Chapter 3

Divided Attention

Contents

3.1 Definitions and Domain

In the last chapter we introduced selective attention, which concerns the use of one source of information rather than another. We now turn to *divided attention*, which concerns the use of multiple sources of information rather than a single source. Divided attention in vision is fundamentally about the dependence versus the independence of visual processing across stimuli. As with selective attention, we take pains to distinguish between phenomena, or *effects* of divided attention, and theoretical concepts that are used to explain effects of divided attention in terms of the relevant internal processes.

Consider first phenomena. Effects of divided attention are behavioral consequences (such as impaired performance) of manipulating the number of relevant stimuli. We can again use reading as an example. If we showed you a display of this page for a third of a second or so, and asked you to read the word that is printed in **bold** in this paragraph, you might be able to do that fairly well. However, if we asked you to read all of the words on the page in that period of time, you would probably be much less successful, and depending on which other words you read during the brief period, you may or may not have gotten to the word in bold. In this example, reading performance changes as the number of to-be-read words increases from one to many, thus reflecting a dependence of reading one word on reading other words. This is an effect of divided attention across words.

Our focus in this example is to make clear it is an attentional effect rather than a non-attentional sensory effect. We did this by varying the number of *relevant* stimuli rather than the total number of stimuli. The total number of stimuli was actually the same across the two situations. To be clear, a difference in the ability to read the word “bold” when it is the only word on the page versus when it is one word of many on a full page of text should not be taken as definitive evidence of an effect of divided attention. This is because there are multiple sensory differences, unrelated to attention, that could lead to a difference in reading ability across those two situations. Divided attention effects are effects of the number of relevant stimuli, and must be distinguished from stimulus effects that depend on stimuli whether they are task relevant or not.

Now consider some corresponding theoretical terms used to refer to the nature of internal processes that give rise to divided attention effects. An extreme example, is *serial* processing. Some aspect of visual processing, say lexical access, might be capable of handling only one stimulus at a time. Such a theoretical statement predicts that any task that requires lexical access, such as reading, will show divided attention effects; performance will depend on the number of task-relevant stimuli. A contrasting extreme to serial processes would be those that proceed simultaneously (i.e., in *parallel*) for multiple stimuli and are unaffected by the number of to-be-processed stimuli. For some situations, a set of completely independent parallel process is expected to suffer no divided attention effects. Besides serial versus parallel processing, there are other types of dependencies that can lead to divided attention effects. We will expand on these possibilities in a later section of this chapter.

In this early chapter, we introduce two basic paradigms that have been used to study divided attention: *visual search* and *dual task*. We first ask whether there is evidence from these paradigms that divided attention effects occur, starting with simple stimuli and tasks as we did with selective attention. We then offer an initial theoretical analysis, asking what aspect of processing is the source of the divided attention effects. As was the case for selective attention in the last chapter, this initial consideration of divided attention is limited to a consideration of simple stimuli and tasks and focuses on divided attention across space. The purpose is to introduce the paradigms, recognize some of their strengths and weaknesses, and understand the kinds of theoretical questions that can and cannot be addressed by each. A more fully developed treatment of divided attention is offered in Chapter xxx after we have considered a richer set of stimuli and tasks.

3.2 The Visual Search Paradigm

We first consider *visual search* which is a paradigm in which observers search a spatially distributed display of stimuli for a target stimulus. For example, you might have to search for a stimulus that is red among other-colored stimuli and respond “yes” when a target is present and “no” when it is absent. Although target presence versus absence is a common task, there are other ways of asking observers to report the outcome of their visual search. They might, for example, be asked

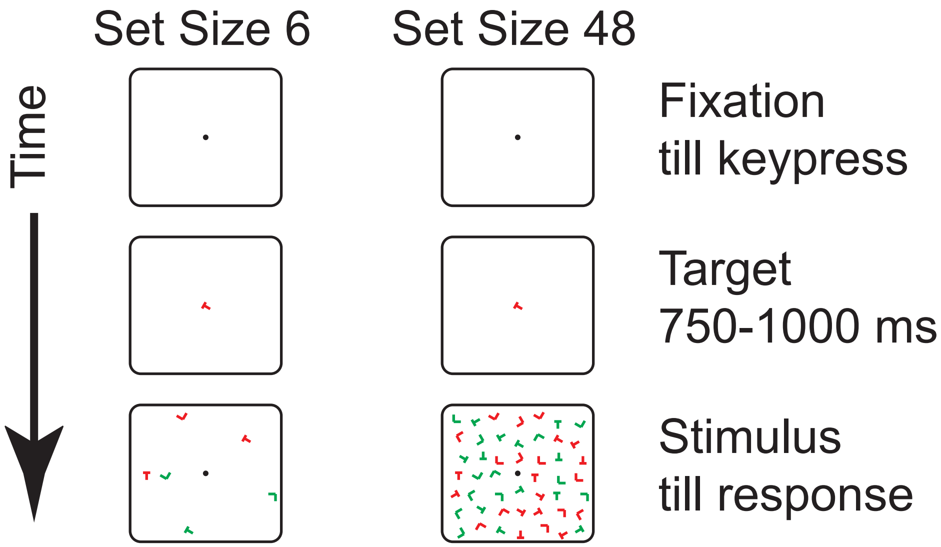

Figure 3.1: An illustration of the set-size conditions in Motter & Simoni (2008): Set Size 6 on the left and Set Size 48 on the right. Each trial begins with a fixation point until the observer indicates they are ready with a keypress. Then the target is presented for 750 to 1000 ms. In this example, the target is a left-tilted, red "T" shape. This is followed by the stimulus display which remains until the response. The task is to indicate the presence or absence of the target by a keypress.

to indicate the location of the target stimulus by indicating which of four quadrants it appeared, or by clicking on a particular location with a mouse. Visual search is a paradigm for studying divided attention because multiple stimuli are relevant to the task.

A common manipulation in visual search is to vary the number of stimuli in the display. Performance is measured as a function of *display set size* to yield what are known, more briefly, as *set-size effects*. On first blush, set-size effects appear to be divided attention effects, and are indeed often interpreted as such. Set-size effects, however, can have multiple causes and need to be interpreted with caution. Consider a visual search experiment conducted by Motter and Simoni (2008). The procedure is, illustrated in Figure 3.1 and a larger view of the stimulus displays in Figure 3.2. This example includes typical elements of what must be hundreds of different visual search experiments in the literature.

In this experiment, observers viewed an initial fixation display, and when ready to proceed they pressed a key. This was followed by a target display that specified the target for that trial. Targets changed from trial to trial. In this example, a left-tilted, red "T" shape is the target. This was followed by the stimulus display that remained until the response. These displays had set sizes of 6, 12, 24 and 48 stimuli. The stimuli were all either "T" or "L" shapes that could be red or green and could be rotated to any of six possibilities. Thus, there were 24 possible stimuli of which only one was the target. The observer's task was to indicate whether the target was present or absent with a key press. It was present on half of the trials.

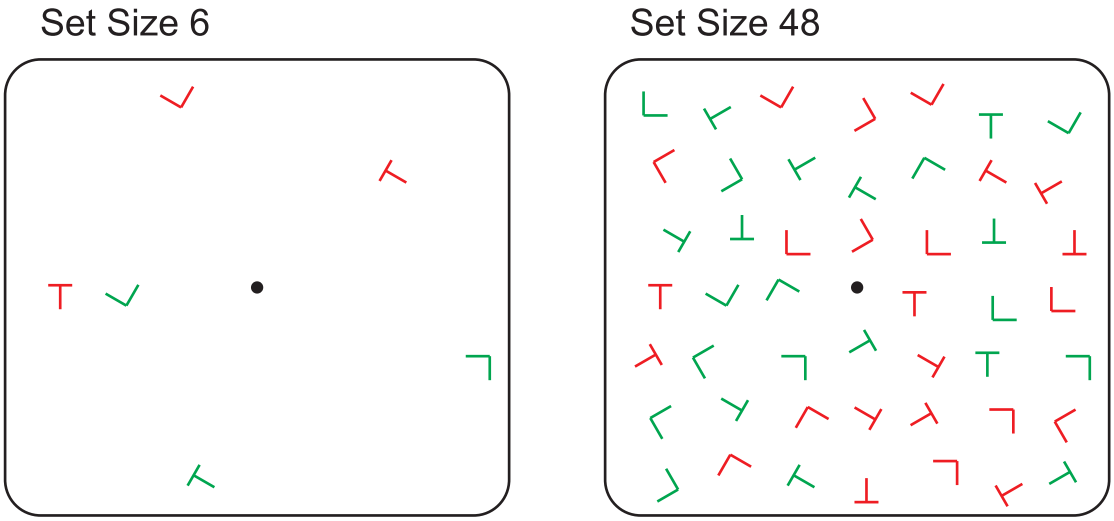

Figure 3.2: An illustration of two set-size conditions in Motter & Simoni (2008): Set-Size 6 on the left and Set-Size 48 on the right. The task was to detect a tilted-to-the-left, red "T" shape among a variety of distractors. The target is present in both of these examples in the upper right.

3.2.1 Example 1: Visual search with and without eye movements

This experiment was conducted in two ways. First, the observers were allowed to move their eyes freely to find the target. This is typical of many early visual search experiments beginning with Neisser (xxx) and Atkinson et al. (xxx). The results are shown in the top two panels of Figure 3.3. On the top left, correct response time is plotted as a function of set size and on the top right the percent errors is plotted by set size. Both functions are further subdivided by the presence or absence of the target. For both measures, performance declines with set size. The response time increases for both target present and target absent conditions. The increase is about twice as large for target absent compared to target present. The larger effect for target absent trials is from about 900 ms to 3000 ms. One account of such an effect is that groups of items are processed in sequence and one terminates the trial when one finds the target in the target present conditions but must go through the entire sequence for target absent. Indeed the eye movements allowed in this condition may contribute to the appearance of such serial processing. Regarding errors, there are relatively few errors on the target absent trials (false alarms) and they were not reported broken down by set size. In contrast, errors on the target present trials (misses) were more common and increased with set size from around 1% to 10%. In sum, there were effects of set size on both response time and errors but average errors remained relatively low (average misses of about 5%).

The second way the experiment was conducted was to require the observers to maintain central fixation and not move their eyes. To enforce this, eye position was monitored and trials rejected in which there was an eye movement. After a bit of practice, observers could do this and less than 1% of trials were excluded because of eye movements. Conditions with enforced fixation are not common in the literature.

