Divided attention effects in visual search are caused by objects not by space

Cathleen M. Moore¹
James Pai²
John Palmer²

¹University of Iowa
²University of Washington

Intended for: Journal of Vision
Keywords: divided attention, object-based attention, space-based attention, overlapping objects
Short title: Divided attention is limited by objects
Abstract Word count: 174 (must be less or equal to 200 words)
Last revised: April 17, 2022

Looks great!
JP's comments 4/17/22
Abstract

Divided attention effects have been observed across a variety of stimuli and perceptual tasks. To explain these effects, past studies have proposed both object-based and space-based theories. Object-based theories attribute divided attention effects to limited processing of information from multiple objects, whereas space-based theories attribute these effects to limited processing of information from multiple locations. Extant results in the literature are collectively inconsistent with both simple object-based theories and simple space-based theories of divided attention, as well as with single-pathway hybrid theories. Using the extended simultaneous-sequential method to reveal processing capacity limitations, we found evidence that is consistent with fixed-capacity object processing, unlimited-capacity processing of feature contrast information. Both results can be accounted for by a theory with two processing pathways. Tasks that require object processing must follow a fixed-capacity pathway, and therefore incur divided attention effects. Tasks that depend on only feature contrast, however, can follow a separate unlimited-capacity processing pathway, and therefore do not incur divided attention effects. Importantly, both results were inconsistent with a specifically space-based processing limitation for divided attention.

[CM: delete or define?]
Divided Attention Is Limited by Objects

Studies of visual perception have shown that for some tasks, increasing the number of relevant stimuli reduces performance, whereas for other tasks, increasing the number of relevant stimuli has no effect on performance. Such divided attention effects are assumed to be caused by some aspect of processing that is limited, and are explained in terms of the amount of information that can be processed per unit time (e.g., a trial), referred to as capacity. Tasks that show no divided attention effects are inferred to engage only unlimited-capacity processes, whereas tasks that show divided attention effects are inferred to engage one or more limited-capacity process. With divided attention effects, we ask what aspect of processing is limited? The current study tested two theories of divided attention: that the number of objects that can be processed at one time is limited (object-based theories) or that the number of locations from which stimuli can be processed at one time is limited (space-based theories), or both.

According to object-based theories, the effects of divided attention are imposed by having to process multiple objects rather than a single object (e.g., Duncan, 1984). These theories maintain that it is easier to process multiple attributes of a single object than the same number of attributes of different objects. Pure object-based theories (i.e., ones for which object processing is the only source of limitation) maintain that processing multiple attributes of a single object adds no cost relative to processing a single attribute from a single object. In contrast, according to space-based theories, the effects of divided attention are imposed by having to process information from multiple locations rather than from a single location (e.g., Posner, 1980). These theories maintain that processing multiple stimuli at a single location is easier than processing the same stimuli across multiple locations. Pure space-based theories (i.e., ones for which spatial location is the only source of limitation) maintain that processing features
from multiple objects at a single location adds no cost relative to processing features from a single object at one location.

A metaphor that is often used to illustrate space-based theories is a single spotlight that can point to only one location at a time (e.g., Posner, Synder, & Davidson, 1980). The spotlight illuminates a region of space without regard to what is in it. It highlights not only actors in that region, but also the stage and any props that are also in the region. Highlighting actors who are currently outside of the illuminated region requires movement of the spotlight, and after being moved, anything that was previously highlighted no longer is. Thus, what can be highlighted at any one time is limited by the spatial extent of the spotlight. A comparable metaphor for object-based theories is if actors were highlighted by glow-in-the-dark hats. Now the illuminator is specific to the highlighted actor and not the stage or other objects. Actors with hats are highlighted regardless of where they move, and actors without hats are not highlighted regardless of where they are. Highlighting currently unhighlighted actors, requires that hats be passed to them, and whoever passed the hat will no longer be highlighted. Thus, what can be highlighted at any one time is limited by the number of hats.

Object-based and space-based theories of divided attention propose distinctly different sources of processing limitation. However, it is challenging to discriminate between them because the number of locations is often confounded with the number of objects. Two objects, for example, usually appear in two different locations. The general approach to testing between the theories has been to hold constant the number of locations in which relevant attributes appear while manipulating through various methods the number of objects.
Figure 1. Illustrations of the stimuli used in four studies of divided attention. In all four studies, the same stimulus was presented in the critical conditions. The studies illustrated in panels A, B, and C used the strategy of overlapping two objects. The study illustrated in Panel D manipulated figure-ground relations to manipulate whether one or two objects were relevant.
One strategy of testing between object-based and space-based theories of divided attention is to present stimuli so that they are overlapping each other at a single location in the image. This approach was first used by Rock and Gutman (1981; see also Neisser & Becklen, 1975) to distinguish between object-based and space-based selective attention. They presented overlapping shape stimuli (Figure 1a), and tested whether observers could parse them and selectively process information from one of the two stimuli, and found that they could. This is consistent with objects were being selected since there was only one location. Duncan (1984) extended Rock’s overlapping-stimuli strategy to distinguish between object-based and space-based divided attention. He used displays with an outline rectangle and an overlapping tilted line (Figure 1b), and tested whether there was a cost for having to report information from two objects compared to one. The rectangle varied in height and whether it had a small gap on the left or right side. The line varied in orientation and whether its texture was dotted or dashed. Divided attention effects were measured using a dual-task paradigm. Specifically, observers made two judgments of either two features of a single object (e.g. rectangle size and gap location) or two features of different objects (e.g. rectangle size and line orientation), and these were compared to conditions in which only a single judgment was necessary. Dual-task performance was worse than single-task performance when the two judgments were about two different objects (e.g., side of gap and orientation of line), but no worse than single-task performance when the two judgments were about a single object (e.g., side of gap and size of box). Because the stimuli were at a single location, the divided attention effect in this study can be attributed to object processing in particular.

A particularly compelling aspect of Duncan’s (1984) study is that the identical stimulus displays were used across all of the conditions. Another way of achieving this has been to
present multiple overlapping transparent surfaces with various reportable attributes. Following
Valdes-Sosa and colleagues (Valdes-Sosa, Cobo, & Pinilla, 1998, 2000), Ernst, Palmer, and
Boynton (2012) measured divided attention effects using a dual-task paradigm with overlapping
transparent surfaces that were defined by random-dot kinemategrams (Figure 1c). Observers
detected changes in motion and/or changes in luminance from the same surface or different
surfaces. The results were consistent with object-based theories of divided attention in that there
were dual-task deficits for judging attributes on two different surfaces but little or no dual-task
deficit for judging attributes on a single surface. The divided attention effects in that study, like
Duncan's, can be attributed to object processing in particular because the two surfaces subtended
the same region of image space, and moreover identical stimulus displays were used across
conditions.

Baylis (1994; see also Baylis & Driver 1993) was also able to isolate object-specific
divided attention effects using identical stimuli but with a different strategy. He used stimuli
with ambiguous figure-ground interpretations (Figure 1d), and manipulated whether observers
perceived the central region as figure or the two flanking regions as figure. The task was to
report the relative position of the two interior vertices between the central and the flanking regions.
When the central region was perceived as figure, the vertices were part of one object, whereas
when the flanking regions were perceived as figure the vertices were parts of two objects. The
results showed that performance was worse when making judgements about vertices of two
objects than when making judgments about vertices of one object. This cost can be attributed to
limited object processing in particular because the vertices were always in the same locations,
and again moreover, the stimulus displays were identical across conditions; only the perceptual
organization of them differed.
The results of the studies reviewed so far are consistent with object-based theories of divided attention. Other studies, however, have yielded evidence that is inconsistent with both simple object-based theories and simple space-based theories of divided attention. Han, Dosher, and Lu (2003; see also Liu, Dosher, & Lu, 2009), for example, showed subjects displays with two Gabor patches at two different locations that varied in their orientation and phase, and asked them to make judgments about two different features that could either be from the two different Gabor patches (e.g., the orientation of one and the phase of the other) or from a single Gabor patch. They found that performance was better for within-Gabor-patch judgments than for between-Gabor-patch judgments, which is consistent with both object-based and space-based theories of divided attention because the Gabor patches were in two different locations. However, when subjects made judgments about a single feature (e.g., orientation or phase), performance was no worse when making that judgment for both Gabor patches (i.e., the orientations of both or the phase of both) than when making it for a single Gabor patch. This lack of a divided attention effect is evidence of unlimited-capacity processing across both objects and locations, because there were two objects and two locations. It is therefore inconsistent with the simplest versions of both object-based and location-based theories of divided attention. Similar results have been found for other simple features and detection-like dual tasks (e.g. Bonnel, Stein & Bertucci, 1992; Graham, Kramer & Haber, 1985).

