) will be attracted towards the locus of the trailing one (the mask), and will eventually become fused with it, thus leaving no trace of itself in the visual system (metacontrast suppression).

A literal version of the Gestalt account cannot be true for at least two reasons. First, it is known that strong metacontrast suppression can be obtained without any perception of motion (e.g., Stoper & Banffy, 1977); this evidence is contrary to the Gestalt approach which regards metacontrast suppression as contingent upon perception of motion. And, second, no evidence of cortical fields having properties of attraction and fusion has ever been found. However, alternative versions, more closely linked to what is known of the neuroanatomy and neurophysiology of the visual system, may well provide at least a partial explanatory basis for the observed suppression of temporally leading stimuli.

Burr's (1984) model of metacontrast suppression is based on spatial and temporal summation which, thus far, had been investigated only for stationary stimuli (e.g., Barlow, 1958). In a series of elegant experiments, Burr (1981) investigated spatial summation of stimuli in motion. The stimuli consisted of points of light or of sinusoidal gratings of diverse spatial frequencies moving across the face of an oscilloscope. The results of the experiments justified the inference that "there exist visual mechanisms designed both to respond to motion and to pool over time signals from the moving target, thereby rendering it more visible" (Burr, 1981, pp. 322-323). Upon closer inspection, these mechanisms are not unlike the transient-sustained division employed in Breitmeyer's inhibitory model. More specifically, Burr proposes that there are two classes of spatio-temporal channels in vision: a set of "movement-dependent" channels that respond optimally to stimuli of low spatial frequency and high temporal frequency, and a set of "movement-independent" channels that respond optimally to high spatial and low temporal frequencies.

Such a distinction had been drawn before by Tolhurst (1973) who suggested that the movement-dependent channels are responsible for analyzing motion but not pattern, while the motion-independent channels analyze only pattern. Burr (1980, 1981, 1984), on the contrary, maintains that pattern is processed in both classes of channels, the difference being that spatial summation of moving stimuli occurs only in the movement-dependent channels. In a nutshell, Burr maintains that both motion and form are processed within the motion-dependent channels. In these channels, analysis of form is based not only on spatio-temporal summation of contours (which, by itself, would be antithetical to perception of motion), but also on the narrow spatial-frequency tuning of each component channel and on the specific temporal frequency of the channel's natural resonance (acting as a spatio-temporal filter, each channel has an optimal natural resonance).

Metacontrast suppression is explained naturally on this basis. The details of the explanation have been provided by Burr (1984): given that the energy of moving stimuli is summated within the movement-dependent channels, and that the sequence of stimuli in metacontrast displays is the same as the sequence of stimuli in apparent-movement displays, it is to be expected that metacontrast displays would activate the movement-dependent channels which, in turn, would summate the test and masking stimuli thus suppressing perception of the temporally leading test stimulus.

What was explained by Breitmeyer as inter-channel inhibition, is explained by Burr as intra-channel summation. Moreover, Burr states categorically that metacontrast suppression or, equivalently, absence of motion smear ". . . is a direct consequence of the spatiotemporal tuning of motion detectors, and requires no active deblurring process. Inhibition plays a part . . ., but the inhibition serves to sharpen the motion tuning, not eliminate the smear." (Burr, 1984, p. 189).

Just as was the case with the inhibitory models, summation models can account for much of the empirical evidence on metacontrast suppression. The finding that strength of suppression decreases at greater inter-stimulus separations (Section 3.4.4) is expected on the grounds that, to be summated, two stimuli must fall within the confines of the appropriate receptive field. (Loosely defined, a receptive field is the area of retina from which a cortical neural unit receives its input.) The orientation-specificity of metacontrast suppression (Section 3.4.3) can be explained in terms of the orientation-tuning of the individual channels. That is, test stimuli and masks of different orientations are processed in separate channels tuned to the appropriate orientations, and hence intra-channel summation cannot occur. Also, Growney's (1976) finding that optical blurring of the mask has little effect on suppression is handled by noting that the low-pass filtering introduced by the blurring procedure leaves the low-frequency components of the mask intact, hence summation in the motion-dependent channels (optimally tuned to the low spatial frequencies) can proceed virtually unhampered.

As was the case with the inhibitory models, Burr's summation model cannot account for the role of cognitive factors in metacontrast suppression (Section 3.4.7). In addition, the summation model account for instances of suppression not accompanied by percepti motion (e.g., Stoper & Banffy, 1977). This is so because, unlike inhibitory models, the summation model postulates that the mechanism subserving motion perception and metacontrast suppression is one and the same. Burr (1984) realized this inconsistency but was unable to offer a resolution other than to say that, at times, stimulation of motion detectors may result in summation without motion being observed.

Finally, the summation model is unable to account for the increment in the value of the optimal SOA as the intensity of the stimuli is increased (Section 3.4.1). As was noted above (and as stated by Burr, 1984), by virtue of acting as filters, the movement-dependent channels have a natural resonance or, equivalently, a preferred temporal frequency. With reference to metacontrast, the period of natural resonance defines the SOA at which maximum summation of test and masking stimuli will occur (i.e. it defines the optimal SOA). It is also known (e.g. Van Ness, Koenderink, Nas, & Bouman, 1967) that the natural resonance of these channels is not fixed, but varies as a function of several factors, notably luminance of the displays. More specifically, as luminance is decreased, the preferred temporal frequency also decreases. As a consequence, and as also noted by Burr, the value of the optimal SOA should <u>increase</u> as stimulus intensity is decreased. But the empirical evidence is definitely to the contrary: as stimulus intensity is decreased, the value of the optimal SOA also decreases (Alpern, 1953). In this respect, it is curious to note that Burr (1984, p. 189) misinterprets completely the outcome of Alpern's (1953) experiment (see Section 3.4.1) and cites it as evidence in support of the summation model.

3.6 Metacontrast and visible persistence

Suppression of visible persistence may well be regarded as a primary outcome of metacontrast masking. As was suggested by Alpern (1953) at the conclusion of a seminal series of studies, metacontrast suppression is an effective means of removing the wake of smear that would otherwise be seen as trailing a moving image (see Section 1.2). In a general sense, sharp, unsmeared perception of an object in motion is possible only insofar as the object and its persistence are not visible simultaneously. The importance of the de-smearing function of metacontrast has perhaps been best expressed by Stoper & Banffy (1977, footnote 4) as follows: "We emphasize . . . that in the absence of [metacontrast suppression], the appearance of motion even in real life situations might be substantially degraded. Hence, metacontrast, through 'simultaneity suppression' would serve to prevent multiple imaging of cinema displays and to reduce apparent 'streaking' of continuously moving objects."

3.7 Concluding remarks

Despite the wealth of empirical and conceptual work, metacontrast masking still remains essentially unexplained. Admittedly, we have learned much about the phenomenon, as demonstrated by the wide range of variables that have been identified as having a significant effect on suppression, and by the wide range of conditions under which it occurs. But a comprehensive theory of metacontrast is still an elusive goal.

Thus far, all theories have made the implicit assumption that metacontrast suppression is a unitary phenomenon, subject to explanation in terms of a single set of principles. Perhaps it is time to question this assumption. How likely is it, we may ask, that the attenuation of the brightness of the test stimulus in a disk-annulus configuration is brought about by the same set of underlying mechanisms that protect a line from suppression if it forms part of a meaningful object (Section 3.4.7)?

The wide range of variables and the variety of conditions that affect the strength of suppression invite the hypothesis that metacontrast suppression may not be a unitary effect, but a family of effects having distinct underlying mechanisms that vary depending on the locus within the visual system at which the suppression takes place. Thus, while it is possible that retinal or subcortical mechanisms may play a major role in brightness suppression, a different and far more central mechanism must be sought to account for the effect of cognitive variables. From this point of view, many of the empirical inconsistencies reported in the literature may well have arisen because the data were obtained in experiments that differed fundamentally in kind from one another, with the corresponding physiological correlates located in different parts of the visual system.

Perhaps the clearest expression of this sentiment has been provided by Kolers (1972) from whose book on motion perception (Kolers, 1972, pp. 133-134) I wish to quote <u>in extenso</u> as follows:

"In different experiments the subject has been required to name the shape that was presented (such as a letter), to report on the integrity of its contour, to report on variations in its brightness, or to report, using forced-choice procedures, on its spatial location or temporal location within a sequence. These are not only different experimental procedures, they require markedly different judgments. The different judgments are probably based on the processing of different aspects of the stimulus. Hence there is little basis for generalizing from one experiment to another."

There is clear evidence that researchers in this area are beginning to realize that metacontrast is not a unitary effect (e.g., Merikle, 1977; Uttal, 1981). The theories, however, are still unitary and neuroreductionistic. It is to be expected that future models will be of more limited scope but more capable of representing the multidimensional nature of metacontrast suppression.

3.8 Implications for television design

In the preceding chapter, visible persistence was examined in terms of the properties of the inducing display alone. The current chapter suggests that such an approach is incomplete in that subsequent displays may also affect the persistence of information from the inducing display. The forthcoming comments attempt to consider the potential impacts of both persistence and suppressive effects for television design. In the comments, it is assumed that persistence and, by implication, metacontrast and similar suppressive phenomena are important for normal television viewing.

Studies of metacontrast show that, for equally intense test and mask stimuli, the extent of observed suppression is a nonmonotonic function of the temporal interval between stimulus onsets. Although typically on the order of 50 to 100 msec, the SOA associated with greatest suppression is known to vary widely with changes in test and mask properties.

It is well worth considering that the typical critical SOA for metacontrast (50 to 100 msec) is only slightly shorter than the typical duration of visible persistence (100 to 150 msec). It would be wise, therefore, to consider that there may be an irreducible minimum of processing permitted regardless of the properties of test and mask stimuli. Thus, recommendations based on persistence-suppression speculation should be given, and accepted, with reservation.

It has been suggested that television would benefit from greater display intensities. It is unclear what the net effect of such a change would be; a more intense display would persist for a shorter time but, for a relatively short SOA, a subsequent display similar in energy level would exert a lesser suppressive influence on information from the earlier display (Section 3.4.1). Clearly, this is a question for further study; the point remains, however, that research on this topic must be done with display sequences, a procedure rarely followed in television testing.

Increases in the spatial resoluton of displays might have competing effects for persistence and for suppressive mechanisms. The higher spatial frequencies possible with higher resolution displays would tend to persist longer, but both the extent and the immediacy of metacontrast suppression would increase with closer proximity of successive stimuli (e.g., the spatial proximity of successive television fields).

Increases in display size could have even more complex effects. Larger displays project greater amounts of information to non-foveal portions of the retina for which persistence is greater. However, projected eccentricity also re-scales the principal factors of metacontrast, resulting in longer critical SOAs, slower decreases in suppressive effect as test-mask separations increase, and a greater likelihood that even larger targets (e.g., objects within frames) will be suppressed. Clearly, more thorough consideration of display-size effects is warranted.

On the basis of visible persistence alone, it already has been suggested that there might exist a limit beyond which increases in rates of display would fail to provide greater integration of visually presented information. The metacontrast literature reinforces this suggestion; as the compositional similarity of test and mask stimuli increases (an inevitable consequence of increased frame rates, for example), the severity of metacontrast suppression also increases (Section 3.4.3). In this context, it would also be useful to know whether the immediacy of the suppressive influence also increases with configurational similarity.

The discussion thus far has not dealt with chromatic effects in suppression (Section 3.4.2) although such effects may be of relevance to colour television design. Equally, the temptation to relate possible display rates to critical SOAs in metacontrast has been resisted. Chromaticity issues were omitted as having been explored insufficiently and display rate issues were omitted as potentially misleading [definitionally, metacontrast applies only to non-overlapping successive displays (e.g., to adjacent points within and across fields and frames) and it is unclear what metric should be used to define temporal separations in frame-field sequences.]

At this point, it would be worthwhile to consider the discussions of television implications in perspective. Visible persistence has been suggested as a factor to be considered in television design by virtue of the fact that it has been demonstrated to exist under conditions of stroboscopic display. However, the role and importance of visible persistence in television viewing are far from established as are the characteristics of persistence under the complex conditions associated with television presentations. In a similar vein, type-B metacontrast has been suggested as a factor to be considered in design by virtue of its supposed relation to persistence and because it too has been demonstrated with stroboscopic presentations. The role, importance, and characteristics of this effect in television viewing are also far from established. Moreover, it cannot be argued that type-B metacontrast would be the only suppressive influence in television; there is ample paradigmatic opportunity for type-A metacontrast, for masking by light, and for masking by overlapping pattern to occur also.