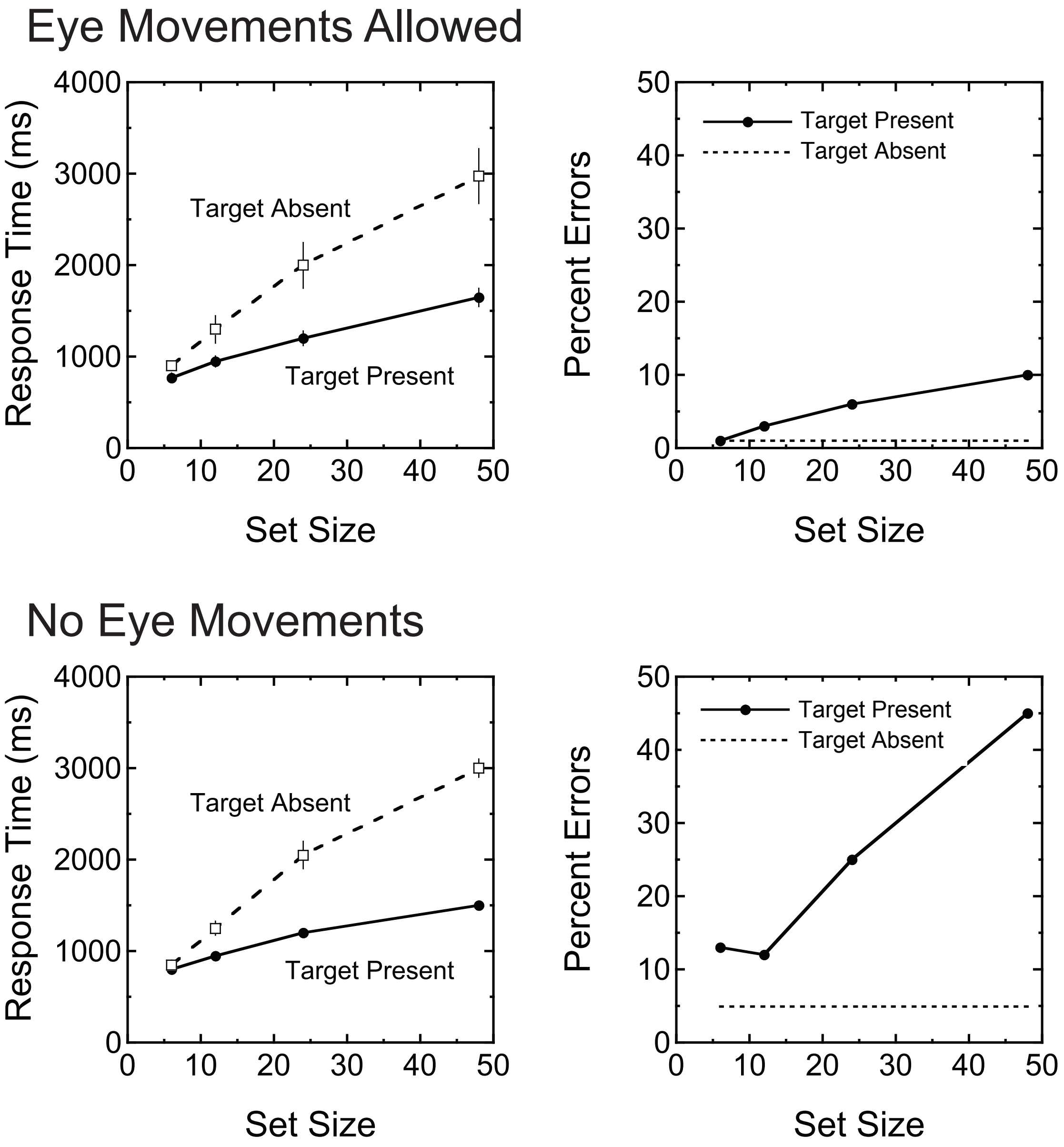

Figure 3.3: Results from Motter & Simoni (2008). The top two panels are for conditions that allow eye movements and the bottom two panels are for conditions without eye movements. On the left side, the mean correct response time is plotted as a function of set size. On the right side, the mean percent errors is plotted as a function of set size. Both are further broken down by whether the target is present or absent. Both with and without eye movements, response time and errors increase with increasing set size. Preventing eye movements has little effect on correct response time but causes a large increase in errors especially with the larger set sizes. We plot accuracy in response time experiments in terms of percent errors rather than percent correct because there are usually few errors and so that increasing values reflect poorer performance in both measures.

The results with no eye movements are shown in the bottom two panels of Figure 3.3 using the same conventions as before. The bottom left panel shows response time as a function of set size and the results are very similar to when eye moments were allowed. The bottom right panel shows percent errors as a function of set size. Here the results are quite different. For target absent conditions, the false alarms are much higher but unfortunately are not broken down by set size. For the target present condition, the misses are also much higher and clearly increase with set size. For the set size 48 condition, the percent misses reach nearly 50% compared to only 10% with eye movements. These errors occurred despite instructions to the observers to be as accurate as possible. Further analyses in the article show that observers were unlikely to do much better if they were given more time. Thus, without eye movements, observers could not perform the task without 50% errors.

Why are their so many errors when observers could not move their eyes? In the next section we describe two stimulus differences between the set-size conditions that are likely to cause this effect as well as contribute to set-size effects generally.

3.2.2 Effects of eccentricity and crowding

One stimulus difference that is often confounded with set size is *stimulus eccentricity.* Recall from the previous chapter that where you point your eyes has substantial consequences for visual processing. Stimuli near fixation are processed with greater accuracy than are stimuli that project to areas more peripheral relative to fixation. This difference in eccentricity can cause sensory effects that are confounded with any attentional effect of set size. This is particularly true when observers are free to move their eyes. In this case, observers can shift stimuli from being in the periphery to being near fixation. Thus, one source of set-size effects can be the use of eye movements to overcome the effects of stimulus eccentricity.

One could control for the effects of eccentricity by presenting stimuli along an iso-eccentric ring of locations and prevent eye movements. Doing so, however, would typically confound *stimulus density* with set size, because larger numbers of stimuli will have to be presented along the same circumference of locations. In fact, even without using isoeccentric placement of stimuli, stimulus density is often confounded with set size in visual search experiments. This is because stimulus locations tend to be selected from a single predefined set of locations thereby forcing more stimuli to be presented within the same spatial area as set size increases.

Confounding stimulus density with set size presents another problem for interpreting set-size effects as due to divided attention. Increases in stimulus density lead to increased visual *crowding*: a decrease in stimulus visibility that occurs when peripheral stimuli are presented in the presence of nearby stimuli. Figure 3.4 provides a demonstration of visual crowding. The task is to identify the orientation of the C-like figure. These *Landolt Cs* can be oriented with the gap to the left, right, up or down. In the demo, the left side has a single Landolt C and the right side has a central Landolt C surrounded by circles. Your task is to fixate the central cross and then judge the orientation of the Landolt C. On the left The Landolt C is alone and the gap size was chosen to make it easy to see. On the right, it is “crowded” by the surrounding figures and is hard to see. You can also shift one’s eyes to look directly at one or the other of the two Landolt Cs. On the left, the direct view illustrates the effect of eccentricity alone. On the right, the direct view illustrates

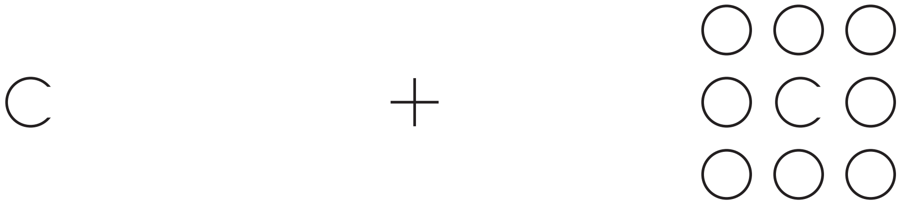

Figure 3.4: An illustration of crowding. Fixate the central cross and compare the visibility of the solitary Landolt C on the left with the visibility of the crowded Landolt C on the right.

the combined effects of eccentricity and the fact that crowding effects largely disappear when the relevant stimulus is directly viewed.

A key feature of this demonstration of crowding is that the relevant stimulus in the two conditions are identical: a single Landolt C. Instead, crowding is the result of a manipulation of the number of task-irrelevant stimuli. That the mere presence of the additional irrelevant stimuli can have a large impact on performance means that one has to control for the effects of crowding in order to interpret set-size effects as effects of divided attention.

The effect of crowding can be quite substantial and can occur for quite widely spaced peripheral stimuli. As a rule of thumb, crowding occurs for spacings that are half of the eccentricity of the relevant stimulus and smaller (Bouma, 1970). Thus, at a 10° eccentricity, stimuli within 5° cause crowding. Clearly, increasing set-size as illustrated in Figure 3.2 will cause more crowding. Indeed, Motter and Simoni (2008) argue that the most if not all of the set-size effect in their experiment are due to a combination of eccentricity, crowding and the eye movements to overcome these effects.

In summary, although set-size effects in visual search have the potential for revealing effects of divided attention, differences in set size are often confounded with stimulus differences that can lead to sensory effects. We now present two examples of visual search experiments that have gone some way toward dealing with the confounds of eccentricity and stimulus density, and ask whether the remaining set-size effects are due to dividing attention across stimuli at multiple locations.

3.2.3 Example 2: Brief displays and minimal crowding

The task in this example (Carrasco, Mclean, Katz and Frieder, 1998, Experiment 2) was to detect the presence of a vertical red line among tilted red lines. The target was present on half the trials and absent on the others, and observers reported "present" or "absent" by making corresponding key presses as quickly as possible following the presentation of the display. Both response time and response accuracy were measured as a function of set size. In the actual experiment, set size varied from 2 to 32. For purposes here, we consider only set sizes 2, 4, 6, and 8, because these conditions

Figure 3.5: An illustration of two set-size conditions in Experiment 2 of Carrasco et al. (1994): Set Size 2 on the left and Set Size 8 on the right. The task was to detect a vertical target among tilted distractors. The vertical target is present in both of these examples.

allowed for stimulus spacings at which visual crowding should have been minimal (Bouma, 1970). The stimuli were distributed over a 6-by-6 array of possible positions with jitter. Thus the same positions (and eccentricities) were sampled for all set sizes. Figure 3.5 provides an illustration of the smallest and largest set sizes that we are considering here (2 and 8).

The conditions that we have described so far are typical of most visual search experiments in the literature. What is unusual about this experiment, however, is that the search displays were presented for only 100 ms, thereby preventing eye movements within the display. Thus, between limiting our consideration to conditions in which crowding should have been minimal and allowing for only a single fixation, this experiment presents an opportunity for asking whether there are set size effects in visual search above and beyond sensory effects. Set-size effects under these conditions can be interpreted as divided attention effects with more confidence.

Indeed, as shown in Figure 3.6 there were set-size effects in this experiment. The left panel shows mean correct response time a function of set size. The right panel shows mean percent error as a function of set size. As set size increased, both response time and errors increased. We can be confident that differences in eye position and eccentricity did not contribute to these set-size effects because no eye movements could be made given the brief displays, and stimulus positions were sampled from the same set of possible positions for all set sizes. In addition, crowding probably did not play a large role for these small set sizes given the large spacing between stimuli. In summary, these set-size effects appear to be examples of an effect divided attention across multiple spatial locations.

3.2.4 Example 3: Relevant set-size

The task for our third example (Palmer, 1994) was to detect the presence of a higher-contrast disk (30%, 40%, or 50% contrast) among distractors of a fixed lower contrast (20% contrast). Observers

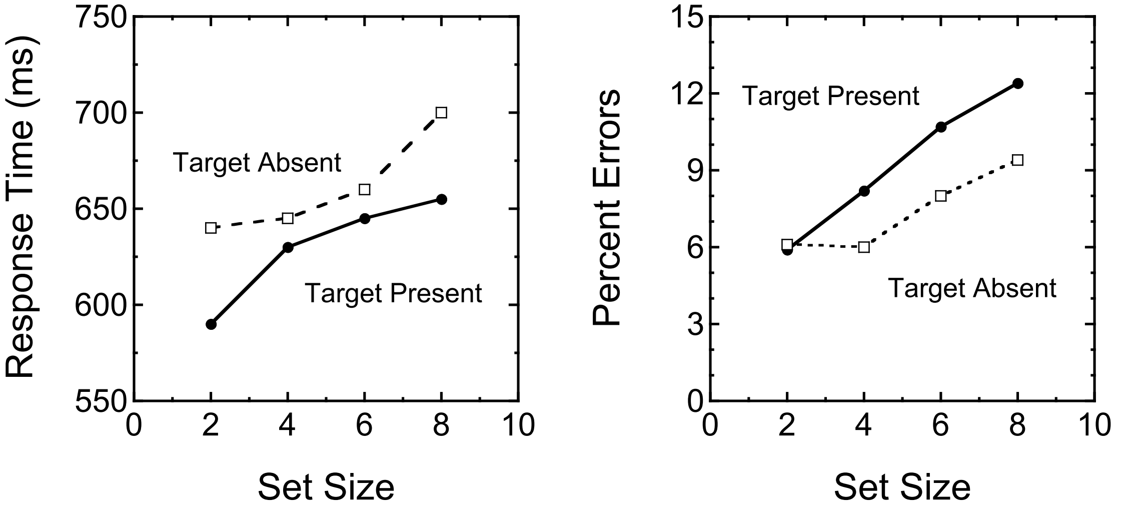

Figure 3.6: Results from Experiment 2 in Carrasco et al. (1998). On the left, the mean correct response time is plotted as a function of set size. On the right, the mean percent errors is plotted as a function of set size. Both are further broken down by whether the target is present or absent. Both response time and errors increase with increasing set size.

reported whether the target was present or absent, and although the displays were brief (100 ms) in order to prevent eye movements within the display, responses were not speeded. Instead observers were encouraged to take their time responding and to be as accurate as possible. Because some of the contrast differences between target and distractor were quite small, observers made errors and performance was measured in terms of response accuracy as a function of set size (2 or 8). The stimuli were presented at eccentricities that were randomly drawn between 5° and 8°. The spacing between the stimuli was at least 3° with approximately equal spacing to the nearest neighboring stimulus in the two set sizes. This spacing, therefore, roughly satisfies Bouma's rule of thumb to avoid crowding (half of the eccentricity). In the article itself, the analysis for this experiment focused on modeling the interaction between set size and discriminability (the contrast increment between the distractor and target). For the current purpose of providing examples of effects of divided attention, however, we focus on an aggregate measure of the set-size effect. Specifically, we collapsed the 20% and 40% target-contrast conditions, and excluded the 50% condition because performance in this condition approached ceiling and was therefore less informative.