In addition to dual-task studies such as those of Dosher and colleagues, many studies using visual search have yielded evidence consistent with unlimited-capacity processing of features across both multiple objects and multiple locations. Specifically, the pattern of little or no effect of the number of stimuli (i.e., set size) on performance when a target is defined by a single feature is consistent with, and has been offered as evidence of, unlimited-capacity
processing of feature information across locations (e.g., Treisman & Gelade, 1980; c.f., Wolfe, Cave, & Franzel, 1989). Moreover, studies using a search task that manipulated whether stimuli were presented all at once or in sequential subsets (i.e., the simultaneous-sequential method), a method that controls for the number of decisions and other factors across conditions (e.g., Shiffrin & Gardner, 1972), also yielded evidence of unlimited-capacity processing of simple-features across multiple objects and locations (e.g., Huang & Pashler, 2005; Scharff, Palmer, & Moore, 2011a, 2013). Because stimuli in these experiments were all distinct objects, presented at different locations within the visual field, all of these results are inconsistent with the simplest versions of both object-based and space-based theories of divided attention. The characteristic that they have in common with each other and with the dual-task studies reviewed above (e.g., Han et al, 2003) is that the tasks depended only on feature information.

In summary, the collective evidence is inconsistent with the simplest versions of both object-based theories and space-based theories of divided attention. It is clear from studies using overlapping objects, that processing information from multiple objects does incur limited capacity. However, it is also clear, from both dual-task studies (Han et al, 2003, Liu et al., 2009) and visual search studies (e.g., Huang & Pashler, 2005; Scharff, Palmer, & Moore, 2011a, 2013; Shiffrin & Gardner, 1972; Treisman & Gelade, 1980), that there is little or no cost to processing information from multiple objects at multiple locations when the judgment is based on feature information. No theory that asserts a single pathway of processing that has an object-based limit on processing (e.g., Duncan, 1984), a space-based limit on processing (e.g., Posner, 1980) or both (e.g., Vecera 1997; Baylis & Driver, 1993) can account for all of the results.

As a resolution to this apparent conflict, we propose that information is processed along multiple pathways, and that performance in any given task reveals only the processing
limitations that are specific to the information that is relevant to that task. More specifically, we hypothesize, that processing feature-contrast information (e.g., Becker, 2010; Northdurft, 1991, 1993, 2000; Palmer, Verghese, & Pavel, 2000), which need not be attributed to any specific object has unlimited capacity, and so any task that is based on feature-contrast information can follow an unlimited-capacity processing pathway from stimulus to response. In contrast, we hypothesize that attributes that are intrinsic to objects, such as global shape (e.g., Kahneman, Treisman, & Gibbs, 1992; Popovkina, Palmer, Moore, & Boynton, 2021; Wolfe & Bennett, 1997), must be processed along a limited capacity pathway. This general hypothesis, which is common to many theories of visual processing (e.g., Hoffman, 1979; Treisman & Gelade, 1980; Wolfe, 1994; 2021), predicts that tasks requiring only judgments based on feature contrast must yield no divided attention effects, whereas tasks that depend on object attributes like global shape, will yield divided attention effects. It makes no predictions of divided attention effects for multiple locations, per se. We tested these predictions, and further, tested whether the divided attention effects that occurred could have been imposed by limited spatial processing.

Overview of Experiments

We used an extended version of the simultaneous-sequential paradigm (e.g., Scharff et al., 2011a), which provides a means of distinguishing between unlimited-capacity processing, fixed-capacity processing, and limited but not fixed capacity processing. Fixed capacity processing refers to when processing is limited to a constant amount of information (e.g., one object or one location) per unit time (Shaw, 1980). Processing can be limited without being fixed capacity, and of course it can be unlimited capacity. The extended simultaneous-sequential method provides a means of discriminating among these alternatives.
Divided Attention Is Limited by Objects

Across experiments, we varied the task and whether stimuli were spatially separate or overlapping. To preview the results, we found large divided attention effects that were consistent with fixed capacity in experiments that used tasks that required object processing, regardless of whether the stimuli were in separate locations (Experiments 1 and 2) or overlapping (Experiment 4). In contrast, we found no divided attention effect in an experiment in which the depended on feature contrast only and stimuli were presented in separate locations (Experiment 3). Together these results are consistent with a multiple pathway theory that has at least one unlimited-capacity processing pathway within which feature contrast is processed, and at least one limited-capacity processing pathway for which the limit is object based, and not space based. The results are inconsistent with all single-pathway models, including pure space-based theories (e.g., Posner, 1980; Posner et al., 1980), pure object-based theories (e.g., Duncan, 1984), and hybrid theories (Vecera, 1997).

Experiment 1: Shape Judgments of Multiple Objects at Separate Locations

Experiment 1 used a global-shape discrimination task in the extended simultaneous-sequential paradigm. The stimuli, which were inspired by Rock and Gutman (1981), can not be discriminated on the basis of simple feature-contrasts (see Figure 2). Stimuli were presented at separate locations.

Method

Stimuli. The stimuli were three sets of novel black outline shapes presented on a gray background with five exemplars each. The sets can be labeled as quadrilaterals, triangles, and curved Rock-like figures (after Rock & Gutman, 1981). The five exemplars from each of the three sets are shown in Figure 2.1 To create each set, a basic shape was chosen and modified.

1 A fourth set of quadrilaterals with one curved side (not shown) was included for some of the observers, but was dropped for the other observers due to being more difficult to distinguish than the other stimulus sets.
For example, the set of five quadrilaterals in Figure 1 were created from a base square by perturbing the vertices. Each exemplar was designed to be asymmetrical to provide a unique image at different orientations. All images were 100 x 100 pixels (~4 degrees of visual angle) with the shapes being approximately equal in size within the image bounds. Finally, exemplars could appear at four possible rotations (0°, 90°, 180°, and 270°), for a total of 20 images per set and 60 images for the entire experiment.

Gaussian pixel noise was superimposed on the outline shapes during every frame to limit performance. The standard deviation of the noise luminance was 50% of the mean luminance and was used to define its contrast (2 observers had 60% noise contrast). Target contrast and stimulus duration were manipulated to adjust task difficulty for each observer. The target contrast ranged from 35% to 50% with a mean of 44%. Stimulus duration ranged from 0.1 to 0.25 s with a mean of 0.18 s.
Figure 2. Three stimulus sets with five exemplars each were used in the study. The stimuli were novel outline shapes that included quadrilaterals, triangles, and curved figures inspired by Rock and Gutman (1981). Not shown are the rotated variations (0°, 90°, 180°, and 270°) of each exemplar. This resulting in 20 images per set and thus 60 images overall.
Task and Design. An extended version of the simultaneous-sequential paradigm was used to measure the effects of divided attention. The task was to report the location of a single pre-specified target among three distractors. The critical manipulation for assessing capacity limitations was whether the four stimuli were presented at the same time (simultaneous) or in sets of two in separate displays (sequential). A third condition in which all four stimuli were presented twice (repeated) extended the basic simultaneous-sequential design.

Figure 3 illustrates the three conditions. All trials began with a study display (2 s) that defined the target object, which was followed by a blank display (0.5 s), a fixation display (0.5 s), one or two stimulus displays (0.2 s each), and a probe display that included a reminder of the target and remained until a response was made. Stimuli within a trial were drawn from a single set (e.g. quadrilaterals). The location of the target was selected randomly for each trial. In order to minimize reliance on simple features to find the target, it was always presented in the stimulus display at a different rotation from that in the study and probe displays. Other than that constraint, stimulus rotation was selected randomly for each stimulus. Dynamic noise was superimposed on stimuli to limit performance (illustrated in the figure by shaded regions).

