EXTRACTION OF INFORMATION FROM COMPLEX VISUAL STIMULI: MEMORY PERFORMANCE AND PHENOMENOLOGICAL APPEARANCE

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I. Introduction

An observer viewing a visual stimulus forms a representation of the stimulus in memory that can later be accessed in a variety of ways. The encoding processes by which the representation is formed are undoubtedly diverse and complex (cf. Potter, 1976; Intraub, 1984; Loftus & Ginn, 1984; Loftus, Hanna, & Lester, 1988). They may, however, be conveniently divided into those that operate on (1) the physical stimulus, (2) the iconic image (hereafter *icon*) that follows the physical stimulus, and (3) the short-term representation of the stimulus that follows the icon's termination. Using the terminology of Intraub (1980), Loftus and Ginn (1984) and Potter (1976), we call the first two types of processes *perceptual* and the third *conceptual*. Our focus in this article is on perceptual processes, and our first goal is to construct and test a model of the relation between the perceptual processing of some stimulus and the quality of the stimulus's eventual memory representation.

Given our definitions of perceptual and conceptual processing, it is evident that perceptual processing occurs in conjunction with conscious (or phenomenological) awareness of the to-be-encoded stimulus. Indeed, it is the existence of such awareness that underlies the perceptual/conceptual dichotomy to begin with; a common intuition is that there must be a raw-

information extraction process that can *only* occur if the stimulus is phenomenologically present. Our second goal is to extend our perceptual-processing model to encompass the phenomenological awareness of a visual stimulus. To briefly anticipate, we will argue and present data favoring the proposition that phenomenological awareness is a consequence of perceptual processing rather than the other way around.

Much of the empirical work described here focuses on extraction of information from an icon and phenomenological awareness of the icon. In keeping with past terminology, we shall often refer to the latter as *visible persistence*. The appropriateness of these issues as topics of scientific investigation is a source of some debate (see Haber, 1983, 1985). While we are not neutral in that debate (cf. Loftus, 1983, 1985b), we note that our present interest is not so much in the icon per se, but rather in the icon as a tool for investigating the relation between information extraction and phenomenological awareness. We start by reviewing evidence that the same perceptual processes operate on a physical stimulus and on an icon. This evidence sets the stage for a series of new experiments in which we investigate factors that influence perceptual processing of the icon and then go on to argue that these same factors are intimately involved in the operation of perceptual processes in general.

Empirically, our starting point is a series of picture-memory experiments reported by Loftus, Johnson, and Shimamura (1985). This work was motivated by the existence of two important similarities between a picture and the icon that follows. First, information that is useful in a subsequent memory test can be extracted from the icon, just as it can be extracted from the physical stimulus. Second, there is no phenomenological dividing line between the offset of the physical stimulus and the onset of the icon; indeed, naive subjects think that an icon *is* a fading extension of the physical stimulus. These similarities led Loftus *et al.* to hypothesize that a stimulus and an icon are equivalent in terms of (1) the potentially extractable information that they contain, (2) the perceptual processes that operate on them, and (3) their influence on whatever mental machinery is responsible for phenomenological awareness.

Loftus *et al.* (1985) were concerned chiefly with information extraction. They reasoned that if icon/stimulus equivalence held, then information extracted from an icon might be parsimoniously characterized in terms of information that could potentially be extracted from a physical extension of the stimulus. To investigate this possibility, Loftus *et al.* assessed memory performance for pictures that had been followed either by an immediate noise mask (which did not permit an icon) or by a 300-msec delayed noise mask (which did permit an icon). Generic results from these experiments are shown in Fig. 1. As expected on the basis of past data (and on the basis of common sense), performance increased with increasing exposure duration.[1] The finding of primary interest, however, was that the physical exposure duration required to achieve any given performance level was approximately 100 msec longer for immediate-masked pictures, relative to delay-masked pictures. This result was independent of the picture's exposure duration; moreover, it obtained for three performance measures, four sets of pictures, and two levels of stimulus luminance. Loftus *et al.* concluded that the additional information that could be extracted from an icon was approximately equal to the additional information that could be extracted from a 100-msec extension of the physical stimulus.

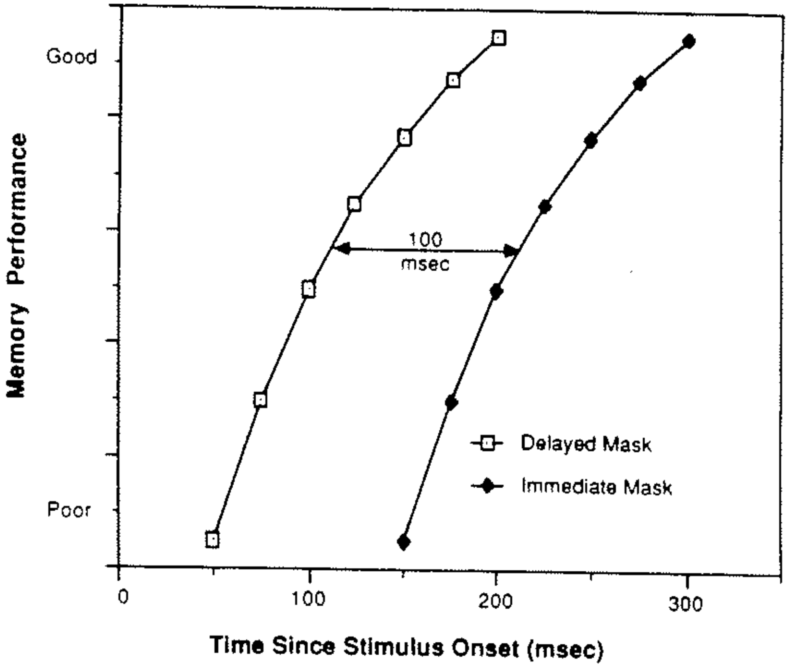

Fig. 1. Generic results from Loftus *et al.* (1985); memory performance (in the experiments, measured by detail recall, recognition, or ratings) as a function of stimulus exposure duration. The two curves are for immediate-mask (no-icon) and delayed-mask (icon) stimuli. The curves are horizontally parallel, displaced from one another by 100 msec.

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[1] The major findings of the Loftus *et al.* experiments held over a variety of dependent variables (detail recall, yes–no recognition, and rated visibility). For this reason, the ordinate of Fig. 1 is simply "performance" rather than some specific performance measure.

Accordingly, they characterized the icon as having an *equivalent physical duration*, or a *worth* of $w = 100$ msec.[2]

This invariance of an icon's worth over such a wide variety of conditions could be entirely coincidental. It seems more likely, however, that the invariance is not coincidental. In particular, it could result from the kind of equivalence hypothesis sketched previously: that from the cognitive system's perspective, an icon is equivalent to a literal (albeit fading) extension of the physical stimulus. In this article, we expand on this idea and show how the invariance of the icon's worth follows from such equivalence. The article is divided into two main sections. In the first section, we propose a formal model, incorporating the notion of icon/stimulus equivalence, that accounts for the Loftus *et al.* (1985) data as well as for other findings in the picture-memory literature. In the second section, we extend this model to account for subjective accounts of visible persistence. In each section we present experiments in support of the model.

Our model incorporates two fundamental propositions. The first is that a stimulus and its icon are equivalent with respect to both the kind of information that they provide the observer and the perceptual processes that operate on them. Given this viewpoint, it is appropriate to use the term *visual stimulus* to encompass both the physical stimulus and any icon that follows. The second proposition, which we formalize in Section II, is that phenomenological experience of a stimulus results from extraction of information from that stimulus. This means that one sees an icon for the same reason that one sees a physical stimulus—the information-extraction process is the same in both cases, so the phenomenology is the same in both cases.

An implication of this second proposition is that extraction of information from a visual stimulus on the one hand and the subjective experience of seeing the stimulus on the other are mediated by the same processes. As applied to the icon, this notion has recently come under attack. The most extensive argument against it was made by Coltheart (1980) who compared degree of information extraction, as assessed in a Sperling (1960) partial-report task, with the duration of visible persistence, as assessed in a synchrony-judgment task (e.g., Efron, 1970) or a temporal-integration task (e.g., Eriksen & Collins, 1967; Di Lollo, 1980). Coltheart noted a particular variable—stimulus duration—that has different effects on the two phenomena. Stimulus duration has little, if any, effect on partial-report performance, but a substantial effect on the estimated duration of visible persistence; longer stimuli show less persistence than do shorter stimuli. Our model accounts for this effect.[3]

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[2] To forestall confusion, it is worthwhile at this point to distinguish between an icon's worth and an icon's duration. These two entities are related, but they are not the same. Worth, as noted, refers to the amount of time by which a masked physical stimulus must be extended in order to extract the same amount of information as would be extracted from an icon. Duration refers to the maximum time following stimulus offset during which the icon continues, by some criterion, to exist. Later we will compare worth and duration in detail.

II. A Model of Information Acquisition and Picture Memory

Our goal in this section is to formulate a model of the relation between picture viewing and later picture memory. After describing the model, we show that it accounts for some robust findings in the visual-memory literature, and we then present three picture-recognition experiments in support of it. We will not be concerned with phenomenological appearance in this section; we defer extension of the model to this domain until Section III.

We present the model in two forms: a general and a quantitative form. The general form is composed of five qualitative assumptions that we believe may correspond to psychological reality. In the quantitative form of the model, two of these qualitative assumptions are replaced with corresponding quantitative forms. These quantitative assumptions are stronger than their qualitative counterparts in that the former imply the latter, but not vice versa. Although we have substantially less faith in the accuracy of the quantitative assumptions, they may be approximately correct and, in any event, are useful for illustrating relationships and predictions.

A. THE MODEL

1. *Overview*

Consider a situation in which an observer views a briefly presented visual stimulus with the intent of being able to remember it later on. Within our model, the stimulus is treated as a bundle of information that must be extracted and eventually encoded in some relatively long-term memory. The model does not precisely characterize what is "information." It does, however, incorprate the assumption that information is *unidimensional*,

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[3] Coltheart also asserted that stimulus luminance has an effect similar to that of stimulus duration; that is, he asserted that luminance has no effect on partial-report performance, but a negative effect on persistence duration. However, as we discuss later, Adelson and Jonides (1980) showed a small effect of stimulus luminance on partial-report performance, while Long and Beaton (1982) showed larger and more robust effects. In addition, the effect of luminance on persistence duration turns out to be somewhat complicated, both empirically and theoretically. We also discuss luminance in some detail later in this article.

i.e., that amount of extracted information is representable by a single value on some ordinal scale. We mention this assumption here because it is crucial: if it is incorrect, the remaining four assumptions make no sense. At the end of this article, we discuss possible limitations on the unidimensionality assumption's validity along with concommitant restrictions on the model itself.

2. *Assumptions*

The model consists of five assumptions involving (1) available (potentially extractable) stimulus information, (2) unidimensionality of information, (3) the rate at which available information is extracted, (4) the relation between extracted information and subsequent memory performance, and (5) the basis of phenomenological appearance. We describe the first four assumptions in this section, and the fifth in Section III.

Assumption 1: Available Information. A stimulus consists of information that is potentially available to a subsequent information-extraction process. While the stimulus is physically present, all information is available; when the stimulus physically disappears, available information decays over time.

The proportion of total stimulus information available at time t following stimulus onset is designated $a(t)$. In the general model,

$$a(t) = \begin{cases} 1.0 & \text{for } t < d \\ b(t-d) & \text{for } t > d \end{cases} \tag{1g}$$

where d is stimulus duration and b is the poststimulus decay function. The function b is assumed to be nonnegative, monotonically decreasing with the constraint that $b(0) = 1.0$, and the integral of b from 0 to infinity is equal to w (recall that w is the icon's worth in units of time).[4] Because the argument of b is $(t - d)$, the shape of d and the value of its integral are independent of d, the picture's duration.

In the quantitative model, b is a negative exponential; thus

$$a(t) = \begin{cases} 1.0 & \text{for } t < d \\ e^{-(t-d)/w} & \text{for } t > d \end{cases} \tag{1q}$$

Equation (1q) is illustrated in Fig. 2 (top) for two values of d: 20 and 270 msec. The icon's worth, w, is set to 100 msec, the value obtained by Loftus *et al.* (1985).

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[4] Note that $a(t)$, being a proportion, is a dimensionless number. Therefore, its integral over time is in units of time.

