Attention in Visual Search: Distinguishing Four Causes of a Set-Size Effect

John Palmer

Visual search is a common task both in naturalistic settings and in the laboratory. Outside the laboratory, one might look for a car in a parking lot, a name in text, or a navigation marker on the horizon. In the laboratory, search is simplified in several ways; commonly, the subject views a set of distinct objects and is asked to detect the presence of a particular object (the target) among a set of distractors. Two examples are shown in Figure 1. The top two panels illustrate the contrast increment task, in which the target is a disk of high luminance and the distractors are disks of lower luminance; the bottom two panels illustrate the line bisection task, in which the target is a rotated *L* and the distractors are rotated *T*s.

One of the most studied aspects of visual search is the effect on performance of the number of objects, here referred to as the *display set size*. Display set sizes of 2 and 24 are illustrated in Figure 1. In the top panels, the target "pops out"—even for a large display set size. More precisely, display set size has little or no effect on search time or accuracy when the target is much brighter than the distractors. In contrast, in the bottom panels, finding the target requires "scrutiny" for the large set size. Display set size has a large effect on both search time and accuracy when the target and the distractors are these different rotated characters. These variations in the *magnitude of set-size effects* pose a central question for research on visual search. In this article, I use signal detection theory to analyze set-size effects on search accuracy. It remains to be seen how this analysis will extend to the more commonly studied set-size effect on search time.

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A GENERIC ATTENTION MODEL

The possible sources of a set-size effect can be understood using a general information processing model inspired by Broadbent.[1] The model is illustrated in Figure 2 by an information flow diagram that identifies four kinds of processing that stimulus information undergoes before yielding a response in visual search. These four kinds of processes are defined by the concepts of selection and decision:

- A *preselection process* occurs without any influence of the selection or allocation of processing that is under the subject's control. Preselection processes include early visual processing and perhaps some more complex perceptual processing, such as categorization.
- A *selection process* is under voluntary control and results in differential processing for different sources of information. For example, a subject may select certain positions in the visual field or certain attributes for processing.
- A *postselection process* is subject to voluntary control by the effects of selection. Theories differ widely in the scope of postselection processing. According to early-selection theories, selection is early in the processing sequence and most of perception is assumed to be postselection. According to late-selection theories, selection is late and most, if not all, of perception occurs before selection.
- A *decision process* is a special kind of postselection process. It is very task-specific. For a typical visual search task, the decision problem is to determine if any of the stimuli are targets. Thus, the decision process must integrate information from all of the relevant stimuli to determine a single response.

I consider all but the first of these processes as attentional processing.

Consider the simple case of visual search of a brief display that does

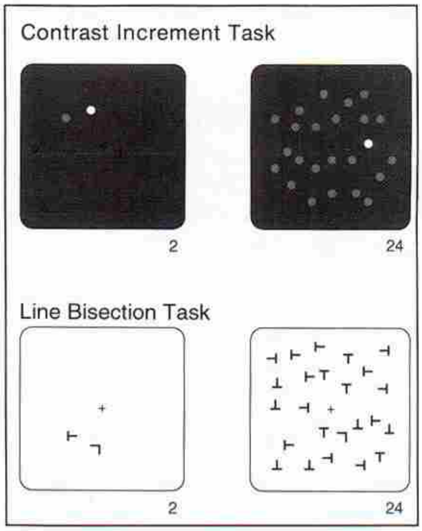

Fig. 1. Two examples of search tasks. The top panels show a contrast increment task. The target is a disk with higher luminance than the distractors. The bottom panels show a line bisection task. The target has an L shape (no bisection), and the distractors have a T shape (bisection). Each task is illustrated with 2 (left) and 24 (right) objects in the display. The cross in the center of each display marks where the subjects were instructed to fixate.