In the simultaneous condition (left column), all four stimuli were presented in a single stimulus display (0.2 s). In the sequential condition, stimuli were presented two at a time (first the upper left and lower right, then the lower left and upper right) across two stimulus displays (0.2 s each), separated by a blank interval (1.8 s). The target was equally likely to appear in the first or second stimulus display. Finally, in the repeated condition, all four stimuli were presented twice (0.2 s each), separated by a blank interval (1.8 s). The displays were identical except for the noise.
Figure 3. Illustration of the task and design used in Experiment 1. Each trial began with a study display that defined the target shape and ended with a probe display of the same shape. The task was to report in which of four locations the target appeared. In the simultaneous condition (left column), the first and only stimulus display contained four objects, a target (presented at a different rotation from that in the study display) and three distractors. In the repeated condition (right column), the first stimulus display is like that of the simultaneous condition, but is followed by a second presentation of the same display. Stimuli in the stimulus displays were superimposed with dynamic noise, indicated by the shaded regions in the figure.
Logic. The logic of the extended simultaneous-sequential method is illustrated in Figure 4. It provides a way of discriminating between unlimited-capacity and fixed-capacity models. The numbered circles represent the four stimuli that are presented on each trial, and the gray bars represent the time within the trial each stimulus is present for each of the three conditions. The black arrows inside of the gray bars represent the hypothetical amount of perceptual processing that can be performed on that stimulus, given the constraints of the different models. First consider the unlimited-capacity model. It predicts no difference between the simultaneous and sequential condition, but an advantage for the repeated condition. This is because under an unlimited-capacity model, the amount of processing that is possible for any given stimulus is unaffected by the number of stimuli that are simultaneously present, and therefore, the amount of processing that any given stimulus receives is the same in the simultaneous and sequential conditions. However, because the displays are presented twice in the repeated condition, each stimulus receives twice as much processing as it does in either the simultaneous or sequential conditions. Now consider the fixed-capacity model. It predicts an advantage for the sequential condition over the simultaneous condition, but no further advantage for the repeated condition. This is because if only two stimuli, for example, can be processed within the time of the display duration, then two stimuli could be processed in the simultaneous condition, whereas four can be processed in the sequential condition, two during the first display and two during the second. Because no more than two stimuli can be processed within a given display duration, however, then repeating displays with all four stimuli present (repeated condition) provides no advantage over just presenting two at a time (sequential condition).
Figure 4. Illustration of the logic of the extended simultaneous-sequential paradigm. The columns correspond to two of the benchmark models and the rows correspond to the three conditions. Each cell illustrates the predictions for a given condition and model. The numbered circles represent the relevant stimuli and the grey bars represent the display time of a stimulus. Within each bar, the black arrows represent the hypothetical processing of the particular stimulus. In the unlimited-capacity model, performance is unaffected by the number of relevant stimuli in a stimulus display. The doubled exposure of each stimulus in the repeated condition yields higher performance. In the fixed-capacity model, the number of relevant stimuli in a stimulus display limits performance. Stimuli can be processed only one after another. In this example, only two stimuli can be processed in a given display. Consequently, two stimuli can be processed in the simultaneous condition and four can be processed in the sequential condition. For this model, the repeated condition gives no advantage over the sequential condition.
Figure 5 shows the predictions for three benchmark models—unlimited capacity, limited (but not fixed) capacity, and fixed capacity—under a single set of assumptions using a common framework of signal detection theory. These models are formally defined in Scharff et al. (2011a). The predictions here are shown relative to performance in the sequential condition which was fixed at 75%, and an assumed overall effect of 8%. We emphasize the contrasting equality predictions of the unlimited-capacity and fixed-capacity models because they are robust to the details of the model (e.g., distributional assumptions).
Figure 5. Example predictions of three models are illustrated relative to 75% performance in the sequential condition. As shown in the left panel, unlimited-capacity processing predicts \( \text{simultaneous} = \text{sequential} < \text{repeated} \). As shown on the right panel, fixed-capacity parallel model or a serial model predicts \( \text{simultaneous} < \text{sequential} = \text{repeated} \). And, as shown in the middle panel, an intermediate effect of limited capacity is revealed by the pattern \( \text{simultaneous} < \text{sequential} < \text{repeated} \). The specific 8% difference between simultaneous and repeated is predicted by the further assumption of a yes-no task and Gaussian distributions.
Observers. Observers were volunteers with normal or corrected-to-normal visual acuity, some were paid in compensation for their time. To determine the appropriate sample size of observers, we examined the results of four similar experiments in Scharff, Palmer and Moore (2013, excluding Experiment 3 with only 2 observers and Experiment 6 with simple shapes). These experiments all used similar methods to estimate the sequential advantage which is the heart of the current experiments. The observed sequential advantage for each experiment was 10.3, 9.3, 8.0 and 7.0% with a mean of 8.7%. The corresponding standard deviation of the sequential advantage was 1.7, 1.8, 3.4 and 4.8% with a mean of 2.9%. Using the mean values, a power analysis was conducted to find the minimum sample size needed to detect a sequential advantage of 8.7% with an alpha of .05 and the power of .95 (beta of 0.05). The result was \( n = 4 \). To be conservative, 6 observers were used as in the Scharff study.

After completing the experiments in this article, we checked how good this strategy was given the results observed here. The sequential advantage in the three global shape experiments were 13.8, 4.9 and 10.5% for a mean of 9.7%. The corresponding standard deviations were 5.0, 3.6 and 4.4% for a mean of 4.3%. For these values, the estimated minimum sample size was \( n=5 \). Thus, our strategy of using a sample size of 6 was appropriate.

Apparatus. Experiment 1 was conducted with two apparatus. Three observers used an original apparatus and three used an updated apparatus. For both, the stimuli were displayed on a flat-screen CRT monitor (19" ViewSonic PF790) controlled by a Power Mac G4 (Dual 1.0 GHz). The initial apparatus used Mac OS 9.2 and the updated version used Mac OS X 10.4. The stimuli were displayed at a resolution of 832 x 624 pixels, a viewing distance of 60 cm (25.5 pixel/degree at screen center), and a refresh rate of 75 Hz (120 Hz for Mac OS X). The monitor had a peak luminance of 119 cd/m², and a black level of 4.1 cd/m², mostly due to room
illuminaton. Stimuli were created in Adobe Illustrator CS3 and displayed using Psychophysics Toolbox 2.44 for MATLAB 5.2.1 (Mac OS X: Psychophysics Toolbox 3.0.9 for MATLAB 7.4; Brainard, 1997). A chin rest with an adjustable chair ensured a fixed distance from the display between observers.

**Procedure.** Observers completed several practice sessions in which the stimuli were high contrast and long duration in order to learn the task. Experimental sessions consisted of 12 single-condition blocks 12 trials each (4 blocks each of the simultaneous, sequential, and repeated conditions), for a total of 144 trials. Each observer completed 10 experimental sessions resulting in a total of 1440 trials per observer. Observers reported the location of the target (upper-left, upper-right, lower-left, lower-right) using a corresponding key press on a number pad. There was no time limit on the response.

**Analysis.** All statistical tests were 2 tailed. Alpha was fixed at .05. All error bars are the standard error of the mean.

**Results**

The results of Experiment 1 are shown in Figure 6. Percent correct is plotted for the three main conditions (simultaneous, sequential, and repeated). Chance performance is 25% correct for this four-alternative localization task. There was a reliable advantage of sequential over the simultaneous presentation with a mean difference of 14% ± 2%, (95% Confidence Interval (CI) = 8.6, 19.0%, t(5) = 6.84, p = .00). There was no reliable difference between the sequential and the repeated conditions, mean differences = 0.5% ± 2.0% (95% CI = -4.8, 5.8%, t(5) = 0.24, p > .1).

