

**Temporal Integration and Attention:  
Contributions of Visible Persistence and Masking.**

By

**DAVID I. SHORE**

B.Sc., McMaster University, 1991

M.A., University of British Columbia, 1993

A thesis submitted in partial fulfillment of the requirements for the degree of

**Doctor of Philosophy**

in

The Faculty of Graduate Studies

Department of Psychology

We accept this thesis as conforming to the required standard:

The University of British Columbia

January 1997

© David I. Shore, 1997

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Psychology

The University of British Columbia  
Vancouver, Canada

Date April 11/97

### Abstract

The perception of moving objects and scenes illuminated by lightning are influenced by the inherent sluggishness of our visual system. This phenomenon, called visible persistence, has been considered a hard-wired aspect of human vision. As such, it has been assumed that its duration was independent of higher level goals. This assumption was tested in this thesis by experiments in which attention was manipulated and the duration of visible persistence was measured.

Visible persistence was measured using a temporal integration task. Observers searched for the letters 'F' or 'h' in displays consisting of two successive frames of complementary line segments. The interval between frames was varied to index the extent to which integration was possible. A review of temporal integration research made it clear that accuracy in such tasks is determined by both visible persistence and masking. To separate these influences, the task was studied under scotopic conditions, where masking does not interfere with persistence. These results were compared with those collected under photopic conditions, where persistence and masking play opposing roles. The observer's focus of attention was manipulated by varying the number of potential search items (set size). The similarity between target and distractor items was varied to distinguish between attentional and non-attentional accounts of the results.

Experiment 1 established baseline performance for search in brief displays under photopic and scotopic conditions. The effect of set size was largest when target and distractor items were most similar. The effect of similarity was least pronounced for scotopic viewing. This reduced effect was attributed to an increase in persistence for scotopic viewing which provided an effectively longer exposure duration and therefore an easier search.

Experiment 2 added the manipulation of frame interval in order to measure temporal integration. The effect of set size was constant across frame interval in the scotopic condition, whereas, it increased with frame interval in the photopic condition. This indicated that attention had no effect on visible persistence, but could reduce the extent of metacontrast masking.

Experiment 3 was designed to rule out non-attentional causes for the set size effects in the photopic condition. Set size was held constant while relevant target locations were indicated by instruction. The effect of frame interval was less pronounced with fewer items to attend.

These results support two main conclusions: attention does not influence visible persistence, and attention reduces the effects of metacontrast masking. In addition, the methodologies used to study temporal integration and visual search were extended in several important ways.

# Temporal Integration and Attention

## Table Of Contents

Abstract .....	ii
Table Of Contents .....	iv
List of Figures .....	vi
List of Tables .....	vii
Acknowledgments .....	viii
Chapter 1: Introduction .....	1
Visible persistence: Empirical findings .....	3
The inverse-duration effect .....	3
The inverse-intensity effect .....	5
The inverse-proximity effect .....	10
Visible persistence: Theoretical accounts .....	12
Storage theories .....	12
Processing theories .....	14
Attention: Moderating the flow of information .....	16
The visual search task .....	16
Spatial cuing .....	18
Neural substrates of visual search and spatial cuing .....	19
Previous research .....	20
Rationale of the present study .....	21
Question 1: Attention and visible persistence .....	21
An additional factor in temporal integration: Masking .....	27
Scope of the present study .....	33
Stimuli .....	33
Observers' task .....	33
Predictions .....	34

## Temporal Integration and Attention

Chapter 2: Experiment 1 .....	38
Method .....	40
Observers .....	40
Apparatus .....	40
Stimuli .....	41
Procedure .....	41
Visibility Calibration .....	42
Design .....	43
Results .....	43
Discussion .....	47
Chapter 3: Experiment 2 .....	48
Method .....	48
Results .....	49
Discussion .....	57
Chapter 4: Experiment 3 .....	58
Method .....	61
Observers .....	61
Procedure .....	61
Results .....	62
Chapter 5: General Discussion .....	65
Attention does not prolong visible persistence .....	66
Attention protects against metacontrast masking .....	70
Alternative strategies for temporal integration .....	74
Conclusions .....	75
References .....	78

List of Figures

Figure 1. Hypothetical impulse response functions .....	8
Figure 2. The predicted results for the scotopic conditions .....	25
Figure 3. The predicted results for the photopic conditions .....	31
Figure 4. Examples of search displays in the present experiments .....	35
Figure 5. Mean correct reaction time and percentage errors in Experiment 1 .....	44
Figure 6. Mean percentage error in Experiment 2 collapsed across similarity .....	50
Figure 7. Mean percentage error in Experiment 2 .....	52
Figure 8. A summary of the main findings of Experiment 2 expressed as search slopes .....	54
Figure 9. Example of relevant set size manipulation .....	59
Figure 10. Mean percentage errors in Experiment 3 .....	63

## Temporal Integration and Attention

### List of Tables

Table 1. Mean reaction time (ms) and percentage error in Experiment 1	....	87
Table 2. Mean percentage error in the photopic condition of Experiment 2	..	88
Table 3. Mean percentage error in the scotopic condition of Experiment 2	...	89



Acknowledgments

I would like to dedicate this work to my late cousin, Dr. Abe Shore, who died in 1991 from Aids. Dr. Shore was a hemophiliac and despite this hardship he worked throughout his life to forward medical research on Juvenile Arthritis. He contracted AIDS through a tainted blood transfusion in the early eighties. While he had no children, his contribution to the medical community will endure for generations to come. I hope my achievements will be as great as his.

The list of people to thank is long since I could not have completed this document without the support of my friends, family and colleagues.

Jim Enns has been the best advisor I could imagine. He is always patient, reasonable, and dependable and has assisted me in more ways than I can count; I know that I would not be where I am without him. Vince Di Lollo has been a mentor, a critic, and a friend. I sincerely appreciate the honest and astute way that he deals with both my strengths and weaknesses.

My wife Trudy deserves the greatest thanks. Her support—irrespective of our running joke—has been unimaginable. My family, both immediate and distant, have provided the resources—material, mental, and spiritual—which have made my education possible. Thank you for the love, support, and understanding. Special thanks to my parents, Abe and Barbara, my brothers Elan and Yorum, and my sister Pearl. A special thanks to cousin David Shore—I've finished writing, now its your turn.

The guys, especially Dave, Joel, and Paul. My five and half years in Vancouver would not have been nearly as fun without you. Thanks for all of the good times.

The Vision Lab: Jamie for his perspective, friendship, and simple straightforward way of communicating. Lana, for her experience, knowledge, and editing help. Jannette, for maintaining the lab and feeding me often.

My fellow graduate students: David Eichhorn, Christine Stager, Jason Carr, Steve Heine, Martin Carroll, Sean Renoylds, David Mandel, and others.

I would also like to thank Jamie Brehaut again, and Karen Laird, for participating as subjects.

## Chapter 1: Introduction

Visible persistence is a pervasive feature of everyday perception. For example, the ability to perceive television pictures depends on it (Fink & Lutyens, 1960): An electron gun fires sequentially, illuminating the screen one pixel at a time, so that the entire image is presented over a 15 millisecond period. The phosphor on the television screen emits light for only a few milliseconds, with the screen remaining blank the rest of the time. Nonetheless, we perceive the picture to be continuously visible.

In the millennia before television was invented, people were known to entertain themselves by waving a burning ember in the air to draw shapes or their names. This observation was first recorded by Boethius at the end of the fifth century C.E. (cited in Allen, 1926). Throughout history, a fundamental issue for researchers has been the determination of the duration of persistence. One method to estimate this duration was first proposed by Newton. A hot coal was spun on the end of a stick. The duration of visible persistence was equivalent to the time to make one revolution when no break in the circle could be perceived. This method was first used by D'Arcy in the 1700's who provided an estimate of 0.133 sec (see Allen, 1926). Since then, many other measures have been proposed (see reviews by Coltheart, 1980; Long, 1980).

In both modern and ancient studies, the assumption has been that visible persistence is linked to the activity of low-level visual mechanisms. Low-level

vision is generally thought to consist of those processes which are independent of goal-directed behaviour and operate in parallel across the visual scene.

Accordingly, visible persistence has been investigated in relation to factors which influence low-level representations, such as intensity, duration, and spatial proximity of display elements. However, other literature cited below contains many examples demonstrating that many of these processes can be influenced by the deployment of attention.

Visual attention refers to problems encountered by an organism with finite resources in an environment with infinite amounts of information. In this thesis, the emphasis is on selectivity for only one of many items in a display. Previous studies of such selectivity have examined perceptual latencies to cued targets (Posner, 1980), identification accuracy of items at precued locations (Eriksen & Hoffman, 1974), and the effects of irrelevant items on visual search (Treisman & Gelade, 1980).

The question prompting the present research was whether focused spatial attention could influence the duration of visible persistence. However, in the course of reviewing literature on visible persistence, it became apparent that the measure used to index persistence was also affected by metacontrast masking. Attempts to rule out this factor led to a second question regarding the effects of attention on masking.

To provide a background to these questions, salient aspects of past research on visible persistence and spatial attention are summarized next.

### Visible persistence: Empirical findings

Empirical studies have identified three major factors that influence the duration of visible persistence: stimulus duration, stimulus intensity, and spatial proximity amongst stimulus components displayed in temporal succession (see reviews by Coltheart, 1980; Dick, 1974; Long, 1980). The duration of visible persistence was found to be related inversely to each of these variables. These relations have come to be known as the inverse-duration effect, the inverse-intensity effect, and the inverse-proximity effect. These three effects are outlined separately below, followed by a brief review of several theories of persistence.

The inverse-duration effect. The duration of persistence is known to be related inversely to the duration of the physical stimulus. This inverse relation was first reported by Efron (1970, 1973), and has been studied extensively by Di Lollo and co-workers using a temporal integration task (Di Lollo, 1980; Di Lollo & Wilson, 1978). This task is worth describing in some detail because it was used in the present studies, albeit in modified form.

As used by Hogben and Di Lollo (1974), the task required the integration of two stimuli displayed in rapid succession and separated by an inter-stimulus

interval (ISI). Viewed separately, the stimuli appeared as random aggregates of 12 dots, but, viewed together, they formed a  $5 \times 5$  square matrix of dots, with one dot missing from a location chosen randomly. The task of the observer was to name the location of the missing element within the matrix. This task can be performed successfully only if all elements are visible simultaneously, which occurs when the ISI is brief. In this case, the empty location stands out clearly against the integrated matrix. When the ISI is long, however, the observer sees a matrix riddled with empty locations, all of which, on analysis, turn out to have been occupied by elements of the first stimulus. Temporal integration requires some form of visible persistence capable of bridging the ISI between the two successive portions of the display. In turn, estimates of the duration of visible persistence can be obtained by increasing the ISI until temporal integration breaks down, and the location of the missing element can no longer be identified. As noted above, temporal integration is achieved easily at brief ISIs but becomes progressively more difficult as the ISI is increased (Hogben & Di Lollo, 1974).

This task was used to study the duration of visible persistence as a function of stimulus duration. The exposure duration of the leading stimulus was varied systematically while holding constant the duration of the ISI and of the trailing stimulus (e.g., Di Lollo, 1980). In agreement with earlier work (Efron, 1970), a strong inverse relation was obtained between the duration of the

inducing stimulus and the estimated duration of visible persistence (i.e., persistence was longer for stimuli of shorter duration).

The inverse-intensity effect. An inverse relation between stimulus intensity and duration of visible persistence (i.e., shorter duration for more intense stimuli) was first reported by Ferry (1892) and has been formalized in the Ferry-Porter Law (Brown, 1965a; Kelly, 1961; Porter, 1902). These researchers used an intermittent light source to provide a measure of the critical frequency at fusion. It was found that as stimulus intensity was increased, the critical frequency increased correspondingly, implying shorter persistence for brighter stimuli. Inverse-intensity effects have also been obtained with other experimental paradigms (Allport, 1968; Castet, Lorenceau, & Bonnet, 1993; Di Lollo, 1984; Di Lollo & Hogben, 1987; Efron & Lee, 1971; Smith, 1969).

A positive relation between intensity and visible persistence (e.g., Long & Sakitt, 1981), or else no change in the duration of persistence with changes in intensity (e.g., Adelson & Jonides, 1980) have also been reported. These findings, however, do not disconfirm the inverse-intensity rule for the following reasons. As noted by Adelson and Jonides (1980), evidence for positive-intensity effects comes from studies in which intense stimuli were presented to dark-adapted observers. These are optimal conditions for producing retinal afterimages, whose duration is known to be related positively to stimulus intensity (see review by Brown, 1965b). Retinal afterimages are not to be confused with visible

persistence since the two phenomena are known to be different and to be separable on several dimensions (Di Lollo, 1984; Di Lollo, Clark, & Hogben, 1988). One of those dimensions is stimulus intensity. This factor affects the duration of retinal afterimages positively (i.e., increases in intensity lead to increases in the duration of retinal afterimages) and the duration of visible persistence inversely (i.e., increases in intensity lead to a reduction in the duration of visible persistence).

Null results (i.e., when changes in intensity have no consistent effect on visible persistence) are found only when all the stimuli are totally confined within the photopic, or within the scotopic, range of intensities (see review by Di Lollo & Bischof, 1995). That is, an inverse relation between stimulus intensity and duration of visible persistence holds true provided that at least some of the stimuli fall within—or span—the mesopic range of intensities. An extreme example of this effect is shown graphically in Figure 1A, where visible persistence under scotopic viewing is seen to last much longer than under photopic viewing. Plausible neurophysiological mechanisms underlying this pattern of results have been discussed by Di Lollo and Bischof (1995).

The differences between photopic and scotopic viewing extend beyond the simple observation that persistence is longer for scotopic viewing. Under scotopic conditions (luminance less than  $10^{-1}$  cd/m<sup>2</sup>) perception is determined solely by the rods whereas under photopic viewing (luminance greater than  $10^2$

cd/m<sup>2</sup>) only the cones are used. In the middle (or mesopic) range there are contributions from both the rods and the cones. For the present purposes, there are two important observations which should be highlighted. First, under photopic viewing, the receptive field of the retinal ganglion cells have a characteristic centre surround antagonism. For example, a given ganglion cell will increase its activity when a light (of suitable luminance and size) is directed onto its receptive field. By increasing the size of the spot, the activity of the cell will decrease because the light is activating the inhibitory surround. If the spot encompasses the entire receptive field, then the activity sponsored by the excitatory centre would be entirely offset by the inhibitory surround, resulting in a near resting rate of activity. This antagonistic arrangement provides a very precise representation of the visual world. As the level of illumination is reduced into the scotopic range, the size of the excitatory centre increases and the inhibitory surround shrinks until under fully scotopic viewing there is no inhibitory surround. This is one contributing factor in determining the relatively poor acuity under dark adapted viewing.