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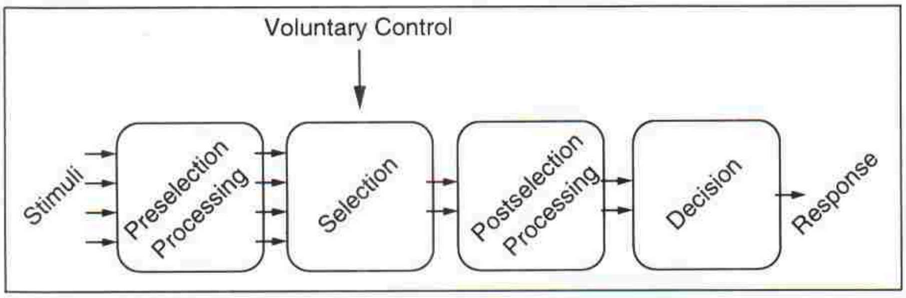

Fig. 2. An information flow diagram of a generic attention model for visual search with a single eye fixation.

not allow time for an eye movement. Even for this simple case, each of the four kinds of processing might cause a set-size effect:

- Preselection processes are limited by early visual processing. For example, limited peripheral vision will cause a decline in performance for large set sizes if they require more eccentric peripheral vision.
- Selection may be limited by how many sources of information can be selected at a time. In the extreme, only one source can be selected at a time. If a subject must switch from stimulus to stimulus, performance will be worse for larger than for smaller set sizes.
- Postselection processes are usually assumed to have limited capacity. For example, suppose the postselection process allows for multiple samples of a stimulus to improve perception. The more samples, the better the perception. Increasing the set size results in fewer samples per stimulus, a poorer perception, and thus reduced performance based on that perception.
- Decision processes must integrate information from multiple sources. The larger the set size, the larger the number of distractors and the greater the chance that one might be mistaken for a target. Thus, even if the perception of individual stimuli is unaffected by set size, the combined probability of discriminating targets and distractors correctly will be affected by set size.

The common *serial scanning hypothesis* involves a combination of two of these processes. It restricts postselection processing to one stimulus at a time, requiring the selection process to iteratively provide stimulus information to the postselection processes. For larger set sizes, the result is a longer response time and possibly more errors if stimulus duration is limited.

Given these multiple possibilities, a large set-size effect cannot necessarily be attributed to limited capacity, to serial scanning, or to any other single cause. The following analysis provides an example of experimental paradigms that determine when each of these four kinds of processing contributes to a set-size effect.[2,3]

PRESELECTION EFFECTS

There is an extensive literature on visual phenomena that can covary with set size.[2] Larger set sizes often require larger visual fields and hence put stimuli at locations more eccentric to the direction of gaze. Thus, set size is confounded with eccentricity. To study the role of attention in set-size effects, one needs to control all of the involuntary effects due to preselection processes.

The first step to controlling sensory effects that occur prior to selection is to eliminate the possible confounds between set size and eccentricity. This has been done by directing the gaze to a central fixation point, by using brief displays to prevent eye movement, and by holding constant the eccentricity of the stimuli from the central fixation.[2,3]

An important additional refinement to this paradigm is to control the discriminability of the target and distractors. One reason that different search tasks have different set-size effects is that lower discriminability between targets and distractors results in larger set-size effects.[4] This by itself may explain the differences between the tasks in Figure 1. To control discriminability in my studies, I measured search accuracy for targets of several different levels of discriminability.[3] The results allowed me to estimate the contrast difference between the target and distractors that produced a correct discrimination 75% of the time. This difference is called the *contrast increment threshold*. In this way, I could ensure that tasks I was comparing were at a comparable level of difficulty.

Consider a prototype experiment in which I used differences in contrast such as shown in the top panels of Figure 1. Accuracy was measured for sets of one, two, four, and eight stimuli and for several contrast increments (i.e., the difference between the target's contrast and the distractor's contrast, which was always 20%). In the left panel of Figure 3, the points represent the mean results of 4 subjects. The contrast increment threshold is plotted as a function of set size, and both axes are scaled logarithmically. Set size has a clear effect, with the threshold nearly doubling. (The curves in this panel are discussed in a later section on decision processing.)