Thus far, the report has concentrated upon persistence and suppression in the perception of images of stationary objects. Clearly, one of the more significant aspects of television images is that, within limits, they capture and represent images of objects in motion. The forthcoming chapter will consider certain aspects of visible persistence for images of objects in motion.

4. SUPPRESSION OF SMEAR OF OBJECTS IN MOTION

4.1 Introductory remarks

Vision researchers sometimes speculate as to the function served by metacontrast suppression in the perception of our visual world. The consensus appears to be that, by suppressing the visible persistence of temporally leading stimuli, metacontrast deblurs the visual image and hence facilitates sharp, unsmeared perception of objects in motion (Section 3.6). Whether the deblurring is achieved through inhibition or through summation is, of course, a separate issue (Section 3.5).

Most metacontrast experiments, however, were designed to study not suppression of visible persistence *per se*, but some other aspect of visual information processing such as visual masking (see Scheerer, 1973). Hence the outcomes of metacontrast experiments often bear only indirectly, though relevantly, on the topic of major interest to the present review, namely suppression of visible persistence.

More recently, especially over the past five years, attention has begun to focus directly on suppression of visible persistence of stimuli in motion, and experiments have been designed specifically for this purpose. The amount of empirical and conceptual work performed in this area thus far certainly does not match what has been done in metacontrast over the past 30 years. However, as detailed below, the experimental outcomes are entirely congruent with what is found in metacontrast suppression, a further testimony to the common basis of tl data. Furthermore, and not surprisingly, theoretical accou recent work can be divided in the same two broad categories .

theories of metacontrast (Section 3.5): inter-channel inhibition or intra-channel summation.

Indeed, the two types of explanation offer a suitable classificatory scheme for reviewing the recent work. In the remainder of this section, the empirical evidence is reported first, followed by a description of the two contrasting theoretical viewpoints. Finally, a suggestion is made for unifying both viewpoints within a single conceptual framework.

4.2 Suppression of smear in apparent motion: empirical findings

Before reviewing the evidence on this topic, it may be appropriate to re-state the distinction between real motion and stroboscopic motion (see section 1.1), and to underline the equivalence of the terms "visible persistence" and "motion smear" when applied to stimuli in stroboscopic motion.

Real motion is continuous, coherent motion observed in the everyday world of people walking, birds flying, and cars moving. Apparent or stroboscopic motion (the two terms are synonymous), on the other hand, is the type of motion observed on a television screen or in a movie film. It is obtained by displaying an image repeatedly in successive temporal frames. To achieve the appearance of motion, each successive frame shows the image in a new adjacent location, displaced in the direction of motion. Under a wide range of viewing conditions, real and apparent motion are indistinguishable; yet, in principle, one (real motion) may be described as an analog process, while the other must be regarded as a series of discrete events. Whether perception of real and stroboscopic motion is mediated by the same underlying mechanisms is not known, although common determination seems likely (e.g., Frisby, 1972;

Wertheimer, 1912; see also discussion of this issue in Section 1.1). In the present review, we are concerned exclusively with stroboscopic motion.

A moment's reflection will show that, as applied to a stroboscopically moving stimulus, the terms "visible persistence" and "motion smear" have equivalent meaning. The rationale is the same as that employed in the method of "stroboscopic illumination" for measuring duration of visible persistence (see Section 2.2.4). In brief, suppose that duration of visible persistence is 100 ms, and that a point of light is plotted briefly and successively at adjacent locations on a screen for one ms every 20 ms. What would be seen is a group of five points moving together across the screen. The fact that the points are plotted at the rate of one every 20 ms, and the fact that five dots are seen together at any one time, permit us to estimate the duration of visible persistence as being 100 ms. But, at the same time, the display may be regarded as a single moving point with a wake of smear trailing behind it. Indeed, if successive points are plotted in close spatial proximity, the visible persistence of the "older" points looks precisely like a wake of smear. The crucial point is that the length of the trail of smear is equivalent to -- and can be translated directly into -- duration of visible persistence, provided that the rate of plotting and the inter-point separation are known.

Early experiments with stroboscopically moving displays were performed with the intention of estimating duration of visible persistence (see Section 2.2.4). In those studies, the conceptual connection between stroboscopic displays and metacontrast suppression (see Section 3.3.1) had not yet been made. Hence Allport (1968) was understandably puzzled when he discovered that duration of visible persistence, estimated with a stroboscopic paradigm, was inversely related to the spatial separation between the component elements of the display.

Puzzlement did not last long. Dixon & Hammond (1972), who also employed a stroboscopic paradigm (moving radial lines) and replicated Allport's finding, realized that the stroboscopic method of estimating visible persistence was akin to the paradigm of metacontrast suppression. They ascribed the decreased persistence of closely-plotted elements to increased strength of lateral inhibition, an account entirely consistent with the inhibitory theory of metacontrast suppression (Sections 3.5.1, 3.5.2). More specifically, the results of Dixon & Hammond's (1972) series of three experiments showed that duration of visible persistence (or, equivalently, duration of smear of the moving lines) was a <u>decreasing</u> function of the luminance of the background field, but an <u>increasing</u> function of the spatial separation between successive lines.

In a more recent study, also employing a rotating radial line, Farrell (1984) confirmed that duration of visible persistence of stroboscopically moving stimuli is a direct function of spatial separation between the component elements of the display. What is more, she showed that duration of visible persistence increased <u>linearly</u> over a range of angular spatial separations up to at least 40 deg.

Despite its popularity, however, the radial line display is not entirely suitable for studying suppressive effects, particularly if the main variable under scrutiny is the spatial separation between successive stimuli. This is so because the spatial separation between two successive radial lines is not constant at every point along the lengths of the lines. Namely, at the point of convergence, (i.e. at the centre of the circle) the spatial separation between two successive radial lines is zero. At the other extreme, separation is at a maximum at the periphery, where the actual value (say, in degrees of visual angle) will depend on the length of the lines and on the radial separation between them. This objection does not invalidate the finding that duration of visible persistence varies inversely with inter-line separation (by increasing radial separation, <u>all</u> distances between corresponding points on successive lines are increased). But the radial-line technique is inadequate if we wish to study the function relating spatial separation between successive stimuli (expressed in degrees of visual angle) and degree of suppression of persistence. Specification of this function is an essential first step in understandiing the suppression effect.

Radial-line displays are equally unsuitable for studying effects of retinal eccentricity: by its construction, a radial line covers a range of eccentricities, hence the effects of single discrete values of eccentricity cannot be studied. By the same token, it is known that the spatio-temporal characteristics of vision vary with retinal eccentricity (see Sections 3.4.4, 3.4.5, and 3.4.6), hence specification of the function relating persistence or suppression to eccentricity is likely t be crucial to our understanding of these phenomena.

These difficulties were resolved quite simply by Di Lollo an (1985) by employing punctate stimuli instead of lines. The bas consisted of a point of light that stepped around a circular face of an oscilloscope. Two major variables were invest proximity of successive points (interpoint separation ig than 0.1 degree to over one degree of visual angle) and retinal eccentricity (the radius of the imaginary circle varied from 0.4 to 1.6 degrees in steps of 0.3 degree). In suit with earlier reports, Di Lollo and Hogben (1985) found that degree of suppression increased with spatial proximity of successive points. They also found that both duration of visible persistence and degree of suppression increased with retinal eccentricity.

Supporting evidence with respect to the relationship between proximity of points and degree of suppression has been reported by Burr (1980). The display consisted of 100 points that appeared to move horizontally on the face of an oscilloscope for a brief duration on each trial. The observer estimated the length of the wakes of smear made by the points as they appeared to move across the screen. Appearance of motion was obtained by displacing all points by a small distance every 5 ms. In addition, the distance by which the points were moved (i.e. the spatial separation between successive points) was varied systematically across trials. Burr (1980) reports that length of smear increases as inter-point separation is increased. Burr's interpretation of this result in terms of spatio-temporal summation, however, is open to question (see Section 4.3).

Employing Burr's (1980) paradigm, Hogben and Di Lollo (1986) investigated the effect of yet another variable on suppression of smear of stimuli in apparent motion: luminous intensities of stimuli and background. The luminance of the points could assume one of five values over a range of over one log unit; background luminance was either 0.3, 3.0, or 30.0 cd/m^2. No effect of stimulus luminance was found, suggesting that contrast may not be a prime determinant of suppression of smear. (This result, however, may well change if a greater range of values were used). On the other hand, degree of suppression was affected powerfully by level of background luminance: at the brightest background level, duration of smear was less than one third that obtained with the dimmest background; the middle background luminance yielded intermediate duration of smear. This study also replicated the earlier finding (Burr, 1980; Di Lollo & Hogben, 1985; Farrell, 1984) that strength of suppression increases as the spatial separation between successive stimuli is decreased. However, inter-stimulus separation did not interact with any other variable, notably stimulus or background luminance.

In summary, the empirical evidence gathered thus far on suppression of smear in stroboscopically moving displays has singled out three salient factors:

a). Strength of suppression increases as the <u>spatial separation</u> between successive stimuli is decreased. This finding is in total agreement with the findings in metacontrast suppression where only two stimuli (test stimulus and mask) are typically employed (see Section 3.4.4).

b). Strength of suppression increases as the <u>locus of stimulation</u> is changed from the central fovea towards the retinal periphery. This finding is also in agreement with the outcome of metacontrast experiments (see Sections 3.4.4, 3.4.5, and 3.4.6).

c). Strength of suppression increases as the level of <u>background illumination</u> is increased. Again, this finding is in suit with the findings in metacontrast suppression (see section 3.4.1).

Such close correspondence between the variables known to govern metacontrast suppression and those affecting suppression of smear in stroboscopic motion strongly suggests that the two phenomena may belong to the same class of events. The parallel is reinforced by the close similarity between the theoretical accounts that have been proposed in the two areas, as is seen in the next section.

4.3 Suppression of smear in apparent motion: theoretical accounts

To be useful, a theory of suppression of smear in apparent motion must be capable of accounting for the salient empirical findings. In the present context, this means ability to explain the effects of spatial proximity, retinal eccentricity, and background luminance. In addition, in view of the close correspondence of findings between metacontrast suppression and suppression of smear in stroboscopically moving displays, the credibility of a theory of suppression of motion smear would be enhanced if it could account for both bodies of evidence.

Three theories -- two based on spatio-temporal summation, and one based on inhibition -- have been proposed to account for suppression of motion smear. They are examined below, in turn.

4.3.1 Burr's summation model

It has been mentioned earlier (Section 3.4.3) that Burr's account of metacontrast suppression is entirely in terms of spatiotemporal summation and eschews any reference to active inhibition of the temporally leading stimulus. His account of suppression of motion smear is entirely consistent.

According to Burr (1980, 1981) whether or not smear is produced by a moving stimulus depends on which of two sets of visual channels is activated by the display. Stationary or slowly moving stimuli activate a movement-independent system consisting of a set of channels tuned to relatively high spatial and low temporal frequencies. By contrast, rapidly moving stimuli activate a movement system consisting of a separate set of channels tuned to relatively low spatial and high temporal frequencies. The movement system is said to summate the energy from successive positions of a moving stimulus and, most importantly, to be free from smear.

Motion smear results from inappropriate activation of the movement-independent system by a moving stimulus. Smear is avoided when the movement system is engaged. Presumably, the movement system has the longer latency so that, at the very beginning of a motion sequence only the movement-independent system is engaged, producing smear. After a delay, the movement system takes over and smear is avoided. This explains why, under some viewing conditions, a point in motion is seen as trailing a tail of smear at the very beginning of a motion sequence but is seen sharply and without smear thereafter (Burr, 1980; Hogben & Di Lollo, 1986).

How does this model account for the finding that duration of smear is less when successive points are plotted close together than further apart? It must be noted (as was noted by Burr, 1980) that, given a fixed SOA, points that are closer together also appear to move more slowly on the screen than points that are plotted further apart. Hence the above question can be rephrased to ask why should duration of smear be less with apparently slow-moving targets. If smear is avoided by engaging the movement system (which is smear-free by definition), it is difficult to see how a slow-moving stimulus should be more effective than a fast-moving one in engaging a system ostensibly attuned to the perception of moving objects.

