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Conceptual Masking: How One Picture Captures Attention from Another Picture

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When a masking picture follows some initial stimulus picture, subsequent memory performance for the stimulus is reduced, even when the mask is delayed by 300 ms following stimulus offset. Such a delay is sufficiently long that all perceptual traces of the stimulus have vanished, and therefore the inferred effect of the mask is to interrupt conceptual as opposed to perceptual processing of the stimulus. We define such a mask to be a *conceptual mask*, and we define its effect on a stimulus to be a *conceptual masking effect*. We report five experiments designed to investigate how conceptual masking operates, and to guide the development of a conceptual-processing model. We first tested the hypothesis that conceptual processing is continuously shared between stimulus and mask. This hypothesis was disconfirmed by the finding of an independent variable, conceptual mask duration, that influences memory for the mask itself, but not memory for the stimulus. We next tested the hypothesis that a mask captures conceptual processing from the target at the instant of mask onset. This hypothesis was disconfirmed by the finding that the conceptual-masking effect of a 50-ms mask can be removed if the mask is itself immediately followed by a second mask. These findings, along with many others in the literature, are consistent with a model which assumes that (1) conceptual processing cannot begin until acquisition of some criterion amount of perceptual information, (2) initiation of mask conceptual processing is a probabilistic event that is influenced by attention demands, and (3) initiation of mask conceptual processing causes cessation of stimulus conceptual processing, thereby constituting conceptual masking. We describe such a model along with its account of a large body of data. © 1988 Academic Press, Inc.

A person viewing a picture carries out a series of encoding processes that result in the picture's eventual memory representation. These encoding processes may be conveniently divided into those that operate on (1) perceptual information that is available while the picture is physically present, (2) perceptual information that is available during the presence of the icon that follows the picture's offset, and (3) information constituting some nonvisual, short-term representation of the picture that is constructed shortly after stimulus onset and that can continue after the icon's

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termination. We refer to processes that operate on the first two kinds of information as *perceptual processes* and to processes that operate on the third kind of information as *conceptual processes*.

PERCEPTUAL AND CONCEPTUAL MASKING

In a *backward-masking paradigm* used to investigate various kinds of picture processing, an initial picture (a *stimulus*) is shown, followed shortly after its offset by a second picture (a *mask*). Memory for the stimulus (and sometimes for the mask as well) is subsequently tested. The mask's effectiveness is assessed by the degree to which subsequent memory performance for the stimulus is reduced when it is followed by a mask, relative to performance in some no-mask control condition. A mask that affects perceptual processing is a *perceptual mask* and exerts a *perceptual-masking effect*. A mask that affects conceptual processing is a *conceptual mask* and exerts a *conceptual-masking effect*.

Under the appropriate circumstances, a mask can exert both a perceptual- and a conceptual-masking effect at the same time. If a mask is to be used as a tool to investigate perceptual and conceptual processing separately, however, then it is necessary to determine conditions under which the mask exerts only one kind of masking effect or the other. Loftus and Ginn (1984) report making such a determination. They found that when a mask occurs 50 ms (or less) following stimulus onset, it exerts only a perceptual-masking effect; at this stage of encoding, potentially maskable conceptual processing has not yet begun. Likewise, Loftus and Ginn found that when a mask occurs 300 ms (or more) following stimulus *offset*, it exerts only a conceptual-masking effect; at this stage of encoding, all perceptual traces of the stimulus have disappeared, and potentially maskable perceptual processing has terminated. In the present paper, we are interested in conceptual processing and conceptual masking. Accordingly, we focus on an experimental paradigm in which a mask exerts only a conceptual-masking effect.

What Causes Conceptual Masking?

Various experiments have shown that the *degree of attention* demanded by a conceptual mask is a powerful determinant of mask effectiveness. For instance, a mask consisting of a naturalistic photograph is more effective than a mask consisting of random noise (Loftus & Ginn, 1984). A naturalistic photograph that changes from trial to trial is more effective than a naturalistic photograph that does not change (Intraub, 1984, Experiments 1 and 3). Instructions emphasizing that attention be paid to the mask render the mask more effective than instructions emphasizing that attention be paid to the stimulus (Intraub, 1984, Experiment 2). These findings allow at least two general explanations of what causes conceptual masking, both of which assume some limited amount of attentional capacity.[1] These two explanations incorporate the ideas of serial and parallel conceptual processing.

Serial Conceptual Processing

The first explanation is that, at any given instant, all attentional capacity is allocated to one picture only—either to the stimulus or to the mask—and encoding proceeds on a serial basis. By this explanation, conceptual masking consists of an attention switch from the stimulus to the mask, and the effects on stimulus performance of the manipulations described above would be mediated by the proportion of trials on which the stimulus-mask attention switch actually occurs. For example, an increasing emphasis on remembering the mask rather than the stimulus (as in Intraub, 1984, Experiment 2) would cause an attention switch on a greater proportion of trials, thereby reducing average stimulus performance.

Parallel Conceptual Processing

The second explanation for conceptual masking is that, following mask onset, attention is shared between stimulus and mask (cf. Kahneman, 1973). By this explanation, the effects on stimulus performance of the manipulations described above would be mediated by the amount of attention allocated to the stimulus relative to the amount of attention allocated to the mask. An implication of this second possibility is that, following mask onset, encoding of stimulus and mask proceeds in parallel. This yields a testable prediction: any encoding manipulation that affects mask performance should affect stimulus performance in the opposite way. If mask-recognition performance, an indicator of conceptual processing allocated to the mask, improves, stimulus-recognition performance should worsen. Conversely, if stimulus-recognition performance improves, mask-recognition performance should worsen. This prediction was tested in the present experiments.

A Model of Conceptual Processing: Preliminary Remarks

More generally, the present experiments were designed to provide two forms of guidance for a model of the relations among perceptual processing, conceptual processing, and picture-memory performance. First, the experiments distinguish between the two explanations of conceptual masking just described; in this sense, they guide the model's qualitative development. Second, the experiments provide parametric data about the time course over which conceptual processing and conceptual masking

[1] This assumption is required by the extant data: if attentional capacity were not limited, there would be no conceptual masking effect.

operates; in this sense they guide the model's quantitative development. We devote a later section of this paper to a detailed and formal account of this model, along with its account of extant data. In order to illuminate the rationale for our experiments, however, we provide a preliminary description of the model here. We sketch first the nature of the model itself, and second our application of the model to data.[2]

The Model

The model has several roots. First, verbal-memory theorists have developed *displacement models,* according to which memory for a verbal list item is determined by the amount of time that the item remains in some conceptual buffer (e.g., Atkinson & Shiffrin, 1968; Waugh & Norman, 1965). Expected amount of time in the buffer, in turn, is determined by the probability that a buffer-resident item will be displaced by a newly-presented item. The relation between these verbal-learning models and our model is straightforward: "being in the buffer" corresponds to "receiving conceptual processing" and "being displaced by a new item" corresponds to "being conceptually masked by a new item."

More recently, Potter (1976) and Intraub (1985) have proposed models that are similar to one another, and are specifically designed to account for picture processing. According to these models, pictures are initially processed to the point that they are identifiable; such processing requires about 100 ms. Following identification, a picture is in a "conceptual buffer." A picture's representation in the conceptual buffer is transient; unless it receives at least about 300 ms of additional (conceptual) processing, it is vulnerable to conceptual masking by subsequent pictures. Thus, these models focus on processing that is done within about 300–400 ms following stimulus onset.

Our model borrows much from the Potter and Intraub models. However, our model, like the verbal-memory models, allows conceptual processing (and thus the possibility of conceptual masking) to continue indefinitely following stimulus onset.

Our model is broadly organized in terms of (1) the fundamental distinction between perceptual and conceptual processing, (2) the switching of conceptual processing from one picture to a subsequent picture, and (3) the relations among amount of perceptual processing, amount of conceptual processing, and observed memory performance.

[2] It should be kept in mind that describing the model prior to describing the experiments is, in some sense, putting the horse before the cart because the experimental results were instrumental in model construction. This organization constitutes poor storytelling, because knowledge of the model provides the reader with answers to experimental questions that are raised in experiment introductions. We hope, however, that knowledge of the model will provide a more complete picture of why the experiments were carried out to begin with.

Perceptual vs conceptual processing. As noted earlier, we broadly divide picture processing into perceptual and conceptual processing. Perceptual processing begins at stimulus onset. The output of perceptual processing is *perceptual information*. Perceptual information constitutes a preliminary representation of the picture that is sufficient for immediate identification of the picture's gist but is insufficient for later recognition of the picture (cf. Potter, 1976). Perceptual processing operates on the physical stimulus, or on the icon that follows the physical stimulus; thus the time course of perceptual processing is constrained by the time course of physical stimulus presentation.

Conceptual processing operates on the output of perceptual processing, and cannot begin until some criterion amount of perceptual information has been acquired. We do not formally explicate the exact nature of conceptual processing. 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 activity. Conceptual processing does not require the presence of the physical stimulus or its icon; in principal, therefore, conceptual processing can continue indefinitely following stimulus offset.

In general, we identify conceptual processing with *attention*. For ease of discourse, we use the terms the terms "conceptual processing" and "attention" interchangeably. Likewise, we use the terms "conceptual masking," "capture of attention," and "switch of attention" interchangeably.

Attention switching. Conceptual processing is assumed to operate on only one picture at a time. Under some circumstances conceptual processing switches from one picture (the stimulus) to a subsequent picture (the mask). As we just noted, a stimulus-mask attention switch constitutes conceptual masking. Attention-switch probability is influenced by the attention demands of the mask, which, in turn, can be controlled by a variety of independent variables. For example, a mask consisting of a naturalistic scene is more likely to demand attention than a mask consisting of random noise. A mask depicting a novel scene is more likely to demand attention than a mask depicting a previously encountered scene. And, as we shall emphasize in our experiments, in the proper circumstances, a long-duration mask is more likely to demand attention than a short-duration mask.

Conceptual processing and memory performance. In most experiments that we consider, the major dependent variable is some measure of memory performance. Also, in most experiments, amount of perceptual processing is held constant; only degree of conceptual processing is allowed to vary. Our model incorporates the assumption that, under such circumstances, memory performance is monotonically related to amount of conceptual processing. Therefore, memory-performance differences among experimental conditions imply corresponding differences in amount of conceptual processing.

Application of the Model to Data

In order to apply the model, we eventually strengthen it by instantiating some of its assumptions as specific mathematical functions. This strengthening allows us to predict exact performance in a wide variety of circumstances, and thereby illustrate how the model can account for data from several paradigms, including the ones used in the present experiments. As we progress through our first four experiments, we provide predicted data along with obtained data for all conditions. Later we describe exactly how these predicted data were obtained.

EXPERIMENTS

In this section, we report five experiments, all designed to investigate conceptual processing and conceptual masking. Throughout all conditions within a given experiment, degree of perceptual processing (and therefore amount of acquired perceptual information) was held constant. This was accomplished by presenting all stimulus pictures for 50 ms, and following stimulus offset by a 300-ms *blank delay,* i.e., a delay during which only a dim adapting field was present. At the end of this delay, some masking event occurred, and we were primarily interested in how the masking event influenced subsequent stimulus-recognition performance. As noted earlier, a 300-ms delayed mask exerts no perceptual effect; it acts only as a conceptual mask.

Experiment 1: Mask Duration and Mask Type

Experiment 1 had two purposes. The first was to replicate a finding by Loftus and Ginn (1984) that a naturalistic photograph is a more effective conceptual mask than is random noise. In the Loftus and Ginn study, 50-ms stimuli were followed by either a random-noise mask or by a naturalistic photograph termed a *photo mask.* Subjects reported as many details as possible from the stimulus at the end of each stimulus-mask trial. When stimulus-mask ISI was 300 ms, stimulus performance was poorer if the stimulus had been followed by a photo mask than if it had been followed by a random-noise mask.

Loftus and Ginn's performance measure—number of reported details—has two limitations. First, it probably depends, at least to some degree, on the subject's criteria for how long to search memory and for what constitutes "a detail" to begin with. Second, because the memory test occurs within a few seconds of the original presentation, the test taps only information in short-term memory. To circumvent these limitations, and thereby generalize the Loftus and Ginn finding, a relatively long-term, old/new recognition test was used in Experiment 1. As in the Loftus and Ginn experiment, the mask consisted of a photo mask on half the trials, and a random-noise mask on the other half.