This pattern of results is consistent with predictions of a fixed-capacity parallel model or a simple serial model and inconsistent with the predictions of an unlimited-capacity parallel model.
We also tested for temporal effects in the sequential condition. Specifically, there was no reliable difference when the target appeared in the first display versus the second display, with a mean difference of $1.5\% \pm 1.1\%$ (95% CI = $0.8\% - 2.2\%$, $t(5) = 1.42, p > .1$) in favor of better performance with the target in the second display. This lack of temporal effects supports the appropriateness of collapsing performance over the two sequential displays.

The results of this experiment show that visual search for a particular global shape in a display of four shapes has fixed capacity. This contrasts with judgments of simple feature contrasts such as luminance and size, which have yielded evidence of unlimited capacity using this method (Huang & Pashler, 2005; Scharff et. al., 2011a). Instead, it is similar to the divided attention effects previously seen in other global shape judgments, animal categorization, and word categorization (Harris, Pashler, & Coburn, 2004; Scharff et. al., 2011a, 2011b, 2013). This experiment is mute with regard to whether the fixed-capacity limit observed here is due to an object-based or space-based processing limitation because the four different objects were presented in four different locations. The method must be adapted to address this further question.
Figure 6. Results of Experiment 1 with a localization judgment of shape. Percent correct is shown for the three conditions. Chance is 25%. There is a sequential advantage for the sequential condition over the simultaneous condition. In addition, there is no reliable difference between the sequential and repeated conditions. This pattern of results is consistent with fixed-capacity parallel or serial models. Error bars are standard error of the mean.
Experiment 2: Shape Judgments of Objects at Separate Locations with a Cued Design

Experiment 2 was logically identical to Experiment 1, but the procedure was refined in anticipation of conducting a version using overlapping stimuli to discriminate between object-based and space-based processing limitations. Specifically, we conducted a version in which the stimuli were identical across all conditions. What differed was how many stimuli were cued as relevant for a given display period. This cued design, first used in Scharff, et al. (2011b, Experiment 2), controls for potential differences in stimulus interactions, separate from processing limitations, which will be an especially significant concern when overlapping stimuli are used. In addition, the task was changed from a localization task, which cannot be used in a single-location version of the experiment, to target-present versus target-absent judgment.

Method

Observers. Six observers with normal or corrected-to-normal vision were volunteers. Some were paid in compensation for their time.

Design. Figure 6 illustrates the three conditions: cued simultaneous, cued sequential, and cued repeated (stimuli in the figure are not to scale). All conditions had the following sequence of events. A trial began with a study display (1 s) that defined the target, which was followed by a brief noise display (0.2 s), a blank display (0.5 s), the first cue display (0.5 s), another blank display (0.5), and then the first stimulus display (~0.2 s), which contained four shapes: two on each side of fixation. This was followed by another blank display (0.5 s), the second cue display (0.5 s), a blank display (0.5 s), and finally the second stimulus display (~0.2 s). Cues indicated which stimuli were relevant for the upcoming stimulus display. On each trial, there was a 50% chance that one of the four relevant stimuli was the target, all other stimuli were distractors. The trial ended with a probe display (not shown) that contained a reminder of the target and remained
until response. Feedback was provided following errors, and the intertrial interval was 1.5 s. Performance was limited by superimposing each stimulus display with dynamic salt-and-pepper noise which is represented in the figure by the shaded region. The purpose of the initial noise display near the beginning of the trial was to equate the contrast adaptation of the two stimulus displays (both were preceded by a noise display).

Conditions differed in which stimuli were cued as relevant. In the cued-simultaneous condition, cues indicated that the stimuli on both sides of either the first stimulus display (half the blocks) or the second stimulus display (half the blocks) and no stimuli were cued as relevant for the other stimulus display. In the example shown in the figure, this simultaneous cue was the two lines to either side of fixation in the first cue interval. In contrast, the second cue interval contained the fixation cross alone. This sequence of cues indicated that the first display was relevant to the task and the second display was irrelevant. For other blocks of trials, the second display was cued instead. Targets were presented in only the relevant displays. For the illustrated example, the target was rotated clockwise 90 degrees in the upper right of the first display.

In the cued-sequential condition, one side was cued for both stimulus displays. In the example, the right side was cued. Thus only the stimuli on the right side were relevant to the task. For other blocks of the cued-sequential condition, the left side was cued for the entire block. Targets only appeared on the cued side, and they appeared equally often in the first or second stimulus display.

In the cued-repeated condition, both sides of both displays were cued. The unique feature was that the stimuli in the first display were repeated for the second stimulus display.
Specifically, the shapes were identical but the noise and jittered location of the shapes was varied from the first to the second display.

**Stimuli.** The stimuli were the same three sets of novel outline shapes as used in Experiment 1. The noise used with the shapes to limit performance was different than Experiment 1. Dynamic salt-and-pepper noise was applied during every frame of the stimulus display. Each pixel in the display had a probability of being replaced with a randomly chosen black or white pixel. This probability $p$ was adjusted for each observer to maintain an intermediate level of performance ($p$ ranged from .40 to .65 with an mean of .53). This high contrast, salt-and-pepper noise was an effective mask for these outline stimuli and also helped preserve the distinctive colors of the outlines, which is important for when we conducted an overlapping stimuli version (Experiment 4). Highly visible stimuli (low noise, long duration) were used for training. The entire monitor had a displayable area of about $33^\circ$ by $24^\circ$. Of this, the stimulus and noise fields occupied the central $14^\circ$ by $10^\circ$. The noise fields were $6^\circ$ by $10^\circ$ and were centered $4^\circ$ to either side of fixation. This left a $1^\circ$ space between the inner edge of the noise field and fixation. The squares were jittered by $\pm 0.5^\circ$ around a mean location that was horizontally centered within the noise field and were centered vertically $2^\circ$ above and below the horizontal meridian. The stimulus duration was adjusted for each observer (range 0.1 to 0.5 s, mean of 0.24 s).
Figure 7. Illustration of the cued procedure used with shape judgments in Experiment 2. As before, each trial consisted of a study display followed by stimulus displays and a probe display (not shown). In each stimulus display, four objects were shown. The cue displays used lines to the left and right of fixation to indicate the relevant stimuli in the following display. In this example of the cued-simultaneous condition, the first cue had lines to the left and right indicating that objects on both the left and right were relevant in the first stimulus display. The second cue had no lines, indicating no objects were relevant in the second stimulus display. In the cued-sequential condition, the first and second cues were lines to the right, indicating the objects on the right were relevant in the first and second stimulus display. In the cued-repeated condition, both lines were present in both cue displays, indicating all objects were relevant in both stimulus displays. The presence of dynamic noise is indicated by shading.
**Apparatus.** This experiment used a further updated apparatus relative to Experiment 1. The stimuli were displayed on the same flat-screen CRT monitor (19" ViewSonic PF790) but now it was controlled by a Mac Mini (2.66 GHz Intel Core 2 Duo) using Mac OS X 10.6.8. The display still had a resolution of 832 x 624 pixels, a viewing distance of 60 cm (25.5 pixel/degree at screen center). But now it had a refresh rate of 120 Hz, a peak luminance of 104 cd/m², and a black level of 3.9 cd/m², mostly due to room illumination. Other details were the same as Experiment 1.

Unlike Experiment 1, eye position was recorded on all trials using an EyeLink II, 2.11 with 250 Hz sampling (SR Research, ON). The EyeLink II is a head-mounted binocular video system and was controlled by software using the EyeLink Developers Kit for the Mac 1.11.1 and the EyeLink Toolbox 3.0.11 (Cornelissen, Peters, & Palmer, 2002). The position of the right eye was recorded for all trials, and trials were included in the analysis only if fixation within a 2° window was confirmed. When fixation failed, five consecutive high frequency tones were sounded and the trial was aborted. The percentage of aborted trials for each observer ranged from 2.2% to 7.7% with an overall mean of 4.8 ± 0.9%. Thus the observers maintained fixation on almost all trials and none of the analyses included trials with blinks or saccades to the stimuli.