Although this experiment controlled some of the obvious sensory factors, such as eccentricity differences, it did not rule out the possibility of more subtle sensory effects contributing to preselection processing. For example, displays with a large set size might form a texture

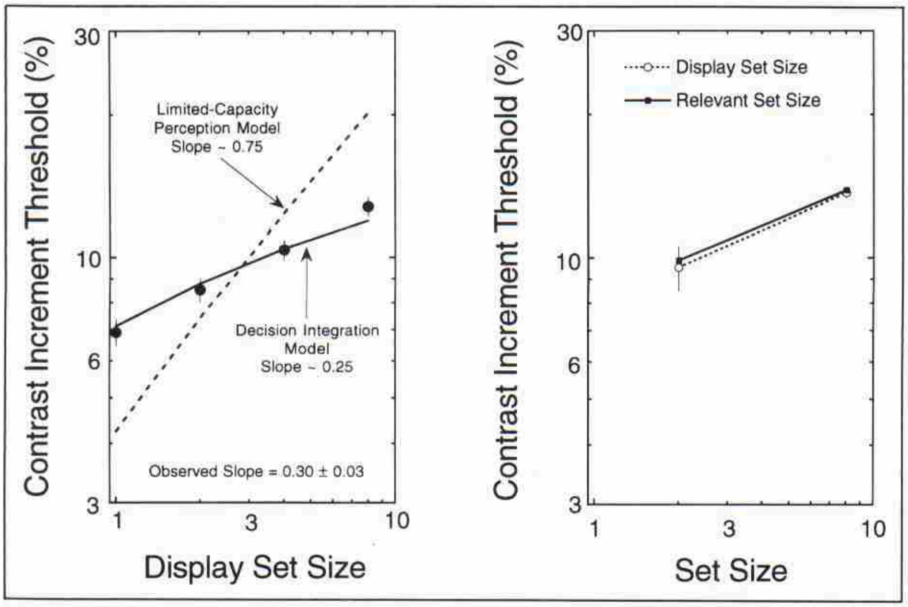

Fig. 3. Results of two experiments on set-size effects. Both graphs show the contrast increment threshold (i.e., the contrast increment necessary to produce a correct discrimination 75% of the time) as a function of set size. In the left panel, subjects' thresholds (points) are shown along with the predictions (curves) of the decision integration model and the limited-capacity model. In the right panel, results are contrasted for manipulations of display set size and relevant set size.

with cues unavailable in displays with a small set size. Such possibilities can be eliminated by keeping the number of stimuli constant and using a cue to show the subject which of the stimuli to pay attention to. Such a cue has its effect by a selection process and thus, by definition, cannot affect preselection processing.

The *cuing paradigm* is shown in Figure 4. The procedure begins with a display containing a central fixation cross surrounded by crosses indicating the locations of the stimuli that will appear in the subsequent stimulus display. Black crosses (cues) indicate the relevant locations (i.e., the locations where the target may appear in the stimulus display), and white crosses indicate the irrelevant locations. By varying how many cues are black, one can measure the effect of relevant set size. Because the judged stimuli are the same for the different cue conditions, any effect of relevant set size cannot be due to preselection processing.

If set-size effects are due to preselection phenomena, then there should be no effect of relevant set size because the display set size is the same for all cue conditions. Alternatively, if set-size effects are entirely due to processes controlled by selection, then the effects of relevant set size should be identical to the corresponding effects of display set size.

The right panel of Figure 3 shows the mean results for 4 subjects tested with varying display set sizes and varying relevant set sizes. The axes (threshold by set size) are identical to those in the left panel. The graph shows an effect of relevant set size. This effect definitely excludes any contribution from preselection processing. Moreover, the effects of relevant set size and display set size are similar. This finding is consistent with both effects being free of contributions from preselection processing. In summary, the cuing paradigm allows one to measure a set-size effect that has no contributions from preselection processing.