The second, and major, purpose of Experiment 1 was to test the prediction of the shared-processing hypothesis that any manipulation affecting mask memory affects stimulus memory in the opposite way. The manipulation we chose was that of mask duration. The results of many experiments have indicated that a picture's duration is a major determinant of the picture's subsequent memory performance (e.g., Loftus & Kallman, 1979; Potter & Levy, 1969; Shaffer & Shiffrin, 1972). Presumably, the longer the duration, the more encoding capacity can be devoted to the to-be-encoded picture. In Experiment 1 mask duration was either 50 or 500 ms. The question was, would mask duration's presumed positive effect on mask memory be accompanied by a concomitant negative effect on stimulus memory? Such a finding would confirm the hypothesis that conceptual processing is continuously shared between stimulus and mask.

Method

A good deal of the methodology was the same over the five experiments. We describe Experiment 1 methodology in detail, noting features that are common to all experiments. In each subsequent experiment, we describe only the methodology that is unique to that experiment.

Subjects. Subjects in all experiments were University of Washington undergraduates who participated in a single, 1-h session for course credit. In the first experiment, 55 subjects were run in eight groups of 5–8 subjects per group.

Materials. In all experiments, photographs were used in many ways. To forestall confusion, we use the following notational conventions. *Stimulus* refers to the initial photograph (always of a naturalistic scene) shown on a given study trial. *Mask* refers to any photograph that followed the stimulus on a study trial. A mask was either a *noise mask* (random visual noise) or a *photo mask* (a scene similar to the stimulus). As usual, *target* refers to a photograph shown in an old/new recognition test trial for which the correct answer is "old," and *distractor* refers to a photograph shown on a recognition test trial for which the correct answer is "new." In all experiments, stimuli were tested in a recognition test; hence there were target and distractor stimuli. In Experiments 1, 3a, 4, and 5, photo masks were also tested; hence there were target and distractor masks as well as target and distractor stimuli.

Two hundred forty naturalistic photographs in the form of 35-mm color slides were randomly placed into three trays of 80 slides per tray. The slides in Trays 1 and 2 (stimulus trays) were designated as stimuli, whereas the slides in Tray 3 (the mask tray) were designated as photo masks. The slides, originally purloined from various "vacation picture" collections, depicted seascapes, landscapes, and cityscapes and included such scenes as sailboats on a lake, a snowcapped mountain, a cement bridge under construction, a white farmhouse, and a rural village from the air. In all experiments except Experiment 2, the complete set of 160 stimuli and 80 masks was used. A single noise mask consisted of a jumble of straight and curved black lines on a white background. The purpose of the noise

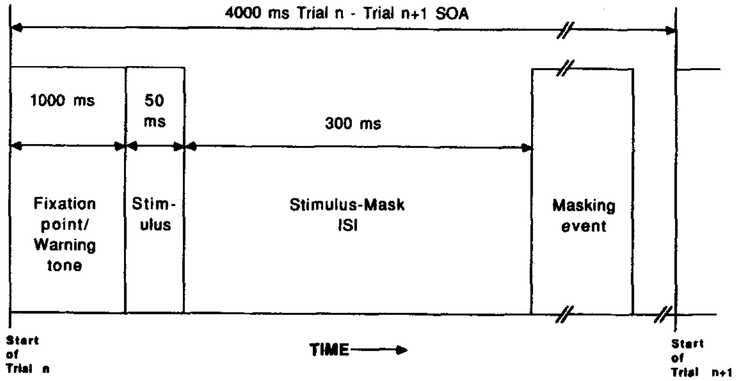

FIG. 1. The sequence of events on a given trial in Experiments 1–5.

mask was to eliminate any iconic image of any picture that it followed. Accordingly, its luminance was such that when it was physically superimposed on a target, no target features could be seen (thereby fulfilling Eriksen's (1980) "minimal criterion" for an adequate mask). A dim adapting field was present throughout all experiments.[3]

Apparatus. The same apparatus was used in all experiments. Stimuli were displayed via a Kodak random-access carousel 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. Timing was controlled by Gerbrands tachistoscopic shutters with rise and fall times of approximately 1 ms. A second random-access projector was used to present the noise mask. Kodak standard projectors were used to present the photo masks and a dim fixation point that began each study trial. All display equipment was enclosed in a soundproof box. All display and response-collection equipment was controlled by an Apple II computer system described by Loftus, Gillispie, Tigre, and Nelson (1984).

Design and procedures. In all experiments, an experimental session consisted of a study phase followed by a test phase using the Tray-1 stimuli and then another study and test phase using the Tray-2 stimuli. In Experiments 1, 3a, 4, and 5, there was also a test of the photo masks. The specific procedures were as follows.

1. Study procedures. Within each stimulus tray, 40 stimuli were presented during the study phase. In all experiments, the nature of the mask that followed a stimulus defined the *experimental condition* into which that stimulus fell. In Experiment 1, the mask was either a photo mask or the noise mask, and was presented for either 50 or 500 ms. In Experiment 1, as in all experiments, photo masks changed from trial to trial; that is, no photo mask was ever seen more than once during the study phases. Stimuli in Experiment 1 thus fell into one of four conditions defined by two values of mask type (photo or noise) combined with two values of mask duration (50 or 500 ms). These four conditions were presented in random order with the restriction that each condition occurred twice within each of the five, 8-trial blocks. All conditions in all experiments were within subjects.

Subjects in all experiments were informed about the sequence and timing of events that would occur and were instructed to try to remember all of the pictures that they would see. Figure 1 shows the sequence of study-trial events that is common to all our experiments. First, a 1000-ms, 1000-hz tone signaled the subjects to fixate a dim spot that concurrently

[3] Stimulus luminances (in millilamberts) were as follows: adapting field, 0.07; projector on, no slide, 38.43; fixation spot, 0.38; pattern mask, bright background, 25.19; pattern mask, black markings, 2.57.

appeared at the center of the viewing field. A stimulus was then presented for 50 ms, followed by a 300-ms blank delay. Following the delay was some masking event. In Experiment 1, the masking event consisted of a photo or a noise mask, shown for 50 or 500 ms. Except in Experiment 5, the stimulus-onset asynchrony (SOA) from trial n to trial $n + 1$ was always 4000 ms.

2. Stimulus test procedures. In a stimulus test phase, that immediately followed each study phase, all target stimuli from the just-shown stimulus tray were randomly intermingled with an equal number of distractors, and the resulting test stimuli were shown one at a time. The target-distractor ordering was different for the different stimulus trays but, for each tray, was identical for all groups throughout the experiment. Subjects judged each test stimulus to be *old* or *new* by pressing one of two designated keys on a response box. After all subjects had responded, there was a 500-ms pause prior to the onset of the next test trial.

3. Mask test procedures. In Experiment 1, as well as in Experiments 3a, 4, and 5, a mask-recognition test occurred at the end of the experimental session, just after the Tray 2 stimulus-recognition test. In Experiment 1 there was a total of 40 study trials involving photo masks over the two study phases (the other 40 involved the noise mask). These 40 masks were thus the target masks and the remaining 40 masks in Tray 3 were distractor masks. The mask-recognition test procedure was identical to the stimulus-recognition test procedure.

4. Counterbalancing. Generally, both stimuli and masks were counterbalanced across target/distractor and across study conditions. Except in Experiment 2, each stimulus occurred as a target for half of the experimental groups and as a distractor for the other half of the groups. In all experiments, each stimulus occurred exactly once in each of the various study conditions over the groups for which it appeared as a target.

In Experiment 1, each of the 80 photo masks occurred twice in the 50-ms mask-display condition, twice in the 500-ms mask-display condition, and four times as a distractor over the eight groups.

Results and Discussion

In all experiments, all study conditions were randomly intermingled during the study phases. There was, therefore, only a single false-alarm probability for the stimuli, which, in Experiment 1, was 0.351. Similarly, there was a single false-alarm probability for the photo masks, which, in Experiment 1, was 0.347. Table 1 shows hit probabilities for both stimulus slides and photo masks as a function of the relevant conditions. In Table 1, as in most of our results tables, we provide the observed mean for each condition (the value preceding the slash) as well as the mean predicted by our model (the value following the slash). The genesis of these predicted means is fully described in a later section of this paper.

The results are quite straightforward. Stimuli that had been followed by a photo mask were recognized more poorly than were stimuli that had been followed by a noise mask, $t(54) = 4.21$.[4] Neither mask duration, nor the mask duration × mask type interaction had a statistically significant

[4] Three comments are in order about our conventions for reporting statistical analyses. First, unless otherwise specified, reported results are significant at the .05 level. Second, we report the results of one-degree-of-freedom ANOVAs as t values. This is because our tests are of specific (directional) alternative hypotheses; thus, one-tailed tests are appropriate. Third, we report standard errors in the notes to the relevant data tables.

TABLE 1
Hit Probabilities: Experiment 1

	Stimuli			
	Mask type			
Mask duration	Photo	Noise	Mean	Photo masks
50 ms	0.509/0.518	0.575/0.591	0.542/0.554	0.593/0.583
500 ms	0.499/0.499	0.570/0.587	0.535/0.543	0.743/0.861
Mean	0.504/0.509	0.572/0.589		

Note. Value preceding slash is obtained mean; value following slash is mean predicted by the model. Standard errors were 0.016, and 0.015 for stimuli and masks, respectively.

effect on stimulus-recognition performance, both *ts* < 1. Five hundred ms photo masks were recognized better than 50-ms photo masks, $t(54) = 8.42$.

Loftus and Ginn (1984) demonstrated that the 300-ms delay between stimulus offset and mask onset is sufficient to allow complete decay of the icon that follows the stimulus. Thus, any masking effect occurring at this delay is, by definition, a conceptual-masking effect. The finding that photo masks are more effective than the random-noise mask replicates a similar finding by Loftus and Ginn, and lends credence to the proposition that conceptual masking is essentially an attentional phenomenon. Any manipulation that causes the mask to demand more attention at the time of mask onset increases its effectiveness *as a conceptual mask.* The emphasis is added here, because it is entirely possible to arrange the display configuration such that a mask does not have a conceptual effect. When Loftus and Ginn showed a mask immediately following the offset of a 50-ms stimulus, photo masks and noise masks were equally effective. Evidently, it requires some period of time longer than 50 ms for conceptual processing to begin, and thereby be in an interruptable state. If a mask is presented before the onset of stimulus conceptual processing, it cannot act as a conceptual mask.

Mask duration, while having the expected substantial effect on subsequent mask performance, had no effect on stimulus performance, contrary to the prediction that any manipulation affecting mask encoding will affect stimulus encoding in the opposite way. This finding allows us to reject any model in which conceptual encoding is shared between stimulus and mask throughout the study trial.

A model suggested by Intraub (1984, 1985; see also Intraub & Nicklos, 1981) bears a superficial resemblance to the just-rejected attention-sharing model. Intraub's model posits a "conceptual buffer" in which up to three pictures can be stored simultaneously. The model does not, however, require that processing occur in parallel on all occupants of the buffer; rather processing may switch among pictures within the buffer. Our model is similar to Intraub's, but it makes the simplifying assumption that conceptual processing operates strictly in the order of picture presentation. We show that this assumption is sufficient to account for most of the extant data.

Experiment 2: Masking the Mask (The Disinhibition Effect)

Earlier, we sketched two possible explanations of conceptual masking. The first is that following mask onset a complete attention switch from stimulus to mask occurs on some proportion of trials. The second is that following mask onset, attention is continuously shared between stimulus and mask. The results of Experiment 1 disconfirmed this second possibility, thereby suggesting that the first is correct: that conceptual masking consists of a probabilistic—but when it occurs, complete—attention switch from stimulus to mask.

At what point during processing does this putative stimulus-mask attention switch occur? One reasonable possibility is that the switch occurs immediately at the mask's onset. If this were true, then any variable affecting mask effectiveness must exert its influence prior to, or immediately at, mask onset. A variable whose state does not become apparent until some time following mask onset could not affect mask effectiveness. An example of such a variable is mask duration, as used in Experiment 1.

In Experiment 2, we implemented another such variable, specifically whether or not a 50-ms photo mask was itself masked by a noise mask. Like mask duration, the state of this variable does not become apparent until 50 ms following photo-mask onset. If the stimulus-mask attention switch occurs at mask onset, then whether or not the photo mask is followed by a noise mask can have no effect on subsequent stimulus memory.

Method

Subjects and materials. Twenty-three subjects were run in three groups of 8, 8, and 7 per group. Only the first 72 slides in each of the two stimulus trays and the first 48 slides in the mask tray were used.

Design and procedure. There were three conditions, defined by which of three masking events occurred on each study trial. In the photo-darkness (PD) condition, a 50-ms photo mask was presented, followed by darkness. In the photo-noise (PN) condition, a 50-ms photo mask was presented, followed by a 300-ms noise mask. In the control condition, no mask was presented. The three stimulus display conditions were presented in random order with the restriction that each condition occurred four times during each of the three, 12-trial blocks within each study phase. The photo masks were not tested in Experiment 2.