The results of this experiment are shown in Figure 3.8. The mean percent correct for 4 observers is plotted as a function of set size. With increasing set size, percent correct fell by $9 \pm 1\%$. Given the controls for eccentricity, eye movements, and crowding, this set-size effect is likely to be an effect of divided attention.

Our near-obsessive concern about controlling for sensory effects is necessary because the question at hand is whether or not we have an attentional effect or something else. Does it reflect a change in visual processing due to what the observer is doing with the stimulus (i.e., what the task is), or does it reflect some difference in the stimulus itself? We believe it is critical to ascertain that there is an effect of attention at all, before pursuing theoretical explanations of those effects. With

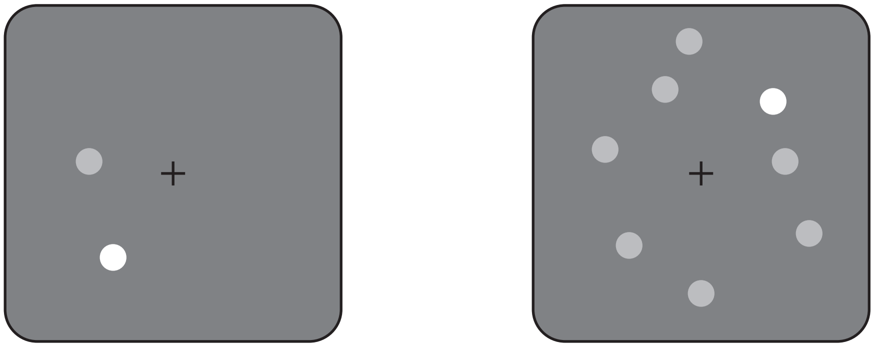

Figure 3.7: An illustration of the two display-set-size conditions in Experiment 2 of Palmer (1994): Set-Size 2 on the left and Set-Size 8 on the right. The task was to detect a contrast increment target which is present in both of these examples. The relative contrasts are exaggerated to make them easily visible.

that in mind, we present a final example that is a follow-up to last experiment described. In this example, all possible stimulus influences on the measured set-size effect were eliminated by having the search displays across the different set sizes be physically identical. In this case, any set-size effect that occurs must be an effect of divided attention because there were no stimulus differences of any kind. Moreover, because this final example relies on a cueing procedure, it highlights the interdependence between divided and selective attention.

The strategy used here, which we will refer to as the *relevant-set-size* strategy, was to provide cues prior to the search display that indicated, in this case, either 2 locations or 8 locations that were relevant to the task. As illustrated in Figure 3.9, an initial display was presented that contained both a fixation cross and additional crosses in the periphery that indicated the location of every stimulus that would appear in the search display. The cues further indicated the relevance of each location with regard to the search task by being either black or white. In the illustrated example, the black crosses indicated relevant locations and the white crosses indicated irrelevant locations. In some experiments, this mapping has been reversed for some observers ensuring an arbitrary relation between cue-color and stimulus. A Relevant Set Size 2 example is illustrated on the left with 2 black cues and 6 white cues. A Relevant Set Size 8 example is illustrated on the right with 8 black cues. After the cue, a search display containing 8 discs was presented. Observers knew that targets would only appear in relevant locations. Thus, the relevant set size was 2 in one case and 8 in the other, even though the number of discs that were physically present in the search display was 8 in all cases. The critical question was would performance depend on relevant set-size?

The results are shown in Figure 3.10. The open squares and dashed line function show mean percent correct as a function of relevant set-size. Despite the fact that the physical displays for these two conditions were identical, there was clearly an effect of dividing attention across 2 versus 8 relevant spatial locations. The solid circles and solid line function are a replotting of the data from the display set-size experiment (see Figure 3.8). The relevant-set-size effect is essentially indistinguishable from the display-set-size effect, and that the absolute performance in the corresponding conditions was also well matched.

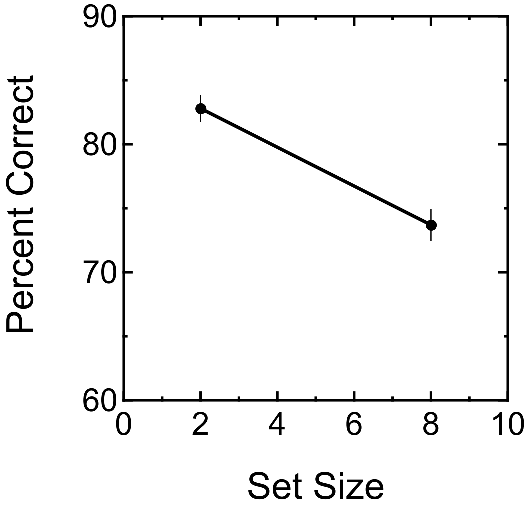

Figure 3.8: Results from Palmer (1994). The mean percent correct of 4 observers is plotted as a function of the display set size. Performance declines with increasing set size. The error bars are standard error of the mean.

The relevant-set-size effect that occurred in this experiment is clearly attentional. The use of identical stimuli makes that certain; there was no possibility of stimulus influences on the set-size effect. The relevant-set-size effect, therefore, is a clear example of a divided attention effect, and this is the most important point for purposes of this introductory chapter on divided attention.

Nonetheless, another important aspect of these experiments is that they provide a case for converging measures of the set-size effect. Consider first the weakness of the relevant-set-size experiment. Observers must be able to use the cues to allow them to search among stimuli at the cued locations and not at uncued locations. If observers either cannot or do not use the cues, then the relevant-set-size effect will be an underestimate of the effect of divided attention. Furthermore, if the selection mechanism is not as effective as actually changing the displayed stimuli physically, then the relevant-set-size effect will be an underestimate of the divided attention effect. Next consider the weakness of the display-set-size experiment. Any contributions of sensory effects would cause the display set-size experiment to overestimate divided attention effect. The fact that the results from the the display-set-size and relevant-set-size experiment were nearly identical is consistent with a particularly simple interpretation of these issues. For relevant-set-size, the observers used the cues reliably, and the selection mechanism was as effective as if the displays were actually changed. For display-set-size, the contributions of crowding and other sensory effects were small relative to the attentional effects. Of course, these conclusions are specific to the conditions of these experiments. But the fact that such conditions are achievable provides an example of isolating attentional effects from effects of the stimulus alone.

The experiments described here to introduce divided attention are success stories in finding converging measures of divided attention effects. They should, however, be considered exceptions in the larger world of visual search because set-size manipulations are often confounded with stimulus differences. If one does not control eye fixation, eccentricity and crowding, the measured effect of

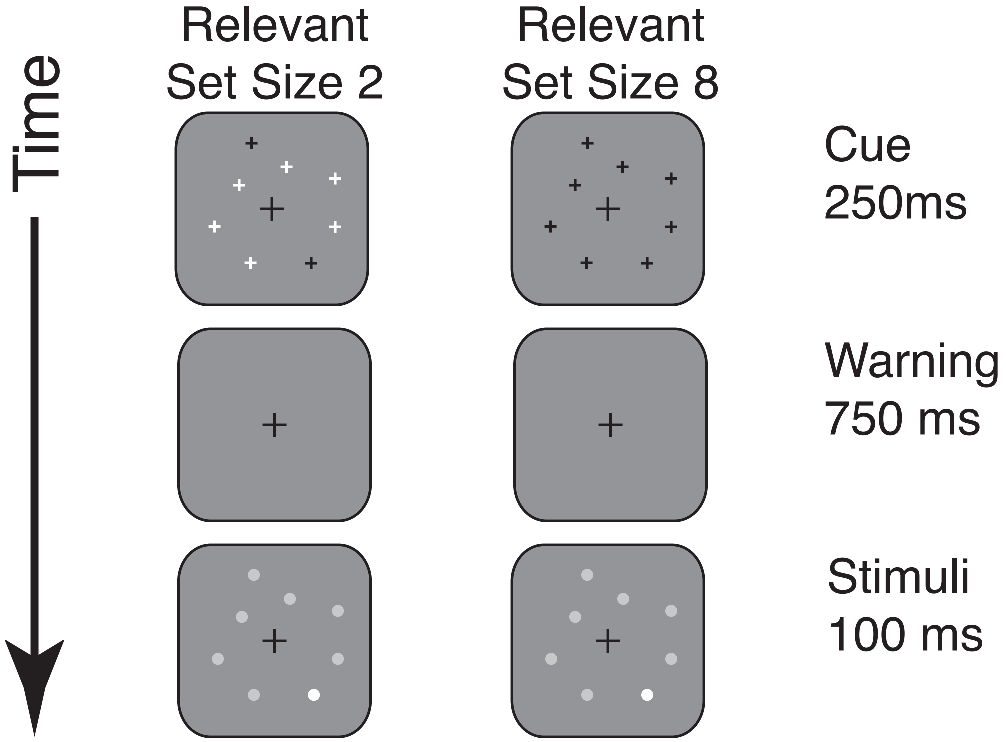

Figure 3.9: An illustration of the relevant-set-size conditions in Experiment 2 of Palmer (1994): Relevant Set Size 2 on the left and Relevant Set Size 8 on the right. The critical displays are identical, and only the cues beforehand indicate the relevant stimuli.

attention will be confounded with sensory effects, making it difficult to test theoretical accounts of attentional processes.

3.3 The Dual-Task Paradigm

We now turn to the *dual-task* paradigm. For this approach to divided attention, observers are required to perform two tasks simultaneously, and performance in a given task is compared to when that task is performed alone as a single task. For example, in a dual-task condition, observers might be asked to detect lights in two different locations giving separate responses (e.g., “yes” versus “no”) for each of the two locations on each trial. Performance for a given location is then compared to performance in a single-task condition in which, although lights might appear in either location, they only had to monitor and offer a response for stimuli that appeared in one of the locations.