Even though this would appear to render Burr's account implausible, the option must be considered that the fundamental variable underlying the effect may not be inter-point separation but velocity *per se*, which would be handled within the visual system by separate channels tuned to different velocities. Although this is a possibility, the relation between activity in the separate velocity-tuned channels and the duration of smear would still be in need of explanation.

Similar difficulties are encountered by this model in explaining the effect of background luminance. The finding that less smear is obtained at higher luminance would suggest that light potentiates the low-spatial-frequency movement system. This is an intriguing assumption that may be worth pursuing, but that must be regarded as entirely *ad hoc* until justified on independent grounds. As for the finding that attenuation of smear increases with retinal distance from the central fovea, the model must resort to the similarly *ad hoc* assumption that the relative prominance of the movement-dependent system increases with retinal eccentricity.

It must be stressed that these difficulties do not invalidate Burr's treatment of the temporal summation of moving images (e.g. Burr, 1981). But the model is clearly in need of elaboration if it is to account for the effects of spatial separation, background luminance, and retinal eccentricity on the reduction of motion smear.

4.3.2 Morgan's interpolation model

A second account of suppression of motion smear can be reached in terms of a filtering model that was initially developed to account for the "interpolation effect" (Morgan, 1976; Morgan & Watt, 1983). The interpolation effect is obtained in a vernier acuity task, with targets apparently moving through successive stations. Suppose, for example, that we employ a typical vernier acuity target consisting of two thin vertical lines displayed one above the other so that, when they are perfectly aligned, they have the appearance of just one straight vertical line having a length twice that of the component lines. To obtain an estimate of vernier acuity, one of the lines (say, the upper one) is displaced horizontally until the observer reports seeing a misalignment. Typically, the target is displayed as stationary. But it can also be displayed in apparent horizontal motion; that is, both halves of the target can be displayed briefly and simultaneously at each of a series of successive stations. If the total duration of the display does not exceed about 200 ms (i.e., if eye movements do not occur), vernier acuity is virtually the same whether the target is stationary or whether it is moving with velocity up to at least 5 degrees per second (Westheimer & McKee, 1975).

Now suppose that a pair of perfectly aligned bars were shown in horizontal apparent motion, but that, at each station, the upper bar were displayed slightly before the lower one. An observer would perceive the two bars in smooth motion, but would also perceive an illusory misalignment, with the upper bar apparently leading the lower bar by a spatial extent proportional to the temporal asynchrony of plotting. On the other hand, if the upper bar is plotted slightly after the lower one, it is seen as spatially trailing. Similarly, actual spatial misalignments of the two bars can be compensated by appropriate temporal delays, so that the bars appear to be in perfect alignment. In brief, given appropriate spatio-temporal conditions, observers perceive the position of the bars as interpolated between stations.

To explain the interpolation effect, Morgan and Watt (1983) postulate the activity of two visual filters, one temporal and the other spatial. A detailed description of the mode of operation of the two hypothetical filters would take us even further from our discussion of suppression of motion smear, and will not be attempted here; the interested reader is referred to Morgan and Watt's (1983) original paper. As applied to motion smear, the temporal filter causes stimuli at successive stations to persist for a period determined by the temporal constant of the filter. The energy output of the temporal filter at each station is a decaying function of the time since stimulation. The spatial filter, on the other hand, is characterized by a difference-of-Gaussian (DOG) function which has traditionally been employed to portray the centre-surround organization of visual receptive fields. To define the apparent spatial location of the bars at any given moment in time, a convolution is performed between the temporal and spatial functions. The perceived spatial location of the target is said to be based upon the location of the zero-crossing in the convolution profile of the temporal and spatial functions.

As long as the convolution profile does not contain more than one zero-crossing, only one stimulus is seen, regardless of the number of stimuli that enter the filter at the same time. Within this conceptual framework, absence of motion smear is regarded as a failure to resolve separate stimuli within the spatial filter. That is, even though several points enter the spatial filter, only one point is seen. On the other hand, presence of smear indicates that the spatial separation between points is sufficient to ensure their resolution. Smear is perceived in the form of multiple stimuli.

The Interpolation Model accounts well for the finding that suppression of smear is greater at small spatial separations. This is so because, at small separations, several points would be encompassed within the constant of the spatial filter which would fail to resolve them, thus giving rise to the perception of a single, unsmeared point. At wider inter-point separations, however, successive points might match or exceed the spatial domain of the filter, thereby becoming resolvable as distinct points which are seen as smear (Morgan & Watt, 1983).

Background luminance is handled less directly. The finding that duration of smear is negatively related to background luminance could be handled within the Interpolation Model by assuming that the constant of the temporal filter decreases as luminance is increased. This would lead to fewer points (i.e., less smear) being perceived simultaneously at higher levels of luminance. In suit with this assumption, there are clear indications in the experimental literature that increments in luminance should reduce the constant of the temporal filter. Roufs and Blommaert (1981), from whom Morgan and Watt (1983) obtained an estimate of the temporal constant, have shown that the temporal impulse function has far greater spread with low than with high background luminance. Kelly (1971) reported the same relationship. In the same vein, it could be assumed that increments in luminance may reduce the constant of the spatial filter thus reducing extent of smear. However, in its present form, the model has no means of accounting for the finding that strength of suppression of smear increases from the central fovea towards the retinal periphery.

In sum, although the Interpolation Model was developed to account for the illusory spatio-temporal alignment of elements in a stimulus train, rather than for smear per se, it seems capable of accounting for suppression of motion smear with only a few plausible additional assumptions. In this respect, it would be of interest to find out how the interpolation effect itself varies as a function of background luminance.

4.3.3 The inhibition hypothesis

It has been proposed (Breitmeyer, 1984; Di Lollo & Hogben, 1985; Hogben & Di Lollo, 1986) that suppression of motion smear (or attenuation of visible persistence) is based on inhibitory processes that may be diverse in character and occur at more than one level within the visual system. Besides such classic studies of retinal inhibition as those of Barlow, Fitzhugh, and Kuffler (1957) and Ratliff (1965), the work of Whitten and Brown (1973) reveals suppression of rod activity by lateral inhibition from the cones; at the level of the lateral geniculate nucleus, Singer and Bedworth (1973) found that activation of Y cells in the cat inhibits ongoing activity of X cells. While, at this stage, it is not possible to be specific as to either locus or mechanism, it is clear that inhibition can provide a plausible basis for suppression of motion smear. Below, we examine how known principles of inhibition can account for the salient empirical findings.

The most reliable outcome is that as background luminance increases, duration of smear decreases. This finding is precisely what would be expected if reduction of smear resulted from a process of suppression based on inhibitory activity. A direct relationship between background luminance and level of inhibition has been confirmed both neurophysiologically and psychophysically. From single-unit recordings in the cat's visual system, Barlow et al. (1957) found that inhibitory activity was high at photopic levels but totally absent in dark adaptation. Similarly, psychophysical studies by Ikeda (1965) showed that inhibition becomes progressively weaker as the adapting luminance is lowered. On this hypothesis, the stronger inhibition associated with higher luminance acts to terminate visible persistence, reducing the duration of smear.

The finding that suppression of smear is greater at smaller inter-point separations is explained naturally by reference to the gradient of inhibition: it has been known for some time (e.g., Ratliff, 1965) that strength of inhibitory interactions, at least at the retinal level, increases with proximity of stimuli. This is the same account provided for the corresponding results in metacontrast suppression (Section 3.5.2).

It must be stressed that this is a most general outline of the inhibition hypothesis, meant to highlight its neurophysiological underpinnings. A more specific inhibitory model such as that of Breitmeyer (described in Section 3.4.2) can be employed to account for the specific findings on suppression of motion smear. As will be remembered, Breitmeyer's model assumes that stimulation activates two sets of visual pathways, or channels, having distinct spatio-temporal response characteristics. The transient channel has short latency and responds optimally to the low spatial frequencies of fast-changing stimuli; by contrast, the sustained channel has longer latency and is attuned to processing figural aspects of the stimulus such as details carried by the higher spatial frequencies. Activity in the transient channel is regarded as having an inhibitory effect on concurrent activity in the sustained channel.

Perceptual suppression of the contours of a temporally leading stimulus is explained in terms of the joint effects of the shorter latency of transient responses and of transient-on-sustained inhibition. Given a train of spatially adjacent stimuli displayed in succession at the appropriate temporal interval, the fast transient activity produced by the temporally trailing stimuli will inhibit the ongoing more sluggish sustained activity produced by the leading stimuli, thus resulting in effective suppression of motion smear.

Breitmeyer's model can account easily for the effects of luminance and of inter-stimulus separation much along the lines described above; the effect of eccentricity (greater suppression of smear toward the retinal periphery) is also explained with ease by noting that the proportion of transient to sustained channels (and hence the potential for transient-on-sustained inhibition) is far greater in the retinal periphery than in the central fovea (e.g., Cleland & Levick, 1974; Peichl & Wassle, 1979).

4.4 Towards a conceptual synthesis

Having examined findings and theories of metacontrast suppression and of suppression of smear in apparent motion, it would be imprudent to ignore the compelling evidence that links the two phenomena empirically and conceptually. Indeed, the theoretical accounts of the two phenomena are virtually indistinguishable. There is, therefore, sound justification for adopting the working hypothesis that metacontrast suppression and suppression of motion smear are separate expressions of the same underlying perceptual mechanisms.

Assuming, for the moment, that this is the case, can we go on to identify the underlying mechanism? From the earlier discussion, it would seem that there are two prime candidates: spatiotemporal summation of energy, or some form of inhibitory interactions. In our discussion of these alternative accounts, it was shown that both were capable, in varying degrees, of accounting for the empirical evidence. Take, for example, the finding that increments in background luminance produce shorter duration of visible persistence. This is a result that is obtained with static as well as moving stimuli. For example, it has been shown that duration of visible persistence of static stimuli is less at higher photopic levels (Coltheart, 1980); put differently, it has been shown that the visual system shows less static summation as light adaptation level increases (see Ganz, 1975, for review). This pat
results can be explained equivalently in terms of suppres
of summation. That is, although inhibition can b
determinant of these findings, it could a
motion smear (or of static temporal int
intensity might indicate a change not in
in the period of summation.

In view of the broad equivalence of th
be possible to view the two accounts as comple

than as mutually exclusive alternatives. Indeed, upon consideration, the suppression and the summation hypotheses turn out to be homologous and probably related as cause and effect. Namely, there are strong psychophysical and physiological suggestions that inhibitory processes provide the basis for reducing the critical period of temporal summation. In a series of psychophysical studies of temporal summation with double pulses, Ikeda (1965) obtained clear evidence that the strength of inhibitory interactions between two pulses increases with background luminance thereby diminishing the period of summation. Even more telling, in this respect, are the findings of Whitten and Brown (1973) who studied inhibitory network interactions between cones and rods in the macaque monkey. They reported that inhibition of rods by cones greatly reduced the period of temporal summation as light adaptation increased. They went on to suggest that ". . . the cone-rod lateral inhibitory pathway may free the cone system from interference by very slowly decaying rod signals at photopic intensities, thereby permitting the cone system to realize its full capability for resolving stimuli in the time domain." (Whitten & Brown, 1973, p. 1652.) A similar relation between summation and inhibition was also pointed out by Barlow (1958) who noted that ". . . the conditions . . . which diminish spatial summation in human experiments are the conditions which accentuate lateral inhibition in animal experiment (Barlow, 1958, p. 348).

In essence, I suggest that the empirical evidence rev foregoing may be viewed just as appropriately in term terms of inhibition. Whether one or the other conce depend on the broader theoretical context and on the le required within that context.

4.5 Implications for television design

This chapter began with the observation that, for displays of moving objects, unchecked visible persistence would result in motion smear. As we normally do not see smear with moving objects, it was suggested that a persistence suppressing mechanism might be involved in the perceptual processing of images of moving objects. A brief review of the admittedly sparse literature on this topic suggested a metacontrast-like aspect to this suppressive mechanism.

It would be entirely premature to attempt to apply motion smear findings to television design. The literature in the area is too sparse and the relationship of motion smear (or its absence) to more fully studied phenomena such as persistence and metacontrast is far from satisfying. Nevertheless, it does appear that further study of motion smear may well be a profitable source of guidance for television design.

The present chapter presented some of the controversy surrounding explanations of motion smear and its suppression. This controversy highlights a critical limitation to the ready applicability of da
motion smear, metacontrast, and visible persistence --
been studied extensively, none of these phe
this point, we have rules-of-thumb tha
caution, to real world concerns. More s
perceptual data to television design requ
explanations not only of these and other ph
involved in television viewing itself.