Of the 144 total stimulus slides, 72 were targets, and the other 72 were distractors. Each of the 72 targets appeared in each of the three conditions over the three groups. Target-distractor was not counterbalanced in Experiment 2. Strictly speaking, this design does not allow an unblemished comparison of hits and false alarms, i.e., an assessment of absolute recognition performance level. Of major interest, however, were comparisons among the three experimental conditions.

Results and Discussion

The false-alarm probability was 0.292. Table 2 shows hit probabilities for the three conditions. Performance was best in the control condition and worst in the PD condition. The differences between the control and PD conditions and between the PN and PD conditions are significant by a Scheffé test, $t(22) = 6.32$ and 4.19, respectively. In contrast, the deleterious effect on stimulus performance of the visually complex PN display sequence—a 50-ms photo mask, followed by a 300-ms noise mask—was surprisingly small. The difference between the control and the PN conditions was only 0.048, and is not statistically significant, even by a simple t test, $t(22) = 1.53$.

If a conceptual mask exerts its entire effect at the start of mask presentation, then the PD and PN conditions cannot differ from one another. Clearly these two conditions do differ. It appears, therefore, that the stimulus-mask attention switch occurs at some time following mask onset.

The facilitating effect of the noise mask reflected by the difference between the PN and PD conditions, resembles an analogous perceptual effect reported by Dember and Purcell (1967) and Robinson (1966). In the Dember and Purcell experiment, for example, a stimulus letter was presented, following either by a single mask (a metacontrast ring) or by two successive masks (the initial ring followed by a second, larger, ring). Stimulus identification was better in the two-mask condition than in the one-mask condition. The explanation was that the first ring by itself *inhibited* the stimulus. However, the second mask masked the first mask, and thereby *disinhibited* the stimulus. An implication of this result is that the stimulus must not have been irrevocably eliminated from the cognitive system by the onset of the first mask; if it had been, then it could not have been lurking about, ready to reappear upon elimination of the first mask.

TABLE 2
Hit Probabilities: Experiment 2

Mask condition		
PD	PN	C
50-ms photo mask/ darkness 0.460/0.474	50-ms photo-mask 300-ms noise mask 0.541/0.502	No-mask control 0.589/0.575

Note. Value preceding slash is obtained mean; value following slash is mean predicted by the model. Standard error was 0.019.

Although the mechanism operating in the present paradigm is probably different from the mechanism operating in the perceptual disinhibition paradigm (the stimulus-mask ISI is such that the present masking must be conceptual rather than perceptual), there are some surface similarities. In both cases, stimuli followed by two masks show better performance than stimuli followed by a single mask. In both cases, there is an implication that the effect of initial mask onset is not to entirely eliminate whatever mental representation of the stimulus existed at the time that the initial mask occurred. This implication is the basis for the term *inhibition*, rather than a fiercer term such as "destruction" to describe the effect of the initial mask on the stimulus.

Experiment 3a: Mask Duration Revisited

The results of Experiment 2 indicate that a stimulus-mask attention switch is not complete by 50 ms following mask onset. The purpose of Experiments 3a and 3b was to extend Experiment 2 by presenting masked photo masks for durations ranging from 50 to 600 ms. Presumably, as mask duration increases, there is a successively greater chance that an attention switch will occur; thus stimulus performance should decline as a function of mask duration.

It might seem as if this prediction was already disconfirmed by the Experiment 1 finding of no mask-duration effect on stimulus performance. However, photo masks were followed by darkness in Experiment 1, but followed by an immediate (perceptual) noise mask in Experiment 3a. Below, we explain in detail why this is an important difference. Briefly, the perceptual information necessary for initiation of photo-mask conceptual processing can be acquired from an arbitrarily short photo mask that is followed by darkness. However the necessary perceptual information can be acquired from a photo mask that is itself followed by an immediate noise mask only if the photo mask lasts for some minimum duration. A major purpose of Experiments 3a and 3b was to estimate this minimum duration.

Experiments 3a and 3b were very similar to one another. The only differences were that (1) the two experiments incorporated different mask-duration values and (2) mask recognition was tested in Experiment 3a but not in Experiment 3b.

Method

Subjects, design, and procedure. Fifty-three subjects were run in eight groups of 5 to 8 per group. There were four conditions, defined by photo-mask duration. The photo mask was displayed for either zero ms (i.e., was not presented at all), or was displayed for 50, 200, or 600 ms. Immediately following the photo mask (including the zero-ms "presentation") was the noise mask, displayed for 300 ms. The four stimulus-display conditions were presented in random order with the restriction that each condition occurred twice during each of the five, 8-trial blocks within each study phase. Recognition performance for both stimuli and masks was measured. Note that masks occurred on three-fourths of the study trials. This means that of the 80 total masks, 60 had been seen, and the other 20 had not been seen during the study trials. Over the eight groups, each mask served twice in each of the four mask conditions.

Results and Discussion

The top row of Table 3 shows recognition data for the stimuli. The far-left column shows the false-alarm probability (0.333), and the remaining four columns show hit probabilities for the four mask-duration conditions. The bottom row shows corresponding recognition data for the masks. The mask false-alarm probability is for the zero-ms mask condition (i.e., nonpresented masks), and the remaining three columns show hit probabilities for the three nonzero mask-display conditions.

As expected, mask hit probability increased with mask duration. This increase was quite substantial: almost 0.34 as mask duration increased from 0 to 600 ms. A planned comparison for monotonic increase was significant, $t(52) = 38.88$.

Stimulus hit probability decreased with increasing mask duration. The decrease was small: only about 0.08 as mask duration increased from 0 to 600 ms. But the decrease is significant, again by a planned comparison for monotonic decrease, $t(52) = 2.95$. Moreover, there is a significant monotonic decrease even if only the 50-, 200-, and 600-ms mask-duration conditions are considered, $t(52) = 2.45$, or even if only the 200-and 600-ms conditions are considered, $t(52) = 1.84$.

Experiment 3b: More Masked Photo-Mask Durations

In Experiment 3a, stimulus-recognition performance decreased with increasing mask duration. However, a limited number of mask durations was used in Experiment 3a. Experiment 3b was like Experiment 3a except that there were eight mask durations ranging from 50 to 600 ms. The purpose of Experiment 3b was thus to replicate and extend Experiment 3a. In particular, we sought to determine the precise mask duration at

TABLE 3
Hit and False-Alarm (FA) Probabilities for Targets and Photo Masks in Experiment 3a

		Photo mask duration (ms)			
		0	50	200	600
Targets:	FA = 0.333	0.548/0.576	0.523/0.531	0.510/0.486	0.471/0.482
Masks:		FA = 0.331	0.348/0.366	0.511/0.569	0.667/0.830

Note. Value preceding slash is obtained mean; value following slash is mean predicted by the model. Standard errors were 0.015, and 0.014 for stimuli and masks, respectively.

which further mask-duration increases had no further effect on stimulus performance. Within the context of various models (in addition to ours, e.g., Potter, 1976) this asymptotic duration is an estimate of the mask duration at which any stimulus-mask attention switch is complete.

Method

Subjects, design, and procedure. Eighty subjects were run in 16 groups of 5 subjects per group. There were eight conditions defined by photo-mask duration, which was: 50, 100, 150, 200, 300, 400, 500, or 600 ms. As in Experiment 3a, a 300-ms noise mask immediately followed each photo mask. The eight stimulus-display conditions were presented in random order with the restriction that each condition occurred once during each of the five, 8-trial blocks. Recognition performance for the photo masks was not tested.

Results and Discussion

The false-alarm probability was 0.388. Table 4 shows the hit probabilities for the eight conditions.

Stimulus-recognition performance decreased as mask duration was increased from 50 to 100 ms. A planned comparison confirmed that hit probability in the 50-ms condition (0.569) was significantly different from the mean hit probability in the other seven conditions (0.523), $t(79) = 2.50$. This comparison accounted for 78% of the between-condition variance.

In contrast to Experiment 3a, performance did not continue to drop from the 200-ms to the 600-ms condition. A planned comparison of the 100-ms condition against the mean of the 200-ms–600-ms conditions was nonsignificant, $t(79) < 1$, and accounted for less that 1% of the between-condition variance. In addition, both a standard F test and a test for monotonic decrease over the 150-ms–600-ms conditions were nonsignificant, $F(5,395) < 1$ and $t(79) < 1$. Recall that in Experiment 3a the decrease in stimulus-recognition performance was small, but statistically significant, over the whole 50–600 ms mask-duration range. Taken together, the results of Experiments 3a and b indicate that the drop in stimulus performance is largely complete as mask duration increases up

TABLE 4
Hit Probabilities: Experiment 3b

Photo mask duration (ms)							
50	100	150	200	300	400	500	600
0.569/0.570	0.524/0.547	0.531/0.535	0.521/0.529	0.533/0.524	0.509/0.524	0.530/0.524	0.516/0.524

Note. Value preceding slash is obtained mean; value following slash is mean predicted by the model. Standard error was 0.017.

to 100 ms, although under some circumstances there might be an additional decrease beyond 100 ms.

Experiment 4: Replication and Control

In some conditions of Experiments 2–3, a noise mask was used to mask the photo mask. The implicit assumption has been that a noise mask, with its seemingly light attentional demands, has no effect on conceptual processing of the stimulus. But this assumption may be incorrect: both the photo mask and the noise mask, could act as conceptual masks. The first purpose of Experiment 4 was to disentangle the conceptual-masking effects of the photo and noise masks. The second purpose of Experiment 4 was to replicate the major results of Experiments 1–3.

Method

Subjects, design, and procedure. One hundred four subjects were run in 16 groups of 6 to 8 per group. There were eight conditions, as indicated in Table 5a. Conditions 1–4 (top row of Table 5a) involved the presentation of a photo mask. In Conditions 1–2, photo-mask duration was 75 ms; in Conditions 3–4, photo-mask duration was 600 ms. In Conditions 2 and 4, the photo mask was followed by a noise mask; in Conditions 1 and 3, the photo mask was not followed by a noise mask; rather, it was simply followed by a blank interval until the start of the next study trial.

Conditions 5–8 (bottom row of Table 5a) were meant to act as control conditions for the corresponding Conditions 1–4. Conditions 5–8 were identical to Condition 1–4 except that the photo mask was not displayed; instead, the 75- or 600-ms interval was blank. Thus,

TABLE 5
Design and Results, Experiment 4

	Photo mask (or blank) duration (ms)			
	75 (no noise mask)	75 (noise mask)	600 (no noise mask)	600 (noise mask)
(a) Design of Experiment 4[a]				
Photo mask				
Present	1	2	3	4
Absent	5	6	7	8
(b) Results of Experiment 4[b]				
Stimulus data				
Photo mask				
Present	0.446/0.450	0.495/0.469	0.450/0.435	0.434/0.431
Absent	0.578/0.560	0.503/0.538	0.578/0.560	0.579/0.553
Photo mask data	0.427/0.564	0.277/0.341	0.519/0.869	0.471/0.814

[a] Condition numbers in cells are referred to in the text.
[b] Value preceding slash is obtained mean; value following slash is mean predicted by the model. Standard errors were 0.015, and 0.014 for stimuli and masks, respectively.

comparing stimulus performance from two cells in a given column provides an assessment of photo-mask effect in that column condition, controlling for any noise-mask effect.

Because the SOA between the onsets of study trials n and $n + 1$ was constant (4000 ms), Conditions 5 and 7 were identical from the subjects' perspective. Both were equivalent to the control condition of Experiment 2 in that the stimulus was followed not by any mask, but rather by a blank interval until the start of the next study trial.

The eight stimulus-display conditions were presented in random order with the restriction that each condition occurred once within each of the five 8-trial blocks. Each photo mask occurred twice in each of the eight conditions over the 16 groups (note that photo masks in the four no-photo-photo mask conditions served as distractors during the photo mask-recognition test.

Results and Discussion

The false-alarm probabilities for both the stimuli and (coincidentally) the masks was 0.267. The top two rows of Table 5b show the stimulus hit probabilities for the eight conditions. The third row shows hit probabilities for the photo masks that had been presented in the four "Photo mask present" conditions.