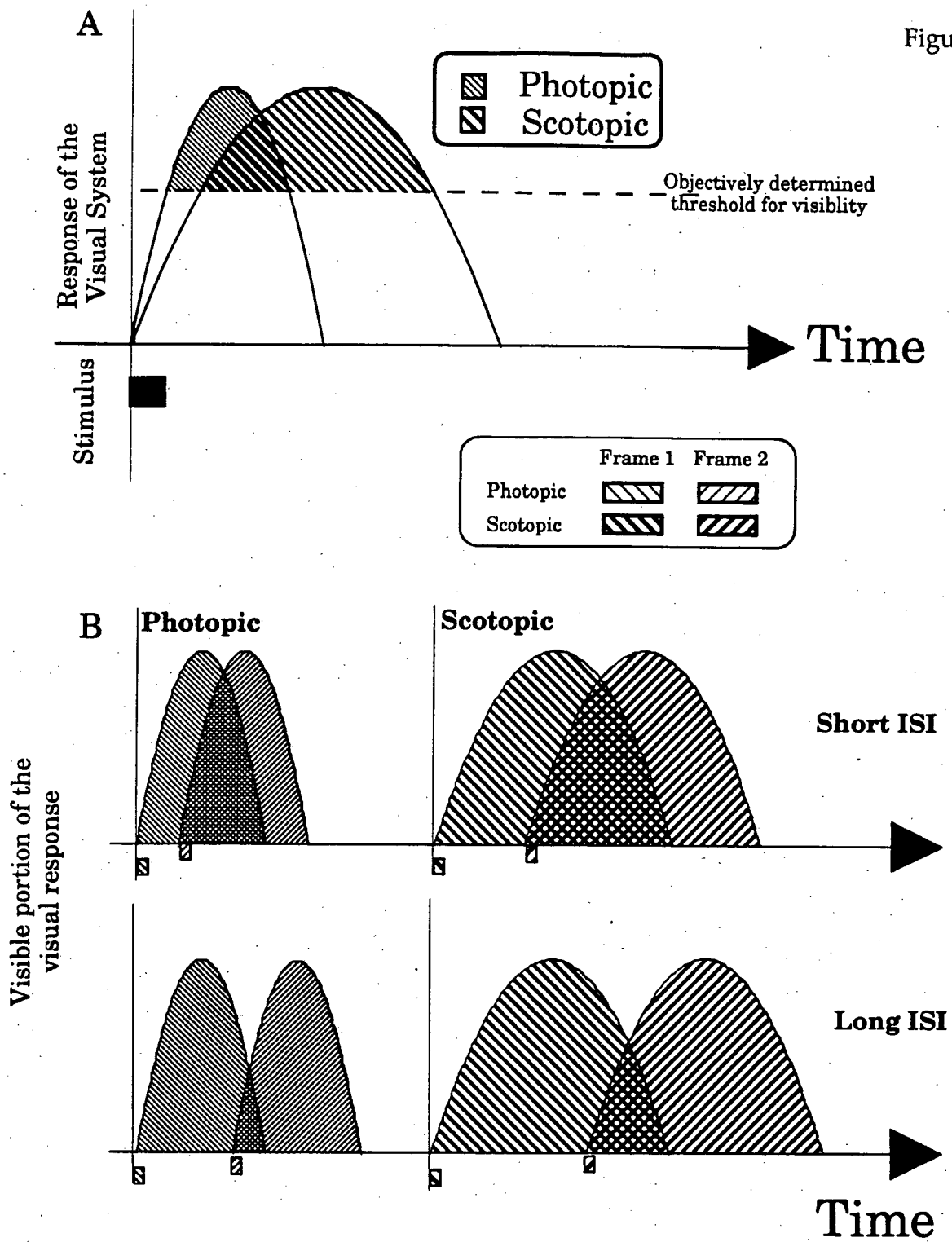
With photopic levels of illumination, a second advantage is utilized by the visual system. Each cone is connected to two bi-polar cells which each respond in an opposite fashion. When light is directed at a single cone, one of the bi-polar cells responds positively, while the other one responds negatively. These cells then connect to amacrine and horizontal cells in the retina to form



## Temporal Integration and Attention

Figure 1. Hypothetical impulse response functions (IRF) which underlie performance in the task used. (A) A representation of the single frame design used in Experiment 1. There are two things to note from this figure. First, the point at which the scotopic curve crosses the threshold line is later, in time, than that for the photopic curve. This represents the longer retinal latency in the scotopic environment. Second, the duration of visible persistence, as shown by the horizontal size of the impulse response function, is longer for the scotopic viewing condition. Results from the Mesopic range of luminance would fall between these two extremes. (B) A schematic representation of the IRFs in the temporal integration task (Experiments 2 and 3). Only the portion above the objectively determined threshold is shown. Note that as the ISI is made longer, the degree of overlap between the two frames is decreased. This is consistent with the poorer performance at the longer ISIs in this task. The scotopic condition, which has longer persistence (see A above), has a larger degree of overlap at both levels of ISI. Note that the ISIs shown are longer for the scotopic condition than the photopic condition since longer ISIs were tested in these conditions.

Figure 1



two mosaics of ganglion cells which have opposing reactions to a light stimulus. The activity of ON centred cells increases when a light is presented to the excitatory centre of its receptive field. OFF centred cells prefer a reduction in illumination. These two pathways appear to remain segregated up until the cortex (Schiller, 1994). Under scotopic levels of illumination, only the ON channel is operational since the rods do not connect to the OFF bi-polar cells.

The lack of an inhibitory surround and the absence of an OFF channel will be important below when discussing the role of masking in the temporal integration task.

The inverse-proximity effect. The question of how spatial proximity between successively-displayed elements affects the duration of persistence was investigated using both static and moving stimuli. With static stimuli (the matrix task described above), it was found that, as the spatial proximity between adjacent matrix-dots was increased, the estimated duration of visible persistence decreased correspondingly (Di Lollo & Hogben, 1987). This spatial and temporal sensitivity is similar to that found in metacontrast masking, where the visibility of a temporally leading target is impaired when a second stimulus is presented nearby and soon after. Following this reasoning, one interpretation given to the inverse-proximity effect is that the dots in the second frame of a temporal integration task act as metacontrast masks (Groner, Groner, Bischof & Di Lollo, 1990).

An inverse-proximity effect is also found with stimuli in motion. A single dot presented at regular intervals and displaced in space, can produce the perception of motion. If the temporal interval between successive displays is brief, the observer sees not one, but a fading trail of dots following the leading dot. This is referred to as motion smear. Its length (or, equivalently, the number of dots visible simultaneously on the screen) provides an index of the duration of visible persistence. It can be used to study the duration of visible persistence as a function of the spatial proximity between successively-presented dots. In agreement with the results obtained with static stimuli, it has been found that the length of motion smear (and hence the estimated duration of visible persistence) decreases as the spatial proximity between successive dots is increased, i.e., an inverse-proximity effect (Burr, 1980; Farrell, 1984; Hogben & Di Lollo, 1985). Thus, research on both temporal integration and motion smear indicates that the duration of visible persistence can be affected by temporally trailing events.

For the purposes of the present study, it is important to note the assumption underlying all work on visible persistence: Persistence is based on mechanisms of low-level vision. This observation is not limited to the studies in this brief outline; rather, it applies to the entire field, as can be verified from several comprehensive reviews (e.g., Coltheart, 1980; Di Lollo & Bischof, 1995; Long, 1980). The assumption that persistence is primarily a low-level visual

phenomenon is also evident in various theoretical accounts to which we now turn.

### Visible persistence: Theoretical accounts

Theories of visible persistence can be grouped into two broad classes based on either the concept of information storage (e.g., Neisser, 1967; Sakitt, 1975, 1976; Sperling, 1960, 1967) or that of information processing (Breitmeyer, 1980, 1984; Di Lollo, 1980; Dixon & Di Lollo, 1994; Irwin & Yeomans, 1991; Loftus & Hanna, 1989).

Storage theories. The initial evidence about visible persistence (e.g., Sperling, 1960) led almost compellingly to the formulation of storage theories. Visible persistence was likened to the decaying contents of a sensory "store". It was hypothesized that the presentation of a brief stimulus (typically an array of letters) charged a sensory store at some low level in the visual system. The sensory store was compared to a leaky capacitor which maintained its charge while connected to a voltage source (i.e., while the external stimulus was displayed) but began to discharge as soon as the voltage source was disconnected (i.e., when the external stimulus was turned off). The contents of the sensory store were thought to be devoid of meaning (i.e., to be "precategory") but to be distinguishable in terms of such physical stimulus characteristics as colour, brightness, and motion (Coltheart, Lea, & Thompson, 1974; Sperling, 1960;

Treisman, Russell, & Green, 1975; von Wright, 1968). The major function assigned to the sensory store was to serve as a buffer from which items could be selectively transferred to more durable storage (Sperling, 1967).

Filling the sensory store was held to be an entirely automatic, stimulus-bound process. The only part of the system deemed to be under voluntary control was the transfer mechanism, which could be selectively directed to specific items on the basis of purely physical aspects of the stimuli. Once selected for transfer, these items were placed in short-term memory where they were categorized and associated with long-term memories. For this reason, the sensory store was labelled pre-categorical. The transfer mechanism did not affect the temporal characteristics of the sensory store but merely probed its passively decaying contents.

Suggestions as to the neurophysiological correlates of the sensory store reflected the view that visible persistence was a phenomenon of low-level vision. A well-known—and, at the time, influential—proposal was that the sensory store was located in the rod photoreceptors (Long & Sakitt, 1980; Sakitt, 1975, 1976). This proposal, however, was soon disconfirmed on empirical grounds (Adelson, 1978; Adelson & Jonides, 1980). First, the role of the rods was questioned when persistence was found for coloured stimuli which would only be registered by the cones (Adelson, 1978). The second empirical observation which undermined all storage models was the inverse duration effect. The

leaky-capacitor, and similar storage analogies break down when it is shown that the relation between the duration of the display and the duration of visible persistence is just the opposite of what should be expected between the duration of the charging agent and the amount of charge in the store. Considerations such as these led to a change in perspective from storage to processing models.

Processing theories. The human information-processing approach treats perception as the result of a series of computational phases, each operating on a representation of a stimulus coded in terms of the current process. This approach can also be used to account for visible persistence (Breitmeyer, 1984; Di Lollo, 1980; Turvey, 1973; 1978). In processing terms, visible persistence is identified with a period of sensory-coding activity triggered by—and time-locked to—the onset of the stimulus. Once triggered by stimulus onset, the burst of activity continues for a fixed period, whether or not the stimulus continues to be displayed. If the duration of the stimulus exceeds the period of activity initiated at stimulus-onset, then no visible persistence will be available when the stimulus is turned off. The duration of visible persistence, in this scheme, is held to be inversely related to exposure duration (the inverse-duration effect).

Although clearly different in many respects, storage and processing theories share the common assumption that visible persistence is unaffected by volitional control. By and large, the processing activity responsible for visible persistence is deemed to take place at relatively low levels in the visual system.

This is evident in the neurophysiological mechanisms that have been suggested as bases for the sensory-coding activity. For example, Duysens, Orban, Cremieux, and Maes (1985) identified single units in area 17 of the cat, which responded in a manner entirely consistent with the inverse-duration effect found in humans for stimuli of comparable duration. That is, once fired, the units responded for a fixed duration, regardless of the duration of the stimulus. If the stimulus was brief, the period of activity extended beyond stimulus termination; if the stimulus was long, the burst of activity abated before stimulus offset.

It should be noted that, among processing theories, the assumption of a solely low-level determination was not as strongly stated. The hypothesis was entertained that the processes underlying persistence may take place at multiple levels in the visual system.

... as the coding of the initial stimulus proceeds from energy transduction at the retina to the emergence of meaning and the ramification of associations at higher centers, concomitant short-lived representations would ensue, each stemming from, and coded in terms of, the prevalent processing activity taking place during a given phase. (Di Lollo, 1980, p. 95)

Despite a readiness to regard higher levels in the visual system as being involved in visible persistence, the implicit—and often unstated—assumption remained that high-level, goal-directed, cognitive factors did not influence its duration. More important, all theories were built on the assumption of a unidirectional flow of information from peripheral to more central parts of the



visual system. The reverse flow of information was never proposed, although at least one researcher contemplated the option, "Nor is the possibility discounted of feedback loops between [processing] stages" (Di Lollo, 1980, p. 93). It is the objective of the present work to explore this possibility.

### Attention: Moderating the flow of information

Almost all theories of visual perception hold to some form of a dichotomy in distinguishing between "seeing" versus "understanding", or sensation versus perception (Broadbent, 1958; Hebb, 1949; Helmholtz, 1867/1967; Neisser, 1967). In modern information-processing theories, this dichotomy is seen in the time-based distinction of early vs. late stages of processing (Enns, 1992; Di Lollo, 1980; Julesz, 1984; Palmer, Ames & Lindsey, 1993; Shaw, 1980; Treisman, 1986; Treisman, Cavanagh, Fisher, Ramachandran, von der Heydt, 1990; Verghese & Nakayama, 1993; Verghese & Pelli, 1992; Zucker, 1987). Early vision consists of those processes which operate in parallel across the visual field and are not affected by goal directed aspects of behaviour. Late vision consists of more complex processes which can be voluntarily applied to specific items in the visual array. The former are often considered to be hardwired, while the latter are considered more adaptive.

The visual search task. The visual search task is a popular tool in the study of early visual operations (Enns & Rensink, 1991; Neisser, 1967; Palmer, 1994; Palmer, Ames, & Lindsey, 1993; Rensink & Enns, 1995; Treisman et al, 1990). In a typical

experiment, the observer's task is to report whether a target is present or absent in a display. Set size (i.e. the number of items in the display) is the critical independent variable as it directly influences how much attention can be devoted to any given item.

The relation between performance (e.g., reaction time or accuracy) and set size is usually represented by the slope of the function relating these two variables. This is referred to as search slope. If the target can be distinguished from the distractors by some simple feature (e.g., size, luminance, colour, or orientation), then the search slope is flat or very shallow and the target is said to pop-out. When pop-out occurs, it is assumed that attention is directed to the target without effort. This has also been referred to as a parallel search because target detection seems to occur across the entire scene at once. On the other hand, if the target differs from distractor items by a conjunction of features, then the time taken to find it increases with set size, and thus, the search slope is steeper. In this case, attention must be directed voluntarily to items in the display and search is considered to be serial (Enns & Rensink, 1991; McLeod, Driver & Crisp, 1989; Nakayama & Silverman, 1986; Treisman, 1986; Treisman, 1988; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Wolf, Cave & Franzel, 1989).

An alternative conceptualization of the feature-conjunction distinction is that of target-distractor similarity (Duncan & Humphreys, 1989). Low target-distractor similarity can result in pop-out search whereas a higher degree of

similarity results in effortful search. The degree of attention required to guide search therefore increases along with target-distractor similarity.

Spatial cuing. It is well known that attention can be directed to spatial locations independent of eye movements (James, 1890; Posner, 1980). The spatial cuing paradigm is a popular method for investigating this aspect of attention. In these experiments, the observer is presented with a cue which indicates, with varying probability, the target location. Experiments using a wide range of stimuli and spatial cuing have shown that detection and discrimination accuracy are both improved by foreknowledge of target location, suggesting an attentional influence on sensory factors (Posner, Snyder & Davidson, 1980). Sensory priming—in the form of increased neural sensitivity and shorter neural latencies—is thought to cause these effects (Posner, 1980). However, other researchers have proposed that these effects are mediated by later decision processes (Shui & Pashler, 1994; 1995; but see Luck, Hillyard, Mouloua & Hawkins, 1996).

The question of the locus of attentional effects has been addressed using the methods of signal detection theory (Bashinski & Bacharach, 1980). The observers' task was to detect a near-threshold target, which could occur on either the right or left side of the screen. A cue was presented prior to the target to indicate the likely side. Manipulations of cue predictability had effects on sensory sensitivity, but not on decision bias, supporting the early locus of attention theory (Bashinski & Bacharach, 1980). Similar conclusions were reached utilizing a discrimination task

(Tsal, Shalev, Zakay, & Lubow, 1994). Observers were required to indicate the brightness of a grey patch by matching it to a memorized standard. It was observed that attention reduced the perceived contrast of the patch.

Direct evidence for the sensory priming account of attention came from the study of temporal order judgments. Observers were cued to attend to one side of the display screen or the other before indicating which of two stimuli appeared first. The relative onset of the two stimuli was varied from 0 to 100 ms. The stimulus in the attended location was seen up to 40 ms before the stimulus in the unattended location (Stelmach & Herdman, 1991). In a second study, observers reported motion from the temporally trailing—although attended—item towards the temporally leading—and unattended—item (Stelmach, Herdman, & McNeil, 1994). This is consistent with attention exerting its influence at the earliest stages of motion perception.

Neural substrates of visual search and spatial cuing. Visual search and spatial cuing have been recently combined in single-cell recording studies of awake monkeys (Motter, 1993; 1994a; 1994b). In these studies, monkeys fixated on the centre of a screen and were presented with a multi-element display. Their task was to indicate the orientation of a target line indicated by a spatial cue. Attending to the target caused an increase in the firing rate of a cell with a receptive field centred on the line. When the same line was unattended (i.e., it was not the target), there was a decline in the firing rate. As set size was increased, the difference in firing rate

between attended and unattended stimuli also increased. These effects were observed in primary visual cortex as well as in several extrastriate areas. Data such as these suggest that target selection affects the firing rate of neurons very early in the visual stream. They also indicate that the selection processes are more active when there are distractors in the visual field to compete with the target. Most importantly for the present thesis, these data indicate that it is plausible that visual selection may exert an influence on the same neural structures thought to produce visible persistence.

### Previous research

A possible relation between attention and visible persistence was addressed previously by Orenstein and Holding (1987). These researchers used a temporal integration task to measure visible persistence. Attention was manipulated by varying the location of the fixation point. Fixation was located either in the centre of the display (distributed attention), or at the position of the to-be-reported target (focused attention). Not only did this manipulation reduce the relevant set size (from twelve to one), but it also allowed the target to be foveated. Thus, any differences between the two conditions could not be attributed uniquely to attention.