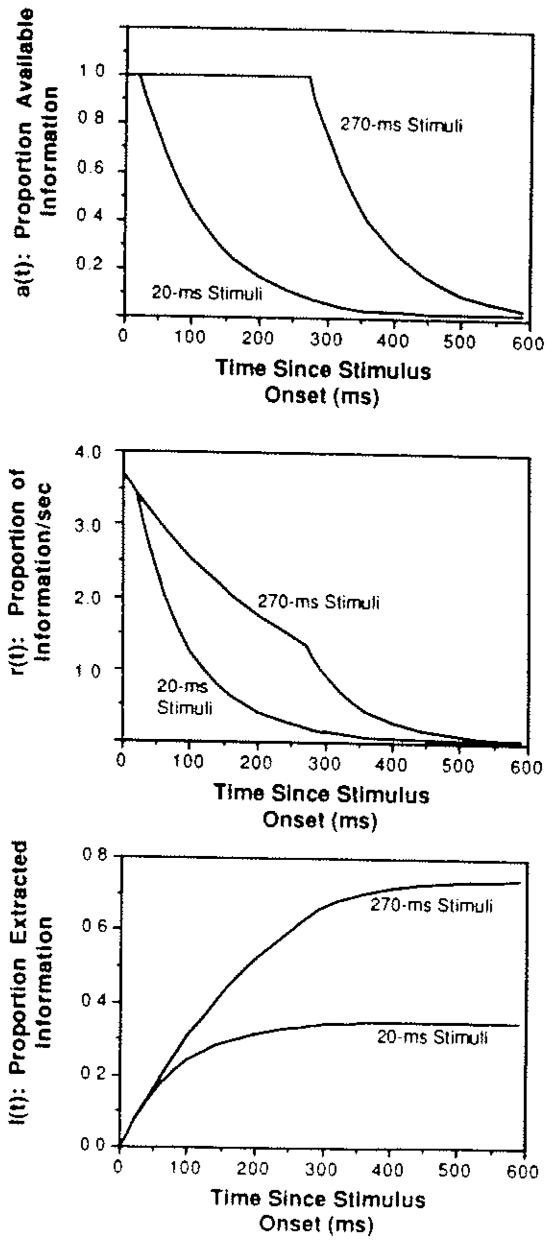

Fig. 2. Quantitative model: illustration of $a(t)$, $r(t)$, and $I(t)$ as functions of time since stimulus onset.

Assumption 2: Unidimensionality. Information is unidimensional; that is, both amount of information available in the stimulus and amount of information extracted by the observer can be represented by a single value on some ordinal scale.

Assumption 3: Information-Extraction Rate. The proportion of total stimulus information extracted by time t is designated $I(t)$. New information is extracted at a rate $r(t)$, where $r(t)$ is the derivative of extracted information with respect to time, i.e., $r(t) = dI/dt$.

The information-extraction rate is determined by two things. First, $r(t)$ is assumed to be a multiplicative function of $a(t)$, the available information [since with zero available information, $r(t)$ should be zero]. Second, $r(t)$ is assumed to be a decreasing function of $I(t)$, the proportion of information already extracted; i.e., earlier information is extracted faster than later information. This assumption (in conjunction with unidimensionality) has been incorporated, in one form or another, into a variety of information-acquisition models (e.g., Kowler & Sperling, 1980; Krumhansl, 1982; Loftus & Kallman, 1979; Massaro, 1970; Rumelhart, 1969). The idea is that easier- (i.e., faster)-to-extract information is acquired earlier than harder- (i.e., slower)-to-extract information (just as, for example, the earlier words in a crossword puzzle are filled in faster than the later words). In the general model,

$$r(t) = a(t)h[I(t)] \tag{2g}$$

where h is a nonnegative, monotonically decreasing function that approaches zero as $I(t)$ approaches 1.0.

The constraints embodied in Eqs. (1g) and (2g) provide the model with certain desirable properties. First, they instantiate the ideas sketched previously that $r(t)$ is multiplicatively related to $a(t)$ but negatively related to $I(t)$. Second, $I(t)$ cannot exceed 1.0. Third, if the stimulus remains physically present indefinitely, $I(t)$ approaches or reaches 1.0.

The general form of $I(t)$ can be derived from Eqs. (1g) and (2g). As shown in Section V, A, it is:

$$I(t) = \begin{cases} H^{-1}[t + H(0)] & \text{for } t < d \\ H^{-1}[d + H(0) + B(t-d)] & \text{for } t > d \end{cases} \tag{3g}$$

where

$$H(I) = \int [1/h(I)]dI$$

and

$$B(t-d) = \int_0^{t-d} b(t-d)\, dt$$

and H^{-1} is the inverse function of H, i.e., $H^{-1}\{H[I(t)]\} = I(t)$.

The interpretation of Eq. (3g) is, essentially, that $I(t)$ is a function, H^{-1}, of two components, which are seen in the bottom part of the equation. The first, indicated by $[d + H(0)]$, corresponds to information extracted from the physical stimulus, and the second, indicated by $B(t - d)$, corresponds to information extracted from the icon. That the same function, H^{-1}, is applied to both components reflects the proposition that the same processes are applied to both the physical stimulus and the icon.

For the quantitative form of h, we have chosen a function that describes a variety of physical situations: $h(I)$ is proportional to $[1.0 - I(t)]$, the as-yet unextracted available information. Thus,

$$h(I) = c[1.0 - I(t)]$$

where c, the constant of proportionality, is a free parameter with units of $\sec^{-1}$. This leads to the equation for $r(t)$:

$$r(t) = a(t)h[I(t)] = a(t)c[1.0 - I(t)] \tag{2q}$$

Equation (2q) is illustrated in Fig. 2 (middle) with $c = 3.7$, a value that was estimated in an experiment to be described in Section II.[5]

The function $h(I)$ is central to the model in that the effects of a variety of independent variables are assumed to be mediated by their influence on $h(I)$. In the quantitative model, on which we will later rely heavily, $h(I)$ is controlled by the parameter c. It is evident from Eqs. (2q) and (2g) that the parameter c and, more generally, the function h determine both the *initial* value of $r(t)$ [that is, the value of $r(t)$ when $t = 0$] and how fast $r(t)$ declines with increases in $I(t)$. When we later characterize some independent variable (e.g., stimulus luminance) as affecting $r(t)$, this effect is instantiated in the quantitative model by variation in c across levels of the independent variable. In general, a high c value (e.g., with bright stimuli) implies an $r(t)$ that is initially high but declines rapidly over time. Conversely, a low c value (e.g., with dim stimuli) implies an $r(t)$ that is initially lower but declines more slowly over time. The proportion of extracted information, $I(t)$, always increases more rapidly the higher the value of c.

The quantitative-model equation for $I(t)$ can be derived from Eqs. (1q) and (2q). It is

$$I(t) = \begin{cases} 1.0 - e^{-ct} & \text{for } t < d \\ 1.0 - e^{-c\{d + a(1.0 - \exp[-(t-d)/a])\}} & \text{for } t > d \end{cases} \tag{3q}$$

Equation (3q) is illustrated in Fig. 2 (bottom)

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[5] The parameter c takes on this value when t is expressed in seconds.

Assumption 4: Memory Performance. Memory performance, however measured, is a monotonic function of extracted information, i.e.,

$$P(d) = m[I(d)] \tag{4g}$$

where $P(d)$ is memory performance for pictures presented for a duration of d sec and m is a monotone increasing function. Concern with the nature of m is beyond the scope of this article (here we will mostly be concerned with model predictions that do not depend on strong assumptions about m). We note in passing, that m is determined by such things as the nature of postperceptual (conceptual) processing of the stimulus, the nature of events occurring during the study–test interval, the nature of the memory test, and the nature of the retrieval process.

B. APPLICATIONS OF THE MODEL

The model as described thus far accounts for several salient aspects of picture-memory performance that we will briefly describe. First, however, we describe how we apply the model to data.

1. Evaluation Procedures

The model allows calculation of $I(t)$, the information extracted by time t. However, because the model specifies the function m relating $I(t)$ to memory performance to be no stronger than monotonic, it is not possible to predict exact performance for a given experimental condition. There are, however, two other ways in which we can apply the model to data. First, the model can predict the *ordering* of performance values across a set of experimental conditions; thus, we can evaluate whether the across-conditions relation between predicted $I(t)$ and observed memory performance is monotonic. Second, the model can, in some instances, predict *equivalence properties*, that is, it can specify the sets of exposure durations that produce equal memory performance under different levels of some independent variable; thus we can test whether these equivalence properties hold. We shall use both evaluation procedures in application of the model to existing data. We use the first procedure only in application of the model to Experiments 1–3.

2. Applications of the Model to Existing Data

In this section we describe application of the model to five kinds of picture-memory data: effects of stimulus exposure duration, stimulus luminance, subjects' age, stimulus priming, and stimulus masked/unmasked. We also describe application of the model to a partial-report paradigm.

a. Stimulus Duration. Numerous experiments have shown that performance increases with increasing stimulus duration (e.g., Loftus, 1972; Loftus & Bell, 1975; Loftus & Kallman, 1979; Potter 1976; Potter & Levy, 1969; Shaffer & Shiffrin, 1972). The model's account of this finding is straightforward: although declining over time, the information-extraction rate, $r(t)$, is always positive. Therefore $I(t)$, the integral of $r(t)$, must increase over time.

b. Three Multiplicative Variables: Stimulus Luminance, Stimulus Priming, and Subjects' Age. Empirically, an independent variable bears a *multiplicative relation* to exposure duration when it is observed that

$$P_i(d) = P_j(cd) \tag{5}$$

Here, $P_i(x)$ and $P_j(x)$ denote performance for two levels, i and j, of the independent variable following some exposure duration, x, and c is a dimensionless constant. The interpretation of Eq. (5) is that the exposure duration required to achieve any given performance level is greater by some factor, c, for level j relative to level i of the independent variable. Note that Eq. (5) defines an equivalence property; it specifies the circumstances under which performance is equal under the different levels, i and j, of some independent variable.

Multiplicative relations have been demonstrated for three independent variables: stimulus luminance (Loftus, 1985a, 1986), subject age (Loftus, Truax, & Nelson, 1986), and stimulus priming (Reinitz, 1987; Tulving, Mandler, & Baumal, 1964). For example, Loftus (1985a) varied luminance during initial viewing in a picture-recognition paradigm. He found that when luminance was reduced by two log units, exposure duration had to be multiplied by approximately 2.0 in order to maintain the same performance level. The form of Eq. (5) that represents this finding is

$$P_{\text{BRIGHT}}\ d = P_{\text{DIM}}(2d)$$

where P_{BRIGHT} and P_{DIM} refer to memory performance for high-luminance (bright) and low-luminance (dim) pictures, respectively.

The model accounts for multiplicative relationships by assuming variation in the information-extraction rate, $r(t)$, across levels of the independent variable. In particular, suppose that for the two levels, i and j, of the independent variable,

$$r_i(t_i) = dI/dt_i = f(I) \tag{6a}$$

and

$$r_j(t) = dIt_j = cf(I) \tag{6b}$$

where f is some monotone function. Note that Eqs. (6a) and (6b) conform to the $r(t)$ functions of the general model [Eq. (2g);[6] in addition, they imply that for any given information-acquisition value, I, $r(t)$ is different by some factor, c, for level i relative to level j of the independent variable. Then, as shown in Section V,C,2, a multiplicative effect of the independent variable will obtain.

c. An Additive Variable: Immediate/Delayed Mask. Empirically, an independent variable bears an *additive relation* to exposure duration when it is observed that

$$P_i(d) = P_j(k + d) \tag{7}$$

Here, $P_i(x)$, $P_j(k)$, and d are defined as in Eq. (5), and k is a constant in units of time. The interpretation of Eq. (7) is that the exposure duration required to achieve any given performance level is greater by k msec for level j relative to level i of the independent variable. Equation (7), like Eq. (5), defines an equivalence property.

As we discussed earlier, Loftus *et al.* (1985) found an additive relation for stimuli masked/unmasked: performance for $(d + 100)$-msec, immediate-masked pictures (i.e., pictures that were not followed with an icon) was equal to performance for d-msec, delay-masked pictures (i.e., pictures that were followed by an icon). The form of Eq. (7) that describes this finding is

$$P_{\mathrm{ICON}}(d) = P_{\mathrm{NO\ ICON}}(100 + d)$$

where P_{ICON} and $P_{\mathrm{NO\ ICON}}$ refer to memory performance for pictures followed by an icon and not followed by an icon, respectively.

To account for this additive relation, we assume that presentation of a noise mask reduces $r(t)$ to zero. We show in Section V, B that the Loftus *et al.* result then follows from the general model.

d. The Partial-Report Paradigm. Sperling's (1960) classic article introduced the partial-report paradigm and provided the foundation for almost three decades of work on the icon. In the partial-report paradigm, a matrix of items is briefly presented to an observer. Suppose, for the sake of illustration, that a 3 × 3 matrix of letters is presented. In a *whole-report* condition, the observer reports as many of the nine letters as possible. In a *partial-report* condition, the observer is cued via a high-, medium-, or low-frequency tone to report only one of the three rows. To estimate the number of available letters in the partial-report condition, the number of reported letters per row is multiplied by the number of rows (three in this example). Sperling and legions of subsequent investigators[7] found that as the interstimulus interval (ISI) between stimulus and cue increases, the estimated number of available letters decreases and asymptotes at the whole-report level (about 4–5 letters) after an ISI of about 300 msec. The explanation was that information was being read out of a rapidly decaying information store, and the notion of the icon was born.