Mask recognition. The recognition data for the photo masks are shown in Table 5b, third row. The pattern is as expected from previous work (e.g., Loftus, Johnson, & Shimamura, 1985). Performance was higher for 600-ms than for 75-ms duration photo masks (when photo masks were followed by darkness, $t(104) = 4.53$; when photo masks were followed by a noise mask, $t(104) = 9.56$). Performance was higher for photo masks followed by darkness than for photo masks followed by a noise mask (for 75-ms photo masks, $t(104) = 7.39$; for 600-ms photo masks, $t(104) = 2.36$). As in Experiment 3a where there was essentially no memory for 50-ms photo masks followed by a noise mask, here there was essentially no memory for the 75-ms photo masks followed by a noise mask; the hit probability was only marginally greater than the false-alarm probability, $t(104) < 1$.

Stimulus recognition: Conceptual masking effects of noise masks. Consider first what happens when no photo mask is presented (Table 5b, second row). Here, variation in stimulus performance is determined strictly by characteristics of the noise mask. Stimulus performance is essentially identical for three of the four conditions, $F(2,208) < 1$. The exception is the 75-ms noise-mask condition in which the noise mask follows stimulus onset by 50 + 300 + 75 = 425 ms. Performance in this condition is about 0.07 lower than in the other three conditions, $ts(104) \sim 3.4$. Evidently, random visual noise can act as a conceptual mask, even at this SOA. Note that in the 600-ms noise-mask condition, performance is approximately equal to that in the two no-mask control conditions, $ts < 1$. It seems that any conceptual deficit engendered by the noise mask has dissipated by 50 + 300 + 600 = 950 ms following stimulus onset. Thus

TABLE 6
Photo Mask Conceptual Effects

		Photo mask duration (ms)	
		75	600
Photo mask	Yes	0.008/0.069	0.145/0.122
Masked?	No	0.132/0.110	0.128/0.125

Note. Value preceding slash is obtained mean; value following slash is mean predicted by the model.

a noise mask depresses stimulus-recognition performance and acts as a conceptual mask at short but not long SOAs. These data are roughly in accord with those reported by Intraub (1980, Experiment 2).

Stimulus recognition: Replications of Experiments 1–3. Now consider what happens to stimulus performance when a photo mask *is* presented (Table 5b, first row). A major result of Experiment 1 is replicated in that stimulus performance does not depend on photo-mask duration when the photo mask is followed by darkness (hit probabilities of 0.446 and 0.450, respectively, $t(104) < 1$). The "disinhibition effect" of Experiment 2 is replicated in that stimulus performance does depend on whether a 75-ms photo mask is followed or not followed by a noise mask (hit probabilities of 0.495 and 0.446, respectively, $t(104) = 2.24$). The major results of Experiments 3a and 3b are replicated in that stimulus performance depends on photo-mask duration when the photo mask is followed by a noise mask (hit probabilities of 0.495 and 0.434, respectively, $t(104) = 2.79$). The noise mask disinhibits a stimulus followed by a 75-ms photo mask. However, the noise mask had no effect on a stimulus followed by a 600-ms photo mask; in this configuration, the photo mask presumably has had ample time to act as a conceptual mask.

Stimulus recognition: Controlled effects of the photo mask. The effects of the photo mask, controlled for noise-mask effects are reflected by the differences between Rows 1 and 2 of Table 5b.[5] These differences are shown in Table 6 as a 2 (photo-mask duration) × 2 (photo mask masked/not masked) arrangement. There are three important aspects of Table 6. First, a 75-ms, photo mask followed by a noise mask has essentially no conceptual-masking effect. Second, the conceptual-masking effect of the

[5] Several comments are in order about these difference scores. First, the scores as they stand have no meaningful theoretical interpretation as they would if, for example, they issued from a correction-for-guessing or a signal-detection model. Instead the scores are meant to be only descriptive. Second, any variation of these difference scores constitutes an interaction of the photo-mask present/absent variable with the other four conditions. This interaction is interpretable in the sense described by Loftus (1978); that is, it holds over all monotone transformations of the dependent variable.

photo mask is affected by its duration only if it is itself followed by a noise mask; if it is not followed by a noise mask, its duration is irrelevant. This constitutes a controlled replication of the major results of Experiments 1, 3a, and 3b. Third, whether or not a 600-ms photo mask is followed by a noise mask does not affect its conceptual masking effect.

Experiment 5: Fifty-Millisecond Masked Photo Mask Detection

In Experiments 3a and 4, there was virtually no memory for a 50- or 75-ms photo mask that was followed by a noise mask. This raises the possibility that such a picture was ineffective as a conceptual mask simply because subjects never detected its presence. Experiment 5 was a control experiment whose major purpose was to measure detectability of a briefly presented, masked photo mask.

Method

Subjects, design, and procedure. Twenty-two subjects were run in four groups of 5 or 6 per group. There were two conditions defined by the presence or absence of a photo mask during a given study trial. Following the 300-ms poststimulus blank delay was either (1) an additional blank 50-ms delay followed by the noise mask, or (2) a 50-ms photo mask followed by the noise mask. Subjects were completely informed about the experimental design and were told that they would later have a recognition test of all pictures that they saw. In addition, they were told that they would be required to respond "yes" or "no" on their response boxes after each study trial, corresponding to whether they thought a photo mask had or had not been presented. Study trials, instead of being presented at a constant SOA, were paced by the probability of detection responding; study trial $n + 1$ did not begin until 500 ms after all subjects had made their detection responses for trial n. Otherwise, the procedures were identical to those of Experiments 1–4.

The two display conditions were presented in random order with the restriction that each condition occurred four times within each of the five, 8-trial blocks. Each photo mask occurred twice as a target and twice as a distractor over the four groups.

Results and Discussion

All Experiment 5 data are shown in Table 7.

Detection data. The hit and false-alarm probabilities for photo-mask detection were 0.737 and 0.179. This difference is significant, $t(21) = 12.68$, $MS_e = 0.0203$; thus detection was substantially above chance. We can reject the hypothesis that a briefly presented, masked picture fails as a conceptual mask simply because it is not detectable.

Stimulus-recognition data. Stimulus performance was poorer in Experiment 5 than in Experiments 1–4; the hit probabilities were only minimally above the false-alarm probability. However, a planned comparison of the two hit probabilities against the false-alarm probability is significant, $t(21) = 2.91$, $MS_e = 0.00479$, indicating that performance is above chance. The

TABLE 7
Data from Experiment 5

Detection data	
Photo mask present (hit probability)	0.737
Photo mask absent (false-alarm probability)	0.179
Stimulus data	
False-alarm rate	0.297
Hit probability: photo mask present	0.361
Hit probability: photo mask absent	0.338
Mask data	
False-alarm probability	0.350
Hit probability	0.349

Note. All entries represent "yes" responses.

two hit probabilities do not differ significantly from one another, $t(21) = 1.10$, $MS_e = 0.00479$. This replicates the corresponding finding in Experiment 4.

The impoverished memory performance for stimuli supports the general view that conceptual masking is an attentional phenomenon under subjects' control (cf. Intraub, 1984). Unlike subjects in Experiments 1–4, subjects in Experiment 5 had a significant task to perform following each study trial; they had to make a detection response, in addition to trying to remember at least one picture. Evidently the additional effort involved in making this detection response inhibited conceptual processing of the stimuli. We defer additional consideration of this finding to a later section.

Masking-recognition data. There is essentially no memory for the photo masks; the hit and false-alarm probabilities differ by only 0.001, $t(21) < 1$. This replicates the corresponding findings of Experiments 3a and 4.

General Summary: Experiments 1–5

The principal findings of Experiments 1–4 are as follows. First, in accord with the data of Intraub (1980, 1984) and Loftus and Ginn (1984), a changing photograph is a more effective conceptual mask than is an unchanging noise mask. Second, the effectiveness of a photo as a conceptual mask does not depend on mask duration (at least in the range 50–600 ms) when the photo mask is followed by darkness. Third, however, the effectiveness of a photo mask *does* depend on mask duration (at least in the range 50–600 ms) when the photo mask is itself masked by a following noise mask.

In Experiment 5, recognition memory for stimuli was considerably reduced relative to Experiments 1–4. The magnitude of the reduction is so great that the effect can be taken seriously even though the comparison is between experiments. Evidently, the necessity of detecting a mask and/or making a detection response seriously impairs conceptual processing.

A MODEL OF CONCEPTUAL PROCESSING

In our introduction, we briefly described our model. We now present the model formally, and in detail. We first present the model as a set of general assumptions. We call this version the *general model*. Then, in order to illustrate the model's predictions and fit it to data, we instantiate it as a *quantitative model*. The quantitative model is *stronger* than the general model, in the sense that the former implies the latter, but not vice-versa.[6]

The General Model

Assumptions

The general model consists of five assumptions. These assumptions, along with some important corollaries, are as follows.

Assumption 1: Perceptual information as input to conceptual processing. Conceptual processing operates on perceptual information. This means that conceptual processing cannot begin immediately at stimulus onset, but must wait until some requisite amount of perceptual information has been acquired.

Assumption 2: Initiation of conceptual processing as a probabilistic event. Even when the requisite perceptual information has been acquired from some candidate picture, conceptual processing of it does not automatically occur; the probability that it *does* occur can vary from 0.0 to 1.0. The probability of conceptual-processing initiation is determined by attention demands of the candidate picture relative to previously presented pictures.

Assumption 3: Conceptual processing as a serial process. Conceptual processing can only be allocated to one picture at a time; thus if conceptual processing begins on one picture (e.g., a mask), it ceases on the preceding picture (e.g., the stimulus). It is this cessation that constitutes conceptual masking.

Assumption 4: A memory representation as the output of conceptual processing. Conceptual processing results in a memory representation. The quality of the memory representation is determined both by the quan-

[6] This asymmetry places limitations on the inferences that we can make about the general model's ability to account for data from the quantitative model's behavior. In particular, a demonstration of the quantitative model's account of a set of data is a demonstration only that some form of the general model is *capable* of accounting for that data—not that the general model must *always* account for the data.

tity of the perceptual information serving as input to the conceptual processing (which, in turn, is determined by such factors as picture duration and luminance), and by the amount of time over which conceptual processing operates on the picture.

Assumption 5: Observed performance. Memory performance is determined by the quality of the memory representation.

Effects of Independent Variables: The Flow of Causality

Figure 2 represents the flow of causality implied by the model in a stimulus-mask experimental configuration (cf. Bamber, 1979). In this figure, independent variables are represented by circles, hypothetical constructs by rectangles, and dependent variables by ovals. Note that the observables (independent and dependent variables) are shaded, whereas hypothetical constructs are unshaded. Arrows represent causal relations. We have included those independent variables that have been manipulated in the present and other conceptual-masking experiments.

In general, a conceptual mask has a deleterious effect on stimulus performance to the degree that (a) attention is demanded by the mask relative to the stimulus (Assumption 2), (b) sufficient perceptual information has been extracted from the mask (Assumption 1), and (c) insufficient perceptual information has been extracted from the stimulus (Assumption 1). These three factors affect the probability that attention is switched from stimulus to mask. The switching probability affects (in opposite directions) the expected duration of conceptual processing on the target and mask. Expected duration of conceptual processing, in turn, affects the memory representation and subsequent performance for both target and mask (Assumptions 4–5). Memory representation and subsequent performance for both stimulus and mask is, in addition, affected by the amount of perceptual information acquired from stimulus and mask (Assumption 4).

The Quantitative Model

In this section, we describe a quantitative version of our model. As we noted earlier, the quantitative model is stronger than the general model, in the sense that the former implies the latter, but not vice-versa. Although the specific functions that we have chosen for the quantitative model are somewhat arbitrary, we have several reasons for developing it. The primary reason is that it is useful for illustrating predictions of the general model, and for demonstrating the general model's capability of accounting for various sets of data. Second, the model provides a jumping-off point for future development of a more refined quantitative model. And finally, the best fitting parameter values that emerge provide information about the nature of some of the hypothesized encoding processes.