An even larger problem of interpretation was that accuracy in the distributed-attention condition did not differ from chance, even when the two frames were presented simultaneously. That is, observers were unable to perform the task even

when persistence was not required. Nonetheless, the researchers made the unwarranted conclusion that persistence did not exist without attention.

### Rationale of the present study

Question 1: Attention and visible persistence. The question behind this study was whether visible persistence was affected by attention. To address it, methodologies were combined that had previously been used separately to study attention (i.e., visual search) and visible persistence (i.e., temporal integration of successive displays). The factor of target-distractor similarity was manipulated in this search task to distinguish between alternative interpretations of the data.

To understand how attention might affect visible persistence, it is helpful to restate the rationale underlying the temporal integration task. In this task, the stimuli to which the observer must respond are presented in two successive frames separated by an ISI. Since the two frames must be integrated if the observer is to respond correctly, visible persistence is necessary to bridge the ISI. In turn, the longer the visible persistence, the longer the ISI which can be bridged. According to this rationale, if attention increases the duration of visible persistence, then attended items would be integrated over longer ISIs. Alternatively, if attention decreases the duration of visible persistence, then attended items would only be integrated over shorter ISIs. This latter situation leads to some counterintuitive

predictions where performance in large set sizes would actually be better than performance in small set sizes. This possibility is not considered further.

In the present work, the focus of attention was manipulated by varying the number of items (i.e., set size) in a two-frame visual search task. It is conventionally assumed that the focus of attention varies inversely with the number of items presented. In this task, upon presentation of the first frame, attention could be focused more sharply on individual items if the set size was small. Alternatively, if set size was large, attention would be distributed more broadly. Therefore, the effect of focused attention on visible persistence would be more evident in search through small rather than large set sizes. If one assumes that attention increases the duration of visible persistence, it follows that longer ISIs would be bridged when the set size is small. This relation between attention and visible persistence predicts an interaction between set size and ISI. As I will show, the existence of masking in the temporal integration task, restricts the validity of this rationale to the scotopic viewing conditions.

Before restricting our consideration to an attentional account of such an interaction, it is necessary to rule out possible non-attentional accounts. To begin with, it is important to consider what happens to performance in visual search when the duration of the display is reduced. This has direct relevance to the manipulation of ISI. The reasoning is as follows: The search display consists of an integrated representation of the contents of two frames. Such a display is available

only if the first frame produces sufficient visible persistence to bridge the ISI. For this reason, the duration of the search display is related directly to the duration of visible persistence and inversely to the ISI (see Figure 1B). We refer to the duration of this integrated search display as the effective exposure duration because it is only during this period that all elements are presumed to be available simultaneously for the search process.

We have noted above that increments in ISI lead to decrements in effective exposure duration. Such decrements, therefore, can be supposed to produce an interaction between set size and ISI. In fact, just such an interaction was reported by Bergen and Julesz (1983). In that study, the exposure duration was varied systematically by presentation of a mask. The observers' task was to detect a target amongst distractors. It was found that as the exposure duration was reduced, the probability of detecting the target was also reduced. This effect was more pronounced when set size was large than when it was small. In other words, the search slope relating number of errors to set size became progressively steeper as exposure duration was reduced. In the present work, precisely the same relation is expected with changes in effective exposure duration. That is, as the ISI is increased, the steepness of the search slope should increase correspondingly. This represents an interaction between set size and ISI which would arise even if attention had no effect on the duration of visible persistence. Yet, this interaction is indistinguishable from that predicted by the attentional account. In other words, the same pattern of

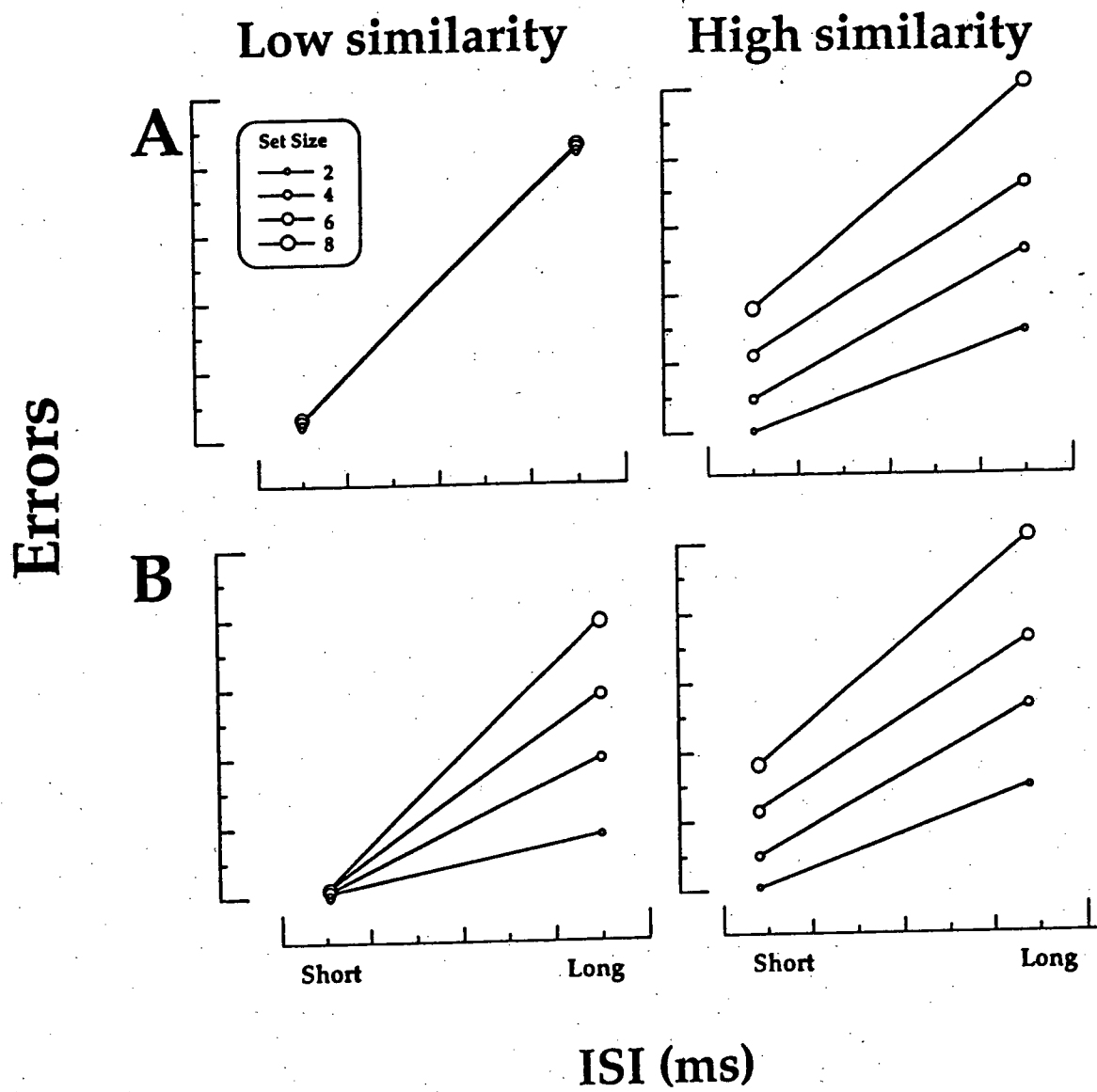


results is predicted by both the attentional and the non-attentional hypotheses for decreases in effective exposure duration.

This said, we must now specify that the predictions from these two accounts are not equivalent under all circumstances. Namely, the two hypotheses can be separated on the basis of their predictions for a pop-out search task, which removes set size as a factor in determining performance. First, consider the predictions made by the non-attentional hypothesis (i.e., attention does not affect visible persistence). To be sure, although the search slope is flat across set size, overall performance will still deteriorate progressively as ISI is increased. This is because increasing the ISI decreases effective exposure duration and performance is correspondingly impaired equally for all set sizes. This prediction was verified by Bergen and Julesz (1983) with displays in which target-distractor similarity was low. The salient issue in this non-attentional account is that search performance for the pop-out search task is influenced by effective exposure duration but not by set size. For the high similarity condition, reductions in effective exposure duration (caused by increases in ISI) could lead to an increase in search slope. Thus, the non-attentional hypothesis predicts an interaction between set size and ISI when similarity is high but not when it is low. This is illustrated in Figure 2A.

Figure 2. The predicted results for the scotopic conditions: (A) Attention does not influence the duration of visible persistence. (B) Attention prolongs the duration of visible persistence.

Figure 2



In contrast, the hypothesis that persistence is prolonged by focused attention predicts an interaction between set size and ISI both for pop-out and for more effortful search. In the case of pop-out search (i.e., when the similarity between target and distractor items is low), the interaction is predicted on the basis of two assumptions. First, that overall accuracy decreases with reductions in effective exposure duration, and second, that the effective exposure duration is expected to be longer for items in smaller displays. The first assumption is in common with the non-attentional hypothesis discussed above and is supported by the results of Bergen and Julesz (1983). The second assumption forms the essence of the attentional hypothesis. Namely, that visible persistence is increased in duration for attended items and that attention can be focused more sharply on individual items if set size is small. On the basis of these two assumptions, visible persistence for any given item should be longer when set size is small. In turn, longer visible persistence of individual items will produce longer effective exposure durations for those items. In essence, this re-establishes set size as a determinant of performance even when similarity is low. This is illustrated in Figure 2B. The baseline effect of set size for the high similarity condition (on the right panel) is predicted on the basis of the known effect of high similarity in visual search.

An additional factor in temporal integration: Masking. Inherent in the above rationale is the understanding that visible persistence of the first frame must continue unabated throughout the ISI so as to overlap with the second frame. On

this basis, it is possible to examine how attending to the first frame might affect visible persistence. The crucial assumption here is that there are no other aspects of the task that interfere with visible persistence. This assumption becomes questionable when it is realized that the sequential displays used in the temporal integration paradigm bear striking similarities with those used in metacontrast masking. In metacontrast masking, perception of a temporally leading target is impaired when a second stimulus (the mask) is presented nearby and soon after. It is conceivable that the second frame in the present temporal integration task may serve a similar masking function. This interference would result in poorer integration. Although this is a general characteristic of the temporal integration paradigm and has been noted in earlier work (Di Lollo & Hogben, 1987; Groner, Groner, Bischof & Di Lollo, 1990), it has not been thoroughly examined.

Clearly, metacontrast masking must be considered when studying temporal integration of successive displays. Suppose that attention acted to prolong visible persistence, thus increasing the ISI over which temporal integration could occur. Metacontrast masking would work in opposition to attention in that it would interfere with persistence. This presents a potential problem for the initial goal of the present research. If it was found that integration performance did not improve with focused attention, the results could be ambiguous. Namely, we would not know whether attention failed to increase the duration of visible persistence or whether such an increase was counteracted by masking.

This ambiguity can be resolved if masking is removed as a consideration in temporal integration. One way in which this can be done is by presenting the stimuli under dark-adapted conditions, as was done by Bischof and Di Lollo (1995). It was shown in that study that metacontrast masking is obtained in light-adapted but not in dark-adapted viewing. The elimination of masking was ascribed to the absence of inhibitory interactions in the dark-adapted visual system (e.g., von Bekesy, 1968). This was the strategy adopted in the present work. By presenting the stimuli under scotopic conditions, masking was removed as a potential source of confounding. Under scotopic viewing, the temporal integration task provides an unbiased index of visible persistence.

Question 2: Attention and masking. Given that masking is a factor in photopic viewing, presenting the stimuli under both scotopic and photopic conditions confers an added advantage. While the scotopic results address the issue of how attention may affect visible persistence, the photopic results are used to address the issue of how attention might influence masking. Indeed, there is evidence that attention can be used to mitigate the effects of metacontrast masking (Enns & Di Lollo, in press; Ramachandran & Cobb, 1995). For the present task, this means that items in the focus of attention may be less susceptible to masking than other items. That is, attending to any given element in the first frame might prevent its being masked by the corresponding item in the second frame. Being

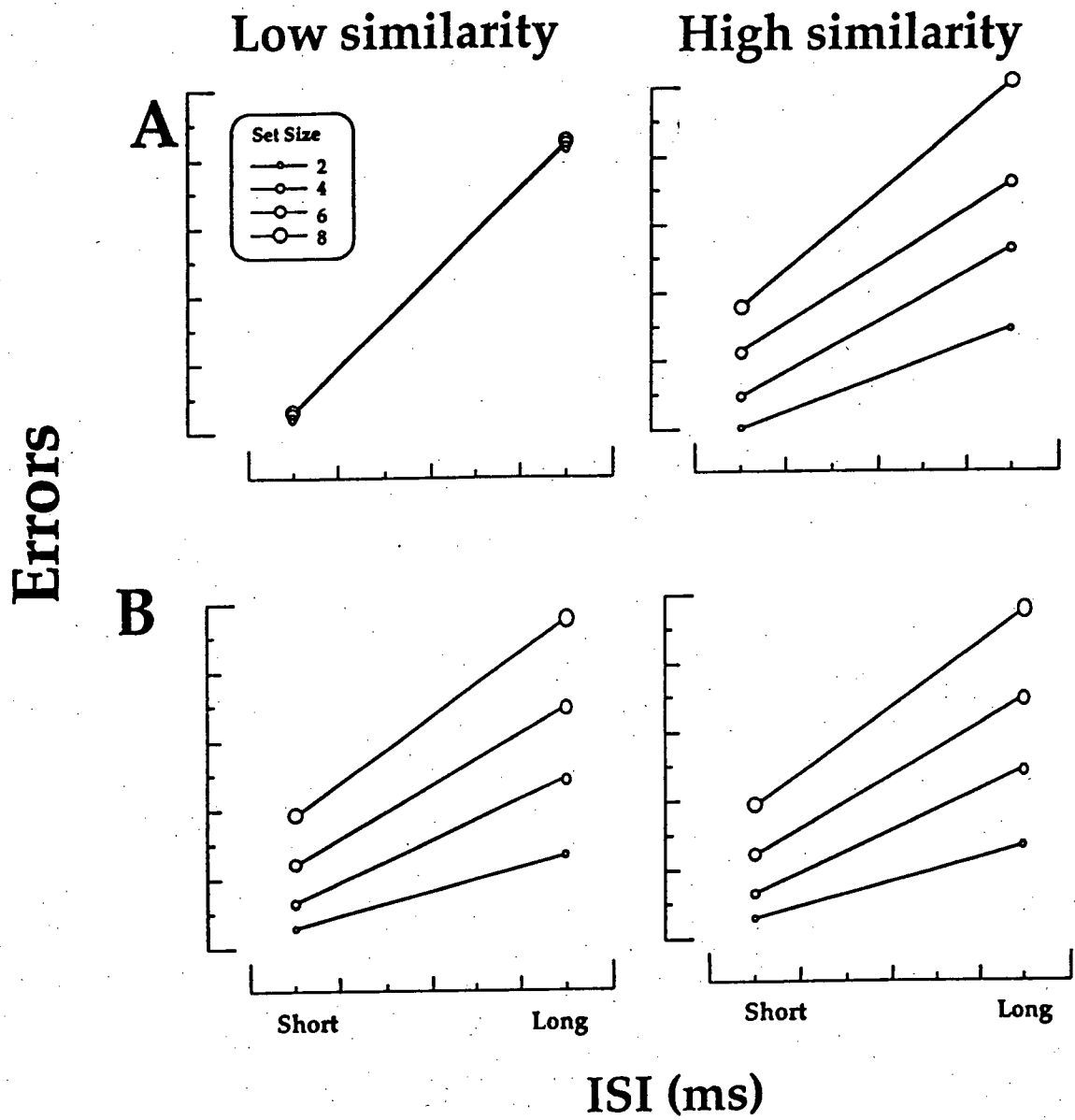
protected from masking, such items would maintain the visible persistence required to bridge the ISI. This would allow temporal integration to occur.

Again, the focus of attention was manipulated by varying set size, namely the number of items in the display. The rationale remained the same: Small set sizes were assumed to allow attention to any given item to be more focused. The relation between attention and masking is again represented by the interaction between set size and ISI (see Figure 3). To assess the precise form of this relation, however, the results obtained in photopic viewing are compared with those obtained in scotopic viewing. This comparison is necessary because performance in the dark is determined solely by persistence, whereas performance in the light may be affected by both persistence and masking. For example, were attention to mitigate masking but to have no effect on persistence, then an interaction between set size and ISI should be obtained in photopic but not in scotopic viewing (Compare Figure 3A and Figure 3B).

Figure 3. The predicted results for the photopic conditions: (A) Attention does not influence masking and attention does not have an effect on visible persistence. If the scotopic results indicate that attention affects visible persistence, then the photopic results would be compared with the scotopic results to determine whether there was any additional influences. (B) Attention reduces the strength of metacontrast masking.