Our model's account of these data rests on the idea that information extraction does not begin until the cue is presented.[8] Essentially, this means that total extracted information—and thus partial-report performance—depends only on the value of a, the available information, at the time of cue presentation. To be more precise, suppose that the cue is presented at a delay of q msec following stimulus offset, i.e., at time $t = (d + q)$. At that time, $I(t) = 0$ and $a(t - d) = a(q)$. Therefore, at time $(d + q)$, we know from Eq. (2g) that

$$r(d + q) = a(q)h(0) \tag{8g}$$

It is evident from Eq. (8g) that $r(t)$ does not depend on d, the stimulus duration; it depends only on q, the cue delay. Therefore, $r(t)$'s integral, $I(t)$, which determines partial-report performance, also depends only on q, in accordance with results reported by Sperling (1960) and Yeomans and Irwin (1986). To illustrate using the quantitative model, the total information extracted from the icon given a cue delay, q, is

$$I(t) = 1.0 - e^{[-(a \exp(-q/d))]} \tag{8q}$$

as shown in Section V, D. Thus, total extracted information, $I(t)$, does not depend on d. However, as q becomes larger, $I(t)$ becomes smaller, which is the classical delay-of-cue finding.

As indicated in Eqs. (8g) and (8q), however, $r(t)$ and therefore its integral, $I(t)$, and partial-report performance *does* depend on the function h. Later, we discuss the influence of stimulus luminance on h. Briefly, if stimulus

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[6] In all experiments in which multiplicative variables have been found, stimuli have been masked at offset. In this configuration, there is no icon and the $r(t)$ functions concern only the situation in which the stimulus is physically present. Therefore, $a(t) = 1.0$.

[7] The partial-report procedure as applied to picture perception is described by Biederman (1972), Biederman, Mezzanotte, and Rabinowitz (1981), and Biederman, Rabinowitz, Glass, and Stacy (1974).

[8] The instructions in the partial-report task may lead the observer either to refrain from extracting information prior to the cue or to extract random information from the array prior to the cue. In each case, we assume that information extraction from the cued row begins anew at the time that the cue is processed.

luminance is low enough, then $h(I)$ is lowered, as demonstrated by Loftus (1985a, Experiment 3, using alphanumeric stimuli). With similarly low stimulus luminance, $r(t)$, and thus partial-report performance, must also be lowered. Adelson and Jonides (1980) have confirmed this prediction.

C. EXPERIMENTS 1–3: NEW DATA CONCERNING THE DURATION OF PERCEPTUAL PROCESSING FOLLOWING STIMULUS OFFSET

The Loftus *et al.* (1985) experiments were designed to assess an icon's *worth*—how much information can be extracted from the icon in terms of additional physical exposure duration. Another salient feature of an icon that has been the subject of substantial investigation and that will play a major role in our arguments is an icon's *duration*. Our goal in Experiments 1–3 was to measure icon duration in the sort of picture-memory paradigm used by Loftus *et al.* Duration here refers to the length of time following stimulus offset during which perceptual processing—i.e., extraction of useful information from the icon—continues to occur. Measurement of the icon's duration in this way constitutes a preliminary test of the proposition that information extraction and visible persistence are two effects of the same process. If this proposition is correct, then the icon's duration should be in the 200–300 msec range found in persistence experiments.

To measure the duration of perceptual processing, we used a paradigm reported by Loftus and Ginn (1984; see also Erwin, 1976; Erwin & Hershenson, 1974; Irwin & Yeomans, 1986), in which briefly presented target pictures are followed by a noise mask that is either bright or dim. The bright mask is such that when it is physically superimposed on a target picture, no features from the target can be seen (thereby fulfilling Eriksen's, 1980, "minimal test" for a mask). The dim mask is such that, while the mask itself can be perceived when target and mask are physically superimposed, target features are still available.

The fundamental assumption underlying this paradigm is that variation in mask luminance affects only perceptual processes. Thus, if mask luminance is observed to affect subsequent picture memory, it is inferred that perceptual processing was ongoing at the time that the mask occurred. If the mask occurred sometime following stimulus offset, a mask-luminance effect further implies the continuing perceptual processing of (i.e., extraction of information from) the icon. Thus, the stimulus-mask interstimulus interval (ISI) at which mask luminance no longer affects memory performance is an estimate of icon duration.[9]

A recognition memory procedure was used in Experiments 1–3. In an initial study phase, target stimuli were presented, one by one, for inspection. Immediately following the study phase was a test phase in which the target stimuli, randomly intermingled with distractor stimuli, were presented, again one by one, in an old/new recognition memory test.

1. *Experiment 1*

In Experiment 1, two independent variables were factorially combined in the study phase. They were target-mask ISI, which ranged from 0 to 300 msec, and mask luminance, which was either high or low (hereafter, bright or dim).

a. Method. University of Washington undergraduates (110) participated in a 1-hr session for course credit. They were run in 22 groups of 5 subjects per group.

Stimuli were 132 naturalistic color pictures, prepared as 35-mm slides, depicting seascapes, landscapes, cityscapes, and weddings. They were randomly placed into two slide trays of 66 slides per tray. A noise mask consisted of a jumble of black lines on a white background. The noise mask could be projected at either of two luminances, bright or dim. The bright noise mask, projected at normal projector luminance, was such that when it was physically superimposed on a stimulus picture, the stimulus could not be seen. The dim noise mask was attenuated by 2 log units relative to the bright mask using a neutral-density filter. The dim mask could be seen when it was superimposed on a stimulus picture, but it did not prevent extraction of any stimulus features. When nothing was being projected, a dim adapting field was present. All relevant luminances are shown in Table I.

The same apparatus was used in all seven experiments that we report. Stimuli were displayed by a Kodak random-access slide projector and subtended a visual angle that ranged from 15 to 22° horizontal and from 10 to 15° vertical, depending on where the subject sat. A Kodak standard projector was used to display the noise mask, and a second standard projector was used to display a dim fixation point that preceded each target. Filter wheels were positioned in front of the stimuli and mask projectors. All projectors were equipped with Gerbrands tachistoscopic shutters with rise and fall times of approximately 1 msec. Subjects made all responses on individual 16-key response boxes. All display and response apparatuses

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[9] Empirically, the question of when asymptote has been reached is not simple to determine. We take the traditional hypothesis-testing approach and, for each stimulus-mask ISI, determine whether there is a significant performance difference between masked and unmasked stimuli. This procedure has the disadvantage that an estimate of asymptotic ISI will systematically depend on experimental power. Across the current experiments, power is approximately constant so results are comparable. However, to compare across different sets of experiments, an absolute criterion masked–unmasked performance difference that defines asymptote should ideally be specified.

TABLE I

STIMULUS LUMINANCE

Stimulus	Luminance (millilamberts)
Adapting field	0.07
Projector on, no slide	38.43
Fixation spot	0.38
Pattern mask	
Bright background	25.19
Black markings	2.57

were controlled by an Apple II computer system described by Loftus, Gillispie, Tigre and Nelson (1984).

An experimental session consisted of a study phase followed by a test phase using the stimuli in the first slide tray and then another study and test phase using the stimuli in the second slide tray. On each study trial, a target stimulus was displayed for 40 msec. A 500-msec noise mask followed most target pictures at one of 5 ISIs: 0, 100, 200, 250, or 300 msec. There were thus 5 ISIs × 2 mask luminances = 10 conditions. In addition, there was a control condition in which no mask was shown; hence, there were 11 conditions in all. Within each tray, 33 stimuli were presented during the study phase. The 11 conditions were presented in random order with the restriction that each condition occurred once during each of the three 11-trial blocks within each slide tray.

The sequence of events on each study trial was as follows. First, a 1-sec tone signaled the subjects to fixate a dim spot that concurrently appeared at the center of the viewing field. A target picture was then presented for 40 msec, followed, except in the control condition, by the mask, presented for 500 msec at its appropriate ISI and luminance. The stimulus onset asynchrony (SOA) between study trials was 3 sec. In the no-mask control condition, only the adapting field was present between the offset of the target picture and the start of the next study trial.

At the time of test, all 66 stimuli in the slide tray were shown in random order. The target-distractor ordering was different for the two slide trays but, for each tray, was identical for all 22 groups in the experiment. For each test stimulus, subjects were asked to respond "old" or "new" corresponding to whether they thought they had or had not seen the stimulus in the just-preceding study phase. Each subject responded by pressing the appropriate key on his or her response box. Each test trial began 0.5 sec after all subjects had responded to the previous test picture.

Each of the 132 stimuli appeared as a target for half of the groups and as a distractor for the other half. Each stimulus appeared once in each of the 11 conditions over the 11 groups for which it appeared as a target.

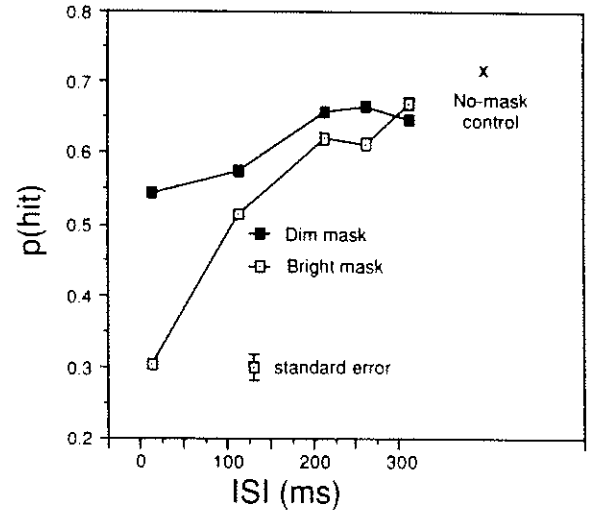

Fig. 3. Experiment 1 data. Each data point is based on 792 observations.

b. Results and Discussion. Because all study conditions were randomly intermingled within a study tray there was only a single false-alarm probability for each tray. Averaged over the two slide trays, the false-alarm probability was 0.278. Figure 3 shows stimulus performance (hit probability) as a function of stimulus-mask ISI. Different curves are shown for the two mask luminances, and the far right-hand point represents control-condition performance.

Performance in the no-mask control condition (0.707) was significantly higher than performance in any of the other conditions, [lowest $t(109) = 2.21$]; thus any mask, be it bright or dim, lowers memory performance for the picture it follows, at least in the ISI range of 0–300 msec.[10] Performance increased as a function of stimulus-mask ISI, both when the mask was dim [$F(4,436) = 8.25$] and when it was bright [$F(4,436) = 50.33$].

Recall that at a given ISI, the presence of perceptual processing (which indicates the continuing existence of the icon) is implied by a superiority of dim-mask performance over bright-mask performance. Accordingly, individual one-tailed t tests comparing the two mask-luminance conditions were performed at each of the five ISIs. The results are shown in Table

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[10] As shown by Loftus, Hanna, and Lester (1988), one effect of a noise mask is to impair conceptual as opposed to perceptual processing. This is why a mask can cause a performance deficit relative to a no-mask condition, even if the mask occurs following icon termination.

TABLE II

EXPERIMENT 1: t VALUES BETWEEN DIM- AND BRIGHT-MASK PERFORMANCE AT EACH STIMULUS-MASK ISI[a]

ISI (msec)	$t(108)$
0	8.16
100	1.80
200	1.35
250	1.95
300	−0.80

[a] Positive values indicate dim-mask performance superiority.

II. It is evident that dim-mask performance significantly exceeds bright-mask performance at ISIs of 0 and 100 msec. At ISIs of 200 and 250 msec, dim-mask performance also exceeded bright-mask performance; however, this difference was significant at 250 msec but not at 200 msec. At a 300-msec ISI, the performance difference was reversed. Collapsed over the 200–300-msec ISI range, the dim-bright difference was not significant [$t(108) = 1.43$].

Perceptual processing appears to be largely complete by 200 msec following stimulus offset and entirely complete by 300 msec. However, given the pattern of t values in Table II, the results are somewhat ambiguous. One purpose of Experiment 2 was to replicate Experiment 1 with additional statistical power.

c. Application of the Model. We applied the quantitative form of our model to the data of Experiment 1. To do so, it was necessary to select a value for the free parameter, c, and also to make assumptions about the effects of the superimposed noise masks.

We set c to 3.7, a value estimated in an experiment to be described in Section III. Based on other data (Loftus & Hogden, 1988; see also Sperling, 1986), we assumed that superimposing a noise mask would lower $r(t)$ and, thereby, constitute a multiplicative effect as defined earlier. That is, we assumed that increasing mask luminance lowers $r(t)$, the rate of extracting stimulus information.

The bright mask is such that its superimposition reduces the information-extraction rate to zero. We allowed the reduction in $r(t)$ due to dim-mask superimposition to be a free parameter. We then found the value of this parameter that maximized the rank-order correlation between I, the predicted extracted information and d', the obtained recognition-memory performance[11] over 33 total conditions: the 11 conditions from Experiment 1 along with 22 conditions from Experiments 2 and 3. The best fitting dim-mask reduction was 51%, which produced an overall rank-order correlation of 0.89. For the 11 conditions of Experiment 1 only, the obtained d'/predicted I correlation was 0.92.

2. *Experiment 2: Information from the Icon and from the Physical Stimulus*

Experiment 2 had two purposes. The first, as noted, was to replicate the essential aspects of Experiment 1 with more statistical power. The second was to begin investigating a central proposition of our model, which is that the same kind of perceptual processing is applied both to a physical stimulus and to an icon. If this proposition is correct, then any independent variable must have the same qualitative effect whether the variable is applied to the physical stimulus or to the icon. In Experiment 1, we discovered that increased mask luminance led to decreased performance when the mask was superimposed on the icon. We inferred this decrement to be mediated by the mask's effect on perceptual processes. If the perceptual processes that operate on the physical stimulus are the same as those that operate on the icon, then increasing mask luminance must similarly lead to a performance decrement when the mask is superimposed on the stimulus. This prediction was tested in Experiment 2.

a. Method. University of Washington undergraduates (110) participated in a 1-hr session for course credit. They were run in 24 groups of 5–8 subjects per group.