**Procedure.** Observers performed a modified yes-no task rather than the localization task of Experiment 1. They had to determine whether the target was present in a given trial using a rating scale with four possible responses: likely-no, guess-no, guess-yes, and likely-yes. The ratings allowed us to perform a Receiver Operating Characteristic (ROC) analysis to control for bias. Specifically, we calculated the percent of the area under the ROC curve. This measure is an estimate of the unbiased percent correct. To encourage accuracy, there was no time limit on the responses. There were 3 main conditions but 5 kinds of blocks. This is because the cued-
simultaneous condition had blocks with the first display relevant or the second display relevant. Similarly, the cued-sequential condition had blocks with the left side relevant and others with the right side relevant. Text instructions at the beginning of each block also specified which condition was to be presented (e.g. cued-sequential, left side). Each condition was presented in a block of 16 trials. A single experimental session consisted of 6 blocks (2 from each main condition), for a total of 96 trials. After practice sessions, each observer ran 16 sessions resulting in a total of 1536 trials per observer.
Figure 8. Results of Experiment 2 with a yes-no judgment of shape and a cueing paradigm. Percent area under the ROC is shown for the three conditions. Chance is 50%. There is a sequential advantage for the sequential condition over the simultaneous condition. In addition, there is no reliable difference between the sequential and repeated conditions. This pattern of results replicates Experiment 1 and is consistent with fixed capacity.
Results

The results of Experiment 2 are shown in Figure 8. The percent area under the ROC is plotted against the three main conditions. Chance performance is 50% correct for this yes-no task. As with Experiment 1, there was a reliable sequential advantage of the cued-sequential condition over the cued-simultaneous condition: a mean difference of $4.9\% \pm 1.5\%$, $t(5) = 3.36$, $p = .02$. There was no reliable deviation of the sequential condition from the repeated condition, mean differences $= 2.1\% \pm 2.1\%$, $t(5) = 1.02$, $p > .1$. This pattern of results is consistent with predictions of a fixed-capacity parallel model or a simple serial model and inconsistent with predictions of an unlimited-capacity parallel model. One might wonder why the sequential advantage is only 5% here when it was 14% in Experiment 1. At least part of the reduction in the size of the effect is due to using a yes-no task (50% chance) instead of a four-choice localization task (25% chance). See Busey and Palmer (2008) for a detailed comparison of models for localization and yes-no.

To test for any temporal effects in the cued-sequential condition, we compared performance for the target in the first and second displays and found no reliable difference, mean difference $= 0.7\% \pm 1.5\%$, $t(5) = 0.43$, $p > .1$. With this cued design, one can also compare performance for targets in the first and second display of the cued-simultaneous condition and again there was no reliable difference, mean difference $= 2.3 \pm 2.5\%$, $t(5) = 0.95$, $p > .1$. Thus, no sign of temporal effects.
Experiment 3: Size Judgments of Cued Stimuli

Before testing whether the capacity limitations observed in Experiments 1 and 2 reflect object-based or space-based limitations (or both), we sought to confirm that using the same general logic, feature-contrast judgments would reflect unlimited-capacity processing. As briefly reviewed in the introduction, the results from studies using feature-contrast tasks are inconsistent with both object-based and space-based theories in their simplest forms. We sought to confirm this finding within the same context as that which we are using to test for object-based and space-based limitations. To this end, Experiment 3 used a size-judgment task in an experiment that was logically identical to Experiment 2. Size is considered a relatively simple feature and a good candidate for processing by the feature-contrast pathway. As such, we expected to find evidence of unlimited-capacity processing.

Method

Design. We used the cued version of the simultaneous-sequential paradigm and kept most of the details the same as Experiment 2. Figure 9 illustrates the four conditions presented in separate blocks: cued simultaneous, cued sequential, cued repeated and cued all. Three of these conditions were the same as Experiment 2 but the cued-all condition was new. All conditions had the following sequence of events. A trial began with a study display (1 s) that defined the target followed by brief noise display (0.2 s), a blank display (0.5 s), the first cue display (0.5 s), another blank display (0.5), and then the first stimulus display (0.2 s). The stimulus display contained four squares: two on each side of fixation in their own noise field. The location of each square was jittered by a small amount as described below in the Stimulus section. On each trial, there was a 50% chance that one of the squares was the target, otherwise they were all distractors. After that there was a similar sequence of blank and cue displays
leading up to the second stimulus display (0.2 s). This was followed by a probe display (not shown) that contained a reminder of the target that remained until response. After the response there was feedback for errors and an intertrial interval of 1.5 s. Performance was limited by superimposing each stimulus display with dynamic salt-and-pepper noise which is represented by the shaded region. The presentation of a noise display near the beginning of the trial was to equate the contrast adaptation of the two stimulus displays.

In the cued-simultaneous condition, there were cues that indicated the relevant stimuli were on both sides of the first display or both sides of the second display. In the example shown in the figure, this simultaneous cue was the two lines to either side of fixation in the first cue interval. In contrast, the second cue interval contained the fixation cross alone. This sequence of cues indicates that the first display was relevant to the task and the second display was irrelevant. For other blocks of trials, the second display was cued instead. Targets were presented only in the relevant displays. For the illustrated example, the target is the larger square in the upper right of the first display.

In the cued-sequential condition, one side was cued in both stimulus displays. In the example, the right side was cued. Thus only the stimuli on the right side were relevant to the task. For other blocks of trials, the left side was cued for the entire block.

In the cued-repeated condition, both sides of both displays were cued. The unique feature was that the stimuli in the first display were repeated for the second stimulus display. Specifically, the squares are identical but the noise and location of the squares was varied from the first to the second display. Performance in such redundant displays provided a benchmark to compare effects of sequential versus simultaneous displays.
We also included a new condition, the cued-all condition, which had cues for both sides of both displays, making all of the stimuli relevant. This provided a larger relevant set size for comparison to the main conditions. Findings such a set size effect would confirm that the cues were being used by the observers. This was a particular concern for this experiment because we expected little or no effects of divided attention.

Observers. Six observers were paid or unpaid volunteers with normal or corrected-to-normal vision.
Figure 9. Illustration of the cued procedure used with size judgments in Experiment 3. As before, each trial consisted of a study display followed by two stimulus displays and a probe display (not shown). In each stimulus display, four objects were shown. The cue displays used lines to the left and right of fixation to indicate the relevant stimuli in the following display. In the cued-simultaneous condition, the first cue had lines to the left and right indicating that objects on both the left and right were relevant in the first stimulus display. The second cue had no lines, indicating no objects were relevant in the second stimulus display. In the cued-sequential condition, the first and second cues were lines to the right, indicating the objects on the right were relevant in the first and second stimulus display. In the cued-repeated condition, both lines were present in both cue displays, indicating all objects were relevant in both stimulus displays. In the cue-all condition, all 8 stimuli were relevant. The presence of dynamic noise is indicated by shading.
**Apparatus.** The apparatus was the same as Experiment 2 and eye position was recorded. The percentage of aborted trials for each observer ranged from 2.4% to 6.3% with a mean of 4.2 ± 0.5%. Thus the observers maintained fixation on almost all trials and none of the analyses included trials with blinks or saccades to the stimuli.

**Stimuli.** In this experiment we turned to judgments of size instead of global shape. The stimuli were outline squares presented for 0.2 s. The distractor width was 1.5° and the targets were incremented by variable amounts (e.g. 3 pixels which was about 0.12°) to achieve overall performance around 80% correct. In fact, all but one observer used an increment of 5 pixels which was about 0.2° (Observer AM used 3 pixels). They were presented as one-pixel thick, black outlines on a mid-gray background. Dynamic salt-and-pepper noise was applied during every frame of the stimulus display to limit performance. Each pixel in the display had a probability (p = .65) of being replaced with a randomly chosen black or white pixel. This high contrast, salt-and-pepper noise was an effective mask for these outline stimuli and also helped preserve the distinctive colors of the outlines for the overlapping stimuli of later experiments. Other details of the stimuli were the same as Experiment 2.

**Procedure.** As in Experiment 2, observers performed the modified yes-no task that was used in Experiment 2. Each condition was presented in a block of 16 trials. A single experimental session consisted of 8 blocks (2 from each main condition), for a total of 128 trials. After practice sessions, each observer ran 16 sessions resulting in a total of 2048 trials per observer.