Figure 3



### Scope of the present study

Stimuli. Each of the search items was composed of four of the segments of a digital figure eight (Yantis & Jonides, 1984). These items could easily be divided into two frames, each frame consisting of two segments drawn randomly. Distractor items for the low similarity condition consisted of closed squares; either the top or bottom half of the figure eight. This target was unique in two respects that produce very rapid search: it was twice as tall as the distractor items, and it had free line endings (Julesz, 1984; Treisman & Gormican, 1988). For the high similarity condition, the distractor items were chosen to be maximally similar to the two targets (see Figure 4).

Observers' task. Observers performed a visual search task in which they were asked to report whether an upper case 'F' or a lower case 'h' was present in the display. Set size, target-distractor similarity and adapting luminance were varied. In order to test the prediction that spatial attention affects visible persistence, the visual search task was combined with the ISI manipulation derived from the temporal integration task. This meant that search could only be accomplished when information in the two frames was unified by visible persistence.

The main factor used to measure persistence was the ISI between the first and second frame. All previous research on temporal integration has assumed that visible persistence decays monotonically over time. Applying this assumption to the present experiments involved the following steps: visible persistence decays

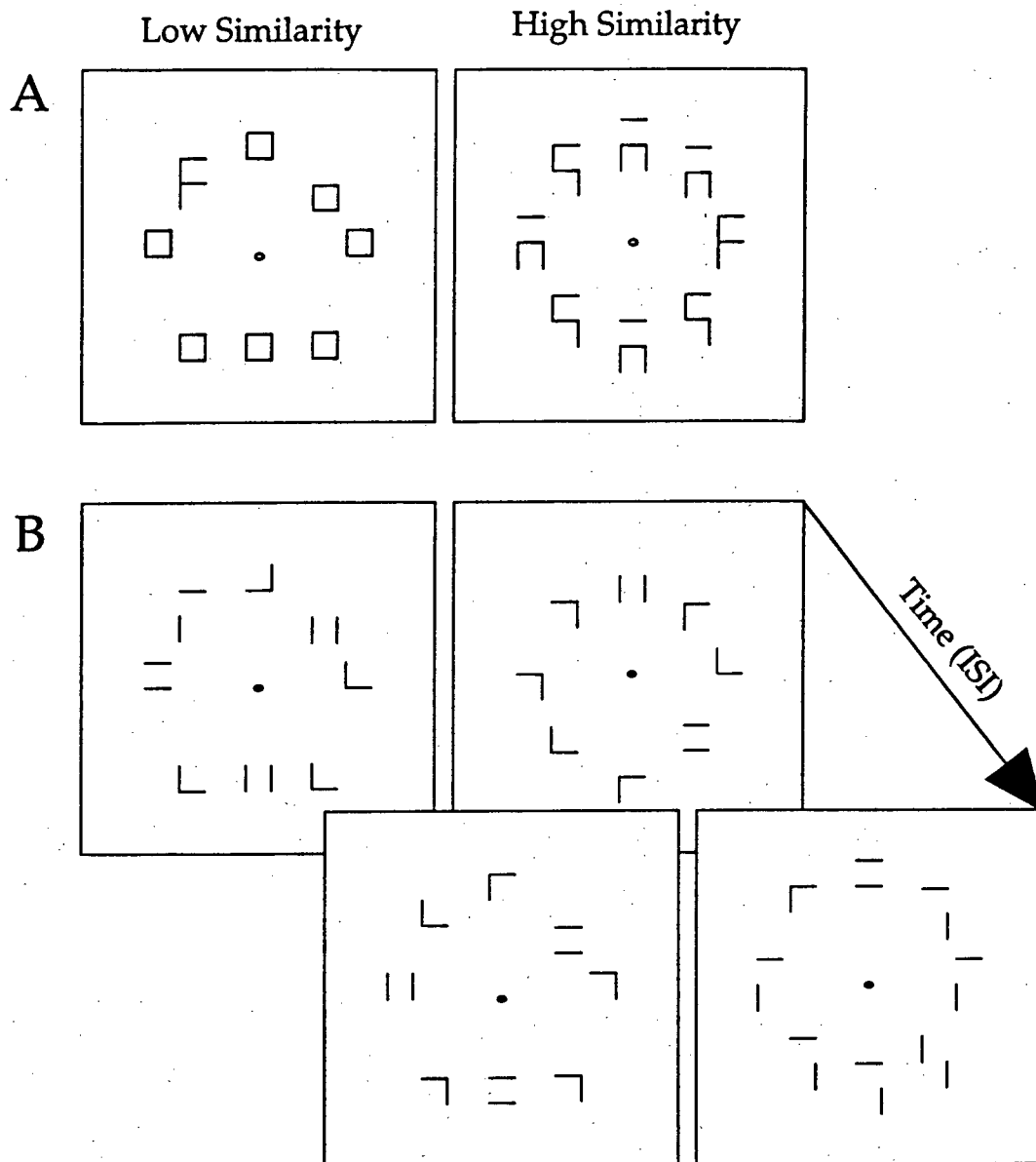
monotonically over time; the duration of the integrated trace from two successive displays declines monotonically with ISI; and visual search accuracy declines monotonically with the duration of the integrated trace.

Predictions. Several possible outcomes for this experiment are shown in Figure 2 and 3. The predictions concerning attention and persistence are considered first, followed by those for attention and masking. Recall that persistence can be assessed in the scotopic condition without interference from masking, whereas the contribution of masking can be assessed by comparing the photopic and scotopic conditions.

Consider first the hypothesis that attention has no influence on the duration of persistence. For low similarity targets, the slope of accuracy over ISI should be the same regardless of set size. This is so because the target pops-out, removing set size as a determinant of performance. To be sure, ISI would remain a factor for the low similarity condition because of the inverse relation between ISI and effective exposure duration. For high similarity targets, an interaction between set size and ISI should occur because any reduction in effective exposure duration (as a result of increases in ISI) will be more detrimental for the larger set sizes (cf. Bergen & Julesz, 1983). These outcomes are depicted in Figure 2A.

Figure 4. Examples of search displays in the present experiments. (A) An example of a set size of eight in the low (left) and high (right) similarity conditions. The target in each case is an upper case 'F'. A lower case 'h' was also used on half of the trials and the observer's task was to indicate which letter was presented. (B) The same search displays, this time divided into two successive frames, as in Experiments 2 and 3.

Figure 4



Next, consider the hypothesis that focused attention prolongs visible persistence. With small set sizes, attention can be focused more sharply on individual items in the first frame. It follows that longer ISIs would be bridged by persistence when the set sizes are small rather than when they are large. On this basis, an interaction between set size and ISI is predicted for both the high and low similarity conditions. This outcome is depicted in Figure 2B. Note that the only result which discriminates between the outcomes shown in Figures 2A and 2B is in the low similarity condition.

The question concerning attention and masking is examined by comparing the results in the scotopic and photopic conditions. If there is no masking in this task, then the interaction between set size and ISI should be the same in these two conditions. Alternatively, if there is masking in this task, then accuracy should be poorer overall in the photopic condition. A corollary of this prediction is that similarity should not have much of an influence on this task, since the elements in the second frame (the effective mask) are equally random and meaningless in the low and high similarity conditions. The influence of attention on masking should be seen in a stronger interaction of set size and ISI in the photopic than in the scotopic condition. Focused attention on elements in the small set sizes should protect them from being masked. A reduction in masking by focused attention would therefore lead to the outcome shown in Figure 3B.

Chapter 2: Experiment 1

This experiment was conducted to establish several baseline findings concerning brief displays and adapting luminance in visual search. These factors have never been examined, either alone or in combination. Displays in typical visual search studies have been presented for a long duration (i.e., until the observer responds) and at luminance levels in the photopic or high mesopic range. The present study used very brief displays (2 ms) presented in both photopic and scotopic ranges. The very brief exposure was necessary to accommodate the temporal integration task, which was the focus of Experiments 2 and 3.

Different levels of adapting luminance have well-known effects on the visual system. The main issue here was how these changes would influence visual search. Two important effects of adapting luminance are shown in Figure 1A (Walraven, Enroth-Cugell, Hood, MacLeod, & Schnapf, 1990; Whitten & Brown, 1973). First, the latency of the retinal response is delayed in the dark. This is represented as the difference between the point where the photopic and scotopic curves first cross the threshold of visibility. Second, the duration of the retinal response is longer in the dark. This is represented as the difference between the point where the photopic and scotopic curves finally cross the threshold.

Retinal latency should have a direct effect on reaction time. Since the signal from the retina is delayed, all subsequent processing should also be delayed. This predicts that reaction time will be slower in the dark by a constant factor.

Duration of retinal response is in essence a manipulation of exposure duration. Because of persistence, displays in the dark are on view for longer than in the light. Several researchers have examined the effect of exposure duration on visual search accuracy (Bergen & Julesz, 1983; Bundesen, 1990). The general finding is that search slopes get steeper with a reduction in exposure duration. For targets and distractors which are highly similar this effect is especially strong.

Note that in order to limit exposure duration, previous studies have always used a masking procedure. That is, at some variable interval after the presentation of the search display, a mask was presented. It was presumed that the mask terminated processing of the display, thereby limiting the time for which a representation of the display was available. In the present experiment, the entire display was presented for 2 ms and the search process was carried out on the internal fading trace of this display. With a less intense representation, more time would be needed to resolve the identity of any one element. Thus, each successively scanned element would require more time to process, with the result that overall reaction time to find the target would be longer for any given set size. For this reason, the prediction of steeper search slopes for shorter exposure durations applies equally well to response accuracy and latency in this experiment.

Search slopes in the high similarity condition should therefore be steeper in the light, where the display is visible for a shorter period of time. For the low similarity condition, performance should be independent of set size at both levels of



adapting luminance. These considerations lead to a prediction of a three-way interaction between set size, similarity and adapting luminance. Specifically, search slopes should be steepest in the high similarity condition. Slopes should also be shallower when displays are viewed scotopically (i.e., a longer exposure) than when viewed photopically. Finally, reaction times should be longer in the dark regardless of visual similarity or set size.

### Method

Observers. Two graduate students (one male 29 yr old - DIS, and one female 23 year old - KAL) and one male post-doctoral student (31 years - JCB) from the Vision Lab at the University of British Columbia volunteered as observers for the first and second experiments. All were right handed and had corrected-to-normal acuity.

Apparatus. A Tektronics 608 oscilloscope with P15 phosphor was used to display the stimuli. At a viewing distance of 57 cm, one side of the 8 cm square screen subtended  $8^\circ$  of visual angle. For the photopic viewing conditions, the screen was illuminated with two Rite-lite florescent bulbs wrapped in neutral density celluloid filter, which provided a uniform 50 cd/m<sup>2</sup> across the entire screen. As well, there was a small degree of ambient light provided by a single 150 watt incandescent ceiling bulb. For the scotopic viewing, the florescent bulbs and the incandescent bulb were extinguished, which left the room in absolute blackness (i.e., after 30 min in the dark, no light spots could be seen). Luminance measurements

for both the background levels and calibration of the oscilloscope were done with a Minolta LS-110 Luminance meter. The oscilloscope was controlled using a fast plotting buffer (Finley, 1985) connected to a 486 IBM-clone computer.

Stimuli. Each search item could appear in one of eight locations around a notional circle which had a diameter of  $4^\circ$  of visual angle (see Figure 4A for an example of set size 8). Each item was created out of four of the seven segments in a figure eight which was  $1^\circ$  tall and  $0.5^\circ$  wide. The two targets were an upper case 'F' and a lower case 'h'. The distractors for the low similarity condition were small squares made up of either the upper or lower half of the figure eight. For the high similarity condition, the distractors were made maximally confusing with the two targets (see Figure 3).

Procedure. The observers' task was to indicate whether an 'F' or an 'h' was presented by pressing one of two keys. A target discrimination task was chosen instead of the traditional presence/absence task in order to reduce any effects of decisional uncertainty. In a detection task, each additional distractor increases the probability of a false alarm, thereby inducing a possible relation between the decision criterion and set size (Palmer et al, 1993). In a discrimination task, this cannot occur because the observer knows that a target is present on every trial.

The observer initiated each trial by pressing a key. A fixation point was presented at the centre of the display from the onset of the trial until the observer responded. After a 300 ms interval, two of the four segments were presented for 1

ms, followed immediately by the other two segments for 1 ms. The screen remained blank (other than the fixation point) until the observer responded, at which time a plus, minus, or circle was presented for 450 ms as feedback which indicated that the previous trial was correct, incorrect, or beyond the 2 second time-out limit.

Observers were told to respond on every trial and that 2 sec would be allowed for a response. If a response was made beyond the 2 sec limit, that trial was repeated. The luminance of the fixation was 30 cd/m<sup>2</sup> in the light and 1 cd/m<sup>2</sup> in the dark. The luminance of the feedback was one log unit below that of the fixation.

Visibility Calibration. Prior to each session, the luminance of the search items was determined separately for each observer in order to equate item visibility across observers and levels of adapting luminance. Observers were asked to discriminate an 'F' from an 'h' that appeared randomly in one of the eight item locations. The luminance of these items was adjusted using an adaptive staircase procedure. On each trial, the luminance was either increased or decreased, based on the observer's average accuracy in the preceding trials. A 75% threshold was used to determine reversals in the direction of luminance change. After three reversals, the average luminance used in the next 16 trials was used as an estimate of the 75% threshold. Three such estimates were used to determine a best estimate.

Luminance of the items in the visual search task was set at one log unit above the best estimate for each observer. The average luminance was 698 cd/m<sup>2</sup> [range =

616 - 780cd/m<sup>2</sup> ] in the photopic condition and 1.25 cd/m<sup>2</sup> [range = 0.85 - 1.65 cd/m<sup>2</sup>] in the scotopic condition.

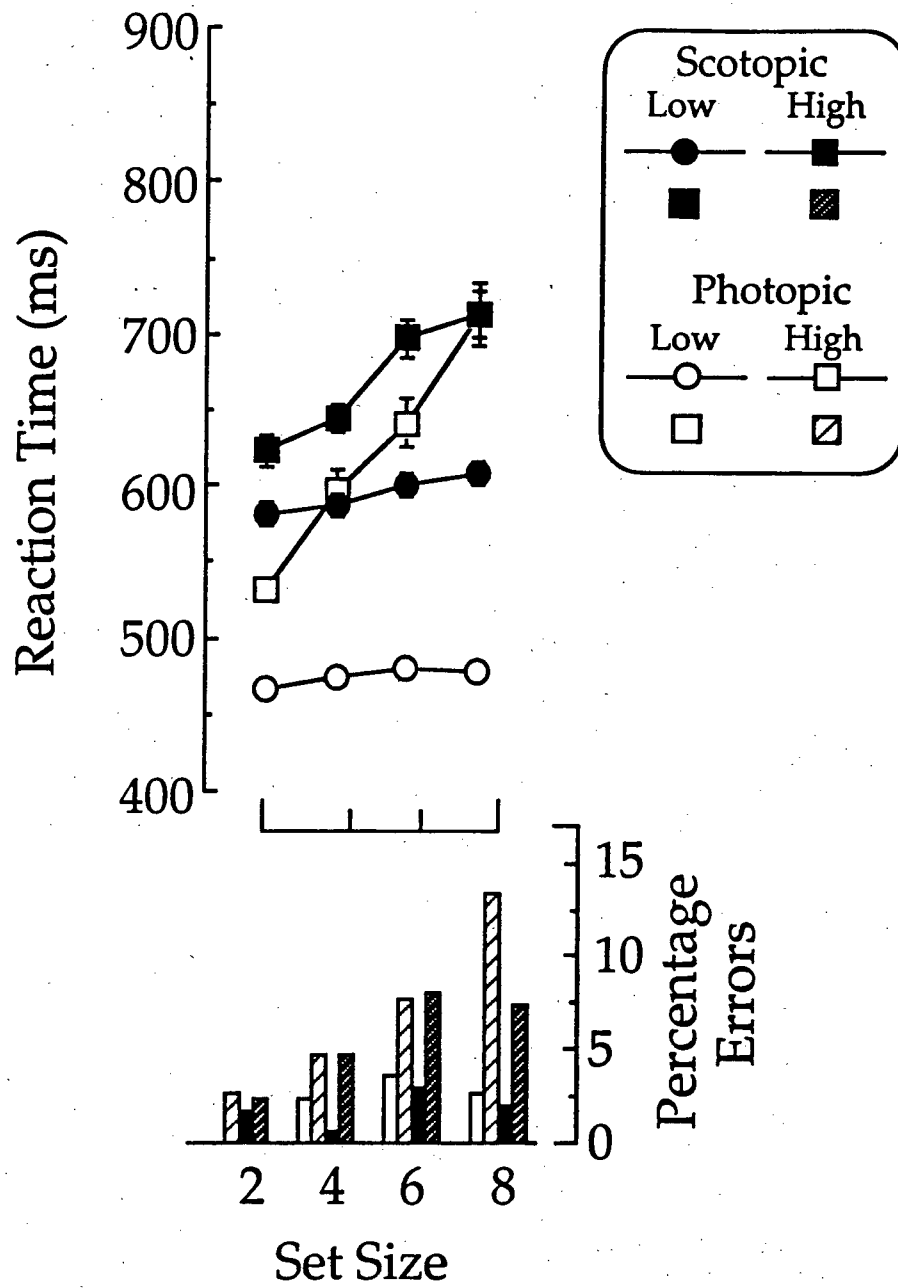
Design. There were three factors in this experiment: set size (2, 4, 6, 8), similarity (low, high), and adapting luminance (photopic, scotopic). Observers were tested in two sessions on consecutive days. Each session consisted of four blocks of 200 self-paced trials at one level of adapting luminance. Trial blocks within a session were further subdivided between similarity conditions. Set sizes were randomly varied within each block. Order of session and similarity condition were randomly varied between observers.