At this point, the review ends. The forthcoming section will present new empirical studies that relate to the questions and issues raised thus far. These studies are intended to provide new data in the field. More important in terms of this report, however, they are intended to illustrate how research is done in this field and to demonstrate the difficulty of "teasing apart" some factors in display.

THE EFFECT OF STIMULUS SIZE ON SUPPRESSION OF VISIBLE PERSISTENCE: PRELIMINARY EMPIRICAL STUDIES

ES:1.1 Introductory remarks

The purpose of this preliminary empirical work is not to arrive at a definitive statement regarding the effect of stimulus size on suppression of visible persistence. Although the empirical evidence gathered in this work will undoubtedly add to our knowledge of the factors that influence visible persistence, the major aim is to illustrate the type of conceptual issues and design considerations that are encountered in this area of research.

Seldom, if ever, a complete answer to an experimental question can be provided in a single study, or even in a set of studies. The present work is no exception. Nevertheless, the studies reported below clarify some important methodological considerations encountered in this area of enquiry, and arrive at the tentative conclusion that stimulus size *per se*, is probably not a major determinant of suppression of visible persistence.

ES:1.2 Conceptual background

As was seen in the preceding review of the literature, suppression of visible persistence has several determinants. Among these, the two most powerful are spatial separation between temporally successive stimuli, and level of luminance of the background on which the stimuli are displayed (e.g., Dixon & Hammond, 1972; Hogben & Di Lollo, 1986). The consistent finding is that duration of visible persistence dec (i.e., suppression increases) as spatial separation be stimuli is decreased. Also, duration of persistence dec level of background luminance is increased.

As was noted in the review of the literature (Sections 3.4.1, 3.5.2, 4.2 and 4.3.3), these findings can be explained in terms of inhibitory interactions between successive stimuli, and are entirely consistent with other psychophysical and neurophysiological evidence showing that strength of inhibition increases with spatial proximity and background luminance (e.g., Barlow, 1958; Barlow, Fitzhugh, & Kufler, 1957; Ratliff, 1965; Whitten & Brown, 1973).

A third stimulus attribute said to affect the strength of inhibition within the visual system is size of the inducing stimulus. There are clear indications that strength of inhibition increases as the angular size of the stimulus is increased (Barlow, Fitzhugh, & Kufler, 1967; Vrolijk & Van Der Wildt, 1982).

Stimulus size has been investigated as a factor in metacontrast suppression (see Section 3.4.5), but never in experiments designed explicitly to examine its effect on duration of visible persistence. The present work is a step in that direction.

ES:1.3 Experiment 1: Method

The method employed in the present studies is that of "integration of form" (see Section 2.2.5). In this method, a meaningful configuration is displayed in two successive parts, each of which is meaningless when viewed singly. Perceptual integration of the two parts can be achieved if the visible persistence produced by the first display is sufficient to bridge the temporal gap that separates the two components. The duration of the temporal gap is systematically varied so as to encompass th which perceptual integration breaks down, thus permitting an be made of the duration of visible persistence.

More specifically, the basic display employed in these studies was a 25-element square matrix, with the elements arranged in five rows and five columns. On any one trial, one element (chosen randomly on each trial) was missing from the matrix. The observers' task was to identify the location of the missing element, a task that is typically both easy and engaging. To study duration of visible persistence, the matrix was shown in two brief displays of 12 elements each, separated by a temporal gap during which the screen remained blank.

Briefly stated, the rationale underlying this task is as follows: if 24 of the 25 matrix elements are displayed in virtual simultaneity, observers have no difficulty in identifying the location of the missing element. At the other extreme, if the two sets of 12 elements are separated by a sizable temporal gap (say, 200 ms), the two sets are perceived as separate configurations and the task becomes impossible. For the task to remain feasible, there needs to be sufficient visible persistence from the first stimulus to bridge the temporal gap and thus support perceptual integration of the two displays. On this basis, the level of success at identifying the location of the missing element can be employed as an index of the duration of visible persistence.

ES:1.3.1 Observers

One male and one female observer, each aged about 25 years, served in all experiments. Both had normal or corrected-to-normal vision.

ES:1.3.2 Visual displays

All stimuli were displayed on a Hewlett-Packard 1333A oscilloscope equipped with P15 phosphor. At the viewing distance of 57 cm, on the 8 x 8 cm display surface subtended a visual angle of 8 deg.

The testing room was dimly illuminated by a shielded incandescent lamp placed in one corner of the room. The light reflected by the blank display surface was 1 cd/m^2, as measured by a Spectra Spotmeter. For all displays, the intensity gain of the oscilloscope was set so that a standard test-patch plotted continuously on the display surface yielded a reading of 10 cd/m^2.

The display consisted of a square matrix of 25 elements arranged in five rows and five columns. To examine the effect of stimulus size on duration of visible persistence, the size of the matrix elements was varied systematically, as described below. It must be stressed that, on any given trial (i.e., for any given display of the total matrix form), all elements in the matrix were of the same size. Variations in element size took place between trials. Except for the smallest element, which consisted of a single dot, all matrix elements were square patches of light containing different numbers of tightly-packed dots, so that the element appeared as a smooth, homogeneous surface. The number of dots in an element could be either 1, 4 (a 2 x 2 square), 9 (3 x 3), 16 (4 x 4), or 25 (5 x 5). The corresponding angular sizes of the square elements were: 0.03, 0.06, 0.09, and 0.12 deg., respectively.

Spatial separation between adjacent matrix-elements decreased as element-size increased. This deliberate confounding between element-size and inter-element separation was introduced in order to keep the overall size of the matrix approximately the same for all element-sizes. The effects are unconfounded in Experiment 2. The inter-element separation was 0.15 deg. for single-dot elements, and it decreased to 0.12, 0.09, 0.06, and 0.03 deg. for progressively larger element-sizes.

ES:1.3.3 Procedure

Observers viewed the display binocularly from a distance of 57 cm, set by a headrest. At the beginning of each trial, four fixation points delimited a square area whose side was 2 deg. of visual angle. On each trial, the matrix was displayed briefly in the centre of the square area. The observer initiated a display by pushing a button. Any given trial consisted of the following sequence of events: first, 12 elements -- chosen randomly on each trial from the pool of 25 elements -- were displayed on the screen for a duration of approximately 2 ms. Next, a brief temporal interval (see below) was permitted to elapse, during which the screen remained blank. Finally, the second set of 12 elements -- chosen randomly on each trial from the remaining pool of 13 elements -- was displayed for a duration of approximately 2 ms. The task of the observer was to identify the location of the missing element, and to name its coordinates within the matrix. The experimenter entered the coordinates on the terminal of a PDP-11/34A computer that performed all plotting, timing, and scoring functions.

The temporal separation between the two portions of the display was based on stimulus-onset asynchrony (SOA) rather than on inter-stimulus interval (ISI). As was pointed out in the review of the literature (e.g., Section 3.1), SOA -- rather than ISI -- is by far the more powerful determinant of visible persistence and its suppression.

Two values of SOA (one brief, the other long) were chosen separately for each of the two observers. The brief SOA was a control condition aimed at demonstrating that increments in element size do not increase the intrinsic level of difficulty of the matrix task when all elements are displayed in virtual simultaneity. For each observer, the brief SOA was defined as the longest SOA that yielded an error rate of no more than 10% across all element sizes. Preliminary trials yielded brief-SOA values of 10 ms for Observer LDB, and 25 ms for Observer BDJ. Preliminary trials also showed that a satisfactory long SOA could be obtained by adding 15 ms to the values of the brief SOAs. Therefore, the long SOA was set at 25 ms for Observer LDB, and at 35 ms for Observer BDJ.

For each observer, therefore, the experiment had a factorial design with two factors: SOA at two levels, and element size at five levels, yielding a total of 10 conditions. One experimental session, which lasted approximately 10 min, contained 100 trials, 20 at each stimulus size. The 100 trials were ordered in a different random sequence for each session. The SOA remained fixed in any given session at either the low or the high value. Values of SOA were sequenced haphazardly through the experiment. Each observer served for 10 sessions, thus yielding a total of 100 observations per condition.

ES:1.4 Results and discussion

Figure 1 shows the results of Experiment 1 separately for each observer. The two lines in each graph represent performance at the two SOAs across all five levels of element size.

Insert Figure 1 about here

It is immediately clear that level of performance is strongly affected by both SOA and element size. At the brief SOAs, both observers exhibited virtually errorless performance at all element sizes. This result attests that, when all elements are seen in virtual simultaneity, the level of difficulty of the task is unaffected by the size of the elements. This is particularly notable in the case of the largest size, in which the spatial separation between adjacent elements was the same as the inter-dot separation within an element; consequently, when displayed simultaneously, the 24 elements formed a single uniform square of light, with one small unlit black square on its surface. Despite the lack of spatial separation amongst the elements, the matrix location of the "black square" could be identified with ease. The slight tendency shown by Observer BDJ towards a greater incidence of errors for the largest elements at the brief SOA, was due entirely to the relatively long SOA (20 ms) that was defined as "brief". At shorter SOAs, this observer made no errors at any element size.

The pattern of results changed dramatically at longer SOAs: while performance remained virtually errorless at the smallest element size, it deteriorated rapidly as element size was increased. Whether the deterioration was due to increasing element size or to other variables (see below), there is little doubt that it was brought about through some form of suppression of visible persistence. This is so for two major reasons: first, large numbers of errors were made at durations of SOA (25 and 35 ms) that are far shorter than the typical estimate of duration of visible persistence (100-150 ms; see Section 2.3). It seems likely that visible persistence was cut short under these display conditions. The phenomenological appearance of the displays lends credence to this interpretation: while the small-element displays were seen to cor

one empty location, the larger-element displays appeared to missing elements from which the observer had to guess the correct response. The second reason is illustrated in Figure 2, in which the errors made at each element size were partitioned into two categories: errors that were made by incorrectly naming as missing an element that had been plotted in the leading portion of the display, and errors that were made by naming one of the elements in the trailing portion. As seen in Figure 2, errors were made preponderantly by confusing the empty location with a matrix location in which an element had actually been plotted in the *first* portion of the display. This strongly suggests that the second display was in some way instrumental in foreshortening the visible persistence of at least some elements of the first display, to an extent to which an element that had actually been plotted could be confused with the empty location.

Insert Figure 2 about here

From Figure 1, it is also clear that the suppressive effectiveness of the second display increased as element size was increased. Despite appearances, however, this pattern of results cannot be attributed unambiguously to the effect of stimulus size. It has been noted earlier that, in the present experiment, increments in stimulus size were entirely confounded with decrements in spatial separation between adjacent elements. In turn, it is well-known that suppression of visible persistence increases rapidly as spatial proximity between successive stimuli is increased (see Sections 3.4.4, 3.4.6, 4.2). Furthermore, the changes in spatial proximity brought about by variations in element size in the present experiment, were well within the range (up to about 0.2 deg) found by Di Lollo & Hogben (1986) to be most effective in suppressing persistence. Clearly, the option must be considered that the deterioration in performance illustrated in Figure 1 might be due not to increments in element size but, at least in part, to decrements in spatial separations among adjacent stimuli.

A second source of confounding might also have played a part in this study. Variation in element size was achieved by increasing the number of points within an element. As a consequence of this manipulation, the total light flux produced by any given element increased as element size increased. In turn, brighter stimuli are known to produce shorter visible persistence (see Section 2.3.1 for a discussion of the "inverse intensity effect"). Unlike spatial proximity, which can bring about dramatic changes in visible persistence, the inverse intensity effect is less powerful, and would be unlikely to underly the large differences illustrated in Figure 1. Nevertheless, the changes in brightness that occurred concomitantly with changes in element size might have been a contributing factor.

The effects of proximity and brightness are separated from the effect of element size in Experiment 2.

ES:2.1 Experiment 2: Introduction

Three factors might have contributed towards the results of Experiment 1: angular size of the elements, inter-element separation, and total light-flux. In the present experiment, angular size was varied so that elements could be either large or small, while holding the other two factors constant.

Light flux was controlled by constructing all elements with the same number of points, i.e., 25. To vary element size, the inter-point separation within an element was varied so that the dots could be either tightly packed (small elements) or more widely spaced (large elements). Regardless of size, all elements produced the appearance of an unbroken, continuously lit surface, within which the individual component dots could not be resolved.