There is a wide variety of dual-task experiments in the literature. Among other things, they differ with regard to whether the two tasks are the same kind of task or not (e.g., detection versus identification), whether the stimuli are the same for the two tasks or not (e.g., disks versus letters), what the response measure is (e.g., speeded response time versus unspeeded response accuracy) and whether the displays are identical across dual- and single-task conditions. Our goal is to introduce

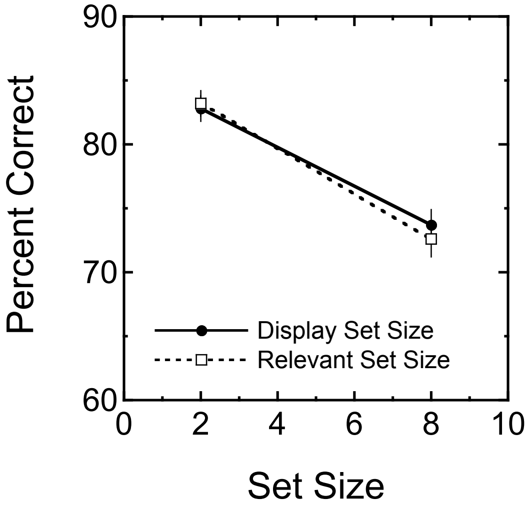

Figure 3.10: Results from Palmer (1994). The mean percent correct of 4 observers is plotted as a function of the display set size for both display set size and relevant set size. Performance declines with increasing set size in a similar fashion for both manipulations. This is consistent with both effects being attentional.

examples of clear effects of divided attention in order to set the stage for developing a theoretical understanding of attentional processes. With that in mind, we start by describing an experiment in which the the two tasks were simple and identical (i.e., two luminance detection tasks), and performance was measured in terms of response accuracy. In dual tasks, response time introduces significant complications because dual-tasks (usually) require two separate responses. By speeding responses and measuring how long they take, contributions from the response processes themselves can contribute to differences between the dual- and single-task conditions. This is a topic of intense study in the larger world of attention (e.g., *the psychological refractory period*, Welford, xxx; Pashler, xxx). Our focus, however, is visual attention, and so we will limit our discussion to dual tasks in which observers are allowed as much time to make their responses as they need and performance is measured in terms of accuracy rather than time. Finally, we focus on tasks in which the stimuli are presented briefly and simultaneously. This prevents eye movements and the potential sensory contributions that we've discussed before. Indeed, most dual-task experiments are similar to the relevant-set-size experiment in that identical stimuli are used in all conditions. We will call experiments that satisfy these constraints *dual search tasks* to distinguish them for dual tasks more generally.

The procedure for our example dual-search experiment (Bonnel, Stein and Bertucci, 1992) is illustrated in Figure 3.11. Observers were asked to detect luminance increments that could appear on either the left or right side of a display, which consisted of two small LEDs on either side of a video camera lens (used to record eye position). Observers fixated the center of the lens of the camera which put the LEDs 7° from fixation. Cues at the beginning of each trial indicated whether observers were to monitor only a single location (single-task condition) or monitor both locations (dual-task condition). Following the cue, observers indicated that they were ready by pressing a footswitch. After a short delay, a small luminance increment was (or was not) presented briefly (20

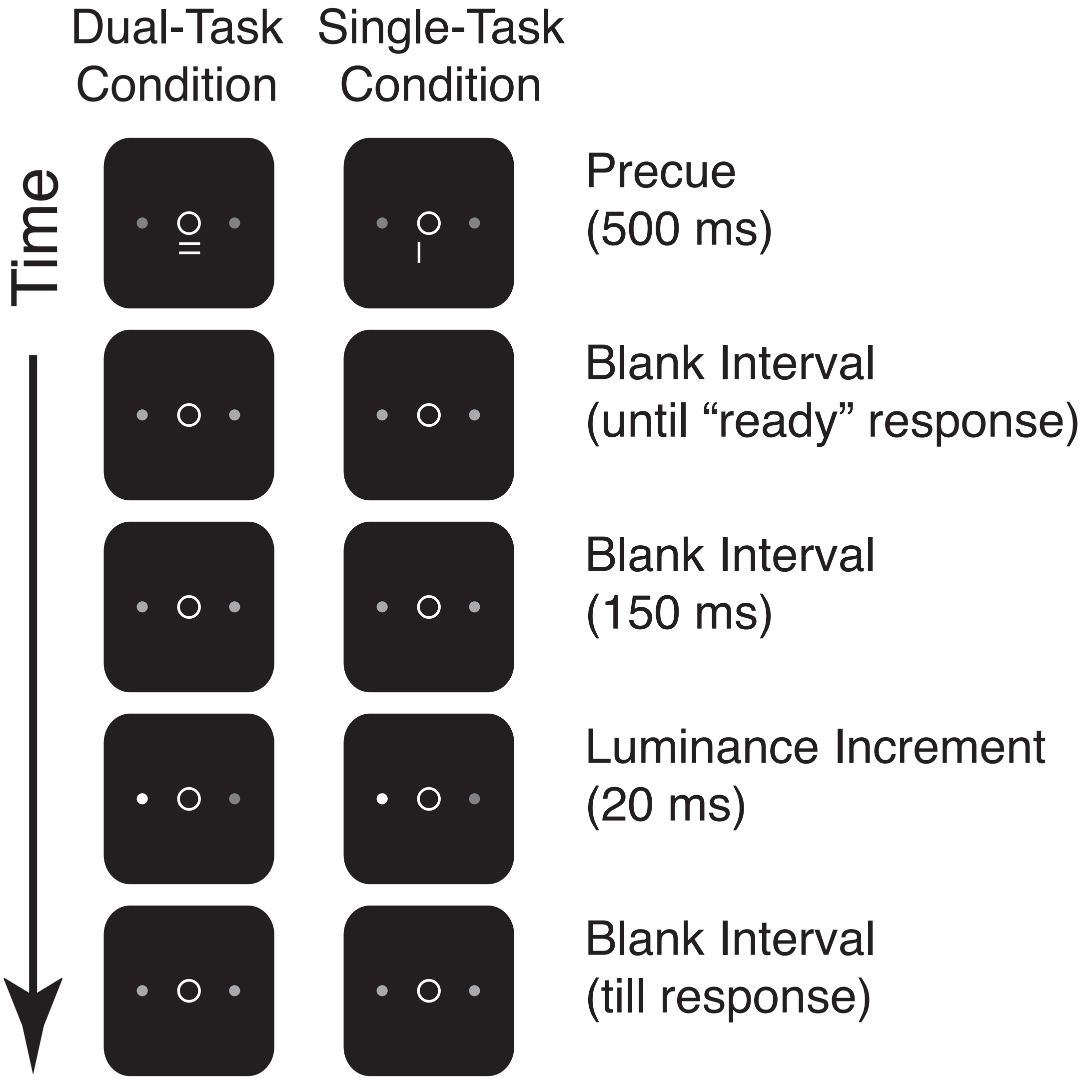

Figure 3.11: An illustration of the dual-task procedure used by Bonnel et al. (1992). The left column shows the dual-task condition and the right column shows the single-task condition. The displays are identical except for the precue that identifies the condition (two horizontal lines for the dual task and left or right vertical lines for the single task).

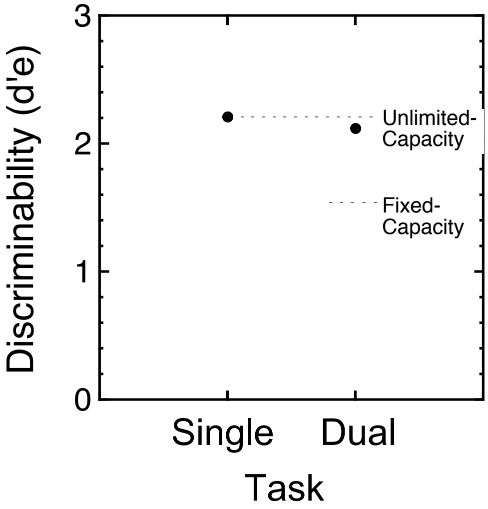

Figure 3.12: The results the luminance detection experiment in Bonnel et al. (1992)). The mean $d'e$ of 4 observers is plotted for the single- and dual-task conditions. Performance is similar in the two conditions. Given the single-task performance, the prediction of the unlimited-capacity and fixed-capacity models are shown for comparison. These models are defined in the following section on theories of divided attention.

ms). The probability of a luminance increment was 0.5 for each of the two sides, independently. Thus, on any given trial, a luminance increment could appear in one, neither, or both sides of the display. In the dual-task conditions, observers made separate responses ("yes" or "no") for the two sides. In the single-task conditions, they made a response for the cued side only.

Results for dual-task performance versus single-task performance (collapsed across the two sides) are given in Figure 3.12. Accuracy is plotted as a function of single- versus dual-task conditions. (Accuracy is reported in terms of $d'e$ which is a bias-free measure of performance based on signal detection theory. Details of signal detection theory are given in Chapter xxx, where we consider quantitative models of attention. For the moment, however, it is sufficient to think of this as a theoretical measure of performance similar to response accuracy. The main result of this experiment is that there is no dual-task effect. The graph also shows two theoretical predictions that are developed in the following section. The "limited-capacity prediction" is that performance in the dual task will match the single task. In contrast, the "fixed-capacity prediction" is that performance will decline by the amount predicted by a model in which only half the information can be extracted from each stimulus in the dual task (details in Chapter xxx). Clearly, the near-zero effects are much less than predicted by such a model.

Another way to consider the results of this experiment is to look at performance as a function of the *congruency* of the stimuli and their associated responses across the two locations on each trial. *Congruent* trials are ones in which there are either stimuli on both sides or stimuli on neither side and so the associated response is the same for the two sides, both "yes" or both "no". *Incongruent* trials are ones in which there is a stimulus on one side but no stimulus on the other side and so the associated responses are opposite for the two sides, one "yes" and one "no". If performance is different for congruent and incongruent trials, then it would imply a dependency of processing across the two stimulus locations. In other words, an effect of congruency is another kind of attention effect. For this experiment, there was a hint of a congruency effect in the dual-task condition, but it was not statistically reliable (82% versus 67% correct for congruent and incongruent trials, respectively). There was not even a hint of a congruency effect for the single-task trials (78% correct in both conditions). We mention these congruency effects because they will show up in future chapters on both selective and divided attention. In particular, this is the kind of analysis that motivates the concept of interactive processing (e.g. crosstalk) in the next section.

In summary, for contrast detection with dual search tasks, there is no evidence of an effect of dividing attention across two locations. The lack of divided attention effects in this case seems to contrast with the divided attention effects found in the visual search experiments described in the previous sections. But before pursuing such interpretations, one must put some theory on the table.

3.4 Theoretical Accounts of Divided Attention

We now turn to theoretical accounts of divided attention. What aspects of internal processing can lead to dependence of processing across stimuli, and thereby effects of divided attention? To begin, we introduce three different kinds of processing dependence. Various combinations of these dependencies can lead to a variety of models, some of which make distinctive predictions. In this introductory chapter, we describe three theoretical distinctions and consider four generic models.

3.4.1 Unlimited versus limited capacity processing

The first theoretical distinction regarding potential processing dependencies is between *unlimited* and *limited* (processing) *capacity.* This distinction, like all of the processing dependencies we consider, can be thought of as involving a kind of independence property. Is the processing of an individual stimulus independent of the number of relevant stimuli? To make this concrete, consider the Bonnel and colleague's experiment with two lights that was described above. Does the perception of a given light depend on whether one must judge that light alone or must judge both lights?

The term "capacity" derives from considering perceptual processing as a communication channel (Broadbent, 1958). The idea is that if additional stimuli do not impact the quality of information that is transmitted per unit time about each stimulus, then that processing has unlimited capacity. Unlimited capacity does not imply perfect processing. "Unlimited" simply refers to the usual quality of processing being unchanged by having to process additional stimuli (independence). In contrast, if processing has *limited capacity* then the quality of the information for a given stimulus declines as increasing numbers of stimuli are processed (dependence). The idea is that the outcome of a given process is either limited or not by how many stimuli must be processed.

Unlimited capacity is one extreme of the capacity distinction. The other extreme is a specific version of limited-capacity processing that we refer to as *fixed-capacity* processing, and it is worth considering separately. For fixed-capacity processing, only a fixed total amount of information can be transmitted per unit time. As a consequence, the amount of information about any individual stimulus will be limited directly by the number of stimuli that must be processed. Fixed-capacity models imply an extreme dependence of processing and as a consequence they make specific predictions regarding divided attention effects that can be useful in testing among alternative models. We will consider some of these in a later section of this chapter.

