

Extending the Simultaneous-Sequential Paradigm to Measure Perceptual Capacity for Features and Words

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In perception, divided attention refers to conditions in which multiple stimuli are relevant to an observer. To measure the effect of divided attention in terms of perceptual capacity, we introduce an extension of the simultaneous-sequential paradigm. The extension makes predictions for fixed-capacity models as well as for unlimited-capacity models. We apply this paradigm to two example tasks, contrast discrimination and word categorization, and find dramatically different effects of divided attention. Contrast discrimination has unlimited capacity, consistent with independent, parallel processing. Word categorization has a nearly fixed capacity, consistent with either serial processing or fixed-capacity, parallel processing. We argue that these measures of perceptual capacity rely on relatively few assumptions compared to most alternative measures.

Keywords: divided attention, visual perception, capacity limitations, reading

Visual perception often occurs under conditions of *divided attention*, in which multiple stimuli are relevant to the current task. The effects of divided attention on perception depend on the task. As an intuitive example, consider the difference between checking to see if a light bulb is burned out and checking to see if a word is spelled incorrectly. Typically, both tasks are easy when there is only one stimulus. However, consider the same tasks under divided attention: how is the quality of the individual percepts affected? Glancing at the ceiling to see if any of 20 light bulbs are burned out is still quite easy—as if the quality of the individual percepts has not been affected. On the other hand, checking to see if any of 20 words in a paragraph are misspelled is more laborious; it seems that we extract only a single high-quality word percept at a time.

To measure the effect of divided attention on perception, we use the simultaneous-sequential paradigm, a variant of accuracy visual search. We expand the usefulness of the paradigm by adding a new condition. With this extension, the paradigm can distinguish among several models of divided attention: unlimited-capacity, fixed-capacity and intermediate models. We apply this paradigm to two test cases, contrast discrimination and word categorization, and find dramatically different effects of divided attention on each. In the general discussion, we put this paradigm in the context of

the other approaches to assessing the effects of divided attention. We argue that this extended simultaneous-sequential paradigm is the most direct way to measure capacity using accuracy visual search and that these measures of perceptual capacity rely on relatively few assumptions compared to most alternative measures.

Capacity Models for Divided Attention

The effects of divided attention can be described in terms of *perceptual capacity*. Perceptual capacity describes the relationship between the number of relevant stimuli and the quality of corresponding percepts (Broadbent, 1958; Kahneman, 1973; Townsend, 1974; Townsend & Ashby, 1983). We focus on two primary models. Under an *unlimited-capacity, parallel model*, analyses of stimuli are parallel and independent, so that divided attention has no effect on perception, though it may affect memory and decision processes. Under a *fixed-capacity model*, there is a limit to the total amount of information processed per unit time, so that the overall quality of the percepts is degraded as a function of the number of stimuli under inspection. These two models can be considered as two opposing extremes on a continuum of limited-capacity models.

To quantify perceptual capacity, we use a statistical sampling framework. In statistics, large numbers of samples permit precise estimates of population parameters, while smaller numbers of samples allow only imprecise estimates. In perception, we assume that an observer forms an internal representation of a stimulus by collecting perceptual samples. The more perceptual samples obtained, the more accurate the internal representation. The number of samples is related to the viewing duration, and may also be affected by divided attention. We describe our models of divided attention in terms of their prescribed effect on perceptual sampling. Formal definitions are in Appendix A.

Unlimited-Capacity, Parallel Models

According to unlimited-capacity, parallel models, multiple items can be analyzed in parallel and each item analysis is inde-

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pendent of the others (Gardner, 1973). Perceptual sampling of each item is unaffected by the number stimuli under inspection. There is considerable evidence that perception of simple features has unlimited-capacity, parallel processing under divided attention (e.g., Bonnel, Stein, & Bertucci, 1992; Palmer, 1994; Doshier, Han, & Lu, 2004; Thornton & Gilden, 2007). Unlimited-capacity processing is most easily observed under ideal conditions, in which stimuli are sufficiently spaced to prevent crowding, are isoecentric, and are configured to prevent inter-stimulus cues.

Fixed-Capacity Models

Under a fixed-capacity model, only a fixed amount of information can be processed per unit time. In terms of sampling, this is a fixed number of samples per unit time. One example of this class of models is the standard serial model, in which an observer scans through the items one-at-a-time (e.g., Sternberg, 1969). In sampling terms, an observer samples one stimulus until a satisfactory representation has been formed, and then moves on to sample the next stimulus. A parallel, fixed-capacity model is also possible, in which the observer samples from multiple items in parallel, dividing the samples among them (Shaw, 1980; Palmer, 1990). The experiments presented in this article do not distinguish between serial and parallel accounts of fixed-capacity processing. However, we will use the standard serial model to illustrate fixed-capacity predictions in this article. In Appendix A, we derive specific predictions to show the parallel, fixed-capacity model and a standard serial model make similar predictions. Examples of fixed-capacity processing in cognition are memory retrieval for order information (e.g., McElree & Doshier, 1993) and response selection (e.g., Pashler, 1998), both of which are interpreted as serial processes.