The same stimuli used in Experiment 1 were used in Experiment 2; however, the number of stimuli per tray was increased from 66 to 72, and a third 72-slide tray was added. The noise mask was the same as in Experiment 1, and was displayed at the same two luminances.

An experimental session consisted of a study phase followed by a test phase using each of the three slide trays in sequence. On each study trial, a target was displayed for 100 msec. A noise mask accompanied each target presentation at a target-mask ISI of −50, −25, 0, 40, 100, or 200 msec.[12] There were thus 6 ISIs × 2 mask luminances for a total of 12 experimental conditions. Within each tray, 36 stimuli were presented in the study phase. The 12 conditions were presented in random order with the restriction that each condition occurred once during each of the three 12-trial blocks.

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[11] We used d' scores to correct for false-alarm probabilities across the different experiments.

[12] When the ISI was negative, the mask temporally overlapped with the physical stimulus.

The sequence of events on each study trial was similar to that in Experiment 1. Following the warning tone/fixation point, a 100-msec target stimulus was presented in conjunction with the 500-msec noise mask at its appropriate ISI and luminance. The SOA between study trials was 3 sec.

The test phase was identical to that of Experiment 1, except that 72 test stimuli were presented in each of the three trays.

Each of the 216 stimuli appeared as a target for 12 of the 24 groups and as a distractor for the other 12 groups. Each stimulus appeared once in each of the 12 conditions over the 12 groups for which it appeared as a target.

b. Results and Discussion. The false-alarm probability was 0.309. Figure 4 shows hit probability as a function of stimulus-mask ISI; different curves are shown for the two mask luminances. The vertical dashed line indicates stimulus offset.

All essential aspects of Experiment 1 were replicated in Experiment 2. Performance increased with increasing ISI, both when the mask was dim, [$F(5,645) = 5.84$] and when it was bright [$F(5,645) = 92.58$]. As indicated in Table III, t tests were again used to contrast the two masking conditions at each ISI in order to assess the duration over which perceptual processes operate. These $t(129)$s were significant over ISIs from -50 to 100 msec. At an ISI of 200 msec, the difference of less than a percentage point between the masking conditions was not significant. At this ISi, the probability of a Type II error is less than .05 if the true bright-mask/dim-mask performance difference is greater than .03. Taken together, the results of Experiments 1 and 2 suggest that perceptual processing is largely complete by about 200 msec following stimulus offset.

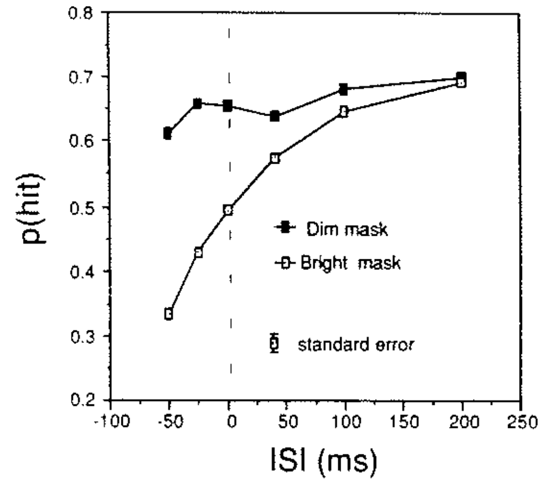

Fig. 4. Experiment 2 data. The dashed vertical line represents stimulus offset. Each data point is based on 1170 observations.

TABLE III

EXPERIMENT 2: t VALUES BETWEEN DIM- AND BRIGHT-MASK PERFORMANCE AT EACH STIMULUS-MASK ISI[a]

ISI (msec)	$t(129)$
-50	12.86
-25	11.00
0	7.06
40	3.04
100	1.93
200	0.53

[a] Positive values indicate dim-mask performance superiority.

Note in Fig. 4 that ISIs less than zero correspond to a superimposition of mask over the physical stimulus plus the icon, whereas ISIs of zero or more correspond to a superimposition of the mask over the icon only. The mask-luminance effect is qualitatively the same in these two situations. This is consistent with the proposition that the same perceptual processes govern information extraction from the physical stimulus and from the icon.

c. Application of the Model. The predicted I values for the 12 conditions of Experiment 2 were computed using the 51% dim-mask $r(t)$ reduction estimated from the 33 total conditions of Experiments 1–3. The across-conditions, rank-order correlation between predicted I and obtained d' for Experiment 2 was .92.

3. *Experiment 3: Is Icon Duration Controlled by Time Since Stimulus Onset or by Time Since Stimulus Offset?*

Di Lollo (1980, 1985) has proposed a model that is similar to ours in the sense that visible persistence is assumed to result from active processing. In Di Lollo's model, as in ours, the magnitude of active processing depends on time since stimulus onset; thus, persistence duration similarly depends on time since stimulus onset. Based on data from his missing-dot paradigm (Di Lollo, 1980, described in detail later in this section), Di Lollo contends that the kind of processing that generates visible persistence should be complete by roughly 150 msec *following stimulus onset*. Accordingly, Di Lollo (1985) argued that the sort of processing that immediately follows short stimuli (shorter than about 200 msec) is qualitatively different from the sort of processing that immediately follows longer stimuli. Di Lollo claims that the former is based on a visible representation of the stimulus (an icon) whereas the latter is based on a nonvisible representation of the stimulus. In our terms, Di Lollo would claim that any processing following the offset of a stimulus that is longer than about 150 msec is conceptual, not perceptual.

Experiment 3 was designed to evaluate Di Lollo's prediction and used the same paradigm as Experiments 1 and 2. Again, the presence or absence of an icon was inferred from the presence or absence of a mask-luminance effect. Stimulus duration was either 20 or 270 msec, and stimulus-mask ISI was either 0 or 250 msec. Of particular interest was a comparison of the 20-msec stimulus/250-msec ISI condition with the 270-msec stimulus/0-msec ISI conditions. Time since stimulus onset is the same in these conditions (270 msec), while ISI differs (0 vs. 250 msec). If, as Di Lollo argues, information extraction is determined by time since stimulus onset, then any mask-luminance effect must be the same in these two conditions.

a. Method. University of Washington undergraduates (133) participated in a 1-hr session for course credit. They were run in 20 groups of 5–8 subjects per group.

The two slide trays used in Experiment 1 were used in Experiment 3; however, there were 80 slides in each of the two trays. The noise mask was the same as in Experiments 1 and 2 and was displayed at the same two luminances.

An experimental session consisted of a study phase followed by a test phase using each of the two slide trays. On each study trial a target was displayed for either 20 or 270 msec, and the stimulus-mask ISI was either 0 or 250 msec. As in Experiments 1 and 2, the mask was either bright or dim. In addition to the 2 × 2 × 2 = 8 conditions produced by this factorial design, there were two no-mask control conditions involving stimulus durations of 20 and 250 msec. There were thus 10 conditions in all. Within each tray, 40 stimuli were presented at a study. The 10 conditions were presented in random order with the restriction that each condition occurred twice during each of the two 20-trial blocks.

The sequence of events on each study trial was similar to that of Experiments 1 and 2. Following the warning tone/fixation point, the target was presented for its appropriate duration and followed by the appropriate ISI, which was followed, except in the control conditions, by a 500-msec mask at its appropriate luminance. The SOA between study trials was 3 sec.

The test phase was identical to that of Experiments 1 and 2 except that 80 test pictures were presented in each of the two trays.

Each of the 160 stimuli appeared as a target for 10 of the 20 groups, and as a distractor for the other 20 groups. Each stimulus appeared once in each of the 10 conditions over the 10 groups for which it appeared as a target.

b. Results and Discussion. The false-alarm probability was .294. Figure 5 shows performance (hit probability) as a function of stimulus-mask ISI. The top panel shows performance for the 270-msec targets, while the bottom panel shows performance for the 20-msec targets. In both panels, different curves represent the two mask luminances, and the far right-hand points represent control-condition performance.

Under what circumstances does perceptual processing occur? Essentially, the results shown in Fig. 5 indicate that the mask-luminance effect

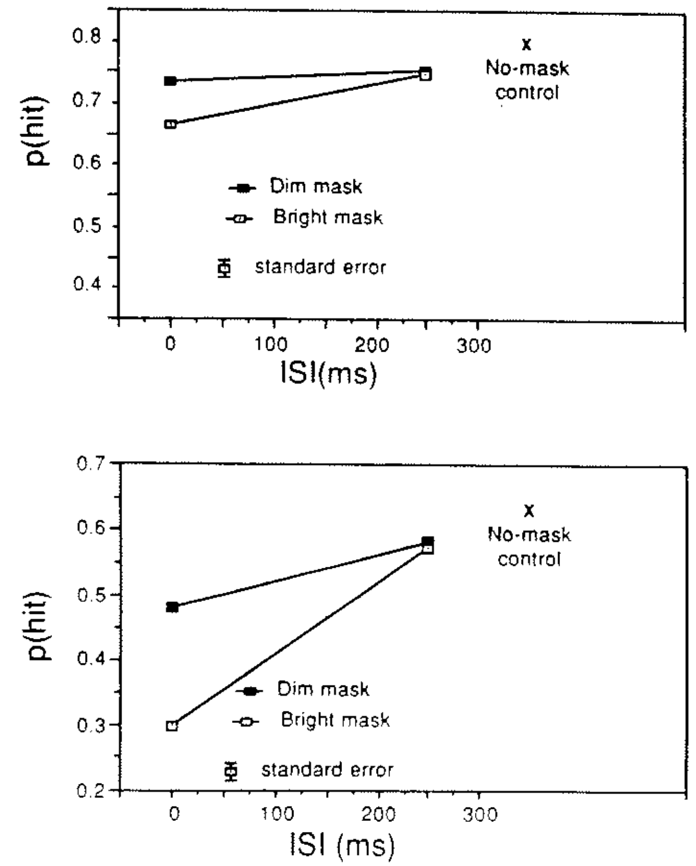

Fig. 5. Experiment 3 data. Top, 270-msec stimuli; bottom, 20-msec stimuli. Each data point is based on 1064 observations.

is present—and, by inference, perceptual processing is ongoing—at 0-msec ISI following both short and long stimuli. The results also indicate that there is no perceptual processing following a 250-msec ISI, for either short or long stimuli. Of particular interest is a comparison of the two 270-msec SOA conditions. For the 270-msec stimulus/0-msec ISI condition, the mask-luminance effect is relatively large (about 8%), whereas for the 20-msec stimulus/250-msec ISI condition, the mask-luminance effect is relatively small (less than 1%). In short, the results of Fig. 5 provide evidence for a decaying icon following the offset of both short and long stimuli.

Table IV provides the statistical evidence for these assertions. It shows t values contrasting the dim and bright-mask conditions for the four combinations of stimulus duration and ISI. For both stimulus durations, the differences are statistically significant at the 0-msec ISI, but are nonsignificant at the 250-msec ISI.

c. Application of the Model. The predicted I values for the 10 conditions of Experiment 3 were computed using the 51% dim-mask $r(t)$ reduction estimated from the 33 total conditions of Experiments 1–3. The across-conditions, rank-order correlation between predicted I and obtained d' for Experiment 2 was 1.00.

d. Why Do Our Conclusions Differ from Di Lollo's? Recall that, based on his data, Di Lollo concluded that visible persistence is determined by time since stimulus onset. The stimuli in Di Lollo's missing-dot paradigm consist of 24 dots that occupy 24 of the 25 squares in an imaginary 5 × 5 grid. The observer's task is to detect the location of the missing dot—an easy task if all 24 dots are presented simultaneously. To investigate the properties of visible persistence, Di Lollo presented the 24-dot array as two 12-dot groups separated in time. The idea is that detection of the missing dot depends on the degree to which the two 12-dot groups can be visually integrated, which in turn depends on the magnitude of group 1 visible persistence at the time of group 2 presentation.

TABLE IV

EXPERIMENT 3: t VALUES BETWEEN DIM- AND BRIGHT-MASK PERFORMANCE IN EACH STIMULUS-MASK ISI/STIMULUS DURATION CONDITION[a]

Stimulus duration (msec)	ISI (msec) 0	250
20	8.93	0.40
270	3.37	0.84

[a] Positive values indicate dim-mask superiority, and each t is based on 132 degrees of freedom (df).

Two factors affect performance in the missing-dot paradigm. First, as group 1/group 2 ISI increases, performance decreases. Second, however, as the *duration of the group 1 presentation* increases, performance decreases in virtually an identical manner. Even with a group 1/group 2 ISI of zero, performance is essentially at chance when group 1 duration is longer than about 200 msec. This finding formed the primary basis of Di Lollo's claim that visible persistence is determined by time since stimulus onset (SOA), rather than time since stimulus offset (ISI).