3.4.2 Parallel versus nonparallel processing

The second theoretical distinction regarding potential processing dependencies is between *parallel* and *nonparallel* processing. With parallel processing, the timecourse of the processing of any one stimulus is independent of the number of relevant stimuli. In contrast, nonparallel processing implies the timecourse of processing any one stimulus depends on the presence of other relevant stimuli. Consider again the Bonnel two-light example. Parallel processing implies the timecourse of processing one of the lights is unaffected by the relevance of the other light. The processing of each light has independent and identical timecourses.

The best known example of a nonparallel model is the *standard serial model*. In this model, information from each stimulus is processed one at a time in sequence. Eye movements provide a concrete example of a serial process. To directly view two lights, you have to move your eyes to view each light one at a time in sequence.

3.4.3 Noninteractive versus interactive processing

The third theoretical distinction regarding potential processing dependencies concerns the interactive processing of individual stimuli on individual trials. If channels of processing are *noninteractive*, then the processing of one stimulus is unaffected by the specific value of other stimuli that are being processed at the same time. If channels of processing are *interactive*, then the value of a given stimulus affects the processing that occurs for another stimulus. Consider the Bonnel example again. A example of interactive processing is to have the processing of one light affected by the value of the other light. For such a case, congruent lights have an advantage compared in incongurent lights.

The best known example of interactive processing is what we call the *standard crosstalk model* (e.g. Ernst, Palmer & Boynton, 2012; Navon & Miller, xxx). In this model, the stimuli are processed in parallel and without general dependencies on the number of stimuli (limited capacity). But, there are dependencies among the specific stimuli being processed. Specifically, there is some degree of pooling across the different stimuli.

3.4.4 An illustration of the three dependencies

These three dependencies are illustrated in Figure 3.13. The cube represents all combinations of the three dependencies. Each axis represents a different dependency. On the bottom are labels

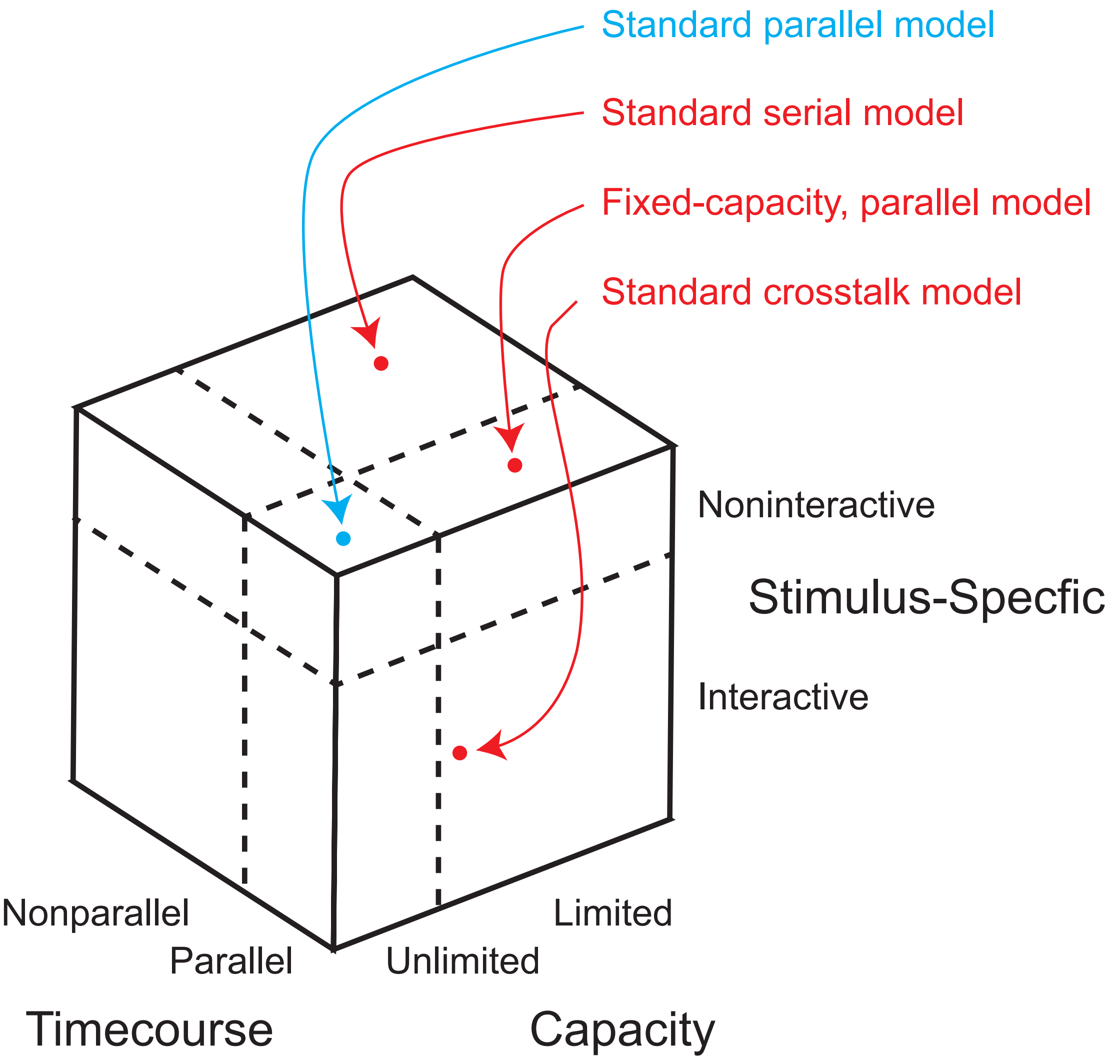

Figure 3.13: An illustration of the possible dependencies in processing multiple stimuli. The cube illustrates all combinations of the three possible dependencies: capacity, timecourse and stimulus-specific. All three of these are independent for the standard parallel model. In contrast, the other three models illustrate relatively pure versions of each of the three possible dependencies.

for the dependencies in timecourse and in capacity. On the right, is the label for the dependency on interactive processes. This cube is more than a 2-by-2-by-2. One value of each dependency represents independence. There is only one way to be independent while there are many ways to have a dependency. Hence the cube has a relatively small volume to represent the independent side of each possible dependency.

3.4.5 Four example models

There are many different ways in which properties of these three potential sources of processing dependency can be combined to form specific process models. For purposes of illustration, we briefly introduce four different models and illustrate them in our figure of possible dependencies. The figure uses a cube to illustrate the range of all possible models. We use black to denote the cube and its labels; and, we use color to denote the four specific models.

The first and simplest model is the *standard parallel model.* As the name implies, this model assumes parallel processing. In addition, the modifier "standard" is used to indicate the further assumptions of unlimited-capacity and noninteractive processing. This is the simplest possible model within the context of the three potential sources of processing dependency described above. Each of the three properties – parallel, unlimited capacity, noninteractive stimulus-specific processing – implies independence of processing. This unique model is shown in blue.

The second model is the *fixed-capacity, parallel model.* Like the standard parallel model, this model assumes parallel processing. However, it also assumes fixed-capacity processing, which implies a particular processing dependence. This model and the other models with dependencies are shown in red.

The third model is the *standard serial model.* It assumes serial processing, which implies a specific dependence in the timecourse of processing. The modifier "standard" is used to indicate the further assumptions of limited capacity and noninteractive processing.

Finally, the fourth model is the *standard crosstalk model.* This parallel model is built around a dependency in stimulus-specific processing. The term "standard" refers to the assumption of parallel processing and independence of any general effect of the number of relevant stimuli (unlimited capacity).

These four examples are intended as generic process models that can be applied to specific task contexts in order to build theories of divided attention. Such theories must elaborate how the model applies to a given task and stimulus set. Detailed examples are given in Chapter xxx on quantitative models.

3.4.6 Comment on terminology

The three dependencies of capacity, timecourse and interactive processing each have a history. The terminology of capacity has long been used in theories of attention from Broadbent (1958), to Kahneman (1973) to Pashler (1998). We maintain their usage in our treatment. But, in the literature more generally, one must take care exactly how the term is used. Some authors (e.g. Townsend & Ashby, 1983) use it in a slightly different way to contrast capacity with dependencies in the timecourse of processing.

We depart from convention in contrasting parallel and nonparallel processing rather than parallel and serial processing. Our purpose is to distinguish the larger idea of independent time courses (parallel processing) from the specific example of nonparallel processing that is the standard serial model. This hopefully will make more clear the parallels between the three distinctions.

Finally, we differ from recent attention texts in considering dependencies due to interactive processing on par with dependencies due to capacity limits and nonparallel processing. We were drawn to this by the mounting examples of interactive processing we found in the literature. For this case, the terminology in the literature varies quite widely. Interactive processing (xxx) refers to any possible dependence between stimuli in separate channels. Crosstalk (xxx) refers to the partial "pooling" of stimulus information across channels. Stochastic dependence (xxx) refers to the trial-by-trial "noise" correlation of otherwise identical stimuli. For purposes of introduction, the concepts of interactive processing, crosstalk and stochastic dependence can be considered essentially interchangeable.

We now turn to one of the major challenges to building theories of divided attention. Effects of divided attention (e.g., set-size effects or dual-task effects) are measured using tasks that unfold through multiple processes. Some of the processes might function independently for multiple stimuli, while others might have dependencies. Moreover, some of the processes may fall into the broader domain of interest (e.g., vision), whereas others that are necessary to do that task, nonetheless fall outside of domain of theoretical interest (e.g., response execution). One challenge, therefore, is ascertaining what component processes gave rise to the effect of interest. In the next section, we consider a first-pass through visual processing similar to what we did for selection in the last chapter. Specifically, we ask whether observed effects of divided attention reflect processing dependencies in perception, in decision, or perhaps in both.

3.5 The Locus of Processing Dependencies

Building toward a general theory of divided attention, we seek to ask which visual processes possess dependencies of one kind or another, as assessed by evidence of divided attention effects. This is the divided attention version of the locus question that we raised for selective attention in the last chapter. In that case, we asked about the locus of *selection*. Here we ask about the locus of *processing dependencies*. For selective attention, we began by contrasting the selective-perception hypotheses with the selective-decision hypotheses. For divided attention, we contrast *dependent-perception* hypotheses with *dependent-decision* hypotheses.

3.5.1 Dependent perception

The most common interpretation of set-size and dual-task effects is in terms of dependent perception. Specifically, they are interpreted as evidence that one or more perceptual process has dependencies across stimuli (e.g., is serial or limited-capacity parallel). A well-known example is feature integration theory (Treisman & Gelade, 1980). In this theory, a serial process is required to represent a stimulus as a conjunction of features (e.g., red and vertical, as distinct from just red or just vertical). This processing dependency predicts poorer performance (e.g., slower and/or less accurate) with larger set sizes for any task that depends on feature conjunctions; that is, it predicts set-size effects. This is an example of a *dependent-perception* hypothesis. More generally, any hypothesis that assumes the relevant perceptual process to be serial, limited-capacity parallel, or interactive would be an example of a dependent-perception hypotheses.

3.5.2 Dependent decision

An alternative interpretation of set-size or dual-task effects is in terms of dependent decision. Specifically, it is assumed that all perceptual processes for a given task are entirely independent, but that decision processes are subject to dependencies across stimuli. The starting assumption of this hypothesis is that the representation of each stimulus is noisy and that such noise is the source of errors in decision. Because visual search has multiple stimuli that contribute to the decision, each additional stimulus will contribute additional opportunity for an error to be made. As a consequence performance will decline as set size increases. This decision effect occurs without there being any dependencies within perceptual processes. This is an example of a *dependent-decision* hypothesis for visual search.