Test Cases

For our analysis of divided attention effects, we rely on two test cases. The first test case, a *contrast discrimination task*, is presumed to rely on unlimited-capacity, parallel processing. The second test case, a *word categorization task*, is presumed to rely on fixed-capacity processing. These test cases provide a starting point for comparing alternative paradigms that measure capacity limits.

Contrast discrimination. In the first task, observers indicated the location of a higher-contrast target disc among lower-contrast distractor discs. We refer to this as an instance of contrast discrimination. Figure 1 shows a sample display from our study, in which the discs are embedded in dynamic random visual noise. The observer's task is to indicate the location of the higher-contrast target disc. There is considerable evidence that simple visual discriminations such as this have unlimited-capacity, parallel processing (e.g., Bonnel et al, 1992; Palmer, 1995; Palmer, Verghese, & Pavel, 2000; Huang & Pashler, 2005; Davis et al., 2006; but see Posner, 1980).

Word categorization. In the second task, observers locate a word from a specified semantic category. For example, if the target category is 'animals,' the target word might be 'dog' and distractors might be 'car,' 'belt,' and 'poet'. Figure 2 shows a sample display from our study. This task is closely related to reading, a process that many argue is serial (Karlin & Bower, 1976; Starr & Rayner, 2001; but see Brown, Gore, & Carr, 2002).

Background on the Simultaneous-Sequential Paradigm

Eriksen and Spencer (1969) introduced the simultaneous-sequential paradigm. In the decades since, many authors have used the paradigm to address a variety of questions about capacity

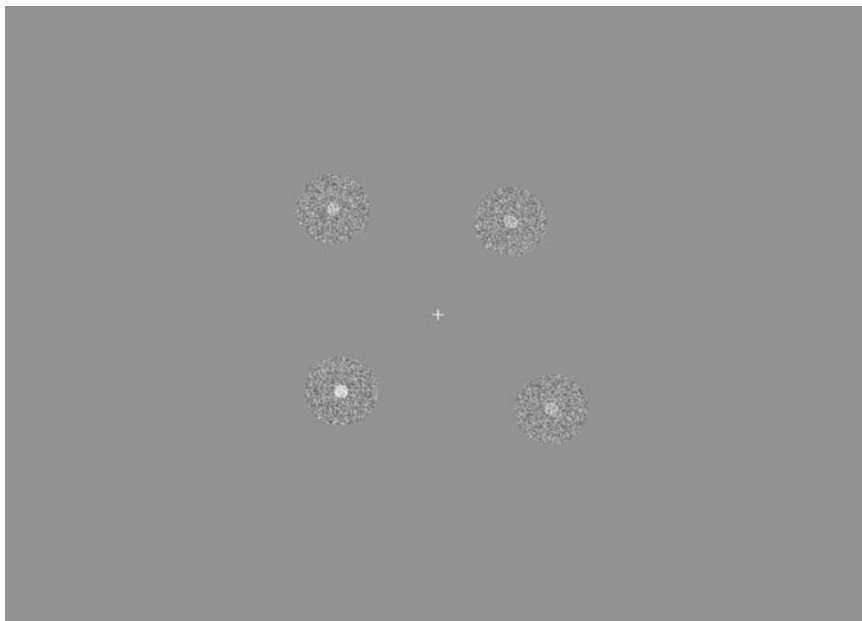


Figure 1. Sample display from the simultaneous condition of the contrast discrimination task. The three distractors are discs of lower contrast and the target is a single disc of higher contrast. In this illustration, the contrast values have been exaggerated. The stimuli are embedded in dynamic Gaussian noise patches.