Inter-element separation was controlled by holding constant the edge-to-edge separation between adjacent elements. In selecting the inter-point separation, the main consideration was to make it large enough to minimize the suppressive effects of proximity, while keeping the total matrix form within the confines of the central fovea. The separation employed in this study was chosen on the basis of Di Lollo & Hogben's (1986) finding that, with this type of stimulus, inhibitory interactions are much reduced or totally absent at inter-element separations beyond about 0.3 deg.

In brief, the question of interest was whether the large elements produced higher levels of inhibition than did the small elements. In practice, it was asked whether perceptual integration could be maintained across longer temporal gaps with the small elements than with the large elements. To this end, both the small-element matrix and the large-element matrix were displayed in two portions, as in Experiment 1, but over a range of SOAs. Longer visible persistence would be evidenced by better performance (i.e., fewer errors) across the range of SOAs.

It must be noted that, since the size the elements was varied while holding inter-element separation constant, an unavoidable confounding was produced between element size and the size of the total matrix. This confounding is discussed below, and is examined explicitly in Experiment 3.

ES:2.2.1 Method

Method and procedures in Experiment 2 were the same as in Experiment 1, with the exceptions noted below.

ES:2.2.2 Displays and procedure

The display could be either a small-element matrix or a large-element matrix. The small elements were composed of 25 dots displayed in five rows and five columns within a square area whose side had an angular length of 0.01 deg. The large elements were also composed of 25 dots which were displayed within a square area whose side had an angular length of 0.12 deg. As was noted above, both small and large elements appeared to have a uniform surface within which the individual dots could not be resolved.

The spatial separation between adjoining edges of adjacent elements was maintained at 0.3 deg., regardless of element size. As a consequence, the size of the total matrix differed, depending on element size: the small-element matrix subtended a visual angle of 1.25 deg., while the large-element matrix subtended 1.80 deg (still within foveal dimensions).

Regardless of element size, the matrix was displayed in two successive portions of 12 elements each, separated by a variable SOA. The SOA could be either 40, 60, 80, 100, or 120 ms.

The experiment had a factorial design with two factors: element size at two levels (matrix elements could be either small -- 0.01 deg. -- or large -- 0.12 deg.), and SOA at five levels, as listed above. This

yielded a total of 10 conditions. The 100 trials in any one experiment
session were composed of 20 trials at each of the five SOAs. The 100
trials were ordered in a new random sequence for each session. El
size remained fixed at either the small or the large value within
session. Each observer served for 10 sessions, thus yielding a
100 observations per condition.

ES:2.3 Results and discussion

The circular symbols in Figure 3 show the results of
The triangular symbols represent the results of Experim
discussed later.

th

Insert Figure 3 about her of

y be a

The performance of one observer (BDJ) w t 1,
element-size at any level of SOA. The perf cal
(LDR) revealed a slight effect (approxima
intermediate levels of SOA, with the sm iments 1
accurate performance. While these re the levels
evidence that element size had no osely
the inference that, if element s comparison,
small, and certainly far small xperiment 1
large effects obtained in Ex pending on

It is worth noting t virtually
large elements to small ment size, at an
performance produced b oyed in Experiment
unreliable. By comparison, nt size between

(between elements whose angular sizes were 0.03 and 0.12 deg.) produced very large and entirely reliable differences at the longer SOAs (see Figure 1). At the same time, it must be noted that the spatial separation between elements was far smaller in Experiment 1 than in Experiment 2.

On the face of it, this pattern of results strongly suggests that element size is not, by itself, a prime determinant of duration of visible persistence. Rather, the option is supported that the large effects obtained in Experiment 1 are attributable not to variations in element size but to the concomitant variations in spatial proximity among adjoining elements. This interpretation is buttressed by the large effects of spatial proximity obtained by Di Lollo and Hogben (1986) with stimuli of uniform size under spatial conditions comparable to those of Experiment 1. It is still possible, of course, that element size may be a factor at the small inter-element separations employed in Experiment 1, but not at the larger separations of Experiment 2. Further empirical evidence would be required to examine this alternative.

A second source of evidence, involving comparison of Experiments 1 and 2, argues for the preeminent effect of proximity. Consider the levels of performance obtained with the large elements at the most closely comparable levels of SOA in the two experiments. To make this comparison, the condition that yielded the largest number of errors in Experiment 1 (Figure 1, largest element-size, at SOAs of 25 or 35 ms, depending on observer) should be matched with a condition that yielded virtually errorless performance in Experiment 2 (Figure 3, large element size, at an SOA of 40 ms). Note that, had an SOA of 40 ms been employed in Experiment 1 (thus permitting a perfect match of both SOA and element size between the two studies), the discrepancy in levels of performance would have been even larger. The dramatic differences in levels of performance cannot be attributed to the effect of element size because size was the same in the two conditions; nor can it be attributed to the effects of SOA, as noted above. What differed between the two sets of conditions was the spatial proximity between adjacent elements: inter-element separation was 0.03 deg. in the condition that yielded large numbers of errors in Experiment 1, but was 10 times larger (0.3 deg.) in the corresponding condition that yielded virtually errorless performance in Experiment 2. The compelling inference invited by these data is that spatial proximity -- rather than element size -- was the crucial variable in reducing the duration of visible persistence. Once again, this pattern of results is entirely consonant with Di Lollo and Hogben's (1986) findings regarding the suppressive effects of increasing spatial proximity within the range employed in the present work.

As was the case in Experiment 1 (Figure 2), most of the errors in Experiment 2 arose from erroneously naming as missing a dot that had actually been plotted in the first portion of the display. The phenomenological appearance of the display also matched that in Experiment 1: as SOA was increased, more and more elements appeared to be missing from the total matrix form, forcing the observer to guess the response from an increasingly larger number of apparently empty matrix locations. As was noted in the discussion of Experiment 1, these findings strongly suggest that the second portion of the display exerted an inhibitory influence on the visible persistence of the first.

We now turn to a brief examination of the confounding between element size and total matrix size, noted in the introduction of Experiment 2.

ES:3.1 Experiment 3: Introduction

Since element size was varied while inter-element separation remained fixed, the size of the total matrix covaried with element size in Experiment 2. As was noted earlier, the small-element matrix subtended a visual angle of 1.25 deg., while the angle subtended by the large-element matrix was 1.80 deg. Thus, the small elements occupied a retinally more central position than the larger elements. This confounding is unlikely to have had a major effect on the results of Experiment 2 for two major reasons: first, both displays were encompassed comfortably within the spatial confines of the central fovea (approximately 2 deg. of visual angle) which is generally regarded as yielding highly uniform visual effects. Second, the presumed effect of total matrix size would hav
depend on an interaction; namely, it would have to be presumed t
hypothetically greater suppressive effects of the larger ele
counterbalanced by the greater eccentricity of the large
This would be predicated on the assumption that dur 3
greater (or that suppression is less) with grea ts
tenability of such assumption, however, is nally
definitive evidence regarding the cour This
suppression in foveal as distinct
2.3.5a, and 4.2). al effect

Despite these considerations, a b. ıot be
on the effect of differences in total matr .ibitory

employing the small-element matrix of Experiment 2 with slightly increased inter-element separations such that the size of the total matrix form matched that of the large-element matrix. This permits a comparison between two small-element matrices: one having total angular size of 1.25 deg. (from Experiment 2), the other having total size of 1.80 deg. (in Experiment 3). Since the inter-point separations were greater than those at which inhibitory interactions are known to occur (Di Lollo & Hogben, 1986), it was reasoned that differences in performance between the two matrices should represent the effect of total matrix size.

ES:3.2 Method and procedure

The matrix employed in the present study was the same as the small-element matrix in Experiment 2, except that the spatial separation between adjacent elements was increased from 0.30 deg. to 0.44 deg. This produced a matrix having total angular size of 1.81 deg. This was the only stimulus employed in the experiment. In every other respect, Experiment 3 was the same as Experiment 2.

ES:3.3 Results and discussion

The results of Experiment 3 are pictured by the triangular symbols in Figure 3, for the two observers, separately. It is clear from Figure 3 that the results of Experiment 3 were essentially the same as the results of Experiment 2. Notably, performance in Experiment 3 was only marginally more accurate than in the small-element condition in Experiment 2. This small difference in results could be attributed to the greater eccentricity of the larger matrix. However, some small beneficial effect of the greater inter-point separation in the larger matrix cannot be entirely ruled out: Di Lollo and Hogben (1986) found that inhibitory interactions between neighbouring points were minimal at spatial separations exceeding 0.3 deg.; but then, the effects illustrated in Figure 3 are minimal indeed.

More to the point, these results support the conclusion that differences in total matrix size did not play a major role in determining the outcome of Experiment 2.

ES:4 Concluding remarks

The expressed aim of these small empirical studies was not to provide a definitive statement regarding the role of stimulus size in suppression of visible persistence. Rather, the work was aimed as much at illustrating the type of problems and procedural difficulties typically encountered in this area as at collecting some initial empirical data.

At this initial stage, the data seem to suggest that stimulus size is not a major determinant of duration of visible persistence. The results also suggest that the strongly diverging levels of performance obtained in Experiment 1 were probably due to the effect of spatial proximity rather than element size.

Despite these indications, however, it would be premature to conclude that stimulus size has no effect on duration of visible persistence. For example, it is entirely possible that the effect of size might be approached more profitably in terms of spatial-frequency analysis. Namely, it is possible that the effect of size may be present in visual channels selectively sensitive to a restricted band of spatial frequencies, but be absent or, indeed, be entirely reversed (i.e., have synergistic rather than inhibitory effects) in channels tuned to a different band of frequencies. To examine these alternatives, a set of appropriately filtered stimuli should be employed, in place of the present stimuli whose frequency spectra are almost certainly extremely broad.

But before expanding the enquiry to the realm of waveform analysis, it would probably be judicious to complete the series of studies reported above by taking the next logical step. To wit, the evidence reported thus far strongly suggests that the results of Experiment 1 were due to variations in inter-element separation brought about by changes in element size. The next step would involve an explicit demonstration that systematic variations in inter-element separation over the range encompassed in Experiment 1 -- but with a single, unchanging, element size -- would reproduce precisely the results of Experiment 1. However, this additional study -- or studies -- would expand the scope of the present empirical work well beyond the initial aim of providing some illustrations of design problems and of procedural details.

REFERENCES

Adelson, E. H. (1978). Iconic storage: The role of rods. Science N.Y., 201, 544-546.

Adelson, E. H., and Bergen, J. (1984). Motion channels based on spatio-temporal energy. Investigative Ophthalmology and Visual Science, 25, 14.

Adelson, E. H. and Jonides, J. (1980). The psychophysics of iconic storage. Journal of Experimental Psychology: Human Perception and Performance, 6, 486-493.

Aguilar, M. and Stiles, W. S. (1954). Saturation of the rod mechanism of the retina at high levels of stimulation. Optica Acta, 1, 59-65.

Allport, D. A. (1968). Phenomenal simultaneity and the perceptual moment hypothesis. British Journal of Psychology, 59, 395-406.

Allport, D. A. (1970). Temporal summation and phenomenal simultaneity: Experiments with the radius display. Quarterly Journal of Experimental Psychology, 22, 686-701.

Alpern, M. (1953). Metacontrast. Journal of the Optical Society of America, 43, 648-567.

Alpern, M. (1965). Rod-cone independence in the after-flash effect. Journal of Physiology, London, 176, 462-472.

Alpern, M. and Rushton, W. A. H. (1965). The specificity of the cone interaction in the after-flash effect. Journal of Physiology, London, 176, 473-482.

Alpern, M., Rushton, W. A. H., and Torii, S. (1970a). The size of rod signals. Journal of Physiology, London, 206, 193-208.

Alpern, M., Rushton, W. A. H., and Torii, S. (1970b). The attenuation of rod signals by background. _Journal of Physiology_, London, _206_, 209-227.

Alpern, M., Rushton, W. A. H., and Torii, S. (1970c). The attenuation of rod signals by bleaching. _Journal of Physiology_, London, _207_, 449-461.

Alpern, M., Rushton, W. A. H., and Torii, S. (1970d). Signals from cones. _Journal of Physiology_, London, _207_, 463-475.

Averback, E. and Coriell, A. S. (1961). Short-term memory in vision. _Bell Systems Technical Journal_, _40_, 309-328.