The modifier "decision" in dependent-decision hypotheses can lead to some confusion that is worth raising explicitly. Dependent-decision hypotheses still concern *visual* processes. The focus is on decision processes within later visual processes that based on the output of earlier visual processes, which for want of a better label are being referred to as "perceptual" processes. This distinction should not be confused with the distinction between sensitivity and decision bias that was introduced in the last chapter. Decision bias refers to influences from beyond the visual system, such as a reluctance to report seeing stimuli that aren't there leading to a bias to report "no" in a yes/no detection task. Decision bias is something to be worried about as a potential contamination of measures if one is interested in visual processing. Dependent-decision hypotheses, however, are statements about where within visual processing – sometimes referred to as early (perceptual) versus late (decisional) – dependencies arise. They still concern vision and, by extension, visual attention.

3.6 Visual Search Revisited: Simultaneous-Sequential Paradigm

Set-size effects, in general, cannot provide a test between dependent-perception and dependent-decision hypotheses. Both hypotheses predict that performance will decrease with increasing set size. One solution to this problem has been to try to make more specific quantitative predictions regarding the expected magnitude of set-size effects in order to discriminate between the two hypotheses. Such efforts have tended to resolve the question in favor of dependent decision over a dependent perception for simple feature tasks (e.g., Palmer, et al., 1993; Shaw, 1984). This approach, however, has a disadvantage. It requires a commitment to fairly specific assumptions about details of the process model that may or may not be warranted.

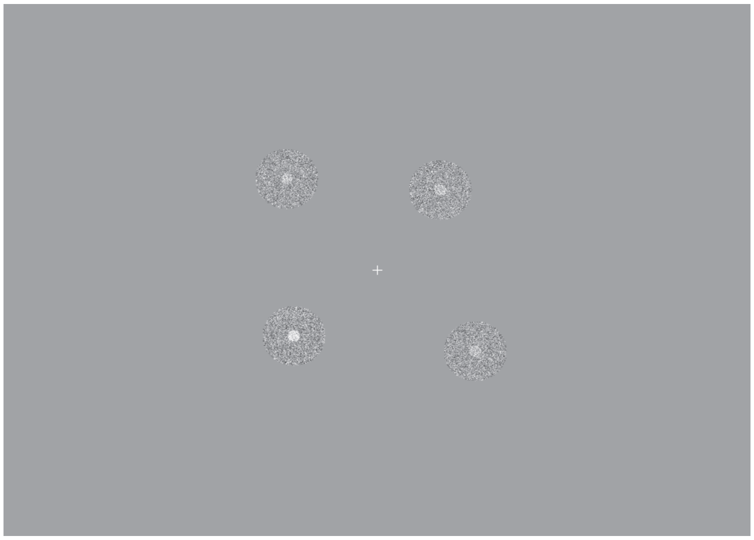

Figure 3.14: An illustration of the displays used for the contrast increment search in Scharff et al. (2011). The distractors were dynamic noise patches containing a small disk of 20% contrast. The single target was a noisy patch with a small disk with an increased contrast. The contrast increment is exaggerated in the figure to make it clearly visible.

What about dual task? In addition to set-size manipulations in visual search, we introduced the dual-task paradigm as a method for measuring effects of divided attention. Does this paradigm allow one to discriminate between dependent perception and dependent decision? Unfortunately, the dual-task paradigm has its own issues. This is because the number of decisions that must be made in a dual task (one versus two) is confounded with the number stimuli that must be processed (single task versus dual task). We will turn to addressing the issues of interpreting dual tasks in the next section.

There is a variation of the set-size manipulation in visual search that is able to discriminate between dependent perception and decision. It is the *simultaneous-sequential paradigm* (Eriksen & Spencer, 1969; Shiffrin & Gardner, 1972). Instead of varying the total number of stimuli that are relevant to the task, it varies the number of stimuli that must be processed at any given time, while holding consent the total number of stimuli that must be processed to do the task. Specifically, in one condition – the *simultaneous* condition – all of the relevant stimuli are presented at the same time. In another condition – the *sequential* condition – stimuli are presented as a temporal sequence of subsets of stimuli until all of the relevant stimuli have been presented. The total amount of time that any given stimulus is present is held constant, as is the total number of the stimuli are presented. What differs across simultaneous and sequential conditions is how many of the to-be-processed stimuli must be processed at one time.

The simultaneous-sequential paradigm allows one to discriminate between perception and decision hypotheses by removing decision from the picture. Because the total number of stimuli that must be processed is constant across conditions, differences in the amount of noise feeding into decision processes across conditions are minimized, if not eliminated. The concerns regarding differences in decision noise that we saw with standard set-size manipulations are therefore avoided in this paradigm. As a consequence, any differences in performance across simultaneous and sequential conditions can be attributed to dependencies within perception and not decision.

In this introductory chapter, we present a few examples of simultaneous-sequential experiments. They differ in the specific task that observers were asked to do, though all are still examples of relatively simple tasks. Several of the experiments revealed evidence of independent processing across stimuli, whereas one experiment revealed evidence of dependent perception. We highlight this contrast because in later chapters we will consider other simultaneous-sequential experiments that used more complex stimuli and tasks as a means of refining the locus question for divided attention – which processes, in particular, have dependencies and which do not? – with a broader goal of building a general theory of divided attention. For the moment, however, the goal is to describe the simultaneous-sequential method and to present cases with and without evidence for processing dependencies within perception.

Example 1: Contrast-increment search

The first example used a simple contrast-increment search task (Scharff, Palmer & Moore, 2011). Displays contained four small (0.5°) disks (3 distractors and 1 target), each presented in a small field of dynamic noise near the corners of an approximately 6° imaginary square around fixation (see Figure 3.14). Distractor contrast was 20%, with target contrast just a bit higher (ranging from 28 to 35%), adjusted so that each observer could perform that task at roughly 75% accuracy. The task was to report which of the four quadrants contained the target with a corresponding key press. Responses were not speeded.

The experiment included three conditions as illustrated in Figure 3.15. In the *simultaneous* condition (left), a brief fixation interval was followed by a 100 ms display with four stimuli, after which the observer was prompted for the localization response. In the *sequential* condition (middle), two stimuli were presented in an initial 100 ms display, followed 1000 ms later by a second 100 ms display containing the other two stimuli. Thus for both of these two conditions, each individual stimulus was displayed for 100 ms. The third condition was the *repeated* condition (right) in which all four stimuli were presented for an initial 100 ms display followed 1000 ms later by a second 100 ms display containing all four stimuli again. Thus each individual stimulus was displayed for for twice the time in the repeated condition than in the simultaneous and sequential conditions.

Figure 3.16 illustrates the logic of the experiment. In six panels, separate representations of how processing unfolds across the simultaneous, sequential, and repeated conditions depending on whether the processes involved were all completely independent (i.e., standard parallel model) or highly dependent (e.g., standard serial model). Each panel illustrates two sequential frames that contain up to four stimuli each. Time is illustrated as moving from left to right, and the different stimuli within a display are depicted as grey bars, separated vertically and labeled 1-4. The processing that each stimulus receives according to the given model is denoted by black arrows superimposed on the grey bars depicting the stimuli. Predictions for performance across the three conditions for each model are shown in the bottom row of the figure. These performance predictions are derived by assuming that longer processing leads to better performance.

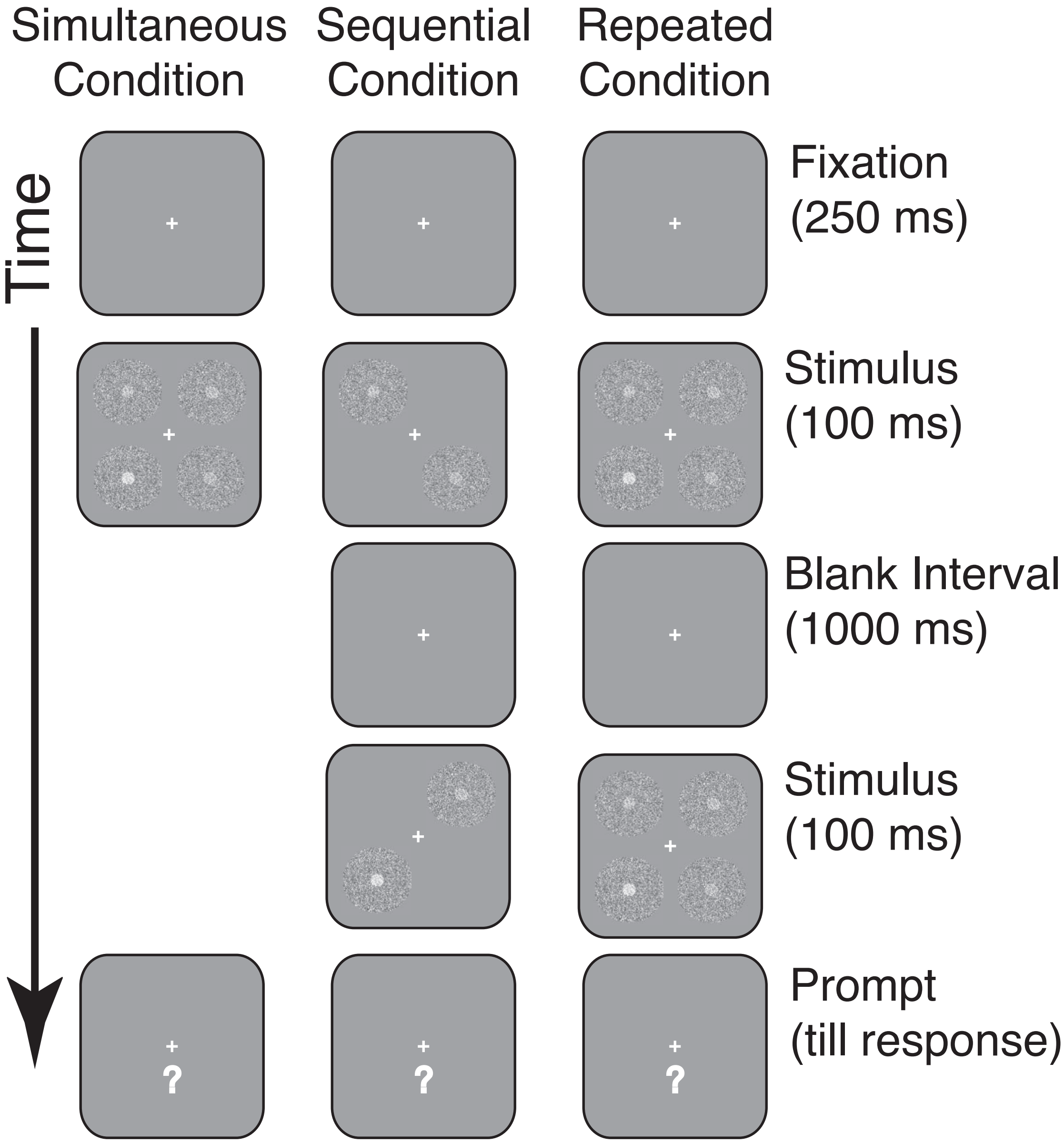

Figure 3.15: An illustration of the three conditions in the extended simultaneous-sequential procedure. The left column shows the simultaneous condition with one display of four stimuli. The middle column shows the sequential condition with two displays of two stimuli. The right column shows the repeated condition with two displays of four stimuli.