### Results

Mean correct reaction time and percentage errors are shown in Table 1 for each observer. Figure 4 shows the average of the three observers. Mean within-observer error bars are shown for the reaction times. No error bars are presented for the accuracy data (bottom panel of Figure 5), since the within-observer standard error is proportional to the mean percentage error.

Figure 5. Mean correct reaction time in Experiment 1 is shown in the upper panel. Error bars represent the average within-observer standard error. Mean percentage error is shown in the lower panel.

Figure 5.



As expected, visual search was most difficult in the high similarity condition. For scotopic viewing, this interaction was less pronounced and reaction times were generally slower. These observations were confirmed for the reaction time data using a repeated measures ANOVA: adapting luminance (2), similarity (2), and set size (4). Follow-up analyses used a simple effects procedure (Keppel, 1982). Tests of sphericity were not conducted, since only three observers were tested.

The main effects of adapting luminance [ $F(1,2) = 23.27$ ,  $MS_e = 3627.75$ ,  $p < .05$ ], and set size [ $F(3,6) = 9.07$ ,  $MS_e = 3217.75$ ,  $p < .01$ ] were significant, while that of similarity was not [ $F(1,2) = 8.4$ ,  $MS_e = 17178.08$ , n.s.]. These main effects were moderated by two significant interactions: similarity  $\times$  set size [ $F(3,6) = 9.28$ ,  $MS_e = 817.75$ ,  $p < .05$ ], and adapting luminance  $\times$  similarity  $\times$  set size [ $F(3,6) = 5.95$ ,  $MS_e = 245.08$ ,  $p < .05$ ]. The interaction of similarity and adapting luminance was not significant [ $F(1,2) = 4.67$ ,  $MS_e = 3217.75$ ], nor was the interaction of adapting luminance and set size [ $F(3,6) = 2.34$ ,  $MS_e = 322.25$ ].

The three-way interaction is explained by examining the search slope for high and low similarity conditions under photopic and scotopic viewing. For the high similarity condition, the effect of set size was significantly different for scotopic [16.1 ms/item] than for photopic viewing [29.3 ms/item;  $F(3,6) = 8.67$ ,  $p < .05$ ]. For the low similarity conditions, the effect of set size was not significantly different between levels of adapting luminance [photopic: 1.9 m/item; scotopic: 4.6 ms/item].

The error data were analyzed in the same way. No significant main effects or interactions were found, but the pattern of results mirrored the reaction time data [adapting luminance:  $F(1,2) = 1.5$ ,  $MS_e = 11.65$ , n.s.; similarity:  $F(1,2) = 15.35$ ,  $MS_e = 12.77$ , n.s.; set size:  $F(3,6) = 3.42$ ,  $MS_e = 13.40$ ,  $p < .10$ ; adapting luminance x visual similarity:  $F(1,2) = 9.28$ ,  $MS_e = 6.27$ , n.s.; adapting luminance x set size:  $F(3,6) = 1.30$ ,  $Mse = 4.78$ , ns; set size x similarity:  $F(3,6) = 4.16$ ,  $MS_e = 7.02$ ,  $p < .10$ ; adapting luminance x similarity x set size:  $F(3,6) = 1.0$ ,  $MS_e = 7.74$ , n.s.]

### Discussion

The main results of this experiment were that the difficulty of visual search increased with target-distractor similarity and that this effect was smaller for scotopic viewing. These results are consistent with the prediction that increasing the duration of visible persistence (i.e., by scotopic viewing) makes for easier visual search. In addition to these effects, there was also an overall increase in reaction time in the scotopic condition, consistent with an increase in retinal latency.



Chapter 3: Experiment 2

The effect of attention on a two-frame visual search task was evaluated by combining factors known to affect attention (set size) and the difficulty of integration (ISI). As described in the rationale, visual search in the scotopic condition is determined solely by visible persistence, whereas performance in the photopic condition may be affected by both persistence and masking. The scotopic condition was therefore used to provide an unbiased index of persistence; a comparison of the photopic and scotopic conditions were used to index masking.

Method

The observers, apparatus and stimuli were the same as in Experiment 1, with the exception that an ISI of variable duration was added between the presentation of the first two random segments of each item and the second two segments. Nine ISIs were tested. However, there were too many conditions to conduct the full range of ISIs within one experimental session, so the entire design was replicated for two different overlapping sets of ISI. The ISIs tested were grouped into two sets of five values which were administered between sessions. Each set included the baseline condition of 0 ms ISI. In addition, set A contained the values 50, 100, 150, and 200 ms for the light, and 100, 200, 300, and 400 ms for the dark. Set B, contained the values 25, 75, 125, and 175 ms for the light and 50, 150, 250, and 350 ms for the dark. Since the conditions were otherwise identical in these two sets of ISIs, the results

were combined into one single analysis for each level of adapting luminance. The average luminance of the stimuli in this experiment was 637 cd/m<sup>2</sup>, range = 616 - 662 cd/m<sup>2</sup> (photopic) and 1.02 cd/m<sup>2</sup>, range = 0.67 - 1.37 cd/m<sup>2</sup> (scotopic). The design of the experiment was a 2 (adapting luminance) x 2 (similarity) x 9 (ISI) x 4 (set size).

Each observer participated in eight sessions spread over several months. There were four light (two each of set A and B) and four dark sessions (two each of set A and B). Within a session, blocks were divided equally between low and high similarity. The factors of set size and ISI were randomly distributed within each block of 500 trials.

### Results

The mean percentage error for each observer is shown in Tables 2 and 3. The mean of the three observers is shown in Figure 6 averaged over both levels of similarity. Figure 7 shows the same data separately for each level of similarity.

The two most important findings in this experiment are summarized in Figure 8, which shows how search slopes vary with ISI in the two adapting luminance conditions. First, search slopes did not change significantly with increases in ISI in the scotopic condition. Second, search slopes increased significantly with ISI in the photopic condition. These findings were supported by two repeated measures ANOVAs, one for each of the viewing conditions.

Figure 6. Mean percentage error in Experiment 2 is shown averaged over the two levels of similarity.

Figure 6

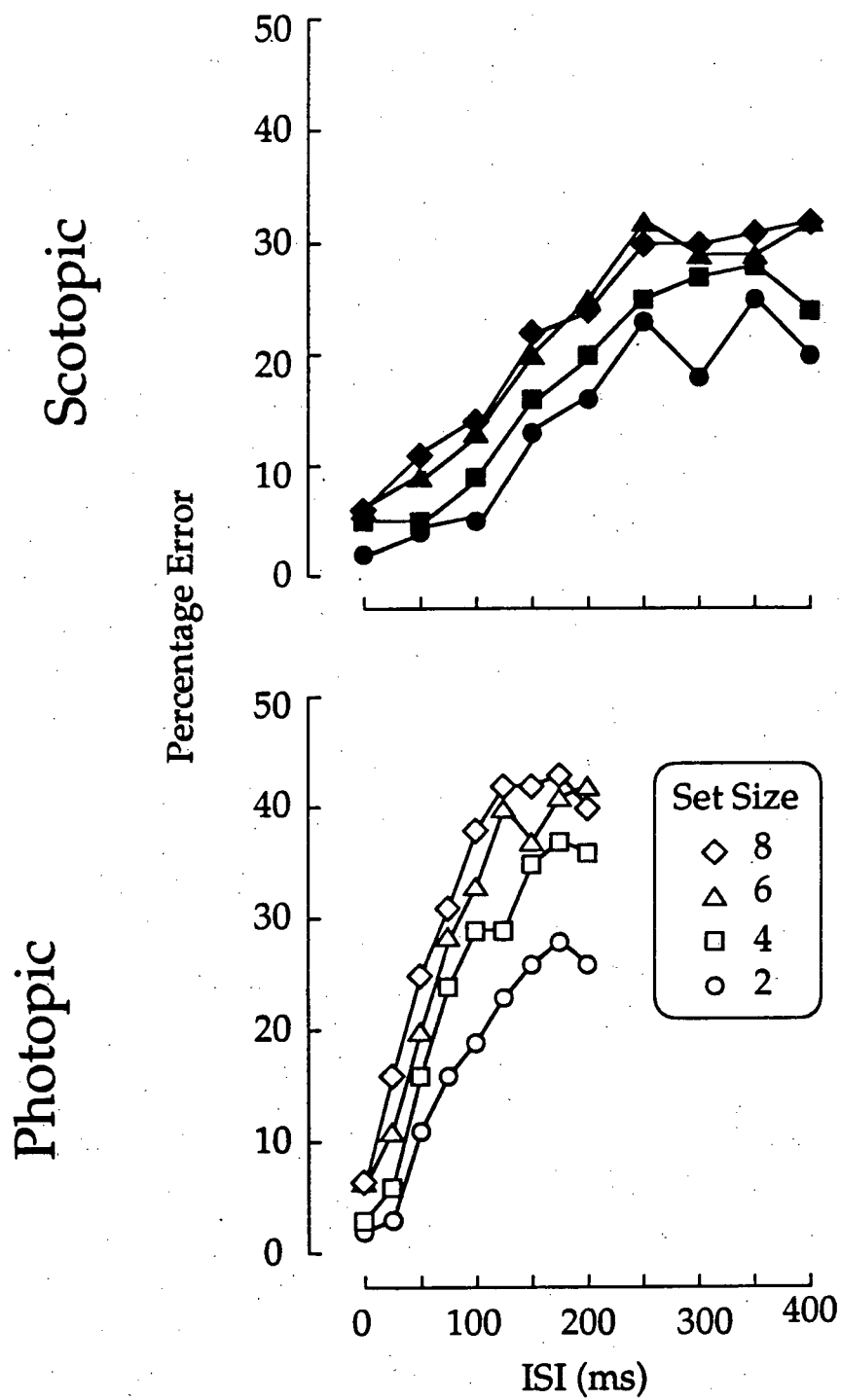


Figure 7. Mean percentage error in Experiment 2 is shown separately for low and high levels of target-distractor similarity.

Figure 7

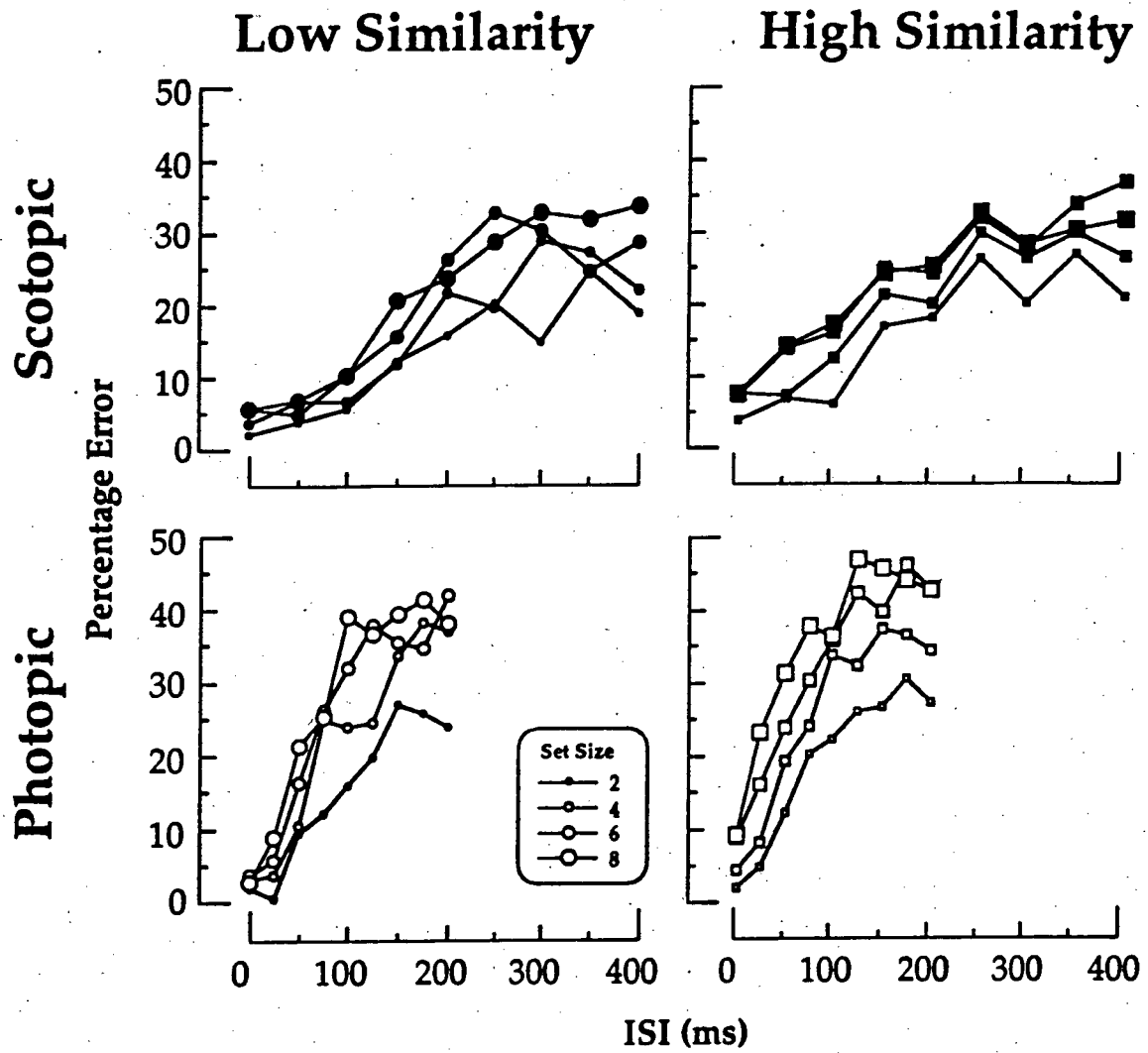
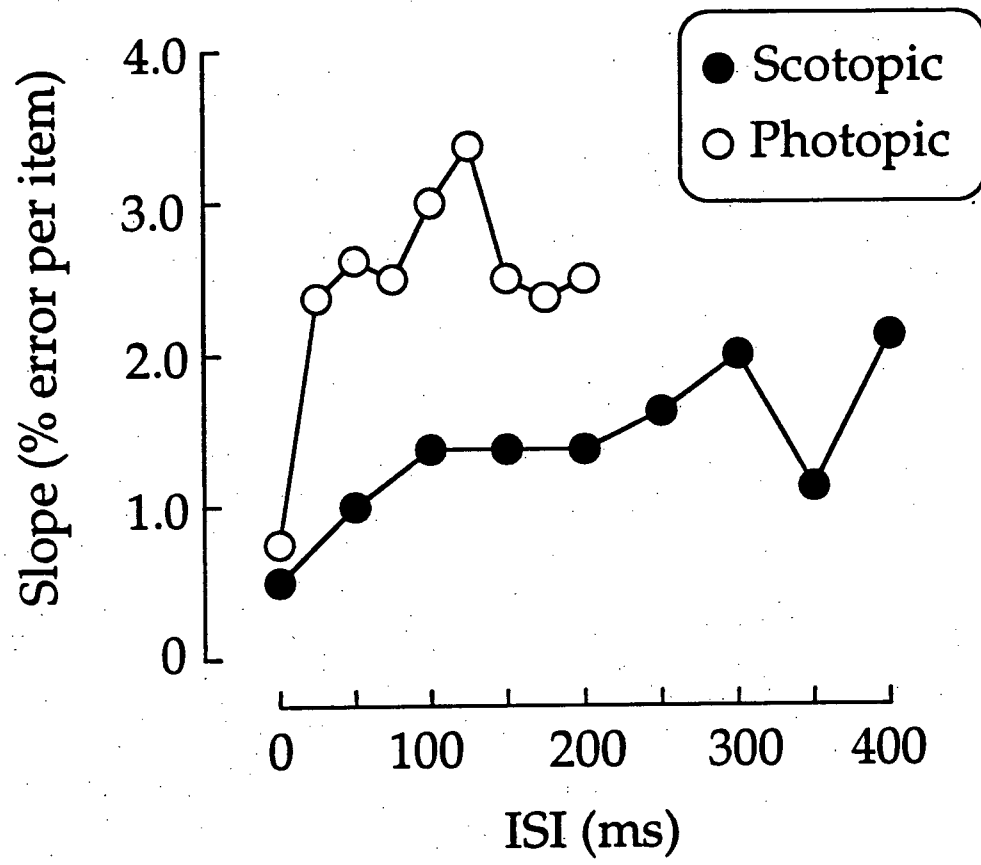


Figure 8. A summary of the main findings of Experiment 2 expressed as search slopes.