Why does the paradigm used in the present experiments yield a different conclusion? There are several possibilities. First, as Coltheart (1980) argues, it may be that visible persistence (underlying performance in the missing-dot paradigm) and information extraction (underlying performance in the present paradigm) are mediated by fundamentally different processes. Second, it may be that the same process mediates the results of both paradigms, but that some quantitative difference between stimuli in the two paradigms is responsible for the difference in results.

We argue for the latter possibility. We suggest, in particular, that relevant information is extracted much faster from relatively simple dot patterns than from relatively complex naturalistic pictures. In our model, faster information extraction is represented by a higher value of the function h—or, in the quantitative model, a higher c value—for dots relative to pictures. Figure 6 shows the predicted Experiment 3 I values for two situations. The top panel shows predictions for c value of 3.7 used so far. The bottom panel shows predictions for a much higher value, $c = 15$. (We will demonstrate later that $c = 3.7$ is appropriate for the complex pictures used in the present experiments, whereas $c = 15$ is appropriate for the simple dot patterns used by Di Lollo.)

When $c = 3.7$, $r(t)$ is still about 0.368 at the offset of a 270-msec stimulus [because $r(t)$ is in units of the proportion of total stimulus information/sec, a value of 0.368 is relatively high]. In contrast, when $c = 15$, $r(t)$ has fallen to about 0.017 at the offset of a 270-msec stimulus. In general, when $c = 3.7$, the predicted results correspond well to our obtained Experiment-3 results. When $c = 15$, the predicted results correspond to Di Lollo's (1985) prediction: perceptual processing on the 270-msec stimulus has ceased by the time of stimulus offset.

4. *General Discussion: Experiments 1–3*

Experiments 1–3 produced several noteworthy empirical findings. First, the results of Experiments 1 and 2 indicate that perceptual processing continues for approximately 200 msec followng stimulus offset, at least

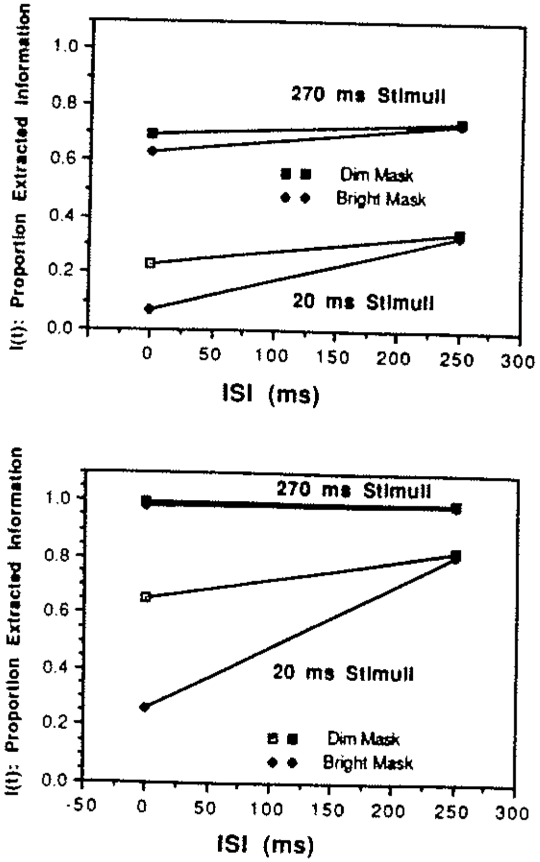

Fig. 6. Quantitative model: Experiment 3 predictions for two values of c. Top, results corresponding to present Experiment 3 ($c = 3.7$, complex stimuli), bottom, results predicted by Di Lollo (1985) ($c = 15$, simple stimuli).

when stimuli are complex pictures presented for 40–100 msec. Second, the results of Experiment 2 indicate that the effect of mask luminance is qualitatively the same whether the mask luminance is applied to the physical stimulus or to the icon that follows. Third, the results of Experiment 3 indicate that perceptual processing continues following stimulus offset, even when stimuli are as long as 270 msec. The Experiment 3 results also indicate that perceptual processing has ended by 250 msec following stimulus offset at least for pictures ranging from 20 to 270 msec in duration.

a. Model–Data Comparisions. Qualitatively, the data were in accord with the model. The estimated poststimulus duration of perceptual processing was about 200 msec, which is within the range of visible persistence durations estimated using other paradigms. The influence of at least one variable—mask luminance—was qualitatively the same when applied to stimulus or to icon.

These qualitative tests of the model are, however, quite weak. Of somewhat more interest is that the quantitative fits of the model to the data were also quite good. Over all 33 conditions of Experiments 1–3, the correlation between model and data was 0.89. Because the three experiments used different subjects, were run at different times, and had different false-alarm probabilities, one would expect the within-experiment fits to be better than the between-experiment fits, and indeed the within-experiment correlations ranged from 0.92 to 1.00.

b. The Relation between Icon Worth and Icon Duration. In Experiments 1 and 2, we estimated the duration of poststimulus perceptual processing to be roughly 200 msec; this was the duration at which mask luminance no longer had a statistically significant effect. This estimate agrees reasonably well with previous estimates of icon duration obtained from quite different paradigms (e.g., Eriksen & Collins, 1967; Haber & Standing, 1970; Sperling, 1960), thereby lending credence to the proposition that the same process is being measured in all instances. But does a 200-msec duration estimate correspond reasonably with the 100-msec estimate of icon *worth* obtained by Loftus *et al.* (1985)? Icon worth and icon duration are not the same thing, but they are certainly related, and within the context of our model they are related quite specifically: the icon's worth is the area under $b(t)$, the iconic-decay function (see Fig. 2, top). In particular, as expressed in Eq. (1q), the quantitative model posits exponential decay in which the icon's worth is the decay constant.

Suppose that we take the quantitative model seriously. From Eq. (1q), we can calculate that, at 200 msec following stimulus offset, available information, $a(t)$ is about 0.14. Thus, according to the model, about 14% of stimulus information remains available—and information extraction continues to occur—at a poststimulus interval by which, according to the results of Experiments 1 and 2, perceptual processing has ceased. Does this mean that Experiments 1 and 2 disconfirm the quantitative model?

There are two reasonable answers to this question. The first is yes: exponential decay may be an incorrect description of available poststimulus information. The second, however, is that exponential decay, or something close to it, may be correct, but our experimental power may be insufficient to detect any 200-ms ISI, bright-mask/dim-mask any performance difference that actually exists. To assess this possibility we can use the model to calculate total extracted information in both the dim- and bright-mask 200-msec ISI conditions. For a 40-msec stimulus (as used in Experiment 1), these values are $I = 0.389$ and $I = 0.374$ for the dim and bright-mask conditions, respectively. For a 100-msec stimulus (as used in Experiment 2), the corresponding I values are 0.511 and 0.498.

In both cases, the predicted I difference between the 200-msec ISI dim- and bright-mask conditions is quite small. What about predicted *performance* differences? Although the function m that maps I onto performance is not specified by the model, it can nonetheless be estimated. Recall that we obtained a rank-order correlation of 0.89 between predicted I and obtained d' over the 33 conditions of Experiments 1–3. This $d'(I)$ function is an estimate of the particular m that maps I onto d'. From it, along with the observed false-alarm probabilities, we can obtain a corresponding estimate of the m that maps I onto hit probability (the performance measure on which the statistical analyses were performed.) In the range of interest—roughly $I = 0.3$ to $I = 0.5$—this latter function is approximately unit-slope linear. This means that the 200-msec ISI, dim-mask/bright-mask performance differences are predicted to be only about 0.015 and 0.013 for the 40- and 100-msec stimuli of Experiments 1 and 2. These predicted differences are less than the standard errors of the mean.

In summary, given a 100-msec icon worth, the model specifies that approximately 14% of stimulus information remains available at a 200-msec poststimulus interval and that information extraction continues to occur. However, a close examination reveals that the predicted difference in amount of available information that is actually *acquired* in the dim- vs. bright-mask conditions—and the corresponding performance difference—is too small to be detected experimentally. This, in turn, means that a 100-msec icon worth is consistent with the results of Experiments 1 and 2.

III. Phenomenological Appearance

As we noted earlier, a salient characteristic of an icon is that it appears to be an extension (albeit a fading extension) of the physical stimulus. We now concern ourselves with this phenomenology. We first extend our model to account for the conscious experience of a stimulus, and we then present four experiments in support of this extension.

A. EXTENSION OF THE MODEL

1. Overview

What might underlie phenomenological appearance? Sperling (e.g., 1960, 1963, 1967; Averbach & Sperling, 1961; see also Erwin, 1976) characterized a fading icon in terms of decay of available information. This suggests an extension of the model in which phenomenological appearance is equated with $a(t)$, the proportion of available information. By this notion, the icon would remain phenomenologically present until $a(t)$ dropped below some criterion, a_{crit}. This model is illustrated in Fig. 7 where $a(t)$ is shown as a function of time since stimulus onset for 20- and 270-msec stimuli. The horizontal line represents a_{crit}, and duration of visible persistence is represented by the double-headed arrows between the time of stimulus offset and the time at which $a(t)$ crosses a_{crit}.

Figure 7 indicates one obvious property of this model: persistence duration is independent of physical stimulus duration. However, this property conflicts with data from a variety of paradigms in which estimated persistence duration is found to be a decreasing function of physical stimulus

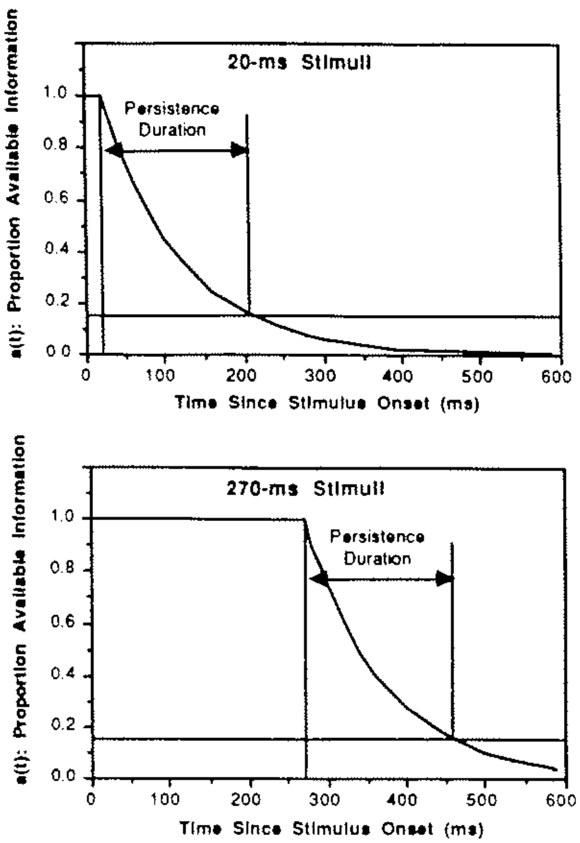

Fig. 7. Quantitative model: an extension in which phenomenological appearance is represented by $a(t)$, the available information. The horizontal line represents the criterion $a(t)$ below which the stimulus is reported to have disappeared.

duration. One such paradigm is the Di Lollo missing-dot procedure described earlier. Another, which we use in Experiments 4–7, is a *synchrony-judgment paradigm* (e.g., Efron, 1970). In a synchrony-judgment paradigm, a target stimulus is presented for some duration *d*. Following stimulus offset is a variable interval, at the end of which is a *synchrony signal*, such as an audible click or a second visual stimulus. The observer's task is to adjust the stimulus-signal interval such that the signal appears to just coincide with the phenomenological disappearance of the target stimulus. The duration of the interval set by the observer thereby constitutes an estimate of visible persistence duration.

2. *The Information-Extraction Rate as a Mediator of Persistence*

We have seen that equating phenomenological appearance with $a(t)$ will not account for the observed negative relation between stimulus duration and persistence duration. Another means of extending the model is to equate phenomenological appearance with $r(t)$, the rate of extracting information from this stimulus. By this notion, the icon would remain phenomenologically present until $r(t)$ dropped below some criterion, r_{crit}. This idea is not entirely new; similar proposals have been made by Di Lollo (1980) and Erwin (1976; Erwin & Hershenson, 1974). As we illustrate below, such an extension accounts for the relation between stimulus duration and persistence duration. It also accounts for other data showing effects on persistence duration of the amount of to-be-extracted information in the stimulus (Avant & Lyman, 1975; Erwin, 1976; Erwin & Hershenson, 1974).

Assumption 5: Phenomenological Appearance. An observer remains phenomenologically aware of a stimulus until $r(t)$, the rate of extracting information from the stimulus falls below some criterion, r_{crit}. This model is illustrated in Fig. 8 where $r(t)$ is shown as a function of time since stimulus onset for 20- and 270-msec stimuli. The horizontal line represents r_{crit}, and duration of visible persistence is represented by the double-headed arrows between the time of stimulus offset and the time at which $r(t)$ crosses r_{crit}.

Assumption 5 is essentially that conscious experience of a stimulus results from extracting information from the stimulus. This notion is similar to one in the selective attention literature that conscious experience results from attending to the stimulus (cf. James, 1890; Norman, 1976).