**Results**

The results of Experiment 3 are shown in Figure 10. The percent area under the ROC is plotted against the three main conditions. As with the previous experiment, chance performance
is 50% correct for this yes-no task. Performance in the cued-sequential condition had no
advantage over the cued-simultaneous condition: a mean sequential advantage of -1.0% ± 1.5%,
\(\left(95\% \text{ CI} = -4.7, 2.8\%, t(5) = 0.65, p > .1\right)\) Instead, there was a reliable difference between the
cued-sequential condition and the cued-repeated condition of 6.4 ± 1.7% \(\left(95\% \text{ CI} = 2.0, 10.8\%,
?7.7 > \right)\ t(5) = 3.78, p = .01\) This pattern of results is consistent with the predictions of an unlimited-
capacity model and is inconsistent with predictions of a fixed-capacity model.

To test for any temporal effects in the cued-sequential condition, we compared presenting
the target in the first and second displays and found no reliable difference, mean difference = -
1.3% ± 2.4%. \(\left(95\% \text{ CI} = -7.4, 4.7\%, t(5) = 0.56, p > .1\right)\) The cued-simultaneous condition was
also examined and showed no reliable difference, 2.0% ± 1.0%. \(\left(95\% \text{ CI} = -0.5, 4.5\%, t(5) = 2.07, p > .05\right)\).

Not shown in the figure is the additional condition in which all of the stimuli were cued.
This cue-all condition was to test whether the observers were using the cues and in this condition
the mean performance was 76.9 ± 2.0%. To test for the use of the cues, we calculated the
difference in performance between the average of the two cued conditions (cued-simultaneous
and cued-sequential) and the cue-all condition, which was reliable, mean difference = 3.7 ±
0.9% \(\left(95\% \text{ CI} = 1.5, 6.0\%, t(5) = 4.23, p = .008\right)\). Thus, the observers were able to use the cues to
improve their performance. But despite this, they were not able to use the sequential condition to
improve their performance over the simultaneous condition. This equivalence of the sequential
and simultaneous conditions is the hallmark of unlimited-capacity processing.
Figure 10. Results of Experiment 3 with a yes-no judgment of size and a cueing paradigm. Percent area under the ROC is shown for the three main conditions. Chance is 50%. There is no reliable sequential advantage for the sequential condition over the simultaneous condition. In addition, there is instead a reliable difference between the sequential and repeated conditions. This pattern of results contrasts with the other experiments and is consistent with unlimited capacity.
Experiment 4: Shape Judgments of Overlapping Stimuli

Experiments 1 and 2 showed evidence of fixed capacity for shape judgments of outline objects presented at multiple locations. While these results demonstrate a clear processing limitation, they are consistent with both object-based and space-based theories because the limit could reflect having to process multiple objects or having to process stimuli at multiple locations. Experiment 4 used the overlapping-stimuli strategy to test between these two alternatives.

Method

Design. Experiment 4 used the cued version of the extended simultaneous-sequential paradigm that was introduced in Experiment 2 so that stimuli were identical across conditions. This was especially important for this experiment because stimulus interactions were expected to be substantial for overlapping stimuli. Using the cued version of the method equated visibility across conditions. Figure 11 shows the three conditions: cued-simultaneous, cued-sequential, and cued-repeated. A trial began with a study display (2 s) followed by a brief noise mask (0.2 s) and a blank display (0.5 s). Then, the first cue (1.0 s) followed by a blank (0.5 s) and the first stimulus display (ranged from 0.15-0.25 s with a mean of 0.19 s), then a second pair of cue and stimulus displays. The cues were colored crosses at fixation that varied in color (red, blue, or black) to indicate the color of the relevant stimulus in the following display. In all trials, there was only a single relevant location and at most two relevant objects. The superimposed dynamic pixel noise is shown by the shaded regions.

In all conditions, two pairs of different colored overlapping objects were briefly displayed in the two stimulus displays. In the cued-simultaneous condition (left column), one of the two pairs was cued as relevant by the fixation cross changing to red and blue. A black fixation cross preceded the other pair indicating that it contained no relevant objects. In the
example, the first pair is cued. In other blocks, the second pair was cued. Text instructions at
the beginning of each block also specified which stimulus display (first or second) contained the
relevant objects.

In the cued-sequential condition, a given color (blue in the example) was cued as relevant
by the fixation cross changing to that color. Objects of that color were relevant in both displays,
and the objects of the other display were irrelevant in both displays. Thus, only one object was
relevant in each stimulus display. The relevant color was the same for all trials within the block
and was also specified by text instructions at the beginning of the block. In the example, the blue
cue indicated the blue outlines were relevant in both displays.

Finally, in the cued-repeated condition, the same pair of colored overlapping objects was
briefly displayed in the two stimulus displays. A multicolored cue preceded each stimulus
display, indicating that both objects were relevant, as in the simultaneous condition. The
difference is that the repeated condition consists of two stimulus displays that contained the same
objects.

**Observers.** Six observers participated in Experiment 4. As in Experiment 1, this
experiment was run using two apparati each used by three of the observers.

**Apparatus.** Same two apparati as Experiment 1. We did no eye tracking for this
experiment with foveal stimuli.
Figure 11. [Color figure] Illustration of the cued procedure used with overlapping objects in Experiment 4. As in previous experiments, each trial consisted of a study display followed by two stimulus displays and a probe display (not shown). In each stimulus display, there was a blue outline and a red outline object. They overlapped at a single location with a slight offset from one another. The cue displays used colored crosses that indicating the relevant stimuli in the following display. In this example of the cued-simultaneous condition, the first cue was blue and red, indicating that both objects were relevant in the first stimulus display. The second cue was black, indicating no objects were relevant in the second stimulus display. In the cued-sequential condition, the first and second cues was one color (e.g., blue), indicating the color of the relevant object in the first and second stimulus display. In the cued-repeated condition, both the first and second cues were red and blue, indicating both objects were relevant in both stimulus displays. The presence of dynamic noise is indicated by shading.
**Stimuli.** The three sets of shapes from Experiment 1 and 2 were also used in Experiment 4. The fourth set from Experiment 1 was used by three of the observers in the early version of the experiment but not by the other observers. Color was used to help distinguish the overlapping stimuli. The stimuli were red or blue outlines with a 1-pixel thickness. To maximize saturation, the two colors were the primaries of the video monitor. Each stimulus display in the experiment consisted of a red-blue pair of shapes. The red and blue colors of the stimuli were matched in luminance using the maximum luminance available for the blue primary. Additionally, a slight horizontal and vertical offset of 5 pixels (~0.2°) was applied to one shape in an overlapping pair. As illustrated in the examples of the figure, this shift reduced the overlap of the outlines themselves. As in Experiment 1 and 2, the target shape was always a different rotation from the study and probe displays.

Following Experiments 2 and 3, dynamic salt-and-pepper noise was applied during every frame to limit task performance. Each pixel in the display had a probability $p$ of being replaced with a randomly chosen black or white pixel ($p = .65$ for three observers, $p = .75$ for the others).

**Procedure.** We used the modified yes-no task that was used in Experiments 2 and 3. To maintain task difficulty, stimulus duration and noise probability was adjusted for each observer based on their performance. Duration ranged from 0.15 to 0.3 s with a mean of 0.19 s and the noise probability ranged from .65 to .75 with a mean of .7. Each session consisted of 12 blocks for a total of 144 trials per session. Each observer ran 10 sessions for a total of 1440 trials per observer.
Figure 12. Results of Experiment 4 with a yes-no judgment of the shape of an overlapping object. Percent area under the ROC is shown for the three conditions. Chance is 50%. There is a sequential advantage for the sequential condition over the simultaneous condition. In addition, there is no reliable difference between the sequential and repeated conditions. This pattern of results generalizes prior results with shape judgments to overlapping displays. As with the other shape judgments, the pattern of results is consistent with fixed capacity.
Results

The results of Experiment 4 are shown in Figure 12. Percent area under the ROC curve is plotted for the three main conditions: cued-simultaneous, cued-sequential, and cued-repeated. Chance performance for this yes-no task is 50%. There was a reliable sequential advantage for the cued-sequential condition over the cued-simultaneous condition, mean difference = 10.5% ± 1.8%, (95% CI = 5.9, 15.1%, \( t(5) = 5.89, p = .002 \)) In contrast, there was no reliable difference between the cued-sequential and the cued-repeated conditions, mean difference = 0.7% ± 1.4%, (95% CI = -2.9, 4.3%, \( t(5) = 0.47, p > .1 \)) As with Experiment 1 and 2, this pattern of results is consistent with a fixed-capacity model, and is inconsistent with an unlimited-capacity parallel model.