Figure 8





The analysis in the scotopic condition revealed significant main effects of ISI [ $F(18,36) = 29.72$ ,  $MS_e = 65.70$ ,  $p < .01$ ] and set size [ $F(3,6) = 13.60$ ,  $MS_e = 49.26$ ,  $p < .01$ ].

As ISI increased, accuracy declined from near perfect to 38% errors. The fact that performance never reached chance (i.e., 50% errors) suggests that even longer ISIs could have been tested before chance levels of performance were reached. The most important result was the absence of an interaction between set size and ISI [ $F(24,48) = 19.05$ ;  $MS_e = 13.63$ ], pointing to no effects of attention on visible persistence. There was also no main effect nor interactions involving similarity [main effect:  $F(1,2) = 3.30$ ,  $MS_e = 144.94$ , n.s.; similarity x set size:  $F(3,6) = 0.88$ ,  $MS_e = 8.88$ , n.s.; similarity x ISI:  $F(8,16) = 1.85$ ,  $MS_e = 22.63$ , n.s.; similarity x set size x ISI:  $F(24,48) = 1.34$ ;  $MS_e = 14.39$ ].

The analysis in the photopic condition revealed a significant main effect of ISI [ $F(8, 16) = 26.24$ ,  $MS_e = 136.06$ ,  $p < .01$ ]. Accuracy ranged from near perfect at the short ISIs to near chance for some conditions at the longest ISIs. The main effect of set size [ $F(3,6) = 445.72$ ,  $MS_e = 4.86$ ,  $p < .01$ ] was also significant, as was the effect of similarity [ $F(1,2) = 99.54$ ,  $MS_e = 12.10$ ,  $p < .01$ ].

The two-way interaction of set size x ISI was significant [ $F(24,48) = 2.00$ ,  $MS_e = 18.51$ ,  $p < .05$ ]. Because the same interaction was not significant in the scotopic condition, finding it here indicated an influence of attention on masking.

Target-distractor similarity was involved significantly in a three-way interaction with set size and ISI [ $F(24,48) = 1.76$ ,  $MS_e = 13.72$ ,  $p < .05$ ]. This interaction could be isolated to the zero and 25 ms ISI conditions, where set size effects were larger in the high similarity condition [0 ms ISI: low = 0.2 %/item, high = 1.3 %/item,  $F(3,6) = 13.92$ ;  $MS_e = 1.04$ ,  $p < .01$ ; 25 ms ISI: low = 1.3 %/item, high = 3.1 %/item,  $F(3,6) = 4.99$ ,  $MS_e = 6.96$ ,  $p < .05$ ]. Otherwise, set size effects varied little with similarity, and overall, there was not a significant set size x similarity interaction [ $F(3,6) = 3.00$ ,  $MS_e = 13.86$ , n.s.]. Finally, the interaction of similarity and ISI was also not significant [ $F(8,16) = 1.05$ ,  $MS_e = 29.66$ , n.s.].

### Discussion

There were two main findings in this experiment. First, the relatively constant search slopes with ISI in the scotopic condition, where masking was not a factor, indicated that the duration of visible persistence was unaffected by the focus of attention. Second, the increase in search slopes with ISI in the photopic condition, where persistence and masking could play a role, indicates that focused attention can prevent masking in this two-frame visual search task. This conclusion was also supported by the negligible effect of similarity in the photopic condition.

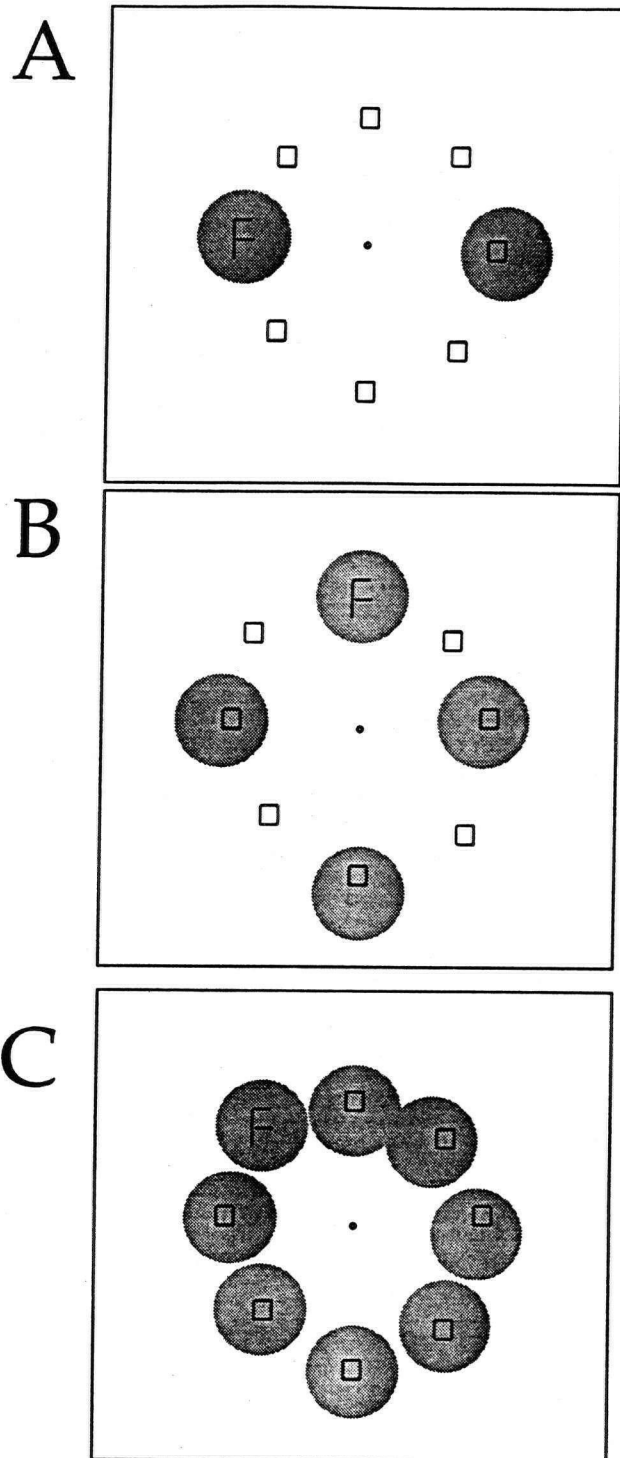
Chapter 4: Experiment 3

Variations in set size in Experiments 1 and 2 were believed to be manipulations of spatial attention. However, it is also possible that non-attentional factors associated with larger set sizes were also partially responsible for the effects (Palmer et al, 1993). Such factors include lateral masking, crowding and item density. Consider the density factor in the previous experiments. As set size increased, so did the probability that two items would appear close to one another in the display. This would have the effect of confounding set size with item density. To the extent that increased proximity introduces the possibility of lateral masking between items, this factor may have contributed to search slopes.

Experiment 3 used a relevant set size manipulation (Palmer, 1994) in an effort to control non-attentional factors such as this. A fixed number of items (eight) was presented on every trial. Attention was manipulated in separate blocks of trials by instructing observers to monitor different subsets of the display locations for a target. In an effort to control for eye movements, each subset included items that were equal in their distance from fixation and on opposite sides: set size two (three and six o'clock), set size four (twelve, three, six, and nine o'clock) and set size eight (all locations). Since the physical characteristics of the search displays did not now vary with set size, only attention could account for any differences in accuracy with changes in relevant set size.

Figure 9. Example of relevant set size manipulation. Relevant target locations are indicated by grey shading. The actual display had no shading, but subjects were told beforehand which of the eight items could contain the target. Examples of a relevant set size of 2 (A), 4 (B), and 8 (C) locations are shown.

Figure 9.



This experiment tested only the low similarity-photopic condition from Experiment 2, since this condition was central in distinguishing among the various predictions spelled out in the Introduction. It also tested a larger number of observers ( $n = 10$ ) than Experiments 1 and 2 ( $n = 3$ ). The observers were all volunteers from the psychology subject pool, naive to the purpose of the experiment.

### Method

Observers. Ten Undergraduates (3 right handed females; 1 left handed female; 4 right handed males; 2 left handed males) from the subject pool at the University of British Columbia volunteered in this experiment. All had normal or corrected-to-normal vision and were naive to the purpose of the study.

Procedure. The procedure was the same as Experiment 2 with several exceptions. All observers participated in only one session (low-similarity, photopic), consisting of two sets of three blocks (one set size per block). Each block contained 100 trials. Attention was manipulated by instructions indicating that the target would appear in only certain locations within a block. For set size two, the target could appear either to the left or right of fixation; for set size four, the target could appear at any of the four cardinal locations; for set size eight, the target could appear in any of the eight locations. Within each block, four ISIs were tested (0, 50, 100, and 150 ms).

After completing the visibility calibration procedure described in Experiment 1, each observer practiced with a set size of eight and zero ISI until they were comfortable with the task (between 10 and 20 trials). Following this, they were given the instructions regarding relevant target locations and additional practice of 5-10 trials with each set size. Order of set size was randomly varied within a set of three blocks. The average luminance of the stimuli was 705 cd/m<sup>2</sup>, range = 320 - 990 cd/m<sup>2</sup>.

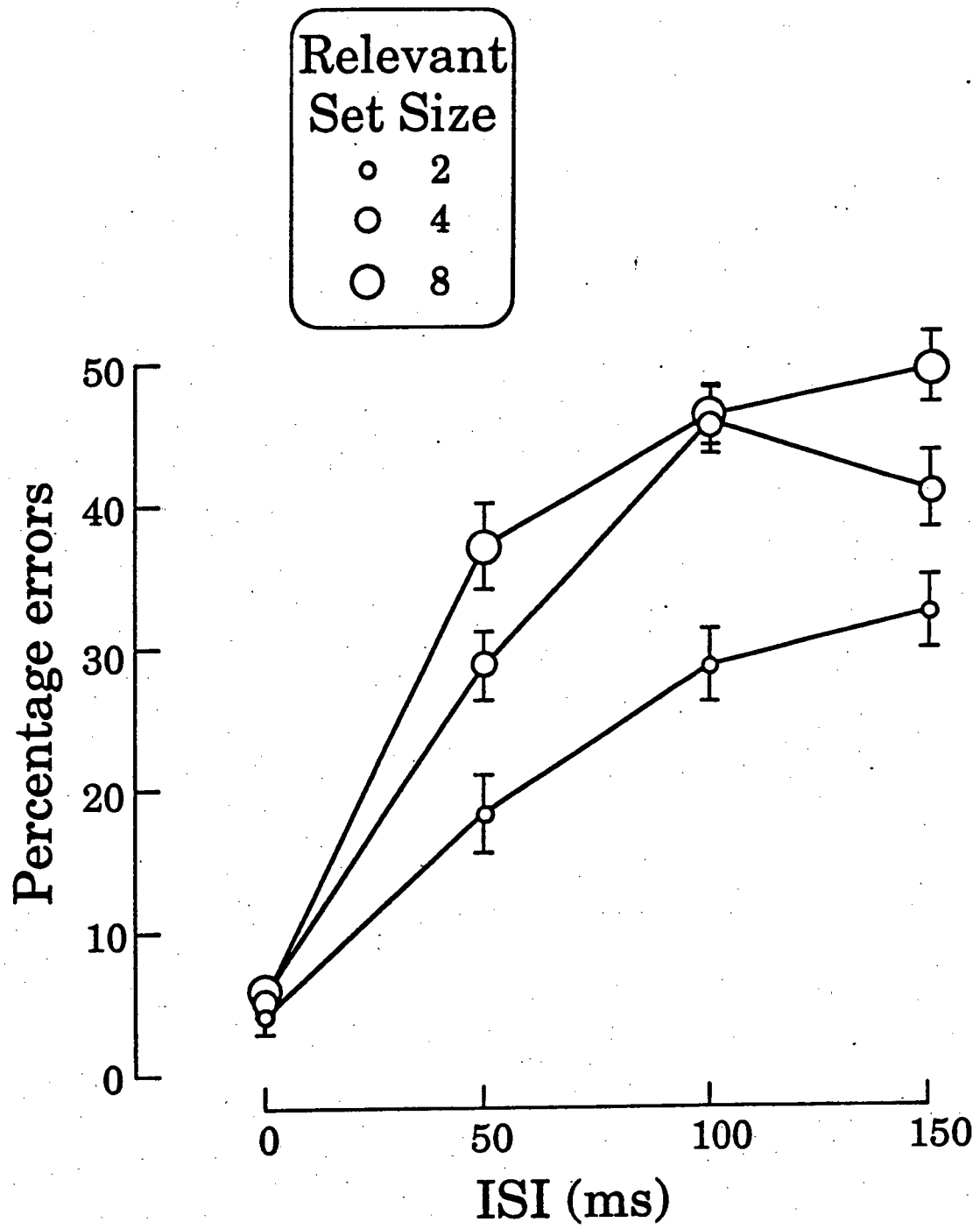
### Results

Mean percentage errors are shown in Figure 8. Between-observer standard error bars are presented for these means because there were now enough observers to warrant it. The data were submitted to a repeated-measures ANOVA (3 levels of set size, 4 levels of ISI). Each of the main effects were significant [set size:  $F(2,18) = 35.24$ ,  $MS_e = 3.49$ ,  $p < .01$ ; ISI:  $F(3,27) = 152.84$ ,  $MS_e = 3.47$ ,  $p < .01$ ], as was the two-way interaction [ $F(6, 54) = 4.84$ ,  $MS_e = 2.91$ ,  $p < .01$ ]. There were no violations of sphericity (Greenhouse & Geisser, 1959; Huynh & Feldt, 1979). This confirms that non-attentional influences, such as crowding, are not responsible for the interaction between set size and ISI in the two-frame visual search task. It also replicates the finding that focused attention can prevent masking in observers who are both inexperienced in the methods used and naive to the purpose.

Figure 10. Mean percentage errors in Experiment 3. Error bars represent the between-observer standard error.



Figure 10



Chapter 5: General Discussion

The experiments reported in this thesis were conducted to answer two questions: Does attention prolong visible persistence? and Does attention protect against masking? Observers performed a two-frame visual search task in which the focus of attention was manipulated by varying the number of items in the display. Since two successive display frames had to be integrated for the observer to respond correctly, visible persistence was necessary to bridge the interval between frames. If attention increased the duration of visible persistence, then items that received more attention (i.e., those in small set sizes) would persist longer and therefore be integrated over longer intervals.

An analysis of the temporal integration task showed, however, that presentation of the second frame could also result in metacontrast masking of the first frame. Such masking would work in opposition to the proposed role of attention in that it would interfere with visible persistence. This ambiguity was resolved by presenting the stimuli under dark-adapted conditions, which removed metacontrast masking as a consideration (Bischof & Di Lollo, 1995). The results from this condition (Experiment 2) showed that search difficulty (i.e., search slopes) remained relatively constant as the interval between frames was increased. This indicates that the focus of attention had no measurable effect on visible persistence.

Since two-frame visual search under photopic conditions is determined by both visible persistence and metacontrast masking, whereas search under scotopic

conditions is influenced only by persistence, a comparison of these conditions permitted an assessment of attention on metacontrast masking. The results from the photopic condition showed that search difficulty (i.e., search slopes) increased as the interval between frames was increased. This indicates that attention reduced the effects of metacontrast masking in the temporal integration task.