B. APPLICATIONS OF THE MODEL

1. *Evaluation Procedures*

This extension of the model makes a global prediction: any variable that affects $r(t)$, the information-extraction rate, must concomitantly affect

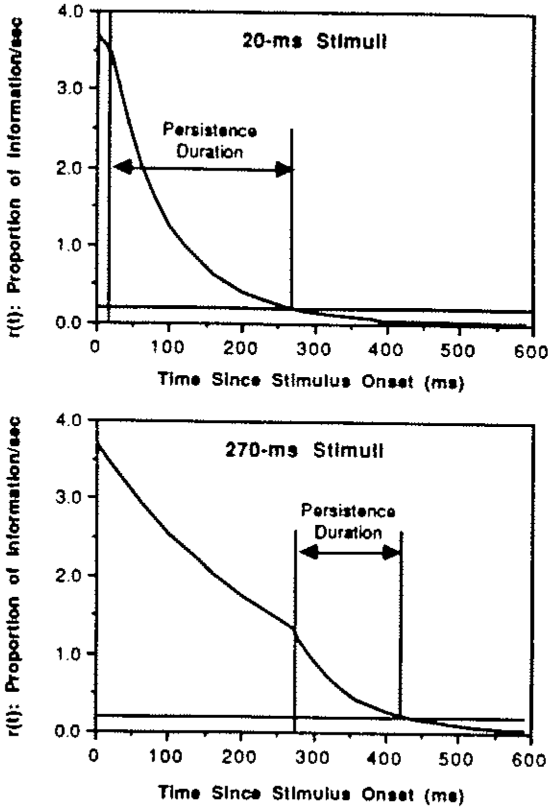

Fig. 8. Quantitative model: an extension in which phenomenological appearance is represented by $r(t)$, the information-extraction rate. The horizontal line represents the criterion $r(t)$ below which the stimulus is reported to have disappeared.

persistence duration. We show for both existing data and for the new data of Experiments 4–7 that this prediction is confirmed when $r(t)$ is manipulated in a variety of ways.

Most versions of our model, including the quantitative version described earlier, make strong predictions about the effect of one particular independent variable—stimulus duration—on persistence duration. In Experiment 4, we vary stimulus duration and find the best-fitting value of the model parameter, c. Using the best-fitting c value we then illustrate predictions about the effects on persistence duration of several other independent variables. Following our evaluation of these predictions in Experiments 5–7, we discuss the limitations of this kind of model-evaluation procedure.

2. *Application of the Model to Existing Data*

In this section, we describe application of the model to stimulus duration, stimulus luminance, and stimulus informational content.

a. Stimulus Duration. It has typically been found that persistence duration decreases with increasing stimulus duration (e.g., Efron, 1970; Di Lollo, 1980; Haber & Standing, 1970). The model's account of this effect is illustrated in Fig. 8, and it can be seen that the model correctly predicts the data for the following reason. Because $r(t)$ decreases with increasing $I(t)$, $r(t)$ decreases over the time during which the stimulus remains physically present. Therefore, following a short stimulus, $r(t)$ is relatively high at stimulus offset and takes a relatively long time to fall to any given criterion level. Conversely, following a longer stimulus, $r(t)$ is lower at stimulus offset and takes less time to fall to the same criterion.

b. Stimulus Luminance. The effects of stimulus luminance on persistence duration are somewhat mixed. The typical effect of increasing luminance is to decrease persistence duration (e.g., Allport, 1970; Bowen, Pola, & Matin, 1974; Dixon & Hammond, 1972; Efron & Lee, 1971), although, occasionally, increasing luminance increases persistence duration (e.g., Sakitt, 1976).

Loftus (1985a) has shown that manipulating stimulus luminance can affect $r(t)$, the information-extraction rate: with sufficiently low luminance, $r(t)$ is decreased. Luminance, or any variable that affects $r(t)$, can have two counteracting effects on persistence duration. The first, and most straightforward, is that decreasing $r(t)$ decreases persistence duration since persistence duration *depends* on $r(t)$. This is illustrated in the left panel of Fig. 9, where bright and dim stimuli have c values of 3.7 and 2.0, respectively. It is evident that bright stimuli are predicted to have longer persistence than dim stimuli, contrary to most (although not all) of the extant data.

Recall, however, that $r(t)$ decreases with increasing $I(t)$. This means that a sufficiently large *initial* $r(t)$ can cause such a rapid increase in $I(t)$ that $r(t)$ itself rapidly declines. Under appropriate circumstances, the decline is such that $r(t)$ eventually becomes less than it would have been had $r(t)$ been smaller to begin with. This seemingly convoluted assertion is illustrated in the right panel of Fig. 9 which depicts a situation in which the *absolute* c values are very large: bright and dim stimuli have c values of 20 and 11, respectively.[13] Here, $r(t)$ is initially much larger for bright than for dim stimuli; however, the bright and dim $r(t)$ curves eventually *cross*, and persistence duration is thus greater for dim than for bright stimuli.

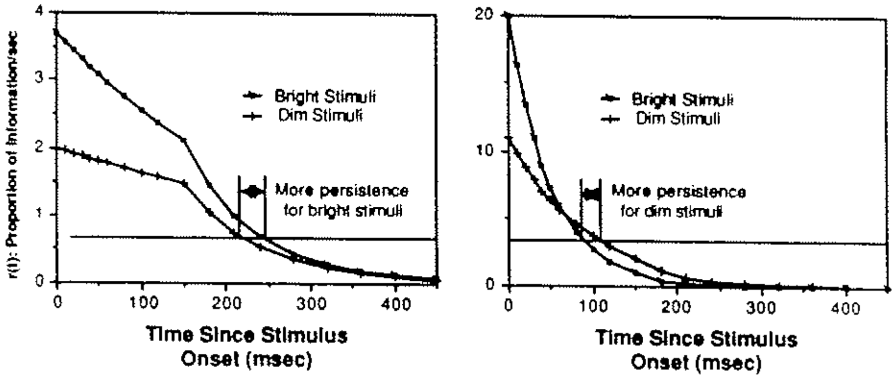

Fig. 9. Quantitative model: predicted information-extraction rate for bright and dim stimuli. Left, variation in stimulus luminance (complex photo stimuli); right, variance in stimulus luminance (simple stimuli). In both panels, the horizontal line represents the criterion $r(t)$ below which the stimulus is reported to have disappeared.

As discussed earlier, large absolute c values are characteristic of simple stimuli from which relevant information is extracted very quickly. Small absolute c values, in contrast, are characteristic of complex stimuli, from which relevant information is extracted more slowly. Thus, the right panel of Fig. 9 describes the simple stimuli typically used, and its prediction is confirmed (e.g., by Bowen *et al.*, 1974). The left panel of Fig. 9 describes the complex stimuli used in the present research. Its prediction—that persistence duration should increase with luminance—was confirmed in Experiment 7 to be described shortly.

c. Informational Content of the Stimulus. Erwin (1976) measured persistence duration of letter strings that varied in terms of approximation to English. In one set of conditions, the letters had to be remembered and eventually reported; in the other set of conditions, the letters did not have to be remembered. Erwin found that persistence duration decreased with increasing approximation to English, but only for to-be-remembered letters. Thus, higher informational content (as instantiated by a lower approximation to English) leads to longer persistence.

The model's account of these data is straightforward. With more information to be extracted, the information-extraction rate must remain higher for a longer period of time; thus, with more information it will take longer for $r(t)$ to fall to any criterion level. This leads to longer persistence duration.

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[13] Note the change in scale in the right relative to the left panel of Fig. 9.

C. EXPERIMENTS 4–7: DURATION OF VISIBLE PERSISTENCE FOLLOWING STIMULUS OFFSET

In Experiments 4–7, we used a synchrony-judgment task to estimate persistence duration. Recall that in a synchrony-judgment task, the observer adjusts the ISI between a stimulus and a synchrony signal such that the signal occurs at the time of phenomenological stimulus offset. In each experiment, we tested the model's prediction that decreasing the information-extraction rate, $r(t)$, must decrease persistence duration.

1. Experiment 4: Decreasing Information-Extraction Rate by Increasing Stimulus Duration

As indicated, previous experiments have demonstrated a negative relation between stimulus duration and persistence duration. However, the stimuli used in these experiments were very simple, often consisting of small, monochromatic light patches. The first purpose of Experiment 4 was to replicate the stimulus-duration effect using the complex scenes from Experiments 1–3. The second purpose was to estimate the model parameter, c.

a. Method. University of Washington graduate and undergraduate students (6) served as paid subjects. Each participated individually in a 1.5-hr session. The stimuli were 12 of the slides used in Experiments 1–3. All stimuli were attenuated by one log unit relative to the projector luminance. The masking slide used in Experiments 1–3 was used in Experiments 4–7 as a synchrony signal.

An experimental session consisted of 12 practice trials followed by 144 test trials. Each trial involved a single target stimulus presented at one of six durations: 20, 80, 140, 200, 260, or 320 msec. A trial consisted of a series of *presentations*, each presentation made up of a 500-msec warning tone/fixation light, followed by the target stimulus, followed by a blank ISI, followed by the noise mask. The subject's task was to adjust the ISI across presentations in such a way that the mask appeared to coincide with the complete phenomenological disappearance of the stimulus. Within a trial, stimulus duration remained constant across presentations.

The stimulus-mask ISI adjustment procedure worked as follows. At the start of each trial, the ISI was set either to 0 or to 480 msec. Following each presentation, the subject requested, via one of two response keys, either an increment or a decrement in ISI. The ISI of the next presentation was accordingly lengthened or shortened by an increment/decrement that was initially set to 80 msec. After each *reversal* (a requested decrement followed by a requested increment or vice versa) the magnitude of the increment/decrement was halved. The persistence duration estimated on each trial was defined to be the mean of the two ISIs just preceding and following the fourth reversal.

The six target durations were factorially combined with the two start intervals to produce 12 conditions. For each subject, the 156 total trials (12 practice trials plus 144 test trials) were divided into 13 12-trial *blocks*. Within each block, each stimulus and condition was presented once. The 12 stimuli were counterbalanced over the 12 conditions across the 12 test blocks via a Latin Square. The initial ordering of conditions across trials within a block was randomized anew for each subject.

b. Results and Discussion. There was no interaction of start ISI with stimulus duration [$F(5,25) < 1$]; accordingly, the data were collapsed across start ISI. Figure 10 shows the function relating persistence duration to stimulus duration, d (the solid lines through the data points are described below). As expected from past results, this function declines. In the present experiment, the decline is approximately linear. The slope—approximately -0.31 msec of persistence duration per millisecond of stimulus duration—is substantially shallower than the -1 slope obtained by others (e.g., Efron, 1970). We shall have more to say about this shallower slope shortly.

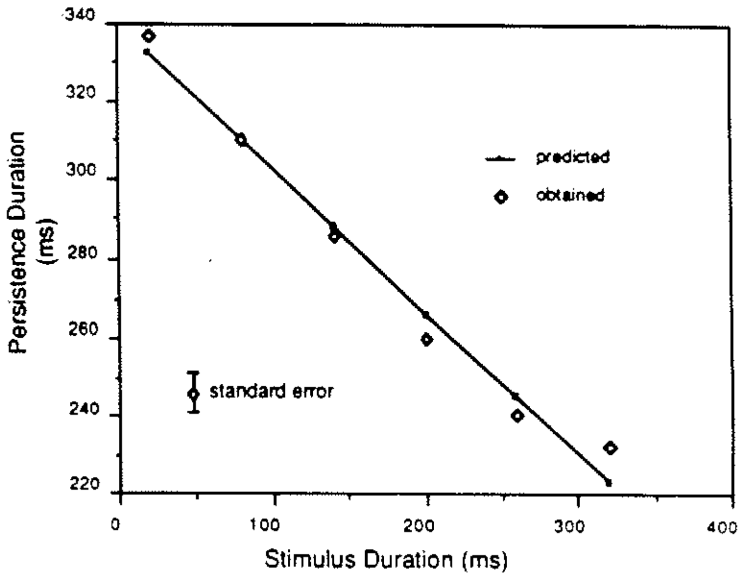

Fig. 10. Experiment 4 data. Diamonds represent data points and the solid line represents the model prediction. Each data point is based on 144 observations.

c. Application of the Model. We applied the quantitative form of our model to the data, allowing two free parameters. The first is c, which reflects how quickly the information-extraction rate, $r(t)$, declines with increases in $I(t)$, the total extracted information. The second is r_{crit}, the criterion rate at which the stimulus is reported to have vanished (see Fig. 8). The best fit was provided by $c = 3.70$ and $r_{crit} = 8.5\%/\text{sec}$.[14] The predictions of the model are shown by the solid lines in Fig. 10.[15] The root-mean-square error between predictions and data (5 msec) is less than the standard error of the data (15.6 msec), indicating a statistical confirmation of the model.

The relatively shallow slope relating persistence duration to physical stimulus duration is consistent with the model. As we have noted, simpler stimuli, such as those used by Efron, are associated with rapid extraction of relevant stimulus information. Within the context of our general model, rapid information extraction is represented by higher values of the function $h(I)$—or, within the context of the quantitative model, a higher c value. Higher h (e.g., c) values, in turn, lead to more dependence of $r(t)$ on stimulus duration and, thus, to a steeper slope. In the quantitative model, for example, a -1 slope emerges when c is about 15.