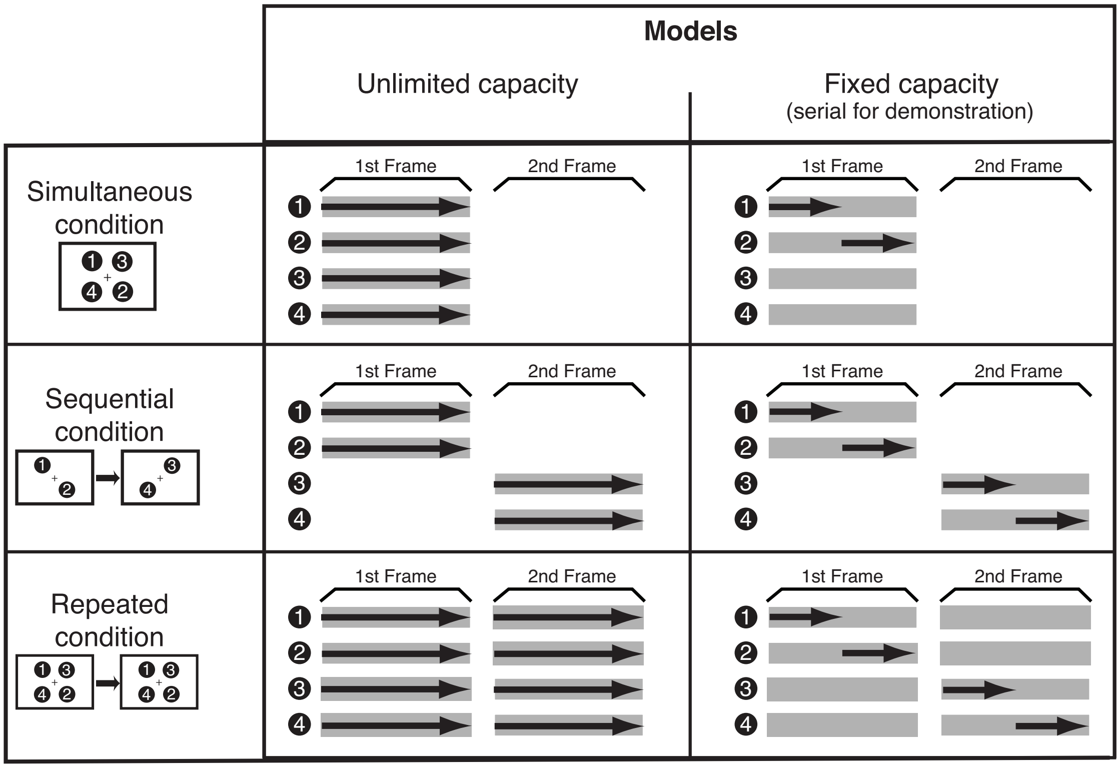

Figure 3.16: An illustration of processing sequences for the three conditions according to two models. On the left are predictions of the standard parallel model and on the right are predictions of the standard serial model. The grey regions represent time when the stimulus is presented and the arrows represent the time a given stimulus is being processed. The standard parallel model predicts equivalent performance for the sequential and simultaneous conditions. The standard serial model (and many fixed-capacity, parallel models) predicts equivalent performance for the sequential and repeated conditions.

Consider first the case in which processing is fully independent for stimuli across space (left column). In this case, processing proceeds independently of the number of stimuli. Therefore, regardless of how many stimuli are presented within a given frame, they will all processed for the entire duration of the frame just as they would were they the only stimulus present. As a consequence, difference in performance across conditions will be determined entirely by differences in display duration. Because stimuli are displayed for the same amount of time across the simultaneous and sequential conditions, performance is predicted to be equal across these two conditions. Because stimuli are presented for twice the amount of time in the repeated condition than in the others, performance is predicted to be better in this condition than in the other two. This is the simplest possible model for how multiple stimuli are processed across multiple locations.

Consider next the case of high dependence such as the standard serial model. For sake of argument, imagine that the limit in processing is that only two stimuli can be processed in the amount of time allowed for processing these displays. For this example, only two of the four stimuli in a simultaneous display could be processed. In contrast, all four stimuli could be processed in the sequential display, two during the first frame and two during the second frame. Performance is therefore predicted to be better in the sequential condition than the simultaneous condition. The repeated condition, like the sequential display, allows for all four stimuli to be processed over the time of the two frames. However, because only two stimuli can be processed within the time of any given frame, despite all four stimuli being presented in both of the two frames, the repeated condition has no advantage beyond that of the sequential condition. Therefore, this case leads to performance in the sequential condition being equal to that in the repeated condition, both of which will be better than that in the simultaneous condition.

Not shown in this figure is the case of a fixed-capacity, parallel model. To understand this model, lets walk through the panels on the left for the unlimited-capacity, parallel model. Unlike the unlimited-capacity case, the fixed-capacity case only obtains a constant amount of information from a set of stimuli. Thus, given equal processing, the simultaneous display will result in half the information per stimulus compared to the sequential condition. In the sequential condition, processing can be focussed on two rather than 4 stimuli. Thus, the fixed-capacity parallel model predicts better performance in the sequential condition compared to the simultaneous condition. In the repeated condition, once again only half the information can be obtained in the 1st frame relative to the sequential condition. But now there is a second frame to get another half of the information. If one assumes perfect integration of information across frames, then the second frame will compensate for the extra stimuli and performance will be equal in the sequential and repeated conditions. In sum, the fixed-capacity parallel model sketched here makes the same prediction as the serial model: performance in the sequential condition is the same as the repeated condition and both are better than the simultaneous condition.

Also not shown in the figure is that lesser degrees of dependence (e.g., a limited-capacity, parallel model) predicts an intermediate pattern of results. Specifically, any limited-capacity model predicts that performance is better in the sequential condition than in the simultaneous condition, but not necessarily as good as that in repeated condition. Thus, performance in the sequential condition falls between that in the simultaneous and repeated conditions. Thus, seeing where the sequential conditions falls with respect to the other two conditions indicates to what extent is capacity limited.

Finally, for convenience of communication, these predictions are illustrated for the special case of the standard serial and standard parallel models. The predictions hold, however, for variety of different models (see Scharff, Palmer & Moore, 2013). We defer a discussion of the generality of such predictions until Chapter xxx when we consider quantitative models.

The results of this experiment are shown in Figure 3.17. The mean percent correct of six observers is plotted for the three conditions. Performance in the repeated condition was better than that in the simultaneous condition by $8 \pm 2\%$. The key comparison is where does performance fall in the sequential condition relative to that in the other two conditions. The range of possibilities is bracketed by the two dashed lines marked as "unlimited capacity" and "fixed capacity", respectively, in order to highlight the predictions of these two extreme models. In fact, performance in the sequential condition for this contrast-increment search task was nearly identical to that in the simultaneous condition ($2.0 \pm 1.4\%$), as well as being reliably below that in the repeated repeated condition ($10 \pm 1\%$). Clearly the processing of contrast across locations is not fully dependent (e.g., serial). That model can be rejected by these data. Moreover, the results are consistent with the

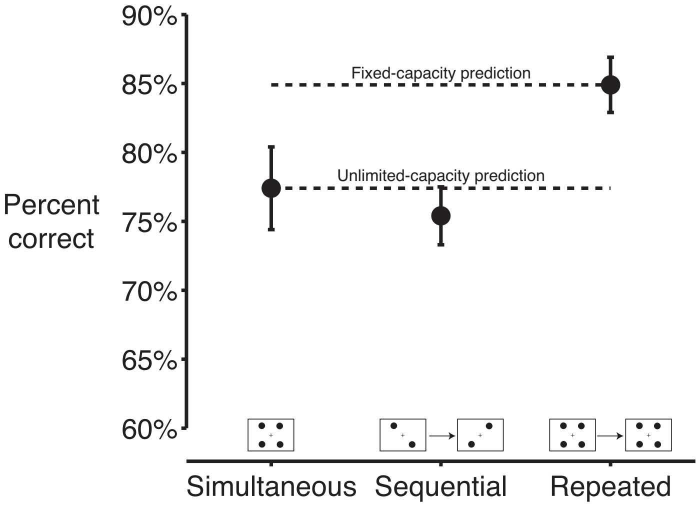

Figure 3.17: The results from the contrast increment experiment in Scharff et al. (2011). The mean percent correct of 6 observers is plotted for the three conditions. Performance in the sequential condition is similar to that in the simultaneous condition and reliably less than in the repeated condition. This pattern of results is consistent with unlimited-capacity perceptual processing.

possibility that processing of contrast across locations is fully independent (i.e., captured by the standard parallel model). This is an answer for contrast-increment search. What about tasks that require other visual processes?

Example 2: Size-decrement search versus a spatial-relation search

The second example that we consider here is especially nice for the goals of this initial chapter. It contrasts the effects of divided attention as measured through set-size effects versus differences across simultaneous and sequential presentation of stimuli, and it does so for two different tasks: size-decrement search and a task in which observers searched for a T that could appear at any orientation among L's that could appear at any orientation (Huang & Pashler, 2005). We characterize this second task as a spatial-relations task because it was the specific spatial relations among oriented bars that defined the target from the distractors. Figure 3.18 provides an illustration of the stimuli, and an illustration of how stimuli were displayed using one frame of a sequential-display condition to illustrate. Stimuli were presented in groups of 4, with each group appearing in one of four quadrants around fixation. Any given display could include all four groups of 4 or just two groups of 4 as shown in the figure. The task was to report "yes" or "no" to the presence or absence of a target in the display.

A schematic of the procedure for the simultaneous-sequential version of the experiments is shown in Figure 3.19, using the size-decrement displays to illustrate. Each trial began with a small fixation cross for 400 ms, followed by a blank interval of 400 ms (not shown in figure). Stimuli were then presented in either all four quadrants or in two of the quadrants for about 150 ms (this duration

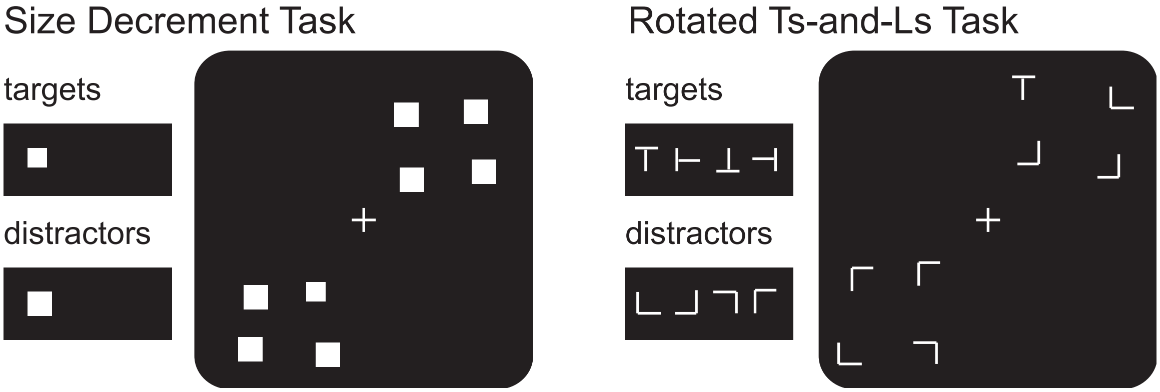

Figure 3.18: An schematic illustration of the displays used for two tasks in Huang and Pashler (2005). The left panel shows the size decrement task: The distractors were fixed size squares and the target was a slightly smaller square. The right panel shows the rotated-Ts-and-Ls task: The distractors were one of 4 L-shaped figures and the target was one of 4 T-shaped figures.

was adjusted for each observer) followed by a 100 ms mask. In the sequential condition, there was a further blank interval of 250 ms followed by the stimuli in the remaining two quadrants (∼ 150 ms) and another mask (100 ms). Observers responded by indicating a yes-no decision about the presence or absence of a target in the displays with a corresponding button press. Responses were not speeded.

For these displays there was probably is some effect of crowding because the spacing is less than half of the eccentricity (remember Bouma's rule of thumb). But this experiment used a different trick to hold the effect of crowding the same for the simultaneous and sequential displays. The stimuli were grouped in sets of four what were more widely spaced between the groups than within the group (2.1° vs 0.8°). Thus, the crowding effect was probably about the same whether there were 2 or 4 groups in the display.

The display set-size version of the experiments used essentially the same displays, except that they (a) did not include the second frame of the sequential condition, (b) there were no masks, and (c) the display remained present until a response was made. These conditions resulted in a standard set-size manipulation of 8 versus 16 stimuli. For this version of the experiments, responses were speeded, and performance was measured in both response time and accuracy.