The support for these conclusions is considered in more detail in the following section, along with the implications of each conclusion for past research and future experiments.

### Attention does not prolong visible persistence

Search under scotopic conditions provided no evidence that attention had an influence on visible persistence. This result, therefore, provides direct support for previous research and theory: Visible persistence is based on the activity of low-level mechanisms that are not within the reach of the higher-level processes of attention (Coltheart, 1980; Di Lollo & Bischof, 1995; Long, 1980).

The generality of this null result, however, is restricted by contrary results obtained with a different paradigm. The overall pattern of results, and its dependency on experimental paradigm, can be described as follows. It is widely accepted that allocation of attention can be manipulated in more than one way. In the present work, it was manipulated by varying set size, on the assumption that more attention could be focused on any given item when set size was small. With this manipulation, degree of focusing was changed systematically, but attentional

locus was held constant, or was varied randomly within narrow limits. In a second paradigm, known as spatial pre-cuing, it is the direction of attention that is manipulated, while focusing is held constant. In this paradigm, a spatial location is cued just before the onset of the stimulus, and the target appears at that location with a high probability. On the remaining few trials, attention is misdirected. With the spatial pre-cuing paradigm, it has been found that attention does affect the duration of visible persistence (Enns, Brehaut, & Shore, 1996). These investigators employed the method of constant stimuli to measure the perceived duration of visible persistence of brief stimuli presented in attended or in unattended locations. They found that the perceived duration at attended locations exceeded that at unattended locations by some 20 or 30 ms.

Clearly, these results are at odds with the present findings, therefore limiting their generality. By the same token, the diverging results introduce useful constraints on the relation between attention and visible persistence. The obvious next step is to pursue the differences between the two paradigms with a view to identifying the underlying mechanisms. For example, one could ask what useful purpose is served by visible persistence in one paradigm that is not served in the other. Conversely, it is conceivable that, far from serving a useful purpose, visible persistence may be an unwanted byproduct of stimulation which may actually hinder perception. In this case, one could ask why visible persistence is a hindrance to be avoided in one paradigm but not in the other.

This line of reasoning raises the more general issue of what function, if any, visible persistence may serve in everyday viewing. It cannot be assumed a priori that persistence serves a useful function. Indeed, since the publication of Enroth-Cugel and Robson's (1966) influential paper, the lower levels of the visual system have been likened to a set of low-pass or band-pass spatial and temporal filters. It is in the nature of such temporal filters to smear brief pulses over time, thus producing the type of decay functions that have been used to model the temporal course of visible persistence (e.g., Groner, Bischof, & Di Lollo, 1989). If we are to understand why attention affects visible persistence in some cases but not in others, it is useful for us to consider the option that, at least under some conditions, persistence may be a hindrance to be removed in the interest of veridical perception.

The point that visible persistence has no apparent benefit was made by Haber (1983). He remarked that almost the only use for visible persistence is reading a newspaper in a lightning storm. But, in fact, without visible persistence, we would be unable to watch TV or work on a computer screen. Only a very small portion of these screens are actually lit up at any one time, but because of visible persistence we see the entire screen all of the time. However, I am sure no one would argue that we evolved to watch TV. In fact, it appears that we have evolved complex mechanisms to suppress the detrimental effects of visible persistence. Experiments investigating motion smear indicate that when a stimulus is in motion, the persistence from the trailing segments is shorter than when there is no motion.

This prevents the object from being blurred by the motion so that a veridical observation can be made.

Another critical situation where visible persistence must be suppressed concerns eye movements, which we make several times every second. If the image from the previous fixation was to persist while the newly fixated image was processed, then an incoherent jumble would result. In fact, several researchers believe that this is exactly the problem with dyslexic children - persistence from the previous fixation interferes with the present fixation making reading a very difficult process (see Farmer & Klein, 1995 for a review of dyslexia literature). There is some evidence that signals from the medial reticular formation serve the purpose of suppressing visible persistence when an eye movement is initiated (Singer & Phillips, 1974).

If indeed visible persistence is a consequence of our biological make up, and the goal of evolution has been to develop mechanisms to suppress it, then future research should be aimed at unravelling these mechanisms. In relation to the present thesis, it would be interesting to explore the effects that attention may have on the suppression of visible persistence. Consider a task where persistence is a problem to be overcome. For example, the two-pulse detection task where the goal is to perceive the gap between two briefly presented stimuli. Will the allocation of attention help in suppressing the persistence of the first item to allow perception of the gap? Or, is the duration of persistence independent of attention? A second line

of research could look at the suppression caused by motion (Hogben & Di Lollo, 1985). Does focusing attention on the moving item, or prior knowledge of the direction of motion help to suppress the persistence from the temporally trailing stimuli? Regardless of the exact question, it seems that the important issue for future research is how we cope with visible persistence and how attention may help to suppress its unwanted effects.

### Attention protects against metacontrast masking

The conclusion that attention protects against masking was based on a comparison of search under photopic and scotopic conditions. It can be supported further by a more detailed comparison of search accuracy in the present task with target visibility in a metacontrast masking experiment. Unfortunately, the precise temporal and spatial parameters needed for the comparison do not exist in the literature, but a conceptual comparison is still possible and instructive. The decline in search accuracy with increases in frame interval in the present study can be compared with the first portion of the traditional U-shaped metacontrast masking function (Breitmeyer, 1984). In those studies, target visibility decreases from near perfect to null within the first 100 ms of the target-mask interval. This aspect of the results is therefore very similar to the decline in search accuracy in the present study. However, in the metacontrast studies, what typically follows is a recovery from masking at longer target-mask intervals. This second portion of the masking

function could not be seen in the present study because the task places different demands on the observer. In a masking study, the task is to identify the stimulus in the first temporal frame; in the search task, it was to identify the stimulus formed by the combined frames. The search task simply became impossible at longer intervals where visible persistence was not of sufficient duration to bridge the gap.

The conclusion that attention protected against metacontrast masking was also supported by the negligible effects of target-distractor similarity on the way in which search difficulty increased with frame interval. Effects of similarity on visual search are premised on the availability of an integrated display containing the search items. On the other hand, metacontrast masking would interfere with such an integrated display and attenuate these effects. In the present displays, the line segments in each of the two frames were chosen to be equally random and meaningless in both similarity conditions. The second frame (the mask) was therefore equivalent in its potential for masking. Thus, the finding that similarity had very weak effects is consistent with search difficulty in this task being governed by metacontrast masking and not visible persistence.

This conclusion is also consistent with recent masking studies in which the focus of attention has been systematically examined. In one study, manipulations of perceptual organization reduced metacontrast masking (Ramachandran & Cobb, 1995). For example, observers instructed to group a target shape with a second, more distant shape, were subject to less masking than observers instructed to group the



target with the mask shape. In another study of metacontrast masking, spatial attention was varied using a set size manipulation (Enns & Di Lollo, in press). When targets were presented along with fewer items or in predictable locations, masking was reduced.

This conclusion has interesting implications for previous research based on the temporal integration task. In particular, the relative contributions of visible persistence and masking must be examined more carefully. Consider the early study by Eriksen and Collins (1967) in which it was concluded that visible persistence lasted about 100 ms. In that task, subjects were presented with two sequential frames of random dots with a variable ISI inserted between them. When the two frames were superimposed, three letters could be discerned. The results showed that accuracy in identifying the three letters declined as the ISI was increased.

In light of the present results, one needs to ask to what extent the decline was due to the decay of visible persistence and to what extent it was due to masking. It is conceivable that attention was distributed amongst all dots of the first frame or, equivalently, was focused on only one subset of dots. In either case, dots in the first frame would have been vulnerable to masking to the extent that they were unattended. Thus, the progressive decrement in performance seen with increments in ISI in Eriksen and Collins's study cannot be attributed unambiguously to decaying visible persistence: masking could also have played a role.

To isolate the effect of passive decay from that of masking, one could use the strategy used in the present work. Namely, the task could be performed under scotopic viewing conditions, thus ruling out masking as a determinant of performance. Similarly, to assess the role of focused attention in the prevention of masking, the number of letters in the display could be reduced, thus increasing the degree to which attention could be focused on any given item.

These concerns are not limited to the letter-identification task of Eriksen and Collins (1967), but extend also to the dot-matrix task described in the Introduction. It seems likely that masking is a factor in this task, as witnessed in the inverse-proximity effect. Namely, as the inter-dot spatial separation is reduced, performance is impaired correspondingly (Di Lollo & Hogben, 1987). This is the same spatial contingency that governs the strength of masking in metacontrast (Breitmeyer, 1984). Again, the task could be done under scotopic conditions to study visible persistence independent of masking. This manipulation alone, however, would not be sufficient to reveal attentional effects on visible persistence. To achieve that objective, it would be necessary to manipulate attention. Note that even without considering attention, such an investigation would be useful because visible persistence in scotopic viewing has not been examined apart from the present study.

The dot-matrix task lends itself less readily to study the effects of attention on masking. The problem lies with defining the number of units over which attention

can be divided. Given a 25-dot matrix, it is not possible to say a priori whether attention is focused on the entire matrix as a single unit, or on the aggregate of dots in each of the two sequential frames, or on each dot separately. To be clear about this issue, in order to introduce a set size manipulation, we first need to know what constitutes a unit in the set. At present, it seems clear that the individual dot is not such a unit: very similar results are obtained whether the matrix contains 25 dots or 16 dots (Di Lollo, 1981). An alternative would be to vary, not the number of dots within a single matrix, but the number of matrices in the display. On the assumption that each single matrix functions as a unit in the set, this would be homologous to varying the number of letters in the type of display employed by Eriksen and Collins (1967).

### Alternative strategies for temporal integration

One outstanding issue that was not addressed in the present study was the possibility that performance at long and short ISIs are governed by different mechanisms. For example, observers may gain some benefit by storing the information in frame one by some other means than visible persistence. These might include schematic (iconic) memory, or even a conscious coding of specific elements. Although stimuli are designed to prevent against this possibility by allowing for a large number of randomly chosen alternatives, the possibility nevertheless exists in this and previous research. In fact, it has sometimes been

used to explain why accuracy does not decline all the way to chance (e.g., Eriksen & Collins, 1967).

In the present experiment, where chance was 50% correct, accuracy appeared to level off at about 42% errors in the light and 32% in the dark. This too points to the possibility that a mechanism other than visible persistence contributed to performance. However, the possible existence of another mechanism does not invalidate the main conclusions. Indeed, it is difficult to see how the main results could have been produced by a second mechanism: (1) the constant set size effects across ISI in scotopic viewing, (2) the set size effects that increased with ISI in photopic viewing, and (3) the absence of a similarity interaction with set size and ISI. Attempts to use this second mechanism to account for one of these results would run into difficulty in accounting for the other two findings.

Future experiments should directly address this issue. For example, by varying the correlation between the segments chosen for frames 1 and 2, the contribution of memory for specific elements in frame 1 could be directly assessed.

### Conclusions

There were five main contributions of the present work. Two have strong theoretical implications; the remaining three improve our understanding of the methods used to study temporal integration and visual search.

1. Attention does not influence visible persistence. This was supported by the relatively constant search slopes over ISI in the scotopic condition, where masking was not a factor.

2. Attention reduces the effects of metacontrast masking in the two-frame visual search task. This was supported most directly by search slopes that increased more with ISI in the photopic than in the scotopic condition. It was also supported by the weak effects of similarity on the search slopes in the photopic condition. Effects of similarity are premised on the availability of an integrated display and masking would work against integration. The potential for masking in the two similarity conditions was equivalent because the letter fragments in the second frame were random and meaningless in each case. Thus, finding no effect of similarity is consistent with the reduction of masking by attention.

3. The present thesis contains the first thorough examination of adapting luminance in a temporal integration task. This comparison allowed masking to be factored out of performance. This is an important development, both for the interpretation of previous work and for the design of future experiments.

4. The present thesis contains the first examination of set size effects in a temporal integration task. This manipulation of attention showed that although visible persistence was unaffected, masking was influenced by attention. Previous studies of temporal integration have not considered attention as a determinant of

performance. Therefore, previous work should be reevaluated in light of the possible relative contributions of persistence and masking.

5. The present thesis contains the first examination of visual search under scotopic viewing. The results showed that generally similar search mechanisms operate when the input consists of photopic (cone vision) and scotopic (rod vision) levels of light. One notable difference was the longer visible persistence for scotopic viewing, thus providing the observer with an effectively longer exposure duration, and therefore an easier search task.

References

- Adelson, E. H. (1978). Iconic storage: The role of the rods. Science, 201, 544-546.
- Adelson, E. H., & Jonides, J. (1980). The psychophysics of iconic storage. Journal of Experimental Psychology: Human Perception and Performance, 6, 486-493.
- Allen, F. (1926). The persistence of vision. American Journal of Physiological Optics, 7, 439-457.
- Allport, D. A. (1968). Phenomenal simultaneity and the perceptual moment hypothesis. British Journal of Psychology, 59, 395-406.
- Bashinski, H. S., & Bacharach, V. R. (1980). Enhancement of perceptual sensitivity as the result of selectively attending to spatial locations. Perception & Psychophysics, 28, 241-248.
- Bergen, J. R., & Julesz, B. (1983). Rapid discrimination of visual patterns. IEEE Transactions on Systems, Man and Cybernetics, 13, 857-863.
- Bischof, W. F., & Di Lollo, V. (1995). Motion and metacontrast with simultaneous onset of stimuli. Journal of the Optical Society of America, 12, 1-14.
- Breitmeyer, B. G. (1980). Unmasking visual masking: A look at the 'why' behind the veil of 'how'. Psychological Review, 87, 52-69.
- Breitmeyer, B. G. (1984). Visual Masking: An Integrative Approach. New York: Oxford University Press.
- Broadbent, D. E. (1958). Perception and Communication. New York: Pergamon Press.
- Brown, J. L. (1965a). Flicker and intermittent stimulation. In C. H. Graham (Ed.), Vision and Visual Perception (pp. 251-320). New York: John Wiley & Sons, Inc.
- Brown, J. L. (1965b). Afterimages. In C. H. Graham (Ed.), Vision and Visual Perception (pp. 479-503). New York: John Wiley & Sons, Inc.
- Bundesen, C. (1990). A theory of visual attention. Psychological Review, 4, 523-547.
- Burr, D. C. (1980). Motion Smear. Nature, 284, 164-165.

- Castet, E., Lorenceau, J., & Bonnet, C. (1993). The inverse intensity effect is not lost with stimuli in apparent motion. Vision Research, 33, 1697-1708.
- Coltheart, M. (1980). Iconic memory and visible persistence. Perception & Psychophysics, 27, 183-228.
- Coltheart, M., Lea, C. D., & Thompson, K. (1974). In defence of iconic memory. Quarterly Journal of Experimental Psychology, 26, 633-641.
- 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. (1984). On the relationship between stimulus intensity and duration of visible persistence. Journal of Experimental Psychology: Human Perception and Performance, 10, 144-151.
- Di Lollo, V., & Bischof, W. F. (1995). Inverse-intensity effect in duration of visible persistence. Psychological Bulletin, 118, 223-237.
- Di Lollo, V., Clark, C. D., & Hogben, J. H. (1988). Separating visible persistence from retinal afterimages. Perception & Psychophysics, 44, 363-368.
- Di Lollo, V., & Hogben, J. H. (1987). Suppression of visible persistence as a function of spatial separation between inducing stimuli. Perception & Psychophysics, 41, 345-354.
- Di Lollo, V., Hogben, J. H., & Dixon, P. (1994). Temporal integration and segregation of brief visual stimuli: Patterns of correlation in time. Perception & Psychophysics, 55, 373-386.
- Di Lollo, V., & Wilson, A. E. (1978). Iconic persistence and perceptual moment as determinants of temporal integration in vision. Vision Research, 18, 1607-1610.
- Dick, A. O. (1974). Iconic memory and its relation to perceptual processing and other memory mechanisms. Perception & Psychophysics, 16, 575-596.