2. *Experiment 5: Reducing Information-Extraction Rate with a Superimposed Mask*

Our model's account of the Experiment 4 data incorporates the idea that stimulus duration affects $r(t)$ at the time of stimulus offset; a longer stimulus leads to a lower $r(t)$, which, in turn, leads to shorter persistence durations. However, there is an alternative explanation involving sensory adaptation. Each stimulus presentation is preceded and followed by relative darkness. Perhaps longer stimuli lead to greater light adaptation, which, in turn, somehow leads to a shorter perceived icon. Experiment 5 was designed in part to evaluate this possibility.

In Experiment 5, all target stimuli were shown for 150 msec. Three conditions were defined by what occurred during the first 50 msec of stimulus exposure. In a bright-mask condition, a bright mask was superimposed over the target for the first 50 msec; in a dim-mask condition, a dim mask was superimposed over the target during this period; in a control condition, no mask was superimposed.

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[14] The parameter c was also fit by Loftus, Hanna, and Lester (1988) in a set of picture-recognition experiments that, apart from using the same stimuli, bore no resemblance to the present Experiment 4. Loftus *et al.* obtained best-fitting c value of 3.4, which is remarkably close to the value of 3.7 obtained here.

[15] The linearity of the model's fit is only approximate, i.e., the assumptions of the model do not imply linearity of this function. With other parameter values, substantial departures from linearity would occur.

We know from the results of Experiment 2 that the greater the luminance of a superimposed mask, the more impaired is information acquisition. According to our model, this means that increased mask luminance can lead to smaller $I(t)$ and, thus, a greater $r(t)$ sometime following stimulus offset. This prediction is illustrated in Fig. 11 for the bright- and no-mask conditions. Here, c is the usual 3.7 for the no-mask condition. We assume that superimposing a bright mask reduces $r(t)$ to 0 during the time the bright mask is physically present and that following bright-mask offset, $r(t)$ returns exponentially to 3.7 with a time constant of 100 msec. The model predicts persistence to be greater in the bright-mask condition. The adaptation-level hypothesis, in contrast, predicts that increased mask luminance should lead to greater light adaptation and, thus, to shorter persistence duration.

a. Method. Members of the University of Washington Psychology Department (12) served as subjects. Each participated individually in a 1-hr session. The stimuli were 60 of the pictures that had been used in Experiments 1–3 and included the 12 pictures used in Experiment 4. Two copies of the noise mask were prepared. The first was used as a synchrony signal, exactly as in Experiment 4. The second was, in some conditions, projected physically superimposed over a target stimulus. The procedures for obtaining estimates of persistence duration were identical to those of Experiment 4.

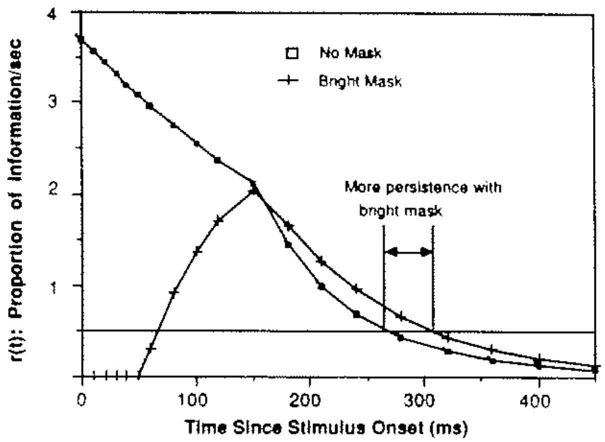

Fig. 11. Quantitative model: predictions of variation in mask luminance for Experiment 5. The curves show information-extraction rate for stimuli over which a bright or a dim mask is superimposed during the first 50 msec of stimulus exposure. The horizontal line represents the criterion $r(t)$ below which the stimulus is reported to have disappeared.

Three mask-luminance conditions were defined by superimposing a bright mask, a dim mask, or no mask on the target picture during the first 50 msec of the target's 150-msec total duration. The dim and bright masks were as in Experiments 1–3. The three mask-luminance conditions were factorially combined with the two start ISIs for a total of six experimental conditions. Each of the 60 stimuli was shown only once to a given subject; thus, there was a total of 60 trials. The six conditions were presented in random order with the restriction that each condition occurred twice during each 12-trial block. Stimuli were counterbalanced over the six conditions across subjects; thus, across the 12 subjects there were two complete replications.

b. Results and Discussion. There was no interaction of start ISI with mask luminance [$F(2,22 = 1.21]$; accordingly, the data were collapsed across start ISI. Table V shows estimated persistence duration for the three masking conditions, again collapsed over start interval. Persistence duration is longer with greater mask luminance, thereby confirming our model and disconfirming the adaptation-level hypothesis.

3. *Experiment 6: Increasing Information-Extraction Rate by Lowering Stimulus Luminance*

It might be argued that the results of Experiment 5 could be explained by simply assuming that the brighter the overall stimulus configuration, the longer the persistence duration. This result has occasionally been found (e.g., Sakitt, 1976), although the opposite relationship—a negative relation between stimulus luminance and persistence duration—is more typical (cf. Coltheart, 1980). Experiment 6 was designed to test this possibility. Experiment 6 was similar to Experiment 5 except that the luminance of the superimposed mask remained constant while the luminance of the target stimulus was varied.

A great deal of evidence indicates that a mask will interfere with dimmer stimuli more than with brighter stimuli (e.g., Eriksen, 1966; Eriksen & Lappin, 1964). According to our model, therefore, dimmer stimuli, from which less information has been extracted, will have a higher information-extraction rate following stimulus offset. This prediction is illustrated in Fig. 12. Here, it is assumed that *r(t)* for a bright stimulus is unaffected by the mask, but that *r(t)* for a dim stimulus is reduced to zero by the mask. It is further assumed that *r(t)* is normally 3.7 for bright stimuli and 3.0 for dim stimuli. Again, following mask offset, *r(t)* returns exponentially to its normal level. The prediction is that dimmer stimuli persist longer than brighter stimuli.

TABLE V

EXPERIMENT 5 DATA: ESTIMATED PERSISTENCE DURATION (MSEC) FOR THE THREE MASK-LUMINANCE CONDITIONS[a]

No mask	Dim mask	Bright mask
217	284	306

[a] Standard error, 11 msec. Each data point is based on 240 observations.

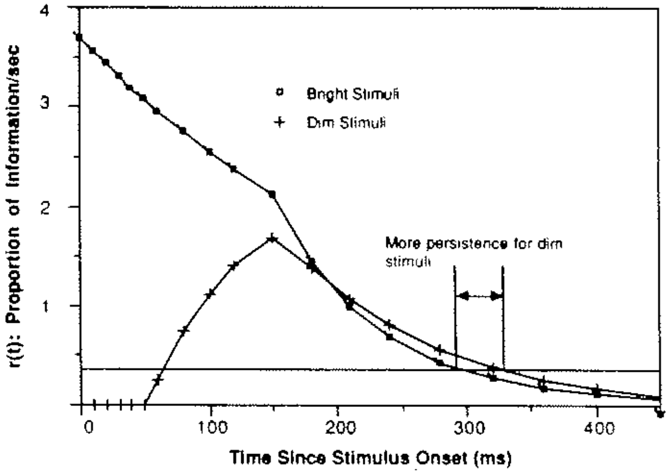

Fig. 12. Quantitative model: predictions of variations in stimulus luminance (superimposed mask) for Experiment 6. The curves show information-extraction rate for bright or dim stimuli over which a mask is superimposed during the first 50 msec of stimulus exposure. The horizontal line represents the criterion *r(t)* below which the stimulus is reported to have disappeared.

a. Method. Members of the University of Washington Psychology Department (6) served as subjects. Four had participated in Experiment 5. Each participated individually in a 1 hr session. The stimuli and noise masks were those used in Experiment 5.

The target pictures were presented for 150 msec. The superimposed mask still occurred during the first 50 msec of target presentation. Target pictures were either the same luminance as they were in Experiment 4, or they were attenuated by 0.5 or 1.0 log units. The concurrent mask that occurred during the first 50 msec of stimulus presentation was attenuated by 1.0 log unit relative to the bright mask of Experiment 4. The three target luminance conditions were factorially combined with the two start ISIs for a total of six experimental conditions. The counterbalancing procedures were identical to those of Experiment 5.

b. Results and Discussion. There was no interaction of start ISI with stimulus luminance, [$F(2,10) < 1$]; accordingly, the data were collapsed across start ISI. Table VI shows estimated persistence duration for the three stimulus-luminance conditions, against collapsed over start interval. Persistence duration is longer with lower stimulus luminance, again confirming our model.

4. *Experiment 7: Reducing Information-Extraction Rate by Lowering Stimulus Luminance*

The effects of stimulus luminance on persistence duration have been described earlier. In most reported experiments, the effect of lowering luminance is to increase persistence duration. However, the experiments that have demonstrated this effect have used simple stimuli in which *absolute* information-extraction rate is higher than with the present complex stimuli. Figure 9 illustrated why our model predicts that reducing luminance should, in contrast, *decrease* persistence duration when complex stimuli are used. Experiment 7 was designed to test this prediction.

a. Method. The same 6 subjects, 12 stimuli, and apparatus used in Experiment 4 were used in Experiment 7. The Experiment 7 procedure was identical to the Experiment 4 procedure, except that the major dependent variable was stimulus luminance rather than stimulus duration.

Stimulus duration in Experiment 7 was 100 msec. Stimulus luminance was either unattenuated or attenuated by 1.0 or 2.0 log units. Initial stimulus-signal ISI was either 0 or 480 msec; thus, there were six experimental conditions. Each subject received six 12-trial blocks for a total of 72 trials. Each of the 12 stimuli occurred once, and each of the six experimental conditions occurred twice during each block. The 12 stimuli were counterbalanced through the six conditions over the six blocks.

b. Results and Discussion. There was no interaction of start ISI with stimulus luminance [$F(2,22) < 1$]; accordingly, the data were collapsed across start ISI. Table VII shows the results. Persistence is longer with higher luminance, again confirming our model.

TABLE VI

EXPERIMENT 6 DATA: ESTIMATED PERSISTENCE DURATION (MSEC) FOR THE THREE STIMULUS-LUMINANCE CONDITIONS[a]

Bright	Moderate	Dim
273	317	336

[a] Standard error, 8 msec. Each data point is based on 120 observations.

TABLE VII

EXPERIMENT 7 DATA: ESTIMATED PERSISTENCE DURATION (MSEC) FOR THE THREE STIMULUS-LUMINANCE CONDITIONS OF EXPERIMENT 7[a]

Bright	Moderate	Dim
345	310	297

[a] Standard error, 14 msec. Each data point is based on 288 observations.

5. *General Discussion: Experiments 4–7*

The results of Experiments 4–7 demonstrated several variables that affect persistence duration. The negative effect of physical stimulus duration (Experiment 4) was expected on the basis of numerous past results. The positive effect of pure variation in stimulus luminance (Experiment 7) was generally unexpected on the basis of past results, although there exist comparable data (e.g., Sakitt, 1976). The effects of superimposed noise masks (Experiments 5 and 6) represent a new manipulation and are, therefore, not predictable on the basis of past results.

The effects of all four experiments, whether expected on the basis of past results or not, can be accounted for by our model. As illustrated in Figs. 8, 9, 11, and 12 in each experiment, the manipulated variable affects $r(t)$, the information-extraction rate, following stimulus offset. To the degree that $r(t)$ is higher (because of a shorter stimulus, a brighter superimposed mask, a dimmer stimulus over a superimposed mask, or a brighter otherwise uncontaminated stimulus) the model predicts the longer persistence that, indeed, was found. It is especially noteworthy, as demonstrated in Fig. 9, that the ordinal effect of luminance on persistence duration is predicted to depend on the state of other variables (such as the stimulus complexity). In a broad sense, this means that the model can account for the somewhat mixed effects of stimulus luminance that exist in the literature.

To be candid, we must point out that we have used the quantitative form of our model with quite specific parameter values in order to formulate the predictions shown in Figs. 9, 11, and 12. Within the context of our quantitative model, other parameter values could be found that would incorrectly predict the outcomes of Experiments 5–7; likewise, other instantiations of the general model could be found that would incorrectly predict the results of all four experiments. So while we have shown the general model to be *capable* of predicting the results of Experiments 4–7, we have not shown that it must *invariably* make the correct predictions for these experiments. [In contrast, for example, we have shown in Section

V, B that any form of the general model must predict the results of the Loftus *et al.* (1985) experiments.] In principle, therefore, the results of Experiments 4–7 place constraints on what forms of the general model are viable, although it is beyond the scope of this article (and probably very difficult) to formally characterize these constraints.

IV. Concluding Remarks

A. INFORMATION ACQUISITION

Assumptions 1–4, discussed in Section II of this chapter, constitute a model of both information extraction and the relation between extracted information and picture-memory performance. Assumptions 1 (available information), 2 (unidimensionality) and 3 (information-acquisition rate) are similar to corresponding assumptions in other information-acquisition models (e.g., Kowler & Sperling, 1980; Krumhansl, 1982; Loftus & Kallman, 1979; Massaro, 1970; Rumelhart, 1969). Assumption 4 weakly ties the main entity produced by assumptions 1–3 [extracted information, $I(t)$] to any observed measure of memory performance.