There was no reliable difference for trials in which the target was in the first display or the second display in either the cued-sequential condition, mean difference = 0.2% ± 1.7%, (95% CI = -4.3, 4.6%, \( t(5) = 0.10, p > .1 \)) or the cued-simultaneous condition, mean difference = 2.7% ± 3.2% (95% CI = -5.5, 10.8%, \( t(5) = 0.84, p > .1 \)) Thus, we are confident that collapsing over the two intervals is appropriate.

The results of this experiment indicate that the divided attention effects that we have observed in previous experiments cannot be attributed to location-based processing limitations. Observers never had to process stimuli from multiple locations in this experiment, and yet the results were again consistent with fixed-capacity processing. This is consistent with the object-based theories of divided attention.
General Discussion

We used the extended simultaneous-sequential method to distinguish between object-based and space-based theories of divided attention. In particular, we used a shape judgment task, which was assumed to engage object processing, with non-overlapping (Experiments 1 & 2) and overlapping (Experiment 4) stimuli, and found evidence of fixed-capacity processing in all cases. A feature contrast task, however, which was assumed to not require object processing, but did require processing stimuli at multiple locations (Experiment 3), yielded evidence of unlimited-capacity processing. Together the results are consistent with object-based theories of divided attention, with no evidence of spatial limitations per se on divided attention, and with there being a separate unlimited capacity processing pathway that can be followed for tasks that depend on feature contrast and no object processing.

Figure 13 summarizes the results using the logic of the extended simultaneous-sequential method (summarized in Figure 5). Panel A shows the sequential advantage for the four experiments, and Panel B shows the sequential-repeated difference for the four experiments.

First consider the results of Experiments 1 and 2, both of which investigated the capacity limitations of global shape judgments of stimuli at multiple locations. In both experiments, there was a reliable advantage of sequential over simultaneous presentation (Figure 13, Panel A), and no reliable difference between sequential and repeated presentations (Figure 13, Panel B). This is the signature pattern for fixed-capacity processing (see Figure 5, right panel). To address whether that fixed-capacity reflects object-based or space-based limitations, consider Experiment 4, which also used the shape judgment task but with stimuli presented overlapping each other at a single location in space. There was again a reliable sequential advantage with no repeated advantage, consistent with the same fixed-capacity processing limitation that was
observed in Experiments 1 and 2. Finally, consider the results from Experiment 3, which measured processing capacity limitations for a feature-contrast task. In this case, there was no reliable advantage for sequential presentation over simultaneous presentation (Figure 13, Panel A), but there was a reliable advantage for repeated displays (Figure 13, Panel B). This is the signature pattern for unlimited-capacity processing (Figure 5, left panel). Thus, the results showed fixed capacity for object processing, regardless of the number of locations, but unlimited capacity for feature contrast, despite multiple locations. One final comment about this summary figure. We emphasize the equality predictions for the unlimited-capacity and fixed-capacity models. These predictions are robust to the details of the models, such as distributional assumptions. The results of the global shape experiments all satisfy the predicted equality between sequential and repeated conditions (see circled points in Panel B). In contrast the results of the size experiment satisfy the predicted equality between sequential and simultaneous conditions (see circled points in panel A).
Figure 13. Summary of results from all experiments. Each experiment is summarized by two difference measures. A. The sequential advantage (sequential - simultaneous) is plotted for all experiments. It is expected to be 0 for unlimited-capacity processing and positive for fixed-capacity processing. B. The sequential-repeated difference (sequential - repeated) is shown for all experiments. It is expected to be 0 for fixed-capacity processing and negative for unlimited-capacity processing. The results for global shape judgments are consistent with fixed capacity (Experiments 1, 2 and 4) and the results for size judgment are consistent with unlimited capacity (Experiment 3). The points circled for emphasis are those that satisfy the equality predictions.
Is there other evidence of space-based processing limitations?

Finding evidence of limited-capacity object processing, does not in itself rule out the possibility that there could also be space-based limitations. The overlapping-stimulus strategy of distinguishing between object-based and space-based divided attention effects does so by excluding the possibility of spatial effects, allowing the attribution of any effects that do occur to limitations on object processing. It is possible that there are further processing limitations when stimuli must also be processed at multiple locations. Vecera and Farah (1994) pursued this question with Duncan's original study using overlapping stimuli, and found no difference in divided attention effects for overlapping versus separated stimuli, suggesting that there is no additional cost associated with the stimuli appearing in multiple locations (see Kramer, Weber & Watson, 1997, Experiment 2).²

An analogous comparison can be applied to the results of the current study. Specifically, both Experiment 4, which used overlapping objects (i.e., one location), and Experiments 1 and 2, which used objects at multiple locations, yielded evidence of fixed capacity. Therefore, capacity was maximally limited with stimuli at a single location. Thus, the evidence from different tasks and different methods for measuring divided attention converge on the same conclusion; divided attention is limited for objects but not for space.

 Strategies other than overlapping stimuli have been used to study object-based divided attention. A method used by Baylis (1994; see also Baylis & Driver, 1993), for example, was

²These experiments have been criticized on grounds that in the overlapping condition, stimuli were at fixation, whereas in the separated case, they were each a bit off of fixation and would, therefore, have been less visible in the separated case (Kramer et al., 1987). However, the eccentricity was quite small (~2°). More important, the finding was that there was no effect of separation on the size of the divided-attention effect. The prediction for a space-based limitation is that the effect would increase with separated stimuli. It is implausible that decreased visibility would have counteracted such an effect of separation. In our opinion, more significant concerns about comparing overlapping stimuli to separated stimuli is that it confounds the number of locations (1 versus 2) with susceptibility to visual crowding. This confound was exacerbated in Experiment 1 of Kramer et al (1997) when the overlapping stimuli were presented off of fixation where visual crowding increases.
described in the introduction (Figure 1d). They found results that were consistent with object-based divided attention. However, no tests for additional costs of spatial processing have been conducted with that method.

A study reported by Kim and Vergheese (2014) tested the effects of monitoring one versus multiple locations (i.e., spatial uncertainty) that were on one versus multiple surfaces, and found that performance improved with reduced spatial uncertainty only when the locations were on separate surfaces; little or no spatial uncertainty effect occurred within a single surface. This is consistent with there being an object-based processing limitation but no spatial limitation.

An adaptation of Duncan’s method that was reported by Lavie and Driver (1996) yielded what looked like an advantage for close-proximity between-object attributes compared to farther-proximity between-object attributes. However, this effect has failed to replicate (Law & Abrams, 2002; Lamy, 2000). Moreover, it is in the opposite direction of what is predicted by an additional cost of spatial processing.

Another method that was reported by Watson & Kramer (1999) has also been cited as supporting object-based divided attention. Unfortunately, that method does not include the key feature of using identical displays across critical conditions (i.e., between-object and within-object comparisons), and sometimes yields better between-object performance than within-object performance (e.g., Davis & Holmes, 2005).

Finally, a number of older studies were focused on measuring the spatial profile of attention and manipulated the spatial separation of individual stimuli in dual-task experiments (Hoffman & Nelson, 1981; Hoffman, Nelson & Houck, 1983; Sagi & Julesz, 1986). They found reduced dual-task effects with smaller separations. However, these studies were not designed to test between object-based and space-based divided attention effects, and cannot rule out the
possibility that proximity modified the perceptual organization of stimuli (i.e., grouping by proximity) and mediated the effect of spatial separation. In addition, the effect is again in the opposite direction of what is predicted by an additional cost of spatial processing.