- Dixon, P., & Di Lollo, V. (1994). Beyond visible persistence: An alternative account of temporal integration and segregation in visual processing. Cognitive Psychology, 26, 33-63.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. Psychological Review, 96, 433-458.
- Duysens, J., Orban, G. A., Cremieux, J., & Maes, H. (1985). Visual cortical correlates of visible persistence. Vision Research, 25, 171-178.
- Efron, R. (1970). Effect of stimulus duration on perceptual onset and offset latencies. Perception & Psychophysics, 8, 231-234.
- Efron, R. (1973). An invariant characteristic of perceptual systems in the time domain. In S. Kornblum (Ed.), Attention and Performance (pp. 713-736). New York: Academic Press.
- Efron, R., & Lee, D. N. (1971). The visual persistence of a moving stroboscopically illuminated object. American Journal of Psychology, 84, 365-375.
- Enns, J. T. (1992). The nature of selectivity in early human vision. In B. Burns (Ed.), Percepts, concepts, and categories: The representation and processing of information (pp. 39-74). Amsterdam: Elsevier Science Publications.
- Enns, J. T., Brehaut, J. C., & Shore, D. I. (1996). Attended objects are on view longer than unattended ones. The Psychonomic Society, Chicago.
- Enns, J. T., & Di Lollo, V. (in press). Attentional masking: Visual interference by object substitution. Psychological Science, accepted Oct., 1996.
- Enns, J. T., & Rensink, R. A. (1991). Preattentive recovery of three-dimensional orientation from line drawings. Psychological Review, 98, 335-351.
- Enroth-Cugel, C., & Robson, J. G. (1966). The contrast sensitivity of retinal ganglion cells of the cat. Journal of Physiology (London), 187, 517-552.
- Eriksen, C. W., & Collins, J. F. (1967). Some temporal characteristics of visual pattern perception. Journal of Experimental Psychology, 74, 476-484.

- Eriksen, C. W., & Collins, J. F. (1968). Sensory traces versus the psychological moment in the temporal organization of form. Journal of Experimental Psychology, 77, 276-382.
- Eriksen, C. W., & Hoffman, J. E. (1974). Selective attention: Noise suppression or signal enhancement? Bulletin of the Psychonomic Society, 4, 587-589.
- Ferrell, J. E. (1984). Visible persistence of moving objects. Journal of Experimental Psychology: Human Perception and Performance, 10, 502-511.
- Ferry, E. S. (1892). Persistence of vision. American Journal of Science, 44, 192-207.
- Fink, D. G., & Lutyens, D. M. (1960). The physics of television. New York: Anchor Books.
- Finley, G. (1985). A high-speed point plotter for vision research. Vision Research, 25, 1993-1997.
- Greenhouse, S. W., & Geisser, S. (1959). On methods in the analysis of profile data. Psychometrika, 24, 95-112.
- Groner, M. T., Bischof, W. F., & Di Lollo, V. (1989). A model of visible persistence and temporal integration. Spatial Vision, 3, 293-304.
- Groner, R., Groner, M. T., Bischof, W. F., & Di Lollo, V. (1990). On the relation between metacontrast masking and suppression of visible persistence. Journal of Experimental Psychology: Human Perception and Performance, 16, 381-390.
- Haber, R. N. (1983). The impending demise of the icon: A critique of the concept of iconic storage in visual information processing. The Behavioral and Brain Sciences, 6, 1-54.
- Hebb, D. O. (1949). The Organization of Behavior. New York: Wiley.
- Helmholtz, H. v. (1867/1967). Treatise on Physiological Optics. New York: Dover.
- Hogben, J. H., & Di Lollo, V. (1974). Perceptual integration and perceptual segregation of brief visual stimuli. Vision Research, 14, 1059-1069.

- Hogben, J. H., & Di Lollo, V. (1985). Suppression of visible persistence in apparent motion. Perception & Psychophysics, 38, 450-460.
- Huynh, H., & Feldt, L. S. (1970). Conditions under which mean square ratios in repeated measurement designs have exact F-distributions. Journal of American Statistical Association, 65, 1582-1589.
- Irwin, D. E., & Yeomans, J. M. (1991). Duration of visible persistence in relation to stimulus complexity. Perception & Psychophysics, 50, 475-489.
- James, W. (1890). Principles of Psychology. New York: World Publishing Company.
- Julesz, B. (1984). A brief outline of the texton theory of human vision. Trends in Neuroscience, 7, 41-45.
- Kahneman, D. (1968). Method, findings, and theory in studies of visual masking. Psychological Bulletin, 70, 404-425.
- Kelly, D. H. (1961). Visual responses to time-dependent stimuli. I. Amplitude sensitivity measurement. Journal of the Optical Society of America, 51, 422-429.
- Laarni, J., Näsänen, R., Rovamo, J., & Saarinen, J. (1996). Performance in simple visual search at threshold contrasts. Investigative Ophthalmology & Visual Science, 37, 1706-1710.
- Loftus, G. R., & Hanna, A. M. (1989). The phenomenology of spatial integration: Data and models. Cognitive Psychology, 21, 363-397.
- Long, G. M. (1980). Iconic memory: A review and critique of the study of short-term visual storage. Psychological Bulletin, 88, 785-820.
- Long, G. M., & Sakitt, B. (1980). The retinal basis of iconic memory: Eriksen and Collins revisited. American Journal of Psychology, 93, 195-207.
- Long, G. M., & Sakitt, B. (1981). Differences between flicker and non-flicker persistence tasks: The effect of luminance and the number of cycles in a grating target. Vision Research, 21, 1387-1393.
- Luck, S. J., Hillyard, S. A., Mouloua, M., & Hawkins, H. L. (1996). Mechanisms of visual-spatial attention: Resource allocation or uncertainty reduction?

Journal of Experimental Psychology: Human Perception and Performance, 22, 725-737.

- McLeod, P., Driver, J., & Crisp, J. (1988). Visual search for a conjunction of movement and form is parallel. Nature, 322, 154-155.
- Meyer, D. E., Schvaneveldt, R.W. (1971). Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations. Journal of Experimental Psychology, 90, 227-234.
- Meyer, D. E., Schvaneveldt, R.W. (1976). Meaning, Memory Structure, and Mental Processes. Science, 192, 27-33.
- Motter, B. C. (1993). Focal Attention produces spatially selective processing in visual cortical areas V1, V2, and V4 in the presence of competing stimuli. Journal of Neurophysiology, 70, 909-919.
- Motter, B. C. (1994a). Neural correlates of attentive selection for color or luminance in extrastriate area V4. The Journal of Neuroscience, 14, 2178-2189.
- Motter, B. C. (1994b). Neural correlates of feature selective memory and pop-out in extrastriate area V4. The Journal of Neuroscience, 14, 2190-2199.
- Müller, H. J., Humphreys, G. W., & Donnelly, N. (1994). SEarch via recursive rejection (SERR): Visual search for single and dual form-conjunction targets. Journal of Experimental Psychology: Human Perception and Performance, 20, 235-258.
- Nakayama, K., & Silverman, G. H. (1986). Serial and parallel processing of visual feature conjunctions. Nature, 322, 264-265.
- Neisser, U. (1967). Cognitive Psychology. New York: Appeton-Century-Crofts.
- Orenstein, H. B., & Holding, D. H. (1987). Attentional factors in iconic memory and visible persistence. The Quarterly Journal of Experimental Psychology, 39A, 149-166.
- Palmer, J. (1994). Set-size effects in visual search: the effect of attention is independent of the stimulus for simple tasks. Vision Research, 34, 1703-1721.

- Palmer, J., Ames, C. T., & Lindsey, D. T. (1993). Measuring the effect of attention on simple visual search. Journal of Experimental Psychology: Human Perception and Performance, 19, 108-130.
- Porter, T. C. (1902). Contribution to the study of flicker. Proceedings of the Royal Society (London), 70A, 313-329.
- Posner, M. I. (1980). Orienting of Attention. Quarterly Journal of Experimental Psychology, 32, 3-25.
- Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). Attention and the detection of signals. Journal of Experimental Psychology: General, 109, 160-174.
- Ramachandran, V. S., & Cobb, S. (1995). Visual attention modulates metacontrast masking. Nature, 373, 66-68.
- Reinitz, M. T. (1990). Effects of spatially directed attention on visual encoding. Perception & Psychophysics, 47, 497-505.
- Rensink, R. A., & Enns, J. T. (1995). Preemption effects in visual search: Evidence for low-level grouping. Psychological Review, 102, 101-130.
- Sakitt, B. (1975). Locus of short-term visual storage. Science, 190, 1318-1319.
- Sakitt, B. (1976). Iconic Memory. Psychological Review, 83, 257-276.
- Schiller, P.H. (1992). The On and OFF channels of the visual system. Trends in Neurosciences, 15, 86-92.
- Shaw, M. L. (1980). Identifying attentional and decision-making components in information processing. In R. S. Nickerson (Ed.), Attention and Performance VIII (pp. 277-296). Hillsdale, New Jersey: Lawrence Erlbaum Associates, Publishers.
- Shiu, L. P., & Pashler, H. (1994). Negligible effect of spatial precuing on identification of single digits. Journal of Experimental Psychology: Human Perception and Performance, 20, 1037-1054.
- Shiu, L. P., & Pashler, H. (1995). Spatial attention and vernier acuity. Vision Research, 35, 337-343.

- Singer, W., & Phillips, W. A. (1974). Function and interaction of on and off transients in vision: II. Neurophysiology. Experimental Brain Research, 19, 507-522.
- Smith, V. C. (1969). Scotopic and photopic function for visual band movement. Vision Research, 9, 293-304.
- Sperling, G. (1960). The information available in brief visual presentations. Psychological Monographs: General and Applied, 74, 1-29.
- Sperling, G. (1967). Successive approximations to a model for short term memory. Acta Psychologica, 27, 285-292.
- Stelmach, L. B., & Herdman, C. M. (1991). Directed attention and perception of temporal order. Journal of Experimental Psychology: Human Perception and Performance, 17, 539-550.
- Stelmach, L. B., Herdman, C. M., & McNeil, K. R. (1994). Attentional modulation of visual processes in motion perception. Journal of Experimental Psychology: Human Perception and Performance, 20, 108-121.
- Treisman, A. (1986). Features and objects in visual processing. Scientific American, 255, 114-125.
- Treisman, A., Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. Psychological Review, 95, 15-48.
- Treisman, A., Cavanagh, P., Fischer, B., Ramachandran, V. S., & von der Heydt, R. (1990). Form perception and attention: Striate cortex and beyond. In L. Spillmann, & J. S. Werner (Ed.), Visual Perception: The Neurophysiological Foundations (pp. 273-316). New York: Academic Press Inc.
- Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. Cognitive Psychology, 12, 97-136.
- Treisman, A., Russell, R., & Green, J. (1975). Brief visual storage of shape and movement. In P. M. A. Robbitt, & S. Dornic (Ed.), Attention and Performance V (pp. 699-721). London: Academic Press.

- Tsal, Y., Shalev, L., Zakay, D., & Lubow, R. E. (1994). Attention reduces perceived brightness contrast. The Quarterly Journal of Experimental Psychology, 47A, 865-893.
- 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 W. K. Estes (Ed.), Handbook of learning and cognitive processes (pp. 91-142). Hillsdale: Earlbaum.
- Verghese, P., & Nakayama, K. (1993). Stimulus discriminability in visual search. Vision Research, 34, 2453-2467.
- Verghese, P., & Pelli, D. G. (1992). The information capacity of visual attention. Vision Research, 32, 983-995.
- von Wright, J. M. (1968). Selection in visual immediate memory. Quarterly Journal of Experimental Psychology, 68, 62-68.
- Walraven, J., Enroth-Cugell, C., Hood, D. C., MacLeod, D. I., & Schnapf, J. L. (1990). The control of visual sensitivity. In L. Spillmann, & J. S. Werner (Ed.), Visual Perception: The Neurophysiological Foundations (pp. 53-102). New York: Academic Press, Inc.
- Whitten, D. N., & Brown, K. T. (1973). The time course of late receptor potentials from monkey cones and rods. Vision Research, 13, 107-135.
- Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. Journal of Experimental Psychology: Human Perception and Performance, 15, 419-433.
- Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. Journal of Experimental Psychology: Human Perception and Performance, 10, 601-621.
- Zucker, S. W. (1987). Early vision. In S. C. Shapiro (Ed.), The Encyclopedia of artificial intelligence (pp. 1131-1152). New York: John Wiley.

Table 1. Mean reaction time (ms) and percentage error in Experiment 1. Numbers in parentheses are within-observer standard errors of the mean.

Adapting Luminance					
Photopic			Scotopic		
Set Size		Low Similarity	High Similarity	Low Similarity	High Similarity
Reaction Time (ms)					
KAL	2	492 (5.4)	579 (7.6)	592 (8.4)	692 (18.9)
	4	488 (4.7)	656 (16.7)	582 (6.7)	714 (13.8)
	6	502 (7.2)	702 (20.9)	617 (10.5)	823 (19.5)
	8	501 (6.6)	853 (36.0)	629 (8.7)	849 (23.7)
JCB	2	431 (6.4)	483 (9.1)	535 (6.7)	546 (6.0)
	4	441 (6.4)	555 (12.3)	549 (9.9)	564 (7.1)
	6	442 (5.7)	600 (16.1)	530 (6.0)	575 (7.4)
	8	440 (5.1)	618 (14.9)	541 (6.8)	586 (10.6)
DIS	2	496 (6.5)	551 (6.5)	621 (7.5)	662 (7.6)
	4	513 (7.0)	596 (8.8)	631 (6.3)	690 (9.5)
	6	511 (6.6)	637 (11.0)	643 (6.3)	738 (12.3)
	8	511 (7.6)	681 (13.0)	654 (8.6)	741 (11.6)
Percentage Error					
KAL	2	0	0	0	2
	4	2	2	0	6
	6	0	10	0	6
	8	1	15	0	7
JCB	2	5	8	4	2
	4	3	9	1	3
	6	5	6	2	7
	8	3	8	2	4
DIS	2	1	0	1	3
	4	2	3	2	4
	6	6	6	4	14
	8	3	15	5	10



Table 2. Mean percentage error in the photopic condition of Experiment 2.

		Inter-stimulus Interval (ms)								
Set Size		0	25	50	75	100	125	150	175	200
Low Similarity										
KAL	2	1	1	4	9	12	15	20	21	19
	4	1	4	8	11	14	18	28	33	38
	6	0	1	11	15	24	34	32	33	36
	8	1	4	12	12	34	33	34	36	38
JCB	2	3	0	9	6	12	12	24	22	22
	4	6	5	5	16	20	21	28	37	37
	6	6	7	12	17	29	30	34	30	45
	8	3	6	14	18	30	36	39	34	38
DIS	2	2	1	16	22	24	32	37	34	31
	4	4	2	19	48	38	35	45	45	36
	6	5	9	26	47	43	49	40	41	45
	8	5	17	38	46	53	41	45	54	38
High Similarity										
KAL	2	1	2	12	17	11	18	23	23	21
	4	1	5	12	14	28	30	31	32	30
	6	5	15	25	24	27	42	34	44	30
	8	7	20	23	26	27	47	51	43	45
JCB	2	3	2	6	14	17	18	20	33	30
	4	5	11	14	22	29	24	34	38	33
	6	8	16	15	27	32	27	36	44	42
	8	9	19	34	33	34	37	33	46	39
DIS	2	2	10	18	29	38	41	36	35	30
	4	6	8	31	35	43	42	46	39	39
	6	13	16	31	39	47	57	48	49	55
	8	11	30	36	53	47	56	52	42	43

Table 3. Mean percentage error in the scotopic condition of Experiment 2.

		Inter-stimulus Interval (ms)								
Set Size		0	50	100	150	200	250	300	350	400
Low Similarity										
KAL	2	0	0	5	10	4	14	13	19	16
	4	0	4	2	7	15	20	30	21	13
	6	0	1	5	10	23	24	24	18	30
	8	1	1	6	14	22	31	35	27	30
JCB	2	2	3	3	14	18	20	7	21	13
	4	5	5	3	16	15	18	21	20	20
	6	8	3	7	14	20	29	25	19	23
	8	4	5	7	17	16	19	21	33	26
DIS	2	4	8	8	12	25	26	24	33	27
	4	6	10	14	12	34	20	35	40	32
	6	8	10	18	22	35	44	41	36	32
	8	11	14	17	30	32	35	41	35	44
High Similarity										
KAL	2	1	0	3	11	18	18	19	21	20
	4	0	4	6	14	19	25	27	22	28
	6	4	4	14	21	28	30	30	26	30
	8	5	9	21	14	22	28	28	24	40
JCB	2	3	8	2	19	11	21	11	23	13
	4	6	5	9	16	13	23	14	25	26
	6	4	13	7	13	13	25	12	30	12
	8	4	9	6	18	13	25	16	25	20
DIS	2	6	12	12	20	24	39	29	36	29
	4	18	12	22	33	27	41	37	42	25
	6	14	24	26	40	31	40	40	45	40
	8	14	24	24	40	40	44	40	41	34