SELECTION

Selection itself can produce set-size effects. For example, the number of stimuli that can be selected during the display duration may be limited to a number less than the set size. To take an extreme example of overt selection, people can direct their gaze in only one direction at a time. If a large set size requires multiple eye fixations, then this limited ability to select the direction of fixation will result in an effect of set size. Furthermore, selection is task-specific. Reading, for example, may require the selection of a single word at a time to facilitate word recognition by preventing confusions between adjacent words.

Although such effects of selection can occur, they have been ruled out for the visual search task described here. If selection were limited, accu-

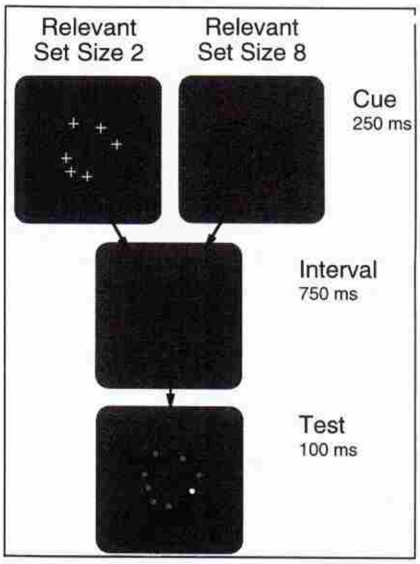

Fig. 4. The cuing paradigm. The display set size was held constant, and the relevant stimuli were indicated by cues. In the cue display, the black crosses indicate the possible locations of the target, and the white crosses indicate locations of distractors. In addition, there was always a black cross in the center of the display for the subjects to fixate. (In the actual display, the fixation cross was smaller than the cues.) After the cue, the same display set size was shown for all conditions.

racy could never be greater than a ceiling determined by the proportion of stimuli that were not selected. Such a prediction has been tested by presenting targets and distractors that are highly discriminable. For the contrast increment experiment just described, large contrast increments do yield perfect accuracy. Thus, all stimuli can be selected, and limits on selection do not contribute to the observed set-size effect.

DECISION PROCESSES

Next, skip ahead to the last process in the information processing sequence. Decision processes relate the information available about a stimulus to a response in a way that is specific to the task. In search, information from many stimuli must be integrated to decide whether a target is among them. For the present purpose, all processing that is task-specific and integrates information from multiple stimuli can be considered a decision process. Processing before decision processing is assumed to be independent for each stimulus and may or may not be task-specific. Although not true in general, these assumptions are plausible for the widely separated stimuli used in the experiments I am discussing here because comparing results for the cuing paradigm and the display-set-size paradigm has ruled out sensory interactions.

The set-size effect caused by the decision process can be calculated using the *decision integration model* based on signal detection theory.[5] The defining assumption for this model is that the internal representation of each stimulus is independent of set size. In addition, two other assumptions must be made. The first is that the stimulus representation is noisy. In other words, the perceived luminance, or brightness, of the target varies from trial to trial even though the actual luminance is kept constant. The brightness of the distractors also varies. Hence, there is some probability that the brightness of a distractor will fall into the range typical of a target and be taken for a target. The more distractors in a display, the greater the chance that the brightness of one will fall in the target range. To reduce the number of these additional *false alarms,* the criterion for deciding a target is present must be raised. Thus, a set-size effect due to decision processing is predicted by any model that assumes noisy stimulus representations.

The second assumption specifies the decision rule. For this model, the most optimal of the common rules is assumed: The decision is determined by the stimulus representation that yields the maximum likelihood of being a target (known as the *max rule*). In the luminance example, the decision depends on the stimulus with the maximum brightness on any given trial.

The consequences of these assumptions are illustrated in Figure 5. The top panel illustrates results for a set size of one, the standard example for introducing signal detection theory. Depicted are the probabilities that subjects will represent the target and distractor as having particular values. For the contrast increment task, the relevant representation might be brightness. By convention, the mean value of the distractor's representation is zero, and its variability is 1 (i.e., most values will fall between −1 and 1).[5] According to signal detection theory, the subject makes a decision by setting a criterion somewhere along the stimulus representation axis and by responding "yes" whenever the stimulus representation exceeds that criterion.