In summary, there was no evidence of space-based divided attention effects in the current study, and our review of the literature revealed none in previous studies either. There is, therefore, no strong evidence of limited spatial processing per se, but rather that processing is limited by objects, which often appear in multiple locations.

**Multiple processing pathways**

The focus of this study has been to test object-based and space-based theories of divided attention, and the results lead to the conclusion that there are object-based limitations, but no space-based limitations. There is, however, an additional aspect of processing that must be considered to understand the full set of results reported here and in the broader literature. Specifically, some attributes of stimuli, such as feature contrast, do not in themselves constitute object properties and can drive responses via a separate unlimited-capacity processing pathway. In Experiment 3 of the current study, the task required only the detection of size contrast, and it yielded evidence of unlimited capacity processing. This is consistent with previous findings from dual-task studies (e.g., Han et al., 2003; Liu et al., 2009), simultaneous-successive experiments (Huang & Pashler, 2005; Scharff et al., 2011a, 2013), and many visual search studies in which performance was unaffected by the number of items in a spatial array (e.g., Treisman & Gelade, 1980). Because these experiments all involved multiple stimuli at multiple locations, it must be the case that the information that was needed from them was processed along a pathway separate from the limited-capacity processing pathways revealed in the current study and elsewhere.
Figure 14 illustrates an example of a multiple pathway theory that accommodates the full set of results. Relevant stimuli (three in the example, represented by $S_1$, $S_2$, and $S_3$) are processed initially in terms of simple feature information, which is assumed to have unlimited capacity. Feature contrast is processed along an unlimited capacity pathway. If the task depends only on feature contrast, then that pathway is sufficient to determine a response, and therefore there will be no effects of divided attention. In Figure 14, this is labeled as the direct route from feature contrast processes to decision and response processes, and it has unlimited capacity. In contrast, attributes that are intrinsic to objects, like global shape, are processed along a limited capacity pathway. If the task depends on one or more object attribute, then there should be effects of divided attention. Notice that according to this multiple pathway account, feature-contrast information could also serve to guide limited-capacity processes to selectively prioritize some stimuli over others for access to decision and response processes. Such guidance is a focus of specific existing models like Guided Search (Wolfe, 1994; 2022). Our data cannot distinguish between direct or guided paths of unlimited-capacity processing.
Figure 14. Illustration of a multiple pathway theory that includes separate paths for feature contrast and object properties. Relevant stimuli are initially processed in terms of their simple features and then, depending on the task, take one of two paths to reach decision and response processes. The arrows on the left represent an unlimited capacity pathway that can be followed when the task depends only on a decision about feature contrast. The arrows on the right represent a limited-capacity pathway that must be followed if the task requires object processing.
There are many precedents for the ideas behind the multiple pathway theory illustrated in Figure 14. Hoffman (1979), for example, proposed an early two-stage model of visual search that included an unlimited-capacity parallel stage and a later serial stage. Feature Integration Theory is a classic elaboration of a two-stage model of this sort. It assumed that the function of the early unlimited capacity stage is feature processing, while the function of the second stage is the binding of features to represent conjunctions via the serial allocation of attention to individual locations within the visual field (Treisman & Gelade, 1980). Kahneman et al. (1992) expanded this work to encompass a larger theory of perceptual organization and visual memory that asserts that the establishment of object representations, in particular, depends on limited-capacity, perhaps even serial, processing. Wolfe and colleagues’ original Guided Search model also included an initial parallel unlimited-capacity processing stage for feature encoding and a later serial stage (Wolfe, 1994; Wolfe et al., 1989). A difference between Guided Search and other two-stage models at the time is that according to Guided Search, the feature stage cannot be accessed directly, it can only contribute to the guidance of the limited capacity second-stage processes. More recent versions of guided search, however, include a non-selective (i.e., direct) unlimited-capacity processing pathway based on global scene statistics (e.g., Wolf, Vo, Evans & Green, 2011; Wolfe, 2021). Finally, other recent two stage theories explicitly incorporate feature contrast, rather than just simple features, into the first stage (e.g., Müller, Heller, & Ziegler, 1995; Wolfe, 2021). This brief review is not intended to cover all previous examples of multiple pathway models. Rather it is to make clear that the general idea of a multiple pathway processing architecture is neither novel nor controversial. We highlight the general idea here because a simple theory of the sort illustrated in Figure 14 is sufficient to account for a large body of results from a wide range divided attention studies. This theory
elaborates the conclusion that visual processing is limited by objects, but not by space, and that tasks that depend feature contrast alone can bypass limited-capacity processing along a separate processing pathway.

What is object processing?

In making the general assertion that any task that depends on properties that are intrinsic to the object requires limited-capacity processing, we have not filled in the details regarding the specific processes that incur this dependency. Global shape seemed to be a safe choice for reliably engaging object processes, because it is clearly not available in the local features nor in any simple conjunction of features. Wolfe and Bennett (1997) made a similar point when contrasting global shape with the kinds of simple feature conjunctions that were a focus of the visual search literature at the time (see also Pizlo, 2008).

How might a task that depends on feature conjunctions be processed within an architecture like that illustrated in Figure 14? In many cases, because conjunctions depend on more than feature contrast, they require processing along the limited-capacity pathway consistent with Feature Integration Theory and other theories. Under the right conditions, however, tasks that depend on feature conjunctions could create feature contrast signals that can be detected by the unlimited-capacity processing path. These can be through of as emergent features of a sort.

Results from a study using the simultaneous-sequential method to measure divided attention effects support this prediction. Specifically, Huang and Pashler (2005) found that search for targets defined by the conjunction of two features (size and orientation) yielded evidence of unlimited-capacity processing in simultaneous-sequential experiments.

More generally, our proposal does not provide specific predictions for all feature conjunction tasks because depending on the specific conditions, might sometimes be extractable
through the unlimited-capacity feature-contrast pathway, but other times not. Rosenholtz (2001), for example, showed that performance in a wide range of visual search tasks was best accounted for by the degree of heterogeneity of the displays, rather than whether the target was defined on the basis of a single feature or a conjunction of features (see also Duncan & Humphreys, 1989). Increased heterogeneity reduces the strength of feature contrast, and increases the likelihood that a given task requires processing along the limited-capacity pathway.

Finally, work by Dosher and colleagues provides a hint about what kind of processing other than global shape representation might constitute “object processing” (Han et al., 2003; Liu et al., 2009). Recall that using a dual-task approach, they found no divided attention effects for multiple judgments of the same feature across two objects (Gabor patches). However, they did find divided attention effects for judgments of two different features across two objects. The first finding is consistent with the feature task being done based on only processing within the feature-contrast pathway, which has unlimited capacity. The second finding is consistent with the hypothesis that associating a particular feature with a particular object and not another object, which is what must be done to report different features of two objects, cannot be done using feature contrast alone. Instead, it requires object representations with which to associate some specific features and not associate other specific features that are simultaneously present. This hypothesis is similar to the need to bind features at a given location in Feature Integration Theory, but is more generally about associating specific information with specific object representations (c.f. Kahneman et al., 1992).

Conclusion

This study revisited the distinction between object-based and space-based theories of divided attention. A review of the literature indicated that collectively, the extant evidence is
inconsistent with both simple space-based theories (e.g., Posner, 1980) and simple object-based theories (e.g., Duncan, 1984), as well as single-pathway hybrid theories (e.g., Vecera, 1997). Using the extended simultaneous-sequential method (Scharf et al., 2011), we found evidence that is consistent with fixed-capacity object processing, and inconsistent with any processing limitation due to spatial processing itself. Furthermore, we also found evidence of unlimited-capacity processing of feature contrast across both objects and locations. Together the results are consistent with a multiple pathway theory in which tasks that require object processing must follow a limited-capacity pathway, whereas tasks that depend only on feature contrast, can follow an unlimited-capacity processing pathway. So while in this broader context there is evidence for object-based theories divided attention, there is no evidence of space-based theories of divided attention.
Author Notes
We thank Dina V. Popovkina and Alec Scharff for helpful comments and thoughtful criticism. This article was partially supported by grant R21 EY029432 to C. M. Moore. The data for this study can be found at the OSF depository: osf.io/fn6x3/.