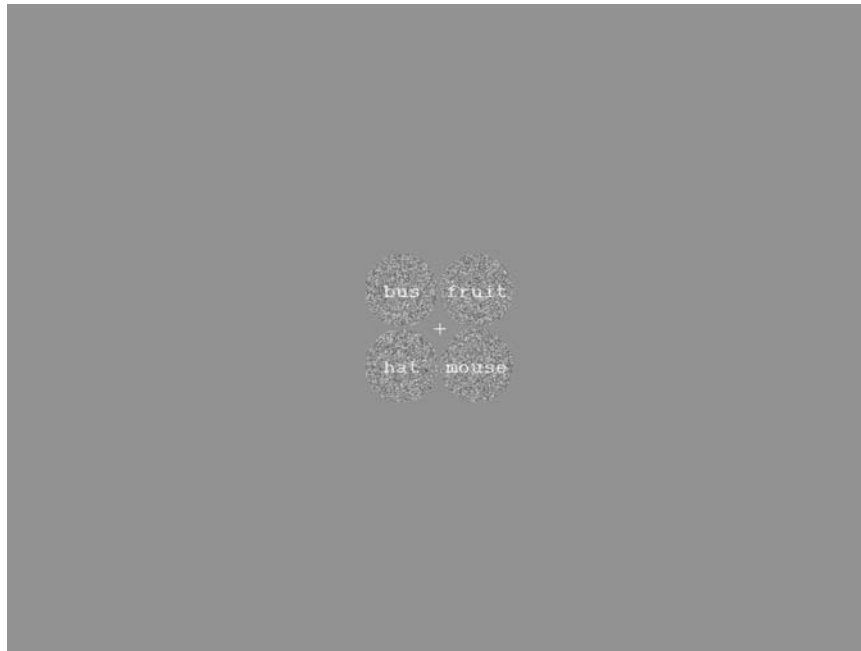


Figure 2. Sample display from the simultaneous condition of the word categorization task. In this illustration, the contrast of the word stimuli has been increased for visibility. The stimuli are embedded in dynamic Gaussian noise patches.

limitations in visual perception (e.g., Shiffrin & Gardner, 1972; Hoffman, 1978; Duncan, 1980; Prinzmetal & Banks, 1983; Fisher, 1984; Kleiss & Lane, 1986; Harris, Pashler, & Coburn, 2004; Huang & Pashler, 2005). Most of these studies involved visual search through displays of alphanumeric characters.

In a simultaneous-sequential experiment, observers make judgments about briefly presented stimuli. The stimuli are presented in two different conditions: simultaneous and sequential. In the simultaneous condition, multiple stimuli are presented concurrently. In the sequential condition, subsets (called frames) of the display are presented one-at-a-time. Critically, the display time of each frame is constant across conditions. For example, in our experiments the display time is 100 ms per frame in both the simultaneous and sequential conditions. Panel A of Figure 3 depicts the simultaneous condition, in which four stimuli are briefly displayed. Panel B of Figure 3 depicts the sequential condition, in which two stimuli are displayed in one frame, and then the remaining two stimuli are displayed in a second frame. The essential manipulation is on the number of simultaneously presented stimuli.

Simultaneous-sequential predictions. In this context, limited-capacity models predict better performance in the sequential condition than in the simultaneous condition. When only a limited amount of information can be processed within a given time interval, it is beneficial to have the stimuli displayed sequentially. The predicted magnitude of the sequential-condition advantage depends on specific assumptions. In contrast, the unlimited-capacity, parallel model predicts that performance must be equivalent between the simultaneous and sequential conditions. Under an unlimited-capacity, parallel model, performance is solely determined by display duration and individual stimulus properties.

Because the stimuli do not compete for processing, the simultaneous-sequential manipulation has no effect on performance.

An example study. Huang and Pashler (2005) directly compared the diagnostic power of the simultaneous-sequential paradigm and set-size effects in response-time visual search. They created analogous experiments in each paradigm using three different search tasks. The tasks were a simple feature search (detect the presence of a slightly smaller square among other squares), a feature conjunction search (detect a large, vertical rectangle among large, horizontal; small, horizontal; and small, vertical rectangles), and a spatial configuration task (detect a rotated “T” among rotated “L” distractors). All three tasks produced substantial set-size effects on response time, about 40 ms per item. In the simultaneous-sequential experiment, however, only the spatial configuration task showed a reliable advantage in the sequential condition. Huang and Pashler conclude that set-size effects are largely determined by target-distracter discrimination difficulty, and that substantial set-size effects on response time do not necessarily indicate the presence of capacity limitations. Thus, search may be slow, inefficient, and inaccurate, but unlimited capacity nonetheless. This study provides an empirical example in which the simultaneous-sequential paradigm distinguished capacity differences that were not detected with set-size effects in response time search.