The critical case is shown in the bottom panel of Figure 5, which shows the probability distributions for a set size of eight: the distribution of the maximum value of eight distractors and the distribution of the maximum value of one target and seven distractors. The effect of increasing set size is to shift the distribution of the maximum stimulus representation generated by just the set of distractors more than the distribution of the maximum stimulus representation generated by the target plus distractors. The right side of the target-plus-distractor distribution is determined almost entirely by the stimulus representation produced by the target and does not vary with set size. In contrast, the maximum stimulus representation from a set of dis-

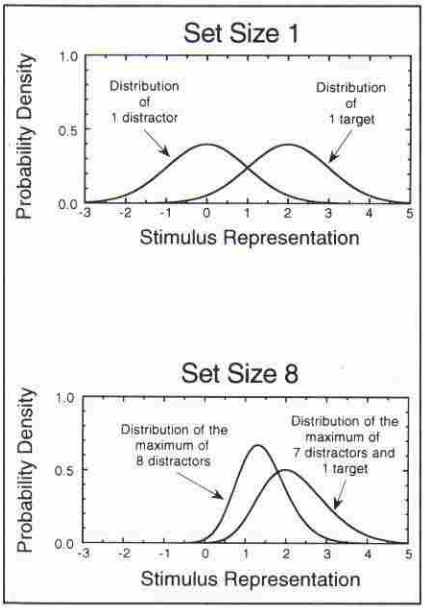

Fig. 5. Illustration of the decision integration model. The top panel illustrates the prediction for a set size of one, and the bottom panel illustrates the prediction for a set size of eight. In each panel, the x-axis is the value of the stimulus representation on some variable relevant to the judgment (e.g., brightness), and the y-axis graphs the probability that subjects will represent the stimulus as having a particular value. The probability distributions are shown separately for the distractor (or distractors) and the target (or target and distractors). For the set size of one, the distribution was chosen to represent a condition of moderate discriminability. The distributions for the set size of eight were calculated from the distributions for a set size of one. Specifically, the distribution for a set size of eight shows the maximum of eight samples, one from each of the eight stimuli in the display.

tractors is determined by whichever distractor happens to generate the highest value. The more distractors there are, the greater the chances that one of them will generate an unusually high value. Hence, the peak of this distribution moves to the right as set size increases.

The set-size effect predicted by this decision integration model[2] is shown by the solid curve in the left panel of Figure 3. On these log-log plots, the predicted curve has a fixed shape that can be shifted vertically to adjust for the absolute values of the observed performance. The result is a curve that does a good job predicting the relative thresholds as a function of set size. Thus, a simple decision model is sufficient to account for the observed set-size effects.

POSTSELECTION PROCESSING

Finally, consider the contribution of postselection processing other than decision. The most extreme view, represented by Posner,[6] is that all perceptual processing has limited capacity. The more stimuli in a display, the fewer perceptual resources can be devoted to each stimulus. Put another way, the more stimuli, the noisier is each individual stimulus representation. Although I cannot go into detail here, I derived a specific prediction[3] about the magnitude of the set-size effect following Broadbent's definition of capacity in terms of information. A limited-capacity perceptual stage followed by a decision integration stage results in the prediction shown by the dotted curve in the left panel of Figure 3. The predicted curve does not fit the data: It predicts a much larger set-size effect than the decision integration model.