1. Perceptual Processing and "Information:" The Unidimensionality Assumption

As indicated earlier, the model does not precisely characterize what is "information." Our crucial unidimensionality assumption, however, is that information, whatever it may be, can be represented by a single number. If one considers a picture's *eventual* memory representation, this assumption is probably incorrect. A picture's long-term representation probably consists of a variety of different kinds of information that differ qualitatively from one another. For instance, a good deal of evidence favors a dual-code model, which incorporates the fundamental assumption that a visually presented stimulus is encoded both visually and verbally (e.g., Paivio, 1971). Within the context of such a model, the information constituting a picture's representation must be characterized by at least two numbers, one representing the state of visual information and the other representing the state of verbal information.

It should be kept in mind, however, that the present model is not designed to characterize *all* of the encoding that results in a picture's eventual memorial representation; it is designed to characterize perceptual processing only. The output of perceptual processing could reasonably be unidimensional.

2. Conceptual Processing

As discussed by others (e.g., Intraub, 1980, 1984; Potter, 1976; Loftus, Hanna, & Lester, 1988), the output of perceptual processing is transient in the sense that, without subsequent encoding, eventual memory performance is very low. The presumed encoding that operates on the output of perceptual processing and produces an ultimate memory representation has been termed conceptual processing. The exact nature of conceptual processing is not formally explicated by anyone. Roughly and informally, however, conceptual processing may be thought of as including rehearsal, verbal recoding, association of features within the picture, association of the picture to other pictures, and other higher-level, controlled cognitive processes. Loftus, Hanna, and Lester (1988) provide a model of conceptual processing that uses extracted information, $I(t)$, as defined in the present model, as input.

3. On the Relation between Extracted Perceptual Information and Memory Performance: The Monotonicity Assumption

Our model assumes a monotonic relation between extracted perceptual information, $I(d)$, and memory performance, $P(d)$. However, monotonicity cannot universally apply at the individual-item level for the following reason. As just discussed, memory performance must be based on some eventual memorial representation of the picture, and this eventual representation constitutes the output of conceptual, as well as perceptual, processing. As we have noted, conceptual processing is not simple; rather it should be viewed as a clsss of diverse cognitive operations that are under the subject's control. Therefore, given the same amount of extracted perceptual information, different patterns of conceptual processing could give rise to different memory representations and, thus, to different values of memory performance. Such a situation could arise, for example, when different subjects see the same picture under identical circumstances or when one subject sees different pictures under identical circumstances. In a properly counterbalanced experiment to which the model is applied, however, the monotonicity assumption could reasonably be correct at the *statistical* level; on the average, two items from which the same perceptual information has been extracted are expected to show the same performance.

B. PHENOMENOLOGICAL APPEARANCE

Assumption 5 extends the model by equating phenomenological experience with information extraction.

1. *The Causal Relation between Phenomenology and Information Extraction*

There are two fundamental ways of viewing the relation between information extraction and phenomenological experience. The first is that phenomenological experience is an automatic process determined strictly by physical stimulus properties (e.g., luminance, contrast, duration). In this view, information extraction from the stimulus requires the phenomenological presence of the stimulus.

The second view is that information extraction takes precedence. In this view, information extraction depends on physical properties of the stimulus and on the goals of the observer, whereas phenomenological experience is a by-product of the information-extraction process. Along with others (most notably, Di Lollo, e.g., 1980; and Erwin, 1976), we favor this second view. We believe that phenomenological experience results from an active process rather than from the passive state of an informational store.

Erwin (1976) has demonstrated a close relation between information extraction and phenomenological appearance. As we described earlier, Erwin showed that persistence duration decreases with increasing approximation to English. In a second experiment with the same stimuli, Erwin used a paradigm very similar to that of Experiments 1–3. He presented the stimuli followed by a mask after varying ISIs and determined the ISI at which further ISI increases had no additional beneficial effect on subsequent memory performance.[16] Erwin found that the approximation to English variable had the same effect on this "crucial ISI" as it did on persistence duration. Erwin claimed this effect as evidence for the proposition that the same variable underlies the icon as a basis for information extraction and the icon as a basis for phenomenological appearance.

Erwin (see also, Erwin & Hershenson, 1974) interpreted these results in terms of a two-component model of persistence that is similar in many respects to our model. Erwin (1976) characterizes these two components as "a physical component whose duration is unrelated to stimulus parameters and an informational component whose duration is inversely related to the efficiency of encoding stimulus information" (p. 191). These two components correspond, in essence, to the $a(t)$ and $r(t)$ of the present model. A crucial difference between the two models is that Erwin ascribes phenomenological properties to both persistence components, whereas our model ascribes phenomenological properties to $r(t)$ only.

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[16] The major difference between Erwin's paradigm and the paradigm used in Experiments 1–3 is that we varied mask luminance whereas Erwin compared all masking conditions (i.e., all ISIs) to a no-mask control condition. As we have noted earlier, however, a mask can have both perceptual and conceptual effects. For this reason, it is probably more accurate to use the mask luminance effect as the measure of perceptual processing.

2. *The "Indefinite-Duration Stimulus" Problem*

Our model makes a seemingly paradoxical prediction. Consider that phenomenological appearance depends on $r(t)$, which declines with increasing $I(t)$. This means that if the physical stimulus is left on indefinitely, $r(t)$ should eventually decline to the point that the observer will cease to be phenomenologically aware of the stimulus. At first glance, this prediction seems unreasonable.

Assuming the model's validity, there are two resolutions to this issue. First, this problem may simply represent a boundary condition on the model; that is, the rules that determine phenomenological experience may change for long relative to brief stimuli. Second, it may be true that the stimulus may phenomenologically vanish after some period of time.

This second view is actually quite reasonable. Anecdotally, we have all had the experience of gazing at a visual stimulus—a page of text, a conversational partner, the scenery outside a car window—and suddenly realizing that "our thoughts have been elsewhere" and we have not been at all aware of what we were looking at. Empirically, the dichotic listening literature supports such a notion, at least in the auditory domain; when a subject is forced to attend to one auditory channel, e.g., by having to shadow it, there is no evidence that there is any conscious awareness of anything on the nonattended channel—subjects can remember nothing from it, and notice nothing that happens on it, even a change in language from English to German (Cherry, 1953; Cherry & Taylor, 1954; Moray, 1969). It may well be that phenomenological experience depends on a good deal more than simply what enters the sensorium.

C. MEDIATING PROCESSES

A major issue that we have sought to address in this article is that of whether information extraction and phenomenological experience are simply two consequences of—i.e., are mediated by—the same process. Bamber (1979) provides an excellent formalization and discussion of the nature of mediation. Among other things, Bamber describes necessary conditions for concluding that two (or more) performance measures are mediated by the same underlying hypothetical variable. One necessary condition is that any independent variable must affect one of the performance measures if and only if it affects the other(s) as well.

As described earlier, Coltheart (1980) and others assert that visible persistence duration and performance in a partial-report procedure cannot be explained by the same underlying process because of certain independent variables (particularly stimulus duration) that affect one performance measure but not the other. If "underlying process" means a single, unidimensional variable, then, by Bamber's logic, this assertion is correct.

In this contribution, however, we have implicitly taken the position that an underlying process can be more complex than a single unidimensional variable. In particular, our model posits that one variable—total extracted information—mediates any kind of memory performance, whereas another variable—information extraction rate—mediates phenomenological awareness and, thus, persistence duration. While not the same, these two variables are intimately related: one is the derivative of the other. It is in this sense that we consider the system, composed of an information-extraction rate, and the resulting extracted information to be a unified process—and it is this process that mediates both memory performance and phenomenological experience.

V. Appendix

A. DERIVATION OF EQUATION (3G)

We start with the equation for $r(t)$, and assume that $t < d$. Thus,

$$r(t) = a(t)h(I) = dI/dt \tag{1}$$

or,

$$dI/h(I) = a(t)dt$$

Since $a(t) = 1.0$ whenever $t < d$,

$$dI/h(I) = dt \tag{2}$$

Integrating both sides of Eq. (2),

$$H(I) = t + x \tag{3}$$

where $H(I)$ is the integral of $1/h(I)$ and x is the constant of integration. To determine x, we use initial conditions of $I = 0$ when $t = 0$; thus, $x = H(0)$ and

$$H(I) = t + H(0) \tag{4}$$

or,

$$I = H^{-1}[t + H(0)] \tag{5}$$

which constitutes the top part of Eq. (3g).

Now assume that $t > d$. The equation for $r(t)$ is the same as in Eq. (1), but $a(t) = b(t - d)$. Thus,

$$dI/h(I) = a(t)dt = b(t - d)dt. \tag{6}$$

Integrating both sides of Eq. (6),

$$H(I) = B(t - d) + x \tag{7}$$

where $B(t - d)$ is the integral of $b(t - d)$ from 0 to $(t - d)$. To determine x, the constant of integration, we use initial conditions deriving from Eq. (5), that $I = H^{-1}[d + H(0)]$ when $t = d$. Furthermore, $B(t - d) = B(0)$ when $t = d$ and, according to the model, $B(0) = 0$. Therefore,

$$x = H\{H^{-1}[d + H(0)]\} = d + H(0) \tag{8}$$

and, substituting Eq. (8) into Eq. (7),

$$H(I) = d + H(0) + B(t - d)$$

Finally,

$$I = H^{-1}[d + H(0) + B(t - d)] \tag{9}$$

which constitutes the bottom part of Eq. (3g).

B. DERIVATION OF THE LOFTUS, JOHNSON, AND SHIMAMURA RESULT

Consider a $(d + w)$-msec masked picture. Because the mask reduces $r(t)$ to 0, there is no icon, and the amount of extracted information is obtained by Eq. (5) Section V, A:

$$I = H^{-1}[d + H(0) + w] \tag{10}$$

Now consider a d-msec delayed-mask picture. Such a picture is followed by an icon, and the amount of extracted information is determined by Eq. (7), with t equal to ∞.[17] By the model, $B(\infty) = w$. Therefore,

$$I = H^{-1}[d + H(0) + w] \tag{11}$$

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[17] The value of t should actually be 300 msec, the delay time of the mask. However, given the actual parameter values, $B(300)$ is approximately equal to $B(\infty)$.

The equality of I in Eqs. (10) and (11) indicates that the amount of information extracted from an immediate-mask, $(d + w)$-msec picture is equal to the amount of information extracted from a delayed-mask, d-msec picture. This is the Loftus, Johnson, and Shimamura finding.

C. Proof That Equations (6a) and (6b) Imply a Multiplicative Effect

Consider level i of the independent variable:

$$r(t_i) = dI/dt_i = f(I)$$

or,

$$dI/f(I) = dt_i \tag{1}$$

Integrating both sides of Eq. (1),

$$F(I) = t_i + x$$

where F is the integral of $1/f$ and x is the constant of integration. With initial conditions of $I = 0$ when $t = x = F(0)$, therefore,

$$F(I) = t_i + F(0)$$

or

$$I = F^{-1}[t_i + F(0)] \tag{2}$$

Now consider level j of the independent variable:

$$r(t_j) = dI/dt_j = cf(I)$$

or,

$$dI/f(I) = c\ dt_j \tag{3}$$

Integrating both sides of Eq. (3),

$$F(I) = ct_j + x$$

Again with initial conditions of $I = 0$ when $t = 0$, $x = F(0)$, and

$$F(I) = ct_j + F(0)$$

or

$$I = F^{-1}[ct_j + F(0)] \tag{4}$$

Equal performance for levels i and j implies equality of I in Eqs. (2) and (4). Setting this equality, applying the function F to both sides and canceling the $F(0)$s yields

$$t_i = ct_j$$

which is the definition of a multiplicative effect.

D. Proof of Equation (8q)

At time $(t - d)$,

$$a(t) = e^{-(t - d)/w}$$

Therefore,

$$r(t) = dI/dt = a(t)c[1.0 - I(t)] = ce^{-(t-d)/w}[1.0 - I(t)]$$

or,

$$dI/[1.0 - I(t)] - ce^{-(t-d)/w} \tag{1}$$

Integrating both sides of Eq. (1),

$$-\ ln\{[1.0 - I(t)]\} + x = -cwe^{-(t-d)/w} \tag{2}$$

where x is the constant of integration. To solve for x, we use initial conditions of $I(t) - 0$ at time $(t - d) = q$. This gives

$$x = -\ cwe^{-q/w}$$

Substituting this value of x into Eq. (2),

$$-\ ln\{[1.0 - I(t)]\} - cwe^{q/w} = -cwe^{(t-d)/w}$$

or,

$$ln[1.0 - I(t)] = cw[e^{(t-d)/w} - e^{-q/w}] \tag{3}$$

Exponentiating both sides of Eq. (2),

$$1.0 - I(t) - e^{\{cw[\exp(-(t-d)/w) - \exp-(q/w)]\}}$$

or

$$I(t) = 1.0 - e^{cw\{\exp[-(t-d)/w - \exp-(q/w)]\}}$$

The amount of information from the array is $I(t)$ when $t = \infty$ (since information extraction continues until available information has vanished). Substituting $t = \infty$ into Eq. (4),

$$I(t) = 1.0 - e-[cw \exp(-q/w)]$$

which is Eq. (8q).

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