The Logic of the Extended Paradigm

In this study, we augment the simultaneous-sequential paradigm by adding a third condition: the repeated condition. The extended paradigm can measure the full range of divided attention effects, from unlimited-capacity to fixed-capacity. Panel C of Figure 3

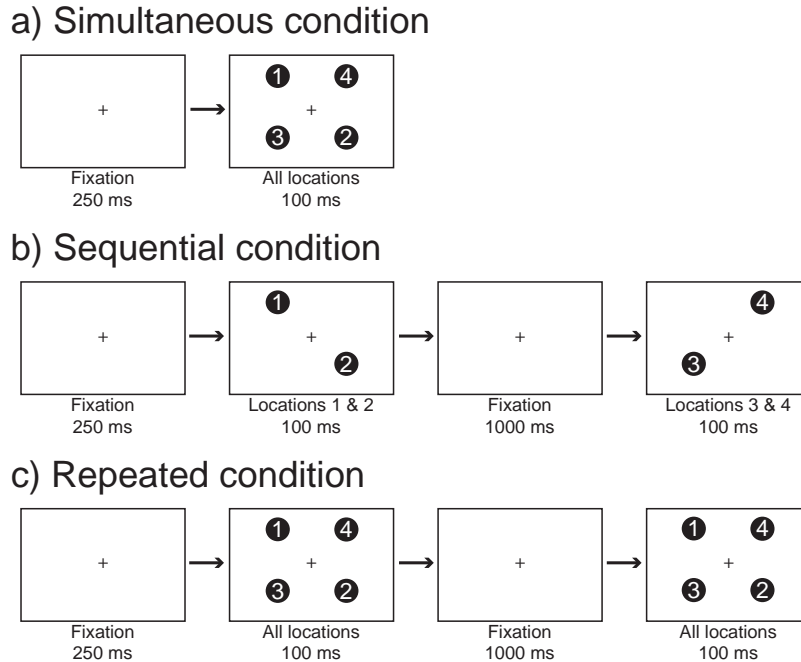


Figure 3. Display conditions used in this study. (a) Simultaneous condition: All four stimuli are displayed in one 100 ms frame. (b) Sequential condition: Stimuli are divided between two 100 ms frames shown sequentially. Each frame displays two stimuli. (c) Repeated condition: All four stimuli are displayed twice in two 100 ms frames shown sequentially.

depicts the repeated condition, in which all four stimuli appear in each of two 100 ms frames. In the sequential and repeated conditions, there is a 1,000 ms blank interval between the presentations, to ensure sufficient time for attention switching (Duncan, Ward, & Shapiro, 1996). Townsend (1981) and Sagi and Julesz (1985) conducted related experiments that manipulated the relative durations of the simultaneous and sequential displays.

Each model predicts a distinct pattern of results across the three conditions. To summarize: all models predict better accuracy in the repeated condition than the simultaneous condition—that is, viewing two exposures of the stimuli yields better accuracy than a single exposure. These simultaneous and repeated accuracies serve as lower and upper bounds, respectively, for expected accuracy in the sequential condition. Unlimited-capacity models predict equivalence between the sequential and simultaneous conditions, fixed-capacity models predict equivalence between the sequential and repeated conditions, and intermediate models predict that sequential accuracy falls between simultaneous and repeated accuracies.

Figure 4 demonstrates the logic behind the predictions. In the figure, the unlimited-capacity and fixed-capacity models are shown in adjacent columns and the three display conditions correspond to the three rows, so that each cell of the figure schematizes performance of a particular model in a particular condition. Each grey bar represents the presence of a stimulus. The placement of the grey bars designate where and when stimuli appear. Locations are listed vertically and numbered one to four; frames are listed horizontally and labeled above the each schematic. The black arrows overlaying the grey bars indicate the observers' active analysis of a stimulus. The pattern of predictions is apparent from comparing the amount of time spent processing each stimulus

in each condition. Under unlimited capacity, simultaneous and sequential conditions allow the same degree of analysis. Under fixed-capacity, sequential and repeated allow for the same degree of analysis. Below, we elaborate on these explanations and discuss the degree to which they generalize to different variations on the models.

Unlimited-capacity, parallel model predictions. Under an unlimited-capacity model, the observer analyzes all visible stimuli independently and in parallel—there is no interference or resource competition between stimuli. The quality of analysis is limited by the total time available to analyze the stimuli: the display duration plus any postdisplay memory persistence. In both the simultaneous and sequential conditions, each stimulus is displayed for 100 ms, so the model predicts equivalent performance between these two conditions. In the repeated condition, each stimulus is displayed two times for 100 ms each, so the model predicts superior performance in the repeated condition than in the other two conditions.

Repeating the display is not necessarily equivalent to doubling the duration of the display. First, the rate of information accrual may not be constant over the course of stimulus analysis; for example, the transient, initial response to the stimulus may be more informative than the subsequent, sustained response. Second, the length of postdisplay memory persistence may not scale with stimulus duration. Taking such dynamics into account, repeating the display doubles the amount of available information (i.e., number of samples), but doubling the duration might not.

The superiority of repeated over simultaneous performance under unlimited-capacity processing can be predicted by either of two mechanisms. By *integration*, the observer combines the information from the two display repetitions in an ideal fashion to