From this calculation, one can reject the limited-capacity model for this contrast increment task. But what about other situations? I have found set-size effects of similar magnitude with tasks involving color, size, and orientation differences; slightly larger effects for a line bisection task; and considerably larger effects for a point orientation task.[3] This last task, which involves judging the orientation among pairs of distinct objects, comes close to the predictions of the limited-capacity model. Shaw has investigated certain letter search tasks and found set-size effects that were consistent with the limited-capacity model.[7] Finally, if the task is changed so that subjects do not know what they are searching for and must remember all of the stimuli, then the set-size effects are consistent with the limited-capacity model.[8] Thus, there are capacity limitations in visual memory even if there are none in the visual perception of the same stimuli. In summary, several lines of evidence are consistent with the limited-capacity model under particular conditions.

DISCUSSION

The generic attention model points to four potential contributions to set-size effects. By using paradigms that control contributions of preselection and selection processes, and theoretical calculations that estimate the contributions of the decision process, I have demonstrated that decision integration by itself is sufficient to account for set-size effects for simple search tasks such as detecting an increment in contrast.

This analysis challenges other theories that interpret a large set-size effect in visual search as a sign of limited capacity or serial scanning. Consider two examples:

- Some early-selection theories[6] do not explicitly consider the possible contributions of decision to set-size effects. Thus, these theories misinterpret cuing and set-size effects as evidence for limited-capacity perception rather than decision integration.
- Theories based on feature integration[8] interpret large set-size effects as evidence for limited-capacity, serial processing. The decision integration model provides an alternative interpretation for the case of highly similar targets and distractors.

Much remains to be done to develop this analysis fully. It needs to be extended to measures of search time,[9] search with multiple eye fixations,[10] and categorical or linguistic stimuli.[5] These extensions will allow us to separate the multiple causes of set-size effects in a variety of visual search tasks.

In summary, set-size effects are due to a variety of causes. The analysis I have presented here distinguishes among contributions from four kinds of processing. This analysis provides an alternative approach to previous work that attributes set-size effects to only one kind of attentional phenomenon.

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The Role of Evaluation Research in Drug Abuse Policy

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Psychologists and other social scientists have contributed to the rapid emergence of evaluation research for social programs in the last 25 years, especially in its application to questions about accountability and efficacy of publicly funded treatment services for substance abusers. In 1995, the amount of federal funds for reducing demand for drugs through prevention and treatment efforts totals nearly $5 billion, about one third the amount allocated for enforcement activities aimed at reducing the supply. Under the general leadership of the late S.B. Sells, our research group at Texas Christian University became involved in this field of work during the 1960s through the unique combination of our professional training, research and methodological capabilities, commitment to the study of applied social problems, and favorable opportunities. This article reviews highlights of the historical context, implementation, and impact of our research program in order to help illustrate the role psychologists have had in shaping public policy in the drug abuse field.