Bachmann, T. (1984). The process of perceptual retouch: Nonspecific afferent activation dynamics in explaining visual masking. _Perception & Psychophysics_, _35_, 69-84.

Badcock, D. and Lovegrove, W. (1981). The effects of contrast, stimulus duration and spatial frequency on visual persistence in normal and specifically disabled readers. _Journal of Experimental Psychology: Human Perception and Performance_, _7_, 495-505.

Barlow, H. B. (1958). Temporal and spatial summation in human vision at different background intensities. _Journal of Physiology_, London, _141_, 337-350.

Barlow, B. H., Fitzhugh, R. and Kuffler, S. W. (1957). Change of organization in the receptive fields of the cat's retina during dark adaptation. _Journal of Physiology_, _137_, 338-354.

Bartlett, N. R., Sticht, T. G., and Pease, V. P. (1968). Effects of wavelength and retinal locus on the reaction time to onset and offset stimulation. _Journal of Experimental Psychology_, _78_, 699-701.

Bell, R. A. (1970). Principles of cathode-ray tubes, phosphors, and high-speed oscillography. Application note 115, Hewlett-Packard Co., Colorado Springs, Colorado.

Bernstein, I., Amundson, V. E., and Schurman, D. L. (1973). Metacontrast inferred from reaction time and verbal report: Replication and comments on the Fehrer-Biederman experiment. Journal of Experimental Psychology, 100, 195-201.

Bowen, R. W., Pokorny, J., and Cacciato, D. (1977). Metacontrast masking depends on luminance transients. Vision Research, 17, 971-975.

Bowen, R. W., Pola, J., and Matin, L. (1974). Visual persistence effects of flash luminance, duration, and energy. Vision Research, 14, 295-303.

Bowling, A. and Lovegrove, W. (1981). Two components to visible persistence: Effects of orientation and contrast. Vision Research, 21, 1241-1251.

Bowling, A., Lovegrove, W., and Mapperson, B. (1979). The effect of spatial frequency and contrast on visual persistence. Perception, 8, 529-539.

Bracewell, R. (1965). The Fourier Transform and Its Applications. N.Y.: McGraw-Hill.

Breitmeyer, B. G. (1978). Metacontrast masking as a function of mask energy. Bulletin of the Psychonomic Society, 12, 50-52.

Breitmeyer, B. G. (1984). Visual masking: an integrative approach. Oxford University Press: New York.

Breitmeyer, B. G., Battaglia, F., and Weber, C. (1976). U-shaped backward contour masking during stroboscopic motion. Journal of Experimental

Psychology: Human Perception and Performance, 2, 167-173.

Breitmeyer, B. G. and Ganz, L. (1976). Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression, and information processing. Psychological Review, 83, 1-36.

Breitmeyer, B. G. and Horman, K. (1981). On the role of stroboscopic motion in metacontrast. Bulletin of the Psychonomic Society, 17, 29-32.

Breitmeyer, B. G., Love, R., and Wepman, B. (1974). Contour suppression during stroboscopic motion and metacontrast. Vision Research, 14, 1451-1456.

Breitmeyer, B. G., Rudd, M., and Dunn, K. (1981). Spatial and temporal parameters of metacontrast disinhibition. Journal of Experimental Psychology: Human Perception and Performance, 7, 770-779.

Bridgeman, B. (1971). Metacontrast and lateral inhibition. Psychological Review, 78, 528-539.

Bridgeman, B. and Leff, S. (1979). Interaction of stimulus size and retinal eccentricity in metacontrast masking. Journal of Experimental Psychology: Human Perception and Performance, 5, 101-109.

Briggs, G. G. and Kinsbourne, M. (1972). Visual persistence as measured by reaction time. Quarterly Journal of Experimental Psychology, 24, 318-325.

Burr, D. C. (1980). Motion smear. Nature (London), 284, 164-165.

Burr, D. C. (1981). Temporal summation of moving images by the human visual system. Proceedings of the Royal Society of London, Series

B, Biological Sciences, 211, 321-339.

Burr, D. C. (1984). Summation of target and mask metacontrast stimuli. Perception, 13, 183-192.

Burt, P. and Sperling, G. (1981). Time, distance, and feature trade-offs in visual apparent motion. Psychological Review, 88, 171-195.

Cleland, B. G. and Levick, W. R. (1974). Brisk and sluggish concentrically organized ganglion cells in the cat's retina. Journal of Physiology, London, 240, 421-456.

Coltheart, M. (1980). Iconic memory and visible persistence. Perception & Psychophysics, 27, 183-228.

De Monasterio, F. M. (1978a). Properties of concentrically organized X and Y ganglion cells of macaque retina. Journal of Neurophysiology, 41, 1394-1417.

De Monasterio, F. M. (1978b). Center and surround mechanisms of opponent-colour X and Y ganglion cells of retina of macaques. Journal of Neurophysiology, 41, 1418-1434.

Didner, R. and Sperling, G. (1980). Perceptual delay: A consequence of metacontrast and apparent motion. Journal of Experimental Psychology: Human Perception and Performance, 6, 235-243.

Di Lollo, V. (1977). Temporal characteristics of iconic memory. Nature (London), 267, 241-143.

Di Lollo, V. (1980). Temporal integration in visual memory. Journal of Experimental Psychology: General, 109, 75-97.

Di Lollo, V. (1981). Hemispheric symmetry in duration of visible persistence. Perception & Psychophysics, 29, 21-25.

Di Lollo, V. (1983). On laterality of visual aftereffects: a rejoinder.

Perception & Psychophysics, *33*, 599-603.

Di Lollo, V. and Bourassa, C. M. (1983). Temporal integration following intensification of long-lasting visual displays. *Vision Research*, *23*, 677-687.

Di Lollo, V. and Hogben, J. H. (1985). Suppression of visible persistence. *Journal of Experimental Psychology: Human Perception and Performance*, *11*, 304-316.

Di Lollo, V. and Hogben, J. H. Suppression of visible persistence as a function of proximity and luminance. (Paper in preparation).

Di Lollo, V. and Woods, E. (1981). Duration of visible persistence in relation to range of spatial frequencies. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 754-769.

Dixon, N. F. and Hammond, E. J. (1972). The attenuation of visual persistence. *British Journal of Psychology*, *63*, 243-254.

Duysens, J., Orban, G. A., Cremieux, J., and Maes, H. (1985). Visual cortical correlates of visible persistence. *Vision Research*, *25*, 171-178.

Efron, R. (1970a). The relationship between the duration of a stimulus and the duration of a perception. *Neuropsychologia*, *8*, 37-55.

Efron, R. (1970b). The minimum duration of a perception. *Neuropsychologia*, *8*, 57-63.

Efron, R. (1970c). Effect of stimulus duration on perceptual onset and offset latency. *Perception & Psychophysics*, *8*, 231-234.

Efron, R. and Lee, D. N. (1971). The visual persistence of a mov stroboscopically illuminated object. *American Journal* *Psychology*, *84*, 365-375.

Enroth-Cugell, C. and Robson, J. G. (1966). The contrast sensitivity of retinal ganglion cells of the cat. *Journal of Physiology*, London, *187*, 517-552.

Eriksen, C. W. (1968). Sensory traces versus the psychological moment in the temporal organization of form. *Journal of Experimental Psychology*, *77*, 376-382.

Eriksen, C. W. and Collins, J. F. (1967). Some temporal characteristics of visual pattern perception. *Journal of Experimental Psychology*, *74*, 476-484.

Eriksen, C. W. and Hoffman, M. (1963). Form recognition as a function of adapting field and interval between stimulation. *Journal of Experimental Psychology*, *66*, 485-499.

Erwin, D. E. (1976). Further evidence for two components in visual persistence. *Journal of Experimental Psychology: Human Perception and Performance*, *2*, 191-209.

Erwin, D. E. and Nebes, R. D. (1976). Right hemispheric involvement in the functional properties of visual persistence. Paper presented at the annual meeting of the Eastern Psychological Association, New York, April.

Fahle, M. and Poggio, T. (1984). Visual hyperacuity: spatiotemporal interpolation in human vision. In S. Ullman and W. Rithards (Eds.) *Image Understanding*. Norwood, N.J., Ablex Publishing Corp.

Farrell, J. M. (1984). Visible persistence of moving objects. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 502-511.

Fehmi, L. G., Adkins, J. W., and Lindsley, D. B. (1969).

Electrophysiological correlates of visual perceptual masking in monkeys. Experimental Brain Research, 7, 299-316.

Fehrer, E. (1966). Effects of stimulus similarity on retroactive masking. Journal of Experimental Psychology, 71, 612-615.

Fehrer, E. and Raab, D. (1962). Reaction time to stimuli masked by metacontrast. Journal of Experimental Psychology, 63, 143-147.

Foster, D. H. (1976). Rod-cone interaction in the after-flash effect. Vision Research, 16, 393-396.

Foster, D. H. and Mason, R. J. (1977). Interaction between rod and cone systems in dichoptic visual masking. Neurosciences Letters, 4, 39-42.

Fox, R. (1978). Visual masking. In Handbook of sensory physiology, Vol. 8, Perception, (ed. R. Held, H. Leibowitz, and H. L. Teuber) pp. 621-653. Springer Verlag, New York.

Frisby, J. P. (1972). The effect of stimulus orientation on the phi phenomenon. Vision Research, 12, 1145-1166.

Fujio, T. (1982). Future broadcasting and high-definition television. N.H.K. Technical Monograph No. 32, 5-13. Tokyo: Japan Broadcasting Corporation.

Ganz, L. (1975). Temporal factors in visual perception. In Handbook of Perception, Vol. 5 (ed. E. C. Carterette and M. P. Friedman) pp. 169-231. Academic Press, New York.

Green, D. M. and Swets, J. A. (1966). Signal detection theory and Psychophysics. New York: Wiley.

Growney, R. (1976). The function of contour in metacontrast. Vision Research, 16, 253-261.

Growney, R. (1978). Metacontrast as a function of the spatial frequency composition of the target and mask. Vision Research, 18, 1117-1123.

Growney, R. and Weisstein, N. (1972). Spatial characteristics of metacontrast. Journal of the Optical Society of America, 62, 690-696.

Growney, R., Weisstein, N., and Cox, S. I. (1977). Metacontrast as a function of spatial separation with narrow line targets and masks. Vision Research, 17, 1205-1210.

Haber, R. N. and Standing, L. (1969). Direct measures of short-term visual storage. Quarterly Journal of Experimental Psychology, 21, 43-54.

Haber, R. N. and Standing, L. (1970). Direct estimates of the apparent duration of a flash. Canadian Journal of Psychology, 24, 216-229.

Hogben, J. H. and Di Lollo, V. (1974). Perceptual integration and perceptual segregation of brief visual stimuli. Vision Research, 14, 1059-1069.

Hogben, J. H. and Di Lollo, V. (1984). Practice reduces suppression in metacontrast annd in apparent motion. Perception & Psychophysics, 35, 441-445.

Hogben, J. H. and Di Lollo, V. (1986). Suppression of visible persistence in apparent motion. Perception & Psychophysics (in press).

Hubel, D. H. and Wiesel, T. N. (1977). Functional architecture of macaque monkey visual cortex. Proceedings of the Royal Society, London, 198B, 1-59.

Ikeda, M. (1965). Temporal summation of positive and negative flashes in the visual system. Journal of the Optical Society of America, 55,

1527-1534.

Ishizuka, M. and Ichihara, S. (1984). Spatial frequency and orientation specificities in metacontrast. Japanese Psychological Research, 26, 68-74.

Jacobson, J. A. and Rhinelander, G. (1978). Geometric and semantic similarity in visual masking. Journal of Experimental Psychology: Human Perception and Performance, 4, 224-231.

Johnson, M. A., and Massof, R. W. (1983). Temporal resolution as a function of eccentricity and target size. Journal of the Optical Society of America, 73, 1872.

Kahneman, D. (1967). An onset-onset law for one case of apparent motion and metacontrast. Perception & Psychophysics, 2, 577-584.

Kahneman, D. (1968). Method, findings, and theory in studies of visual masking. Psychological Bulletin, 70, 404-425.

Kao, K. C. and Dember, W. N. (1973). Effect of size of ring on backward masking of a disk by a ring. Bulletin of the Psychonomic Society, 2, 15-17.

Kelly, D. H. (1971). Theory of flicker and transient responses. I. Uniform fields. Journal of the Optical Society of America, 61, 537-546.