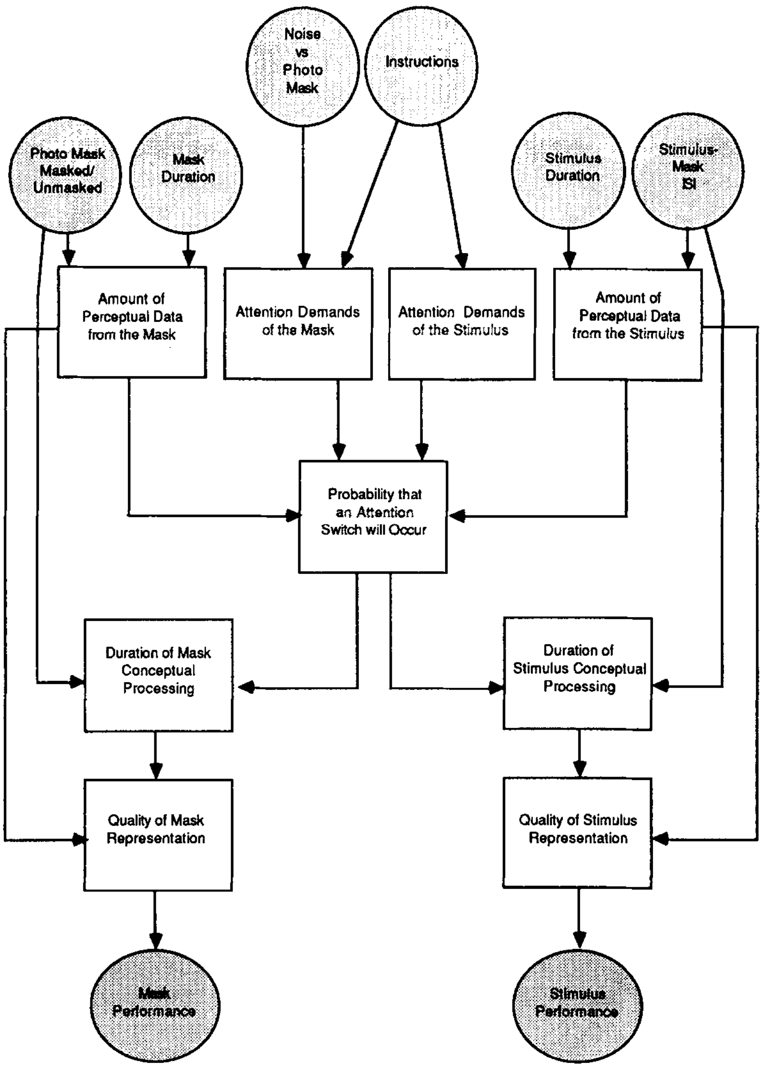

FIG. 2. Flow of causality according to the model presented in the text.

Notation

To facilitate understanding of the equations, we begin with a notation summary. Suppose our goal is to predict recognition memory performance for a particular picture (either a stimulus or a mask). We will use the following notational conventions.

Values of independent variables. Various experimentally controlled durations are designated as follows:

d is stimulus exposure duration.

a is the duration of the stimulus-mask SOA.

m is the exposure duration of any mask that follows the stimulus.

Model parameters. The parameters of the model include both rates (of exponential functions) and probabilities. They are designated as follows:

c is the rate at which perceptual information is acquired from a picture.

k is the probability that attention switches from stimulus to mask.

s is the rate at which the importance of *k* diminishes with stimulus-mask SOA.

r is the rate at which *k* grows as a function of mask duration.

k_p is the maximum value of *k* for photo masks.

k_n is the maximum value of *k* for noise masks.

The parameter *k* is a function of r, k_p, and k_n. Therefore, there are five free parameters in all: c, s, r, k_p, and k_n.

Performance measures. Dependent variables that can be measured either directly or indirectly are designated as follows:

$p(L)$ is the probability that a picture is learned.

$p(H)$ is observed hit probability.

$p(FA)$ is observed false-alarm probability.

Equations

Our goal in this section is to derive equations for various performance measures reported in the experiments with which we are concerned. We begin by deriving equations for acquired perceptual information and for the probability of a stimulus-mask attention switch.

Perceptual information. Processing of either a stimulus or a photo mask begins with acquisition of perceptual information, *I*. When a picture is presented for *d* ms, $I(d)$ is interpreted as the proportion of total perceptual information in the picture, relevant to a subsequent memory test, that the observer has extracted. Loftus and Hogden (1988) describe a detailed perceptual-information-acquisition model. From it, we can derive the general equation for $I(d)$ when a *d*-ms stimulus is followed by a perceptual mask at an SOA of *a* ms. The equation is,

$$I(d) = 1.0 - e^{-c(d + w\,(1.0 - \exp(-(a-d)/w)))} \tag{1}$$

where *w* is a parameter, referred to as the *worth* of any icon that follows the stimulus. Two special cases of Eq. (1) apply to the present experiments. First, when a mask immediately follows stimulus offset (i.e., when there is no icon), $a = d$ and Eq. (1) reduces to,

$$I(d) = 1.0 - e^{-cd}. \tag{1a}$$

Second, when a mask is delayed by 300 ms (i.e., when there *is* an icon), the term $\exp(-(a-d)/w)$ in Eq. (1) is approximately zero, and Eq. (1) reduces to

$$I(d) = 1.0 - e^{-c(d+w)}. \tag{1b}$$

The icon's worth, w, can be understood by comparing Eq. (1a) and (1b). Equation (1b) describes acquired perceptual information from pictures that are followed by an icon. Equation (1a) describes acquired perceptual information for pictures that are *not* followed by an icon. It is evident that having an icon is equivalent, in terms of perceptual-information acquisition, to extending the picture's physical duration, d, by w ms (compare the factor d in Eq. (1a) with the factor $d + w$ in Eq. (1b)). Loftus et al. (1985) estimated an icon's worth to be $w = 100$ ms, a value that we shall use in subsequent development of our model.

The probability of a stimulus-mask attention switch. Equations (1a) and (1b) describe acquisition of the perceptual information that acts as input to conceptual processing. Given the design of our experiments, conceptual processing is assumed to be invariably allocated to a stimulus picture.[7] When a mask is presented, conceptual processing switches to the mask with some probability, k, which is influenced by three factors: (1) m, the mask duration, (2) whether the mask is a noise or a photo mask, and (3) whether a photo mask is itself followed or not followed by an immediate noise mask. The equation for k when a conceptual mask is followed by an immediate (perceptual) noise mask is

$$k = k_p(1.0 - e^{-rm}). \tag{2}$$

Here, k_p is the maximum possible value for k for a photo mask,[8] and r is the rate at which k grows with mask duration.

As noted earlier, Loftus et al. (1985) found that a d-ms picture followed by darkness is equal, in terms of perceptual-information acquisition, to a (d + 100)-ms picture followed by an immediate perceptual mask. We assume the same rule describes a conceptual mask's ability to capture

[7] Recall that, in our experiments, the SOA between the start of one study trial and the start of the next was 4 s. This is sufficient time such that when a particular stimulus picture is presented, any conceptual processing on a previous stimulus or a previous mask has ceased.

[8] Because a noise mask is never itself masked in any of our experiments, we do not consider the case of a noise mask in Eq. (2).

conceptual processing: following a conceptual mask with darkness is equivalent to increasing the conceptual-mask duration, m, in Eq. (2) by w = 100 ms. Therefore, the equation for k for a conceptual mask followed by darkness is:

$$k = \begin{cases} k_p(1.0 - e^{-r(m+100)}) \text{ for a photo mask,} \\ k_n(1.0 - e^{-r(m+100)}) \text{ for a noise mask.} \end{cases} \quad (3)$$

Here, k_n is analogous to k_p; it representes the maximum possible value of k for a noise mask.

Memory performance. At the end of a study trial, the picture has been learned with some probability $p(L)$, that is influenced by (1) the amount of acquired perceptual information, $I(d)$; (2) the stimulus-mask SOA, a; and (3) the attention-switch probability, k. The equation for $p(L)$ is

$$p(L) = (1.0 - ke^{-sa})[\mathrm{I}(d)]. \quad (4)$$

where s is a free parameter. The simplest way of interpreting Eq. (4) is that as a, the stimulus-mask SOA, increases, the stimulus's memory representation that results from conceptual processing becomes progressively more complete. As the representation becomes more complete, a potential stimulus-mask attention switch becomes less important—i.e., k plays less of a role—with respect to eventual memory performance. By this interpretation, the parameter s reflects *how fast* the stimulus representation is completed via conceptual processing: a larger s implies a faster completion rate. Note also that, even with an indefinitely long SOA, the quality of the stimulus representation—and thus, $p(L)$—is limited by the acquired perceptual information, $I(d)$.

Finally, the hit probability reported in our experiments is obtained from a correction-for-guessing model: we assume that a subject responds "old" to target picture with probability 1.0 if the picture has been learned, and with the false-alarm probability if the picture has not been learned. Thus,

$$p(H) = p(L) + [1.0 - p(L)]p(FA)$$

where $p(FA)$ is the false-alarm probability.

Application of the Quantitative Model to Experiments 1–4

Over Experiments 1–4, there were 27 conditions involving stimuli, plus an additional 9 conditions involving masks. In principal, the equations that we have just described allow us to predict performance in all 36 of these conditions. However, mask performance may not be strictly comparable to stimulus performance for several reasons: different sets of pictures were used for stimuli and masks; masks were always tested after a longer study-test interval than were stimuli (recall that masks were always tested last); and, despite instructions, subjects may have treated stimuli and masks differently at study.

Accordingly, our strategy for fitting the model to our data was to consider only the 27 stimulus conditions. For these conditions, we used a grid-search procedure to find values of the five free parameters that minimized the root-mean-square error (*RMSE*) between predicted and observed values. The best-fitting parameter values were: $c = 3.4$; $r = 12$; $s = 2.14$; $k_p = 0.91$; and $k_n = 0.19$.[9] The predicted condition means that issue from these parameter values have been provided in Tables 1–6 for all 36 stimulus and mask conditions. As noted earlier, the value of each table entry before the slash is observed hit probability, and the value following the slash is predicted hit probability.

Goodness of Fit

The *RMSE* is 0.026 when the nine mask conditions are not included, and is 0.130 when the mask conditions are included. Note that *RMSE* is in units of the original dependent variable (hit probability) and is interpreted as the average discrepancy between an observed and a predicted condition mean.

The model fit when the mask data are not included. A no-mask *RMSE* of 0.026 is, in absolute terms, quite small. To assess the fit statistically, we computed a mean square between the 27 stimulus-performance conditions (MSB) based on the null hypothesis that each condition population mean equals the corresponding, best-fitting, predicted model mean. This MSB was based on 27 conditions, minus five estimated parameters, or 22 degrees of freedom.[10] We tested this MSB against the pooled error term from Experiments 1–5. The maximum resulting $F(22,1636)$ was 4.00, which is statistically significant.

A statistical rejection of our quantitative model is not surprising, given the rather substantial experimental power in our experiments (recall that the standard errors were on the order of 0.015), and our somewhat arbitrary choice of specific mathematical functions. It is appropriate to reiterate here that our chief purpose in creating the quantitative model was to illustrate the general model's ability to account for data. Accordingly, we

[9] Actually, these are the best fitting parameters when durations are expressed in seconds. We express them this way for visual and conceptual clarity (e.g., with durations expressed in ms, c would be 0.0034).

[10] The assertion that $dfB = 22$ depends on the assumption that the five parameters are *mutually independent*. However, the five parameters are almost certainly interdependent. To the degree that the parameters are interdependent, MSB, and with it our obtained F-value, would decrease. The $F(26,1636)$ that would emerge if the five parameter values were entirely redundant is 1.62, which is just significant.

are more interested in the qualitative fit than in the quantitative fit. Additional work will be required to develop a quantitative model whose fit to the data cannot be rejected.

The model fit when masks are included. The *RMSE* of 0.130 that emerges when mask conditions are included is quite poor by any criterion. Inspection of Tables 1, 3, and 5, that include mask data, reveals where the problem lies: predicted mask-recognition performance is too high. This discrepancy could stem from a problem in experimental design, and/or a problem in theory construction. From a design perspective, the study-test interval was, as noted earlier, greater for masks than for targets, which could depress observed, relative to predicted, mask performance. From a theoretical perspective, when there is no conceptual masking (i.e., when $k = 0$), $p(L) = I(d)$ (see Eq. (4)). Loftus and Hogden (1988) found the *empirical* function relating $p(L)$ and $I(d)$ to be negatively accelerated, not linear as implied by Eq. (4). Hence, our quantitative model is an incorrect description of the relation between photo mask duration and subsequent mask recognition.

However, the relation between mask duration and mask recognition is not the central focus of our model. Rather, conceptual processing is the central focus. From this perspective, it is important to note that the 27 target conditions of Experiments 1–4 differed extensively in terms of the conceptual-masking variables with which we are fundamentally concerned. The most important result of our grid-search procedure is the close, albeit statistically significant, model fit for these 27 stimulus conditions: this lends credibility to the fundamental conceptual processing-related assumptions of the general model.

Implications of the Best Fitting Parameter Values

We now discuss the best fitting parameter values in more detail. When possible we use these discussions as a forum to provide an intuitive understanding of what a particular parameter value means, in terms of psychological processes.