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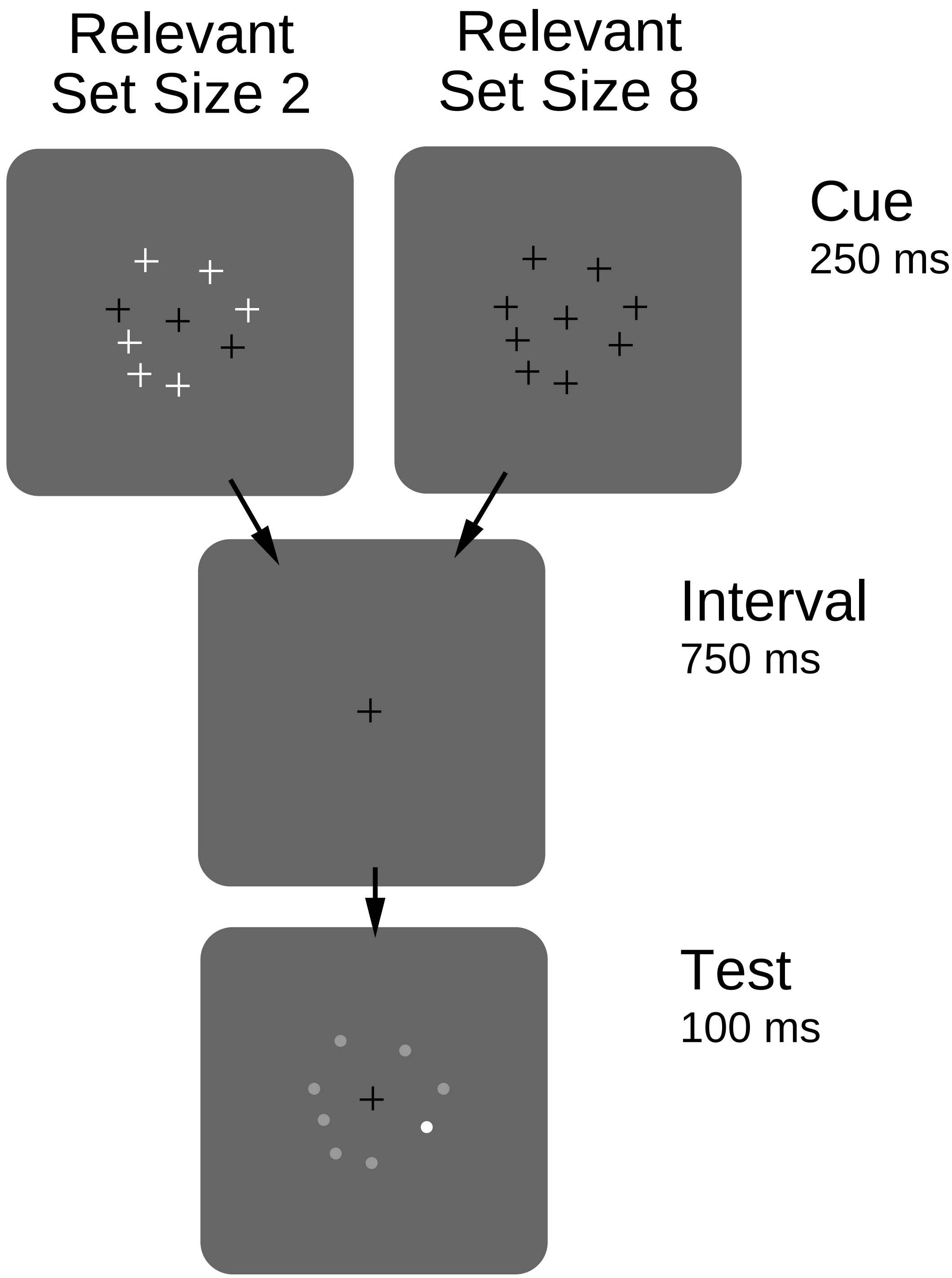
HISTORICAL PERSPECTIVE

As chronicled by Musto,[1] the social and political history of drug abuse in the United States helped set the stage for current public policy regarding drug addiction. The 1960s were especially pivotal years. The Narcotic Addict Rehabilitation Act of 1966 was the beginning of a historical shift from an institution-based approach to a comprehensive community-based treatment system that is now part of the national response to dealing with drug problems. By introducing a civil commitment (mandatory treatment) alternative to prison incarceration for addicted persons charged with certain types of crime, this legislation helped declare drug addiction a "health" problem. Subsequently, in 1972, President Richard Nixon, joined by a unanimous Congress, declared the first "War on Drugs." Through that declaration and an unprecedented infusion of massive funding for community-based treatment programs, the modern era of drug abuse treatment was created. Prior to that time, treatment for drug abuse was available primarily at two large federal institutions—in Lexington, Kentucky, and Fort Worth, Texas—and was offered almost exclusively to persons convicted of federal crimes.

These actions put treatment on the map literally as well as figuratively, establishing services in hundreds of communities and largely removing the hegemony of the criminal justice system over drug abuse. Four fundamental treatment modalities were established: (a) methadone maintenance treatment became available to addicted, chronic users of heroin or other opiate drugs and involved daily medication with an opiate substitute (methadone) accompanied by psychological counseling and social rehabilitation ser-



This is an improved reproduction of Figure 4 from Palmer (1995).