Kling, J. W. and Riggs, L. A. (1971). Experimental Psychology. Third edition. New York: Holt, Rinehart, and Winston.

Koffka, K. (1935). Principles of Gestalt Psychology. New York: Harcourt, Brace.

Kolers, P. A. (1968). Some psychological aspects of pattern recognition. In Recognizing patterns (ed. P. A. Kolers and M. Eden) pp. 4-61.

MIT Press, Cambridge, Ma.

Kolers, P. A. (1972). Aspects of Motion Perception. Oxford: Pergamon Press.

Kolers, P. A. and Rosner, B. S. (1960). On visual masking (metacontrast): Dichoptic observations. American Journal of Psychology, 73, 2-21.

Lefton, L. A. (1973). Metacontrast: A review. Perception & Psychophysics, 13, 161-171.

Lennie, P. (1980). Parallel visual pathways: A review. Vision Research, 20, 561-594.

Lovegrove, W. J. and Meyer, G. E. (1984). Visible persistence as a function of spatial frequency, number of cycles and retinal area. Vision Research, 24, 255-259.

Lyon, J. E., Matteson, H. H., and Marx, M. S. (1981). Metacontrast in the fovea. Vision Research, 21, 297-299.

Marzi, C. A., Di Stefano, M., Tassinari, G., and Crea, F. (1979). Iconic storage in the two hemispheres. Journal of Experimental Psychology: Human Perception and Performance, 5, 31-41.

Matin, E. (1975). The two-transient (masking) paradigm. Psychological Review, 82, 451-461.

Matteson, H. H. (1969). Effects of surround size and luminance on metacontrast. Journal of the Optical Society of America, 59, 1461-1468.

Mayzner, M. S. and Tresselt, M. E. (1970). Visual information processing with sequential inputs: A general model for sequential blanking, displacement, and overprinting phenomena. Annals of the New York Academy of Sciences, 169, 599-618.

Merikle, P. M. (1977). On the nature of metacontrast with complex targets and masks. Journal of Experimental Psychology: Human Perception and Performance, 3, 607-621.

Mewhort, D. J. K., Hearty, P. J., and Powell, J. E. (1978). A note on sequential blanking. Perception & Psychophysics, 23, 132-136.

Meyer, G. E. (1977). The effect of color-specific adaptation on the perceived duration of gratings. Vision Research, 17, 51-56.

Meyer, G. E., Lawson, R., and Cohen, W. (1975). The effects of orientation-specific adapation on the duration of short-term visual storage. Vision Research, 15, 569-572.

Meyer, G. E. and Maguire, W. M. (1977). Spatial frequency and the mediation of short-term visual storage. Science, New York, 198, 524-525.

Morgan, M. J. (1976). Pulfrich effect and the filling in of apparent motion. Perception, 5, 187-195.

Morgan, M. J. and Watt, R. J. (1983). On the failure of spatiotemporal interpolation: A filtering model. Vision Research, 23, 997-1004.

Navon, D. and Purcell, D. (1981). Does integration produce masking or protect from it? Perception, 10, 71-83.

Nelson, J. I. and Frost, B. J. (1978). Orientation-selective inhibition from beyond the classic visual receptive field. Brain Research, 139, 359-366.

Newark, J. and Mayzner, M. S. (1973). Sequential blanking effects for two interleaved words. Bulletin of the Psychonomic Society, 2, 74-76.

Pease, V. P. and Sticht, T. G. (1965). Reaction time as a function of onset and offset stimulation of the fovea and periphery. Perceptual

Motor Skills, 20, 549-554.

Peichl, L. and Wassle, H. (1979). Size, scatter, and coverage of ganglion cell receptive field centres in the cat retina. Journal of Physiology, London, 291, 117-141.

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. Perception & Psychophysics, 16, 283-290.

Proctor, R. W., Nunn, M. B., and Pallos, I. (1983). The influence of metacontrast masking on detection and spatial-choice judgments: An apparent distinction between automatic and attentive response mechanisms. Journal of Experimental Psychology: Human Perception and Performance, 9, 278-287.

Purcell, D. G., Stewart, A. L., and Brunner, R. L. (1974). Metacontrast target detection under light and dark adaptation. Bulletin of the Psychonomic Society, 3, 199-201.

Ratliff, F. (1965). Mach bands: Quantitative studies on neural networks in the retina. Holden-Day, New York.

Reeves, A. (1981). Metacontrast in hue substitution. Vision Research, 21, 907-912.

Reeves, A. (1982). Metacontrast U-shaped functions derive from two monotonic processes. Perception, 11, 415-426.

Rogowitz, B. (1983). Spatial/temporal interactions: backward and forward metacontrast masking with sine wave gratings. Vison Research, 23, 1057-1073.

Roufs, A. J. and Blommaert, F. J. J. (1981). Temporal impulse and step responses of the human eye obtained psychophysically by means of drfit-correcting perturbation technique. Vision Research, 21,

1203-1221.

Rovamo, J. and Raninen, A. (1984). Critical flicker frequency and M-scaling of stimulus size and retinal illuminance. Vision Research, 24, 1127-1131.

Sakitt, B. (1975). Locus of short-term visual storage. Science, New York, 190, 1318-1319.

Sakitt, B. (1976). Iconic memory. Psychological Review, 83, 257-276.

Sakitt, B. and Long, G. M. (1978). Relative rod and cone contributions in iconic storage. Perception & Psychophysics, 23, 527-536.

Scheerer, E. (1973). Integration, interruption and processing rate in visual backward masking. Psychologische Forschung, 36, 71-93.

Schiller, P. H. (1965). Monoptic and dichoptic visual masking by patterns and flashes. Journal of Experimental Psychology, 69, 193-199.

Schiller, P. H. (1968). Single unit analysis of backward visual masking and metacontrast in the cat lateral geniculate nucleus. Vision Research, 8, 855-866.

Schiller, P. H. and Greenfield, A. (1969). Visual masking and the recovery phenomenon. Perception & Psychophysics, 6, 182-184.

Schiller, P. H. and Koerner, F. (1966). Detection in metacontrast. Journal of Experimental Psychology, 71, 32-39.

Singer, W. and Bedworth, N. (1973). Inhibitory interaction between X and Y units in cat lateral geniculate nucleus. Brain Research, 49, 491-307.

Singer, W., Tretter, F., and Cynader, M. (1975). Organization of cat striate cortex: A correlation of receptive-field properties with afferent and efferent connections. Journal of Neurophysiology, 38,

1080-1098.

Sperling, G. (1960). The information available in brief visual presentations. Psychological Monographs, 74, Whole No. 498, 1-29.

Sperling, G. (1967). Successive approximations to a model for short-term memory. Acta Psychologica, 27, 285-292.

Sperling, G. (1970). Binocular vision: A physical and neural theory. American Journal of Psychology, 83, 461-534.

Stewart, A. L. and Purcell, D. G. (1974). Visual backward masking by a flash of light: A study of U-shaped detection functions. Journal of Experimental Psychology, 103, 553-566.

Stiles, W. S. (1939). The directional sensitivity of the retina and the spectral sensitivities of the rods and cones. Proceedings of the Royal Society, London, 127B, 64-105.

Stiles, W. S. (1949). Increment thresholds and the mechanisms of colour vision. Documenta Ophtalmologica, 3, 138-163.

Stiles, W. S. (1959). Color vision; the approach through increment threshold sensitivity. Proceedings of the National Academy of Sciences, Washington, 45, 100-114.

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

Stoper, A. E. and Banffy, S. (1977). Relation of split apparent motion to metacontrast. Journal of Experimental Psychology: Human Perception and Performance, 3, 258-277.

Sturr, J. F. and Frumkes, T. E. (1968). Spatial factors in masking with black and white targets. Perception & Psychophysics, 4, 282-284.

Toch, H. H. (1956). The perceptual elaboration of stroboscopic presentations. American Journal of Psychology, 69, 345-358.

Tolhurst, D. J. (1973). Separate channels for the analysis of the shape and movement of a moving visual stimulus. Journal of Physiology, London, 231, 385-402.

Turvey, M. T. (1973). On peripheral and central processes in vision: Inferences from an information-processing analysis of masking with patterned stimuli. Psychological Review, 80, 1-52.

Turvey, M. T. (1978). Visual processing and short-term memory. In Handbook of learning and cognitive processes, Vol. 5, Human information processing (ed. W. K. Estes) pp. 91-142. Lawrence Erlbaum Association, Hillsdale, N.J.

Tyler, C. W. and Silverman, G. (1983). Mechanisms of flicker sensitivity in peripheral retina. Investigative Ophthalmology and Visual Science, 24, 95.

Ueno, T. (1983). Visible persistence: effects of luminance, spatial frequency and orientation. Vision Research, 23, 1687-1692.

Uttal, W. R. (1970). On the physiological basis of masking with dotted visual noise. Perception & Psychophysics, 7, 321-327.

Uttal, W. R. (1981). A taxonomy of visual processes. Lawrence Erlbaum Associates, Hillsdale, N.J.

Van Ness, F. L., Koenderink, J. J., Nas, H., and Bouman, M. A. (1967). Spatiotemporal modulation transfer in the eye. Journal of the Optical Society of America, 57, 1082-1088.

Van Santen, J. P. H., and Sperling, G. (1985). Elaborated Reichardt detectors. Journal of the Optical Society of America A: Optics and

Image Science, 2, 300-321.

von Grunau, M. W. (1981). The origin of pattern information of an apparently moving object during stroboscopic motion. Perception & Psychophysics, 30, 357-361.

Vrolijk, P. C. and van der Vildt, G. J. (1982). Propagating inhibition as a function of flash diameter and duration. Vision Research, 22, 401-406.

Wade, N. J. (1974). Some perceptual effects generated by rotating gratings. Perception, 3, 169-184.

Watson, A. B. and Ahumada, A. J., Jr. (1985). Model of human visual-motion sensing. Journal of the Optical Society of America A: Optics and Image Science, 2, 322-342.

Weisstein, N. (1968). A Rashevsky-Landahl neural net: Stimulation of metacontrast. Psychological Review, 75, 494-521.

Weisstein, N. (1972). Metacontrast. In Handbook of sensory physiology, Vol. 7/4, Visual psychophysics (ed. D. Jameson and L. M. Hurvich) pp. 233-272. Springer Verlag, New York.

Weisstein, N. and Growney, R. (1969). Apparent movements and metacontrast: A note on Kahneman's formulation. Perception & Psychophysics, 5, 321-328.

Weisstein, N., Jurkens, T., and Onderisin, T. (1970). Effect of forced-choice vs. magnitude-estimation measures on the waveform of metacontrast functions. Journal of the Optical Society of America, 60, 978-980.

Weisstein, N., Ozog, G., and Szoc, R. (1975). A comparison and elaboration of two models of metacontrast. Psychological Review, 82, 325-343.

Weisstein, N., Williams, M., and Harris, C. (1982). Depth, connectedness, and structural relevance in the object-superiority effect: line segments are harder to see in flatter patterns. Perception, 11, 5-17.

Weisstein, N., Williams, M. C., and Williams, A. (1979). Connectedness and three-dimensionality affect different aspects of the metacontrast function. Investigative Ophthalmology and Visual Science, Abstract 18.

Werner, H. (1935). Studies on contour: I. Qualitative analysis. American Journal of Psychology, 47, 40-64.

Wertheimer, M. (1912). Experimentelle Studien uber das Sehen von Bevegung. Zeitschrift fur Psychologie, 61, 161-265.

Westheimer, G. and Hauske, G. (1975). Temporal and spatial interference with Vernier acuity. Vision Research, 15, 1137-1141.

Westheimer, G. and McKee, S. P. (1975). Visual acuity in the presence of retinal image motion. Journal of the Optical Society of America, 65, 847-850.

Whitten, D. N. and Brown, K. T. (1973). Photopic suppression of monkey's rod receptor potential, apparently by cone-initiated lateral inhibition. Vision Research, 13, 1629-1658.

Williams, M. C. and Weisstein, N. (1984). The effect of perceived depth and connectedness on metacontrast functions. Vision Research, 24, 1279-1288.

Yellott, J. I., Jr. and Wandell, B. A. (1976). Color properties of the contrast flash effect: Monoptic vs. dichoptic comparisons. Vision

Research, 16, 1275-1280.