Rate of perceptual-information acquisition. The best-fitting value of c, the perceptual-information-acquisition rate was 3.4. Loftus and Hogden (1988), using the same stimuli in a very different experimental paradigm (a synchrony-judgment procedure, designed to measure duration of visible persistence rather than memory performance) estimated c to be 3.7. The close correspondence of the values estimated by the procedures is quite remarkable, and warrants future exploration.

Growth of the attention-capture probability. The best-fitting value of r, the parameter that describes growth of k with mask duration was 12.0. This value was determined primarily by the results of Experiment 3a and 3b in which the effect of mask duration of stimulus performance was largely complete by a mask duration of about 100 ms. To understand what it *means* to have an r value of 12.0, it is useful to determine, via Eq. (2), how long a conceptual mask will be required for k to reach some criterion proportion of its maximum value. A criterion of 80%, for example, would require a mask duration of 134 ms. A criterion of 95% would require a mask duration of 250 ms.

Reduction of conceptual processing over SOA. The best-fitting value of s, the parameter that describes the effect of SOA was 2.14. To understand what this means, it is useful to determine, via Eq. (4), the amount of time following stimulus onset that is required for conceptual processing to be (loosely speaking) completed by some criterion amount. For conceptual processing to be 80% completed, for example, would require 752 ms. For conceptual processing to be 95% completed would require 1400 ms.

Relative effects of photo and noise masks. Finally, the best-fitting values of k_p and k_n, the maximum k values for photo and noise masks, were 0.905 and 0.190, respectively. This means that any photo mask will have captured conceptual processing with approximately five times the probability of a same-duration noise mask. In this sense, a changing photo mask is approximately five times as effective as a noise mask in terms of its ability to capture conceptual processing from the stimulus.

Other Data in the Literature

In this section, we show how the model accounts for seven general kinds of effects that have been reported: immediate vs delayed memory performance; stimulus-mask ISI; nature of the mask; instructions; grouping of pictures during initial presentation; the nature of feature-integration errors; and the time course of gist acquisition. When appropriate, we apply our quantitative model to the data.

1. Immediate vs Delayed Memory Performance

Potter (1976, Experiments 1 and 2) and Intraub (1981) showed pictures of varying durations, and obtained either an immediate detection response (of the gist of the scene) or a later old/new recognition response. In both studies, successive pictures were presented at ISIs of 0; hence each picture acted as both a perceptual and a conceptual mask for its predecessor. Detection performances was substantially higher than recognition performance. The account offered by the present model is similar to that offered by Potter (1976) and is as follows. If during initial stimulus presentation, sufficient perceptual information is acquired to initiate conceptual processing, a correct detection response can be made. However, a subsequent recognition response not only requires that sufficient perceptual information be acquired, but also depends on subsequent events, such as total amount of perceptual information, and duration of conceptual processing. Subsequently recognizable pictures thus form a subset of initially detectable pictures, so recognition performance must be lower than detection performance. This can be seen in Eq. (4): $I(d)$, which reflects immediate detection performance must be greater than or equal to $p(L)$, which reflects later recognition performance.

2. Stimulus-Mask ISI

A number of experiments have demonstrated a positive relation between stimulus-mask ISI and stimulus performance (Intraub, 1980, Experiments 1 and 2; Loftus & Ginn, 1984; Loftus & Hogden, 1988, Experiments 1–3; Loftus et al., 1985; Potter & Levy, 1969; Potter, 1976, Experiments 1 and 2; see also Turvey, 1973).

Account of the general model. As indicated in Figure 2, ISI affects performance via a multiplicity of routes. Loftus and Hogden (1988) have shown that variation in ISI from 0 to approximately 300 ms affects amount of perceptual information acquired from the stimulus. Amount of perceptual information, in turn, affects the quality of the eventual stimulus representation, both directly, and indirectly via the stimulus-mask attention-switch probability. Finally, even if an attention switch to the mask does occur, variation in ISI affects the duration of whatever stimulus conceptual processing occurs prior to the switch.

A demonstration: Application of the quantitative model. Intraub (1980) varied ISI in two picture-recognition experiments. In both experiments, 150 stimuli seen during a study phase were later tested using an old/new recognition procedure. Stimuli were shown at study in a homogeneous sequence; unlike in the present experiments, a particular picture was not designated specifically a stimulus or a mask. In Intraub's Experiment 1, stimuli were shown in one of four conditions: for 6 s with zero ISI; for 110 ms with a blank, 5890-ms ISI; for 110 ms with a 5890-ms ISI during which another photo was shown;[11] or for 110 ms with zero ISI. In the study phase of Intraub's Experiment 2, pictures were shown in one of six conditions: for 5 s with zero ISI; or for 110 ms with ISIs ranging from 4890 to zero ms.

We fit our quantitative model to the mean recognition probabilities from these 10 conditions. To do so, we assumed that each stimulus in the study sequence could be conceptually masked by the repeating photo that filled the stimulus-stimulus ISI (in Experiment 1, Condition 2) or by any subsequent to-be-attended stimulus. In either case, the attention-switch probability, k, was computed from Eq. (3). We assumed that the maxi-

[11] In this condition, the photo shown during the ISI remained the same throughout the experiment (it was *repeating*, in Intraub's terminology). A repeating photo mask is roughly analogous to the noise mask used in our experiments.

mum k-value was k_n for a repeating photo and k_p for to-be-attended subsequent stimuli. Perceptual information from each stimulus was computed from Eq. (1), and $p(L)$, the dependent variable reported by Intraub, was computed from Eq. (4). Accordingly, there were five free parameters: c, r, s, k_p, and k_n.

The best fitting values of these parameters, along with the obtained and predicted means for Intraub's 10 conditions, are shown in Table 8. The *RMSE* was 0.035. The standard error in Intraub's data, pooled over Experiments 1 and 2, was approximately 0.053. We again established the best fitting model predictions as a null hypothesis. The MSB was based on 10 conditions minus five estimated parameters, or five degrees of freedom. The maximum $F(5,133)$ was 1.32, which is not significant.

The best fitting parameter values estimated from Intraub's data are in varying agreement with the corresponding best fitting values estimated from the present data. The value of c, the perceptual-information acquisition rate was 13.1, which is much higher than the values of 3.7 and 3.4 estimated from the Loftus and Hogden (1988) data and from the present data. Two stimulus differences may account for this: first, Intraub's pictures were relatively simple, and second, Intraub deliberately chose distractors that were relatively dissimilar from the targets. To the degree that stimuli are simple, and distractors are dissimilar, less information must be acquired in order to achieve any given recognition-performance level. Within the context of the model, acquired perceptual information, $I(d)$, is not directly observable; rather, it can only be measured by the recognition test. This means that $I(d)$ cannot be *absolute;* rather it can only comprise that information needed for whatever memory test is used to measure it. Because both simpler stimuli and more dissimilar distractors imply faster acquisition of *test-relevant* information, the higher c value that describes Intraub's experiments is expected.

The value of r, 16.4, is somewhat higher than the $r = 12.0$, estimated from the present data. To compare these two values, it is again useful to determine how long a conceptual mask will be required for k to reach some criterion proportion of its maximum value. With an 80% criterion, for example, the necessary mask durations are 98 ms and 134 ms, for r values of 16.4 and 12.0, respectively. With a 95% criterion, the corresponding durations are 183 ms and 250 ms.

The value of s, 1.47, is somewhat less than the $s = 2.14$ estimated from the present data. Again, to compare these two values, we can compute the amount of time following stimulus onset that is required for conceptual processing to be completed by some criterion amount. For conceptual processing to be 80% completed requires SOAs of 1094 ms and 752 ms, for s values of 1.47 and 2.14, respectively. For conceptual processing to be 95% completed requires SOAs of 2038 ms and 1400 ms.

TABLE 8
Intraub (1980) Data, Corrected Hit Probabilities

	Experiment 1[a]				Experiment 2[b]					
Duration (ms)	6000	110	110	110	5000	110	110	110	110	110
ISI (ms)	0	5890	5890	0	0	4890	1390	620	385	0
	0.94/0.94	0.77/0.85	0.73/0.69	0.21/0.22	0.96/0.94	0.84/0.85	0.84/0.78	0.61/0.61	0.48/0.50	0.20/0.22

Note. Parameter values: r = 16.40; s = 1.47; c = 13.10; k_p = 0.94; k_n = 0.00. Model fit: Root Mean Square Error = 0.035. Value preceding slash is obtained mean; value following slash is mean predicted by the model.

[a] All nonzero ISIs were blank except in condition 3. In condition 3, the ISI was filled with a repeating photo.

[b] All nonzero ISIs were blank.

Finally, the values of k_p and k_n were 0.94 and 0.00, respectively, compared to corresponding values of 0.91 and 0.19 estimated from the present data. A finding of $k_n = 0$ means that the repeating photo mask in Intraub's Experiment 1 *never* captured attention from the stimulus (although, because it followed the stimulus at a zero ISI, it did act as a perceptual mask). The k_p values estimated from Intraub's data and from the present data correspond quite well. This indicates that the tendency of a to-be-attended photo to act as a conceptual mask is roughly the same in the two sets of experiments.

3. *Nature of the Mask*

In the present Experiment 1, a changing photo mask demanded attention with a greater probability than a random-noise mask. The same variable was found to have the same effect by Loftus and Ginn (1984), Intraub (1984, Experiments 1 and 3), and Potter (1976, Experiment 3). In addition, Intraub (1984, Experiment 3) found that a photo mask was more effective when it was displayed upright than when it was displayed inverted. Within the context of the model, the mask-type effect is mediated by the degree to which the mask demands attention; in the quantitative model, the effect is reflected by the maximum value of k for a particular mask type.

4. *Instructions*

Intraub (1984, Experiments 2) presented series of pictures whose durations alternated between 112 and 1500 ms, with ISIs of 0. Subjects were told to attend either to the short pictures only, to the long pictures only, or to all pictures. Regardless of instructions, recognition memory for all pictures was subsequently tested. Intraub's results are reproduced in Table 9; as can be seen, there is, in addition to a main effect of stimulus duration, a strong crossover interaction. In the *attend to long pictures* condition, long pictures were, not surprisingly, recognized better than short pictures. In the *attend to short pictures* condition, however, short pictures were recognized better than long pictures. This result indicates

TABLE 9
Intraub (1984) Data (Averaged over Two Tests and Corrected for Guessing)

		Subject instructed to attend		
		Brief pictures	All pictures	Long pictures
Actual	Brief:	0.60	0.46	0.14
Picture	Long:	0.52	0.69	0.89

Note. Data are corrected hit probabilities.

that the effect of voluntary attention is sufficiently strong to overcome the normal effect of stimulus duration. Within the context of the present model, this attention effect is mediated by the probability that a stimulus-mask attention switch will occur; the attention instructions, via this probability, affect memory for short and long pictures in the opposite way.[12]

5. *Grouping of Picture During Presentation*

Intraub and Nicklos (1981) reported a picture-recognition experiment in which 24 pictures seen for 250 ms apiece during a study phase were later tested in an old/new recognition procedure. In different experimental conditions, the pictures were grouped in different ways at study: they were either shown singly with a 1625-ms ISI, in pairs with a 3250-ms interpair interval, in triplets with a 4875-ms intertriplet interval, or in quartets with a 6500-ms interquartet interval. In a control condition, all 24 pictures were shown continuously. Within a group—a pair, triplet, or quartet—or between all pictures in the continuous condition—there were zero-ms ISIs. The last picture in each group was followed by an immediate random-noise mask. The test phase always began 45 s following the start of the study phase. Intraub and Nicklos found that for two types of stimuli—simple and complex pictures–recognition performance was highest in the single-presentation condition, and decreased through the quartet condition. Quartet performance was higher (although not significantly higher) than performance in the continuous condition.

Account of the general model. These data constitute a *list-length effect:* the more to-be-remembered items in a list, the lower is mean memory performance over the list items (e.g., Postman & Phillips, 1965). The model's account of this effect is similar to the account provided by Atkinson and Shiffrin (1968) for verbal-memory data, and rests on the idea that early and late items in a list have an encoding advantage over middle items. In particular, the first picture in one of Intraub and Nicklos's sequences is remembered better than later pictures because it captures attention with certainty. The closer a picture is to the *end* of the sequence, however, the less is the probability that attention will be captured from it by some subsequent picture, and the better it is remembered. The shorter the list, the greater is the ratio of first and last items to middle items and, therefore, the higher is the mean performance.

A demonstration: Application of the quantitative model. We fit the quantitative version of our model to the Intraub and Nicklos data. The relevant equations are described in Appendix 1. We used three of the

[12] We did not fit the quantitative model to the mask-type or instruction conditions of the Intraub (1984) data. This is because each of the different mask conditions would have required a separate free parameter. In all, there would have been more free parameters than conditions to be fit, and the model would have been overdetermined.

parameters from the model: *c, r,* and *s*. We assume that each stimulus in a sequence has some probability of capturing attention when it is presented (and thus, that each stimulus can potentially act as a conceptual mask for any preceding stimulus).