Results from response time experiments are summarized in Figure 3.20. On the left the response time is plotted as a function of set size or both tasks. On the right, percent errors is similarly plotted Set-size effects occurred for both tasks by both measures. Assuming that there are no sensory effects due to eye movements or other stimulus differences across conditions, these effects imply that one or more processing dependency exists within the processes engaged by these tasks. But what kind of processing dependence might they reflect, perception or decision? Both perception and decision hypotheses predict that set-size effects will occur. Therefore, these results alone cannot discriminate the locus of processing dependence, even at the coarse level of perception versus decision.

Adding the simultaneous-sequential results provides more information about the locus of processing dependence. Differences in performance across simultaneous and sequential conditions cannot

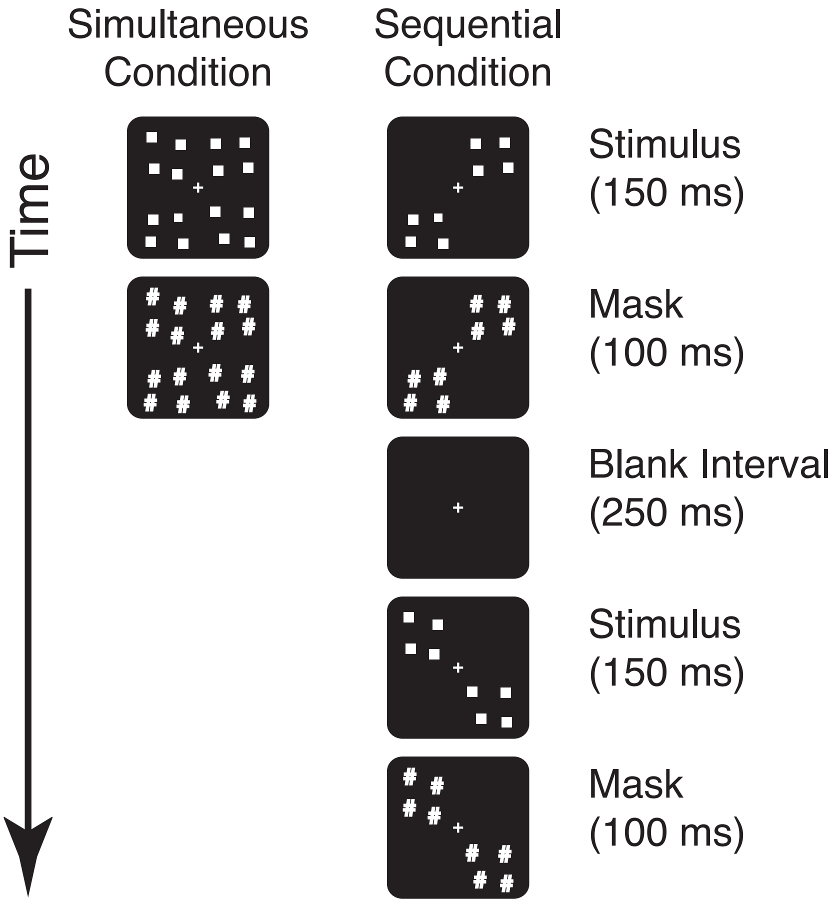

Figure 3.19: An illustration of the simultaneous-sequential procedure used by Huang and Pashler (2005). The left column shows the simultaneous condition with 1 display of 16 stimuli. The right column shows the sequential condition with 2 displays of 8 stimuli.

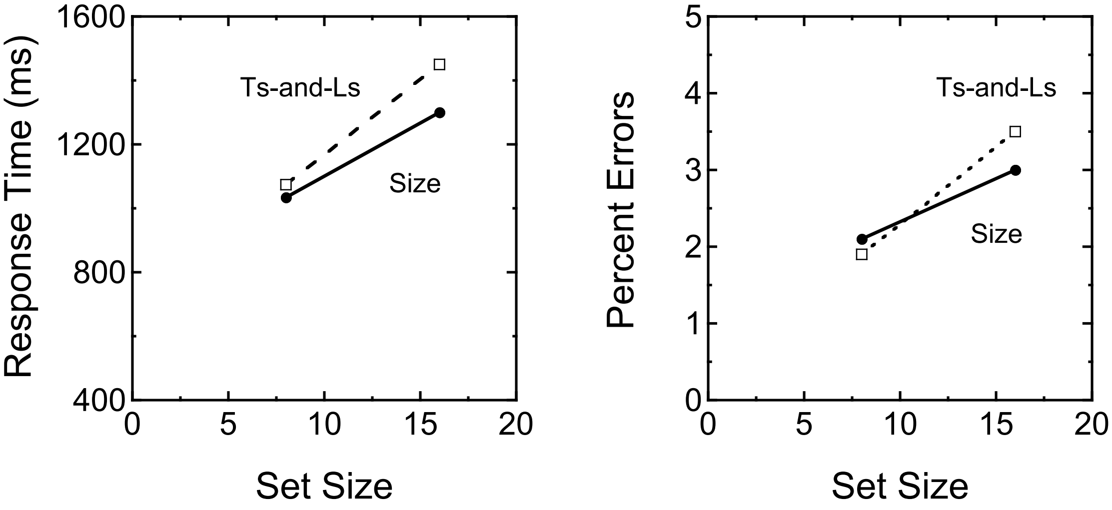

Figure 3.20: The results from two of the response time experiments in Huang and Pashler (2005). In the left panel, the mean response time of 8 observers is plotted for a size decrement and a rotated Ts-and-Ls task. In the right panel, the mean percent error of 8 observers is plotted for the two tasks task. In both tasks, there are reliable effects of set size for both response time and errors.

be attributed to decision dependencies, and therefore imply perception dependencies. As can be seen in Figure 3.21, performance was nearly identical across the simultaneous and sequential conditions for the size-decrement task. However, performance was better in the sequential condition than the simultaneous condition for the spatial-relations task. Taken as a whole, the pattern of results across experiments is consistent with there being independence of processing within perception for the size task, but dependence within perception for the spatial-relations task. Not surprisingly given results from set-size experiments described in previous sections, there appears to be dependence of processing in decision processes regardless of the task.

In summary, this example highlights two things. First, it highlights again the fact that set-size effects, in general, cannot discriminate between dependencies in perception versus decision. The simultaneous-sequential paradigm is better for addressing this question because it holds decision contributions constant across the different conditions. Second, it highlights one can obtain contrasting results in the “perception versus decision” comparison. The perception hypothesis held for the spatial-relation task, but did not for the size-decrement task. That suggests that the spatial-relation task engages additional processes that are the source of the dependency. The question of locus of processing dependency must be asked over and over again in different task contexts in order to identify which specific processes are independent and which are dependent. That will provide the foundations for a general theory of divided attention.

3.7 Dual Tasks Revisited

In the previous section, we described how the visual search paradigm can be improved to address the locus question. Similar issues arise for dual tasks. On the good side, there is no many-to-one

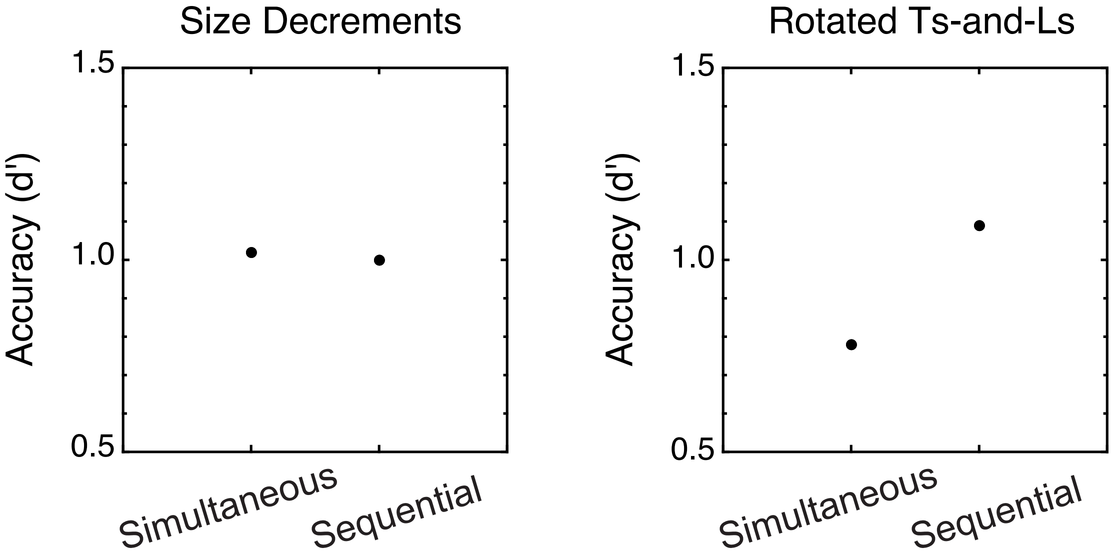

Figure 3.21: The results from two experiments in Huang and Pashler (2005). In the left panel, the mean d' of 8 observers is plotted for a size decrement search task. Performance in the sequential condition is similar to that in the simultaneous condition. In the right panel, the mean d' of 8 observers is plotted for the rotated Ts-and-Ls task. Performance in the sequential condition is reliably better than the simultaneous condition. This pattern of results is consistent with unlimited-capacity, perceptual processing for the size task and limited-capacity, perceptual processing for the Ts-and-Ls task.

mapping in the decision process for comparing single and dual task. On the bad side, the dual task for perception is confounded with a dual task for decision. How can one distinguish these two possible sources of dependency for dual tasks?

[candidate examples: Bonnel and Hafter? Dosher?]

3.8 The Generality of Divided Attention Effects

[to be added]

3.9 Chapter Summary

3.9.1 Three paradigms

We began this chapter by introducing visual search. The search paradigm allows one to manipulate the number of stimuli in a display while holding constant the response choices. This set-size manipulation often has powerful effects on performance. Next we discussed strategies for separating attentional effects from sensory phenomena that are often confounded with set size. The ultimate strategy was to use the *relevant-set-size paradigm* in which the number of relevant stimuli varies but the number of stimuli in the display is constant. This paradigm provides the most convincing evidence that while sensory effects can be large, there are also attentional effects.

Another specialization of visual search is known as the *simultaneous-sequential paradigm.* This paradigm is designed to distinguish set-size effects that are due to perception from those due to decision alone. It does this by varying the number of simultaneous stimuli while holding constant the number of stimuli relevant to the task.

We also introduced a third paradigm that combines visual search with a dual-task paradigm. In these *dual-search* paradigms, one performs the same kind of search task for two parts of the display. The critical comparison is between the dual-task and the single-task conditions. Any resulting dual-task effect is an effect of divided attention. We then considered various interpretations of such dual-task deficits.

3.9.2 Two theoretical questions

Following the prior chapter, we asked two theoretical questions about the phenomena of interest. First was the *attention question*: Is this effect due to attention or some sly stimulus effect? To completely rule out purely stimulus effects, we relied on the use of identical displays and spatial cueing (the relevant-set-size paradigm). Such studies show that while there can be substantial sensory effects that are driven by the stimuli, there are also effects of divided attention itself.

We next addressed a new version of the *locus question*: Are the observed divided attention effects due to dependencies in perception or to dependencies in decision? For the simplest feature tasks, we argue that the observed effects are due to decision processes. Using either the simultaneous-sequential or dual-search paradigms, there is no effect of divided attention for these simple feature tasks.

3.9.3 One theoretical concept

To account for divided attention effects, we introduced the general concept of *processing dependencies.* These can take several forms and we described serial processing, limited-capacity, parallel processing, and crosstalk. For the simple feature experiments of this chapter, none of these dependencies proved necessary. The standard parallel model was enough to describe the perceptual processing of simple features under the ideal conditions considered here.