Yund, E. W., Morgan, H., and Efron, R. (1983). The micropattern effect and visible persistence. Perception & Psychophysics, 34, 209-213.

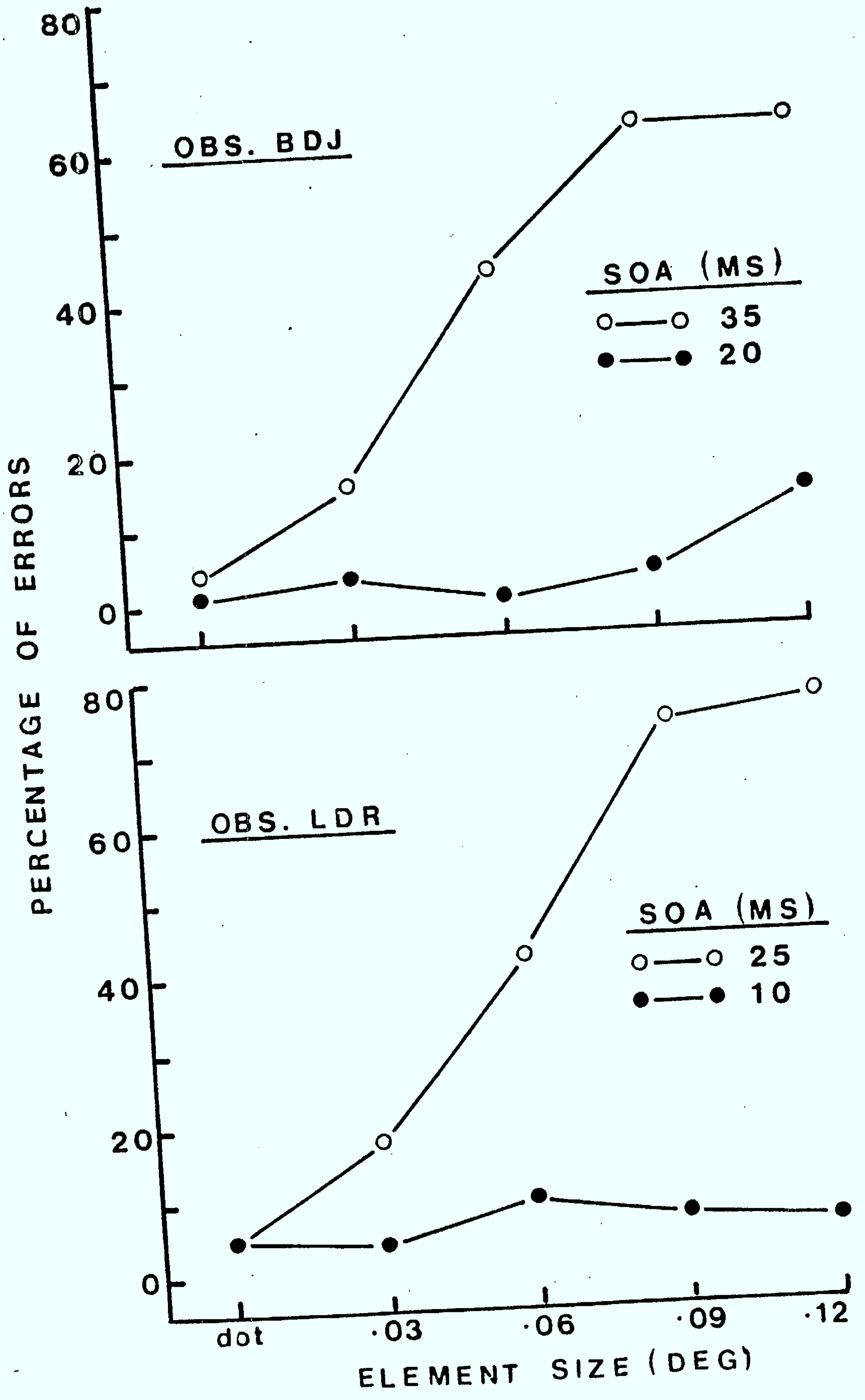
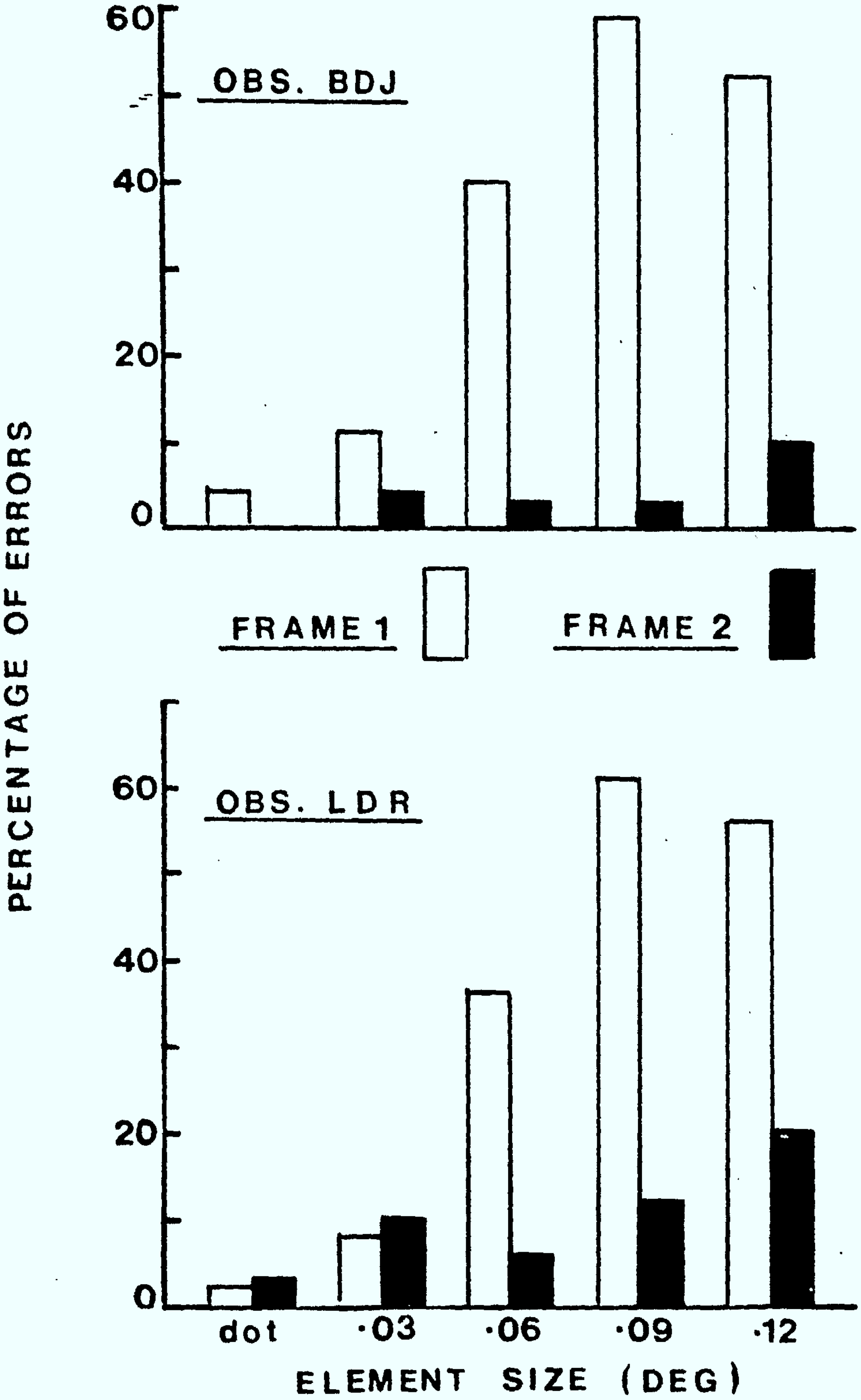

80
60
40
20
0
OBS. BDJ
SOA (MS)
○—○ 35
●—● 20
PERCENTAGE OF ERRORS
80
60
40
20
0
OBS. LDR
SOA (MS)
○—○ 25
●—● 10
dot
·03
·06
·09
·12
ELEMENT SIZE (DEG)

FIG. 1



PERCENTAGE OF ERRORS
OBS. BDJ
60
40
20
0
FRAME 1
FRAME 2
OBS. LDR
60
40
20
0
dot
·03
·06
·09
·12
ELEMENT SIZE (DEG)

Fig. 2

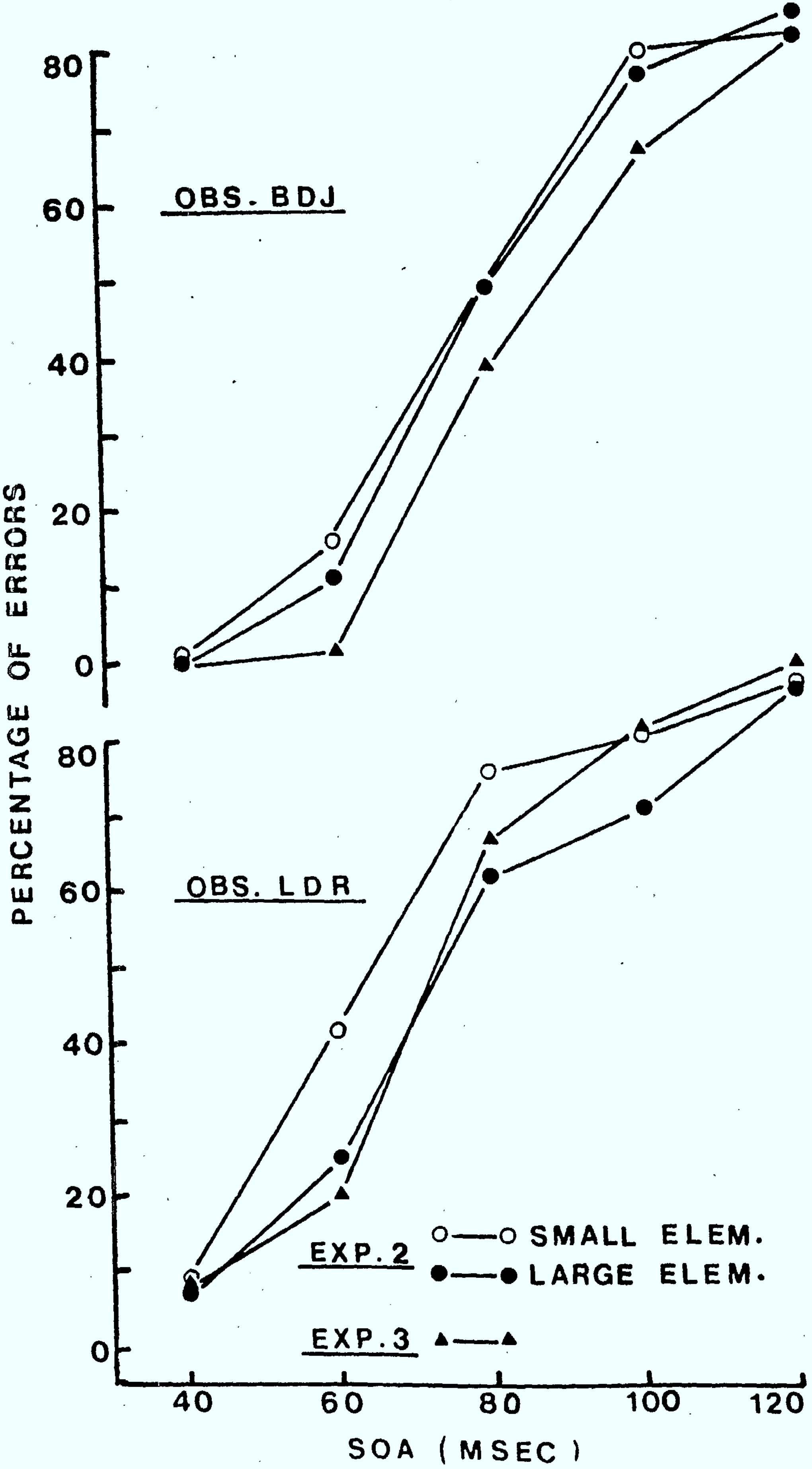

OBS. BDJ
OBS. LDR
PERCENTAGE OF ERRORS
80
60
40
20
0
80
60
40
20
0
40
60
80
100
120
SOA (MSEC)
EXP. 2
○—○ SMALL ELEM.
●—● LARGE ELEM.
EXP. 3 ▲—▲

FIG.