To see how the model is applied to the Intraub and Nicklos paradigm, consider a candidate picture presented somewhere within a group. We define a *trial* to be that time period during which a given picture is physically present. In the Intraub and Nicklos experiment, each trial lasted 250 ms, and the candidate therefore received exactly 250 ms worth of perceptual information (recall that all pictures, including the final picture in a group, were perceptually masked). Also, the candidate captures attention during its trial with probability *k* (unless it is the initial picture in the group, in which case it captures attention with certainty). Given that the candidate captures attention to begin with, conceptual processing continues on it unless and until attention is captured from it by some subsequent picture (i.e., unless or until it is conceptually masked). The stimulus-conceptual mask SOA, *a,* is a random variable whose probability distribution is computed conditional on whether the candidate is eventually conceptually masked. If it *is* conceptually masked, then *a* is the sum of all the 250-ms trials (including the candidate's own trial) that transpire before attention is captured by a new picture. If the candidate is *not* conceptually masked, i.e., if it is still the object of attention at the end of the group presentation sequence, then *a* is the sum of all the 250-ms trials from the candidate's position to the end of the sequence, *plus* the intergroup interval.

The data provided by Intraub and Nicklos (1981, Tables 1–3) allowed us to calculate 10 independent recognition probabilities. These are the mean of the single-presentation condition, Serial Positions 1–2 for the pairs, Serial Positions 1–3 for the triplets, Serial Positions 1, 4, and the mean of Serial Positions 2–3 for the quartets, and the mean of the continuous condition. These data, along with the best fitting parameter values and the resulting model predictions are shown in Table 10.[13]

As can be seen, the data and the model are, for the most part, reasonably well in accord; root-mean-square errors are 0.087 and 0.077 for the simple and complex pictures, respectively. A notable problem is the continuous condition, whose performance is overestimated by the model for both simple and complex stimuli. There is no immediately evident explanation for this discrepancy.

The different parameter values for the simple and complex pictures reveal different processing rates for two kinds of stimuli. Consider first

[13] Intraub and Nicklos provide insufficient information to allow a statistical assessment of our model's fit.

TABLE 10
Intraub and Nicklos (1981) Data: Corrected Hit Probabilities

Grouping	Serial position 1	2	3	4	Mean
Simple pictures[a]					
Single	0.90/0.92				0.90/0.92
Double	0.77/0.70	0.92/0.92			0.85/0.81
Triplets	0.74/0.70	0.82/0.70	0.99/0.92		0.85/0.77
Quartets	0.64/0.70	mean (2,3) =	0.71/0.70	0.89/0.92	0.74/0.75
Continuous					0.54/0.71
Complex pictures[b]					
Single	0.73/0.76				0.73/0.76
Double	0.54/0.52	0.54/0.57			0.54/0.54
Triplets	0.55/0.49	0.57/0.39	0.68/0.57		0.60/0.49
Quartets	0.38/0.48	mean (2,3) =	0.36/0.38	0.49/0.57	0.40/0.47
Continuous					0.29/0.37

Note. Value preceding slash is obtained mean; value following slash is mean predicted by the model.

[a] Parameter values: $r = \infty$ ($k = 1.00$); $s = 5.70$; $c = 10.30$. Model fit: Root Mean Square Error = 0.077.

[b] Parameter values: $r = 5.50$ ($k = 0.75$); $s = 2.30$; $c = 5.70$. Model fit: Root Mean Square Error = 0.087.

the per-trial, attention-capture probability, k, which is determined completely by r, the rate at which k grows with mask duration. With simple pictures, the best fitting value of r is ∞. Essentially this means that k "wants to be" as high as it can, specifically 1.00, which can only happen when $r = \infty$. For complex pictures, $r = 5.5$, which yields $k = 0.75$.

The k-value of 1.0 for simple pictures indicates that *every* simple picture in a group captured attention from the preceding picture. This, in turn, means that each simple picture received conceptual processing for only one trial, i.e., for only 250 ms.[14] For complex pictures, however, the best fitting $k = 0.75$ can be interpreted to mean that, on the average, complex pictures received conceptual processing for $1/k = 1.33$ trials, or approximately 333 ms. This is reasonable: because there is more information inherent in complex than in simple pictures, complex pictures take longer to process.

The values of c, the perceptual-information acquisition rate, were 10.3

[14] We note for consistency that these 250 ms are not exactly those 250 ms during which the picture is physically present. By the assumptions of our model, conceptual processing does not begin until roughly 100 ms after stimulus onset; however, it does not end until roughly 100 ms following onset of the next stimulus in the sequence. Thus a picture's conceptual processing occurs partly during the picture's trial, and partly during the following trial.

and 5.7 for simple and complex pictures, respectively. Both of these are higher than the values of 3.4 and 3.7 estimated from the present data and by Loftus and Hogden (1988), respectively. We have already discussed stimulus difference that can lead to higher *c* values. Briefly, the Intraub and Nicklos simple pictures were like those used by Intraub (1980): they were simple, and were tested with dissimilar distractors. The resultant *c* values were comparable (13.1 and 10.3). The Intraub and Nicklos complex pictures were more like the stimuli used in the present experiments and by Loftus and Hogden; however, the distractors were chosen to be more dissimilar. The *c* value of 5.7 was, accordingly, higher than that obtained from the present data and by Loftus and Hogden, but lower than that obtained with the Intraub and Nicklos simple pictures.

Finally, the values of *s*, which represent the influence of stimulus-mask SOA on performance, were 5.7 and 2.3 for simple and complex pictures, respectively. As we have discussed previously, the value of *s* reflects how quickly conceptual processing is completed. The higher value for simple pictures indicates that conceptual processing was completed more rapidly with simple than with complex pictures.

In summary, simple/complex comparisons of all three parameter values point to the same general conclusion: both perceptual and conceptual processing is completed faster with simple than with complex pictures.

6. *The Frame-Integration Paradigm*

Intraub (1984, 1985) reported a series of experiments using a frame-integration paradigm, in which 12 visual stimuli (generally pictures) are presented in rapid sequence (generally at a rate of 110 ms per stimulus). One stimulus in the series (called the *host stimulus*) contains a salient black frame, either surrounding the stimulus (Experiments 1, 2, and 4) or in the middle of the stimulus (Experiment 2). The subject's task is to identify and report the stimulus associated with the frame. The general finding is that, although the frame is modally reported to be associated with the host, it is often reported to be associated with stimuli that either precede or follow the host.

Account of the general model. The model's account of the frame-integration data is, in many respects, commensurate with the account offered by Intraub (1985). We again define a trial to be that time period during which a given stimulus is physically present, and we define the *host trial*, to be the trial on which the host stimulus is presented. We assume, as usual, that when a stimulus is presented it captures attention with some probability. When the frame is presented, it is attended to with some probability on each trial starting with the host trial. The frame is then reported to be associated with whichever stimulus is being attended to during the trial on which the frame is attended. Because a stimulus can be attended to for multiple trials, a frame is, under some circumstances, associated with a still-lingering stimulus that preceded the host trial. Because a frame can wait for some number of trials before being attended to, it can, under some circumstances, be associated with a stimulus that follows the host stimulus.

Note that the frame is granted a special status within our model. Ordinarily, if a stimulus does not capture attention on the trial during which it is presented it is not, according to our model, *ever* attended to. The frame, however, is permitted to linger for multiple trials prior to first being attended to. In this sense, our model incorporates the kind of multiple-stimulus buffer postulated by Intraub.

A demonstration: Application of the quantitative model. We fit the quantitative version of our model to the Intraub and Nicklos data. The relevant equations are described in Appendix 2. In particular, we assume that, as each stimulus is presented, attention is allocated to it with probability k. The frame is attended to on each trial, starting with the host trial, with probability, q. We derive the probability distributions, across trials relative to the host trial, that any particular stimulus and the frame are attended to on the same trial.

Table 11 presents data, model predictions, parameter values, and goodness of fit[15] from Intraub's (1985) Experiments 1 and 2, in which pictures were used as stimuli. The numbers represent probability of associating a frame with a stimulus as a function of stimulus position relative to the host stimulus. Experiment 1 data are presented both conditional on subjects' confidence in their frame-association responses, and unconditionally. The fits are relatively good: *RMSE* ranged from 0.017 to 0.084 for the conditional data, and was 0.026 for the unconditional data. Experiment 2 data are presented for both a large (surrounding) frame and for a small frame. *RMSE* were 0.078 and 0.037, respectively.

Table 12 presents corresponding results from Intraub's (1985) Experiment 4 in which digits rather than pictures were used as stimuli. Again, data are presented both conditional on confidence and unconditionally. The fit was not, in general, as good as for Experiment 1: *RMSE* ranged from 0.070 to 0.109 for conditional data, and was 0.069 for the unconditional data.

A noteworthy aspect of these data is their asymmetry: errors tend to occur more on stimuli following the host than on stimuli preceding the host. The parameter values reflect this asymmetry; in particular, k, the attention-switch probability, is relatively high. The intepretation of a high k value is that continued attention to a given item is unlikely beyond the

[15] Intraub provides insufficient information to allow a statistical assessment of our model's fit.

TABLE 11
Intraub (1985) Data

	Position relative to host picture						
	−3	−2	−1	0 (Host)	1	2	3
Confidence				Experiment 1			
Sure	0.00/0.01	0.01/0.04	0.19/0.16	0.79/0.69	0.10/0.09	0.01/0.01	0.00/0.00
		(k = 0.77; m = 0.87; Root Mean Square Error = 0.017)					
Pretty sure	0.03/0.02	0.01/0.05	0.20/0.17	0.58/0.58	0.14/0.13	0.02/0.03	0.01/0.01
		(k = 0.70; m = 0.77; Root Mean Square Error = 0.020)					
Not sure	0.07/0.06	0.08/0.11	0.28/0.17	0.26/0.28	0.16/0.14	0.04/0.07	0.11/0.03
		(k = 0.39; m = 0.51; Root Mean Square Error = 0.053)					
Guess	0.19/0.08	0.13/0.11	0.19/0.15	0.19/0.20	0.10/0.11	0.00/0.06	0.21/0.03
		(k = 0.26; m = 0.46; Root Mean Square Error = 0.084)					
Mean	0.05/0.03	0.03/0.08	0.21/0.20	0.47/0.48	0.13/0.13	0.01/0.04	0.05/0.01
		(k = 0.59; m = 0.72; Root Mean Square Error = 0.026)					
				Experiment 2			
Frame type							
Large frame	0.01/0.04	0.00/0.10	0.38/0.21	0.44/0.55	0.16/0.12	0.01/0.03	0.01/0.01
		(k = 0.54; m = 0.74; Root Mean Square Error = 0.078)					
Small frame	0.02/0.01	0.01/0.05	0.21/0.16	0.53/0.53	0.22/0.17	0.00/0.05	0.02/0.02
		(k = 0.70; m = 0.69; Root Mean Square Error = 0.037)					

Note. Numbers represent proportion of times frame is associated with a particular picture, relative to the host. Value preceding slash is obtained mean; value following slash is mean predicted by the model.

trial during which the item is physically present. This, in turn, means that items preceding the frame are unlikely to be receiving attention when the frame is attended to. Thus it is rare that a frame is reported to be associated with an item that temporally preceded it.

A higher attention-switch probability for digits compared to pictures makes sense. A picture contains a relatively large amount of information, and it may well require more than a trial's worth of conceptual processing

TABLE 12
Intraub (1985) Data

	Experiment 4 Position relative to host picture						
Confidence	−3	−2	−1	0 (Host)	1	2	3
Sure	0.04/0.00	0.00/0.00	0.02/0.00	0.35/0.39	0.41/0.24	0.09/0.15	0.09/0.09
		(k = 0.99; m = 0.39; Root Mean Square Error = 0.072)					
Pretty sure	0.06/0.00	0.04/0.01	0.05/0.04	0.28/0.29	0.26/0.20	0.12/0.14	0.19/0.10
		(k = 0.85; m = 0.31; Root Mean Square Error = 0.050)					
Not sure	0.08/0.01	0.06/0.03	0.08/0.08	0.17/0.20	0.19/0.15	0.16/0.12	0.25/0.09
		(k = 0.61; m = 0.23; Root Mean Square Error = 0.070)					
Guess	0.07/0.01	0.04/0.03	0.10/0.07	0.16/0.19	0.15/0.15	0.11/0.12	0.37/0.09
		(k = 0.61; m = 0.21; Root Mean Square Error = 0.109)					
Mean	0.07/0.00	0.05/0.01	0.07/0.05	0.21/0.26	0.22/0.19	0.13/0.14	0.25/0.10
		(k = 0.82; m = 0.28; Root Mean Square Error = 0.069)					

Note. Numbers represent proportion of times frame is associated with a particular picture, relative to the host. Value preceding slash is obtained mean; value following slash is mean predicted by the model.

to process it. A digit, in contrast, contains relatively little information; thus it is more likely that a single trial is sufficient to process it. Indeed, many experiments (e.g., Sperling, 1963) have indicated that a digit can be recognized in as little as 5 ms; the digit presentation rate used by Intraub was 67 ms per digit.

Frame integration and reaction time. Intraub (1986) replicated her frame-integration data, but also recorded reaction time (RT) for frame recognition as a function of whether the frame was reported to be associated with the host picture, the preceding picture, or the following picture. The mean RTs were 332, 327, and 353 ms, respectively. Thus, RT was essentially the same when the frame was associated with the host, or the picture preceding the host; however, it was longer when the frame was associated with the picture following the host.

The model's explanation of these findings is relatively straightforward, and is essentially the same as Intraub's. RT to the frame is determined only by the trial, relative to the host trial, on which the frame is attended. Given that the frame is associated with the host, or any picture preceding the host, the expected number of trials required for frame integration is $1/q$, the reciprocal of the per-trial frame-integration probability. However, given that the frame is associated with the picture following the host, the host trial can be eliminated as a possible frame-integration trial; hence the expected number of frame-integration trials is $(1 + 1/q)$. Thus, the model's predictions are qualitatively in accord with the data.

Difficulties in application of the model. We note two difficulties in applying our model to the frame-integration paradigm. First, the model is incapable of predicting a modal frame-association response to some stimulus other than the host (as in the "Sure," "Not Sure," and "Mean" rows in Table 12). Second, the model does not provide a simple explanation of Intraub's (1985) Experiment 3, in which the actual host was frequently reported to be the picture that *followed* the framed picture. In this experiment, the frame was reported to surround the picture preceding the host, yet the host was still reported. According to the model, a frame associated with the picture preceding the host implies that attention never got switched to the host. Thus the question arises: how could a not-attended host be identified and reported?

A potential answer to this question lies in the distinction between perceptual and conceptual processing. A picture that receives no conceptual processing is not a picture that receives no processing at all; indeed, perceptual processing and the resultant acquisition of perceptual information is assumed to occur for *all* pictures. The issue of what perceptual information can be *used for* (aside from acting as input to conceptual processing) is one that we have not addressed in detail. Other data (e.g., Potter, 1976) indicate that perceptual information is transient, in the sense that it cannot be used for a relatively long-term recognition test. It *can*, however, be used for immediate identification of a single picture. Identification of a single picture is the task in the frame-integration paradigm, although the actual identification response is typically not immediate, but slightly delayed. It remains to be seen whether perceptual information can be used for such a task, or whether Intraub's Experiment 3 constitutes a disconfirmation of the model (at least as it applies to the frame-integration paradigm).

7. *Gist and Conceptual Processing: The Hundred-Millisecond Connection*

The suggestion of Experiment 3b was that the effect of photo-mask duration on stimulus performance is largely complete by a mask duration of about 100 ms. What is special about this particular duration?

Other experiments (e.g., Biederman, 1972; Loftus & Mackworth, 1978; Potter, 1975, 1976) have provided indirect evidence that 100 ms is sufficient time for an observer to acquire the gist of a picture. Golden (1984) has provided direct evidence for this proposition. He presented masked scenes for varying periods of time to subjects who attempted to identify the pictures' gists. Golden found that the function relating correct gist identification to exposure duration asymptoted at a duration between 75 and 100 ms. Potter (1976) in a theoretical account of her findings, estimates that by 100 ms, detection of a target is complete. Within the context of our quantitative model, k has grown to a substantial proportion of its ultimate value by 100 ms following mask onset.

Potter's findings, along with those of the present Experiment 3b, suggest that identification of a picture's gist is intimately related to the initiation of conceptual processing. Such an intimate relationship could take several causal forms. Gist identification may be the first product of conceptual processing. Alternatively, gist identification and the initiation of conceptual processing may be common products of some third factor, e.g., acquisition of some requisite amount of perceptual information. These possibilities could be resolved by experiments in which subjects try to identify the gists of briefly presented, masked photo masks; the crucial datum in such an experiment would be the conditional probability that a stimulus picture is recognized given that mask gist is identified.

The Model: General Summary

We have applied our model both to the data of the present Experiments 1–4, and to a fairly wide variety of experimental paradigms that have been reported in the literature. We have concentrated our model-fitting efforts on experimental paradigms in which conceptual processing and/or conceptual masking was the major focus. There are many other experimental paradigms in which *perceptual* processing is the major focus. Loftus and Hogden (1988) detail the model's account of these paradigms.

In all cases that we have considered, the general model was capable of accounting for the extant data. Where possible, we have applied the quantitative model as well. The fits obtained from the quantitative model are generally reasonable, although clearly unacceptable under some circumstances (e.g., mask performance in the present experiments is strongly overestimated by the model). We reiterate here that the quantitative model was developed not with the goal of perfectly fitting data, but as a means of illustrating our general model's account of data from a variety of experimental paradigms. Accordingly, our choices of specific functions for the quantitative model were guided more by mathematical convenience than by *a priori* considerations; likewise, our interest was more in the quantitative model's ability to predict the general pattern of means than its ability to predict exact performance values. A useful goal of subsequent research will be to refine the specific quantitative functions and to carry out the parametric experiments needed to evaluate them.

As we noted in our introduction, all the data that we consider predated model development. This means that the model fits are actually postdictions, not predictions, and should be treated with suitable caution. For example, different experimental paradigms, even while allowing acceptable fits, have yielded quite different values of presumably comparable parameters (e.g., c was estimated to be 3.4 from the present Experiments 1–4, but was estimated to be 13.1 from Intraub's, 1980, Experiments 1–2). We have provided rationales for these discrepancies that, while reasonable, are *post hoc*. A valuable exercise would be to replicate the experiments that we have described under mutually comparable circumstances—using, for example, the same subject pool, stimulus pool, stimulus luminance, counterbalancing procedures, and so on. Under such circumstances, we would *pre*dict at least the ordering of the resulting parameter values. This would constitute a much more stringent test of the model.

A FINAL NOTE ABOUT THE GENERALITY OF CONCEPTUAL MASKING: IMPLICATIONS OF EXPERIMENT 5

Recall that, in Experiment 5, stimulus-recognition performance was lowered dramatically as a result of subjects having to perform a mask-detection task during each study trial. This effect falls outside the domain of our model, as it evidently does not depend on a switch from stimulus conceptual processing to mask conceptual processing; significant mask processing could not have occurred in Experiment 5, since subsequent mask recognition was at chance. The effect thus implies that conceptual masking is broader than simply a switch from processing of a stimulus to processing of a mask. Rather, it appears that a variety of attention-demanding activities can serve as conceptual masks. In Experiments 1–4, the attention-demanding activity was the presentation of a new picture; in Experiment 5, it was the requirement of a detection response. A more general definition of conceptual masking and an associated generalization of the model are currently under investigation.

APPENDIX 1: ACCOUNTING FOR THE INTRAUB AND NICKLOS (1981) GROUPING DATA

This extension of our model resembles the buffer model described by Atkinson and Shiffrin (1968) to describe paired-associate list learning. Suppose that the subject sees a series of pictures grouped into groups of size N (for Intraub and Nicklos, $N = 1, 2, 3, 4, 24$), with each group followed by some relatively long interval. The time during which a given picture is physically present is called a *trial;* in the Intraub and Nicklos experiment, each trial lasted 250 ms. Subsequently, the pictures are tested in an old/new recognition test. The dependent variable reported by Intraub and Nicklos—and which is predicted by this model—is $p(L)$, the probability that a picture has been learned.

Conceptual processing (attention) is allocated at any given time to a single picture. Attention is allocated to the first picture in a group with probability 1.0. Attention is switched to each subsequently presented picture (and away from the currently attended to picture) with probability k, which is a function of m, the picture duration and r, the k-growth parameter. As described in Eq. (2) of the text, the equation is,

$$k = k_p(1.0 - e^{-rm}).$$

For technical reasons,[16] we set k_p, the maximum value of k to 1.0; thus,

$$k = 1.0 - e^{-rm}.$$

Because all pictures were presented for 250 ms and were masked, $I(d)$ is computed by Eq. (1a) in the text, with $d = 250$ ms:

$$I(250) = 1.0 - e^{-250c}.$$

The learning probability, $p(L)$, under various circumstances, is determined as follows:

$$p(L) = \begin{cases} 0 & \text{for a picture that was never attended to;} \\ I(d)(1.0 - e^{-250si}) & \text{for a picture attended to for exactly } i \text{ trials;} \\ I(d) & \text{for a picture being attended to during an intergroup interval.} \end{cases}$$

[16] Because k does not vary across conditions, it would make no sense for it to be a function of two free parameters; there would be a perfect tradeoff between the two parameters.

Consider now the picture in serial position n of a group ($n = 1, 2, \ldots, N$). The learning probability, conditional on the picture's being attended to when it is presented, is the sum of two joint probabilities: the probability that the picture is not being attended to during the intergroup interval and is learned, plus the probability that the picture is being attended to during the intergroup interval and is learned. The first term is the sum of $N - n$ separate terms, each representing the probability that the picture is attended to for exactly i trials ($i = 1, 2, \ldots, N - n$) times the learning probability conditional on being attended to for i trials. Thus, to obtain the learning probability for the picture in serial position n, conditional on the picture's being attended to in the first place, we sum over i, the possible number of attended-to trials.

$$p(L|\text{attended to}) =$$
$$\Sigma\,\{[(1 - k)^{i-1}k][I(250)(1.0 - ke^{-250si})]\} + [(1 - k)^{N-n}][I(250)].$$

The unconditional learning probability is the weighted sum of the learning probabilities given that the picture is or is not attended to, to begin with. Because the learning probability is zero if the picture is not attended to.

$$p(L) = xp(L|\text{attended to}),$$

where $x = 1.0$ for the first picture in a group ($n = 1$) and $x = k$ for the remaining pictures in the group ($n = 2, 3, \ldots, N$).

APPENDIX 2: ACCOUNTING FOR THE INTRAUB (1985) FRAME-INTEGRATION DATA

In the frame-integration paradigm, the frame is presented somewhere in the middle of a stimulus sequence. The stimulus around which the frame is actually presented is called the *host stimulus;* and the host stimulus is presented on the *host trial*. We designate the host trial and host stimulus as 0. Trials and associated stimuli that precede the host trial are designated $-1, -2, \ldots$. Trials and associated stimuli that follow the host trial are $1, 2, \ldots$.

We assume that any stimulus captures attention with probability k. The frame is attended to independently of the stimulus with probability q on each trial, starting with the host trial. The frame is reported to be associated with the stimulus that is being attended to on the trial that the frame is attended to. We seek the probability distribution of associating the frame with stimuli $\ldots -2, -1, 0, 1, 2, \ldots$.

Consider first stimuli that precede the host stimuli. The probability that stimulus i($i = -1, -2, \ldots$) is associated with the frame is the sum of joint probabilities. Each joint probability is the product of the probability that stimulus i is being attended to on trial n ($n = 0, 1, \ldots$) times the probability that the frame is attended to on that trial. For trial n, this probability is,

$$p\text{ (stimulus } i \text{ and frame attended to on trial } n) = k(1 - k)^{n+1}(1 - q)^{n}q.$$

To obtain the unconditional probability that stimulus i is associated with the frame, we sum over n:

$$p\text{ (stimulus } i \text{ associated with frame)} = \Sigma k(1 - k)^{n+1}(1 - q)^{n}q.$$

Now consider the host stimulus and stimuli that follow the host stimulus. The probability that stimulus $i (i = 0, 1, 2, \ldots)$ is associated with the frame is the sum of similar joint probabilities. The probability that stimulus i and the frame are both attended to on trial n ($n > i$) is,

$$p\text{ (stimulus } i \text{ and frame attended to on trial } n) = k(1 - k)^{n-1}(1 - q)^{n}q.$$

Again, to obtain the unconditional probability that stimulus i is associated with the frame, we sum over n:

$$p\text{ (stimulus } i \text{ associated with frame)} = \Sigma\, k(1 - k)^{n-1}(1 - q)^{n}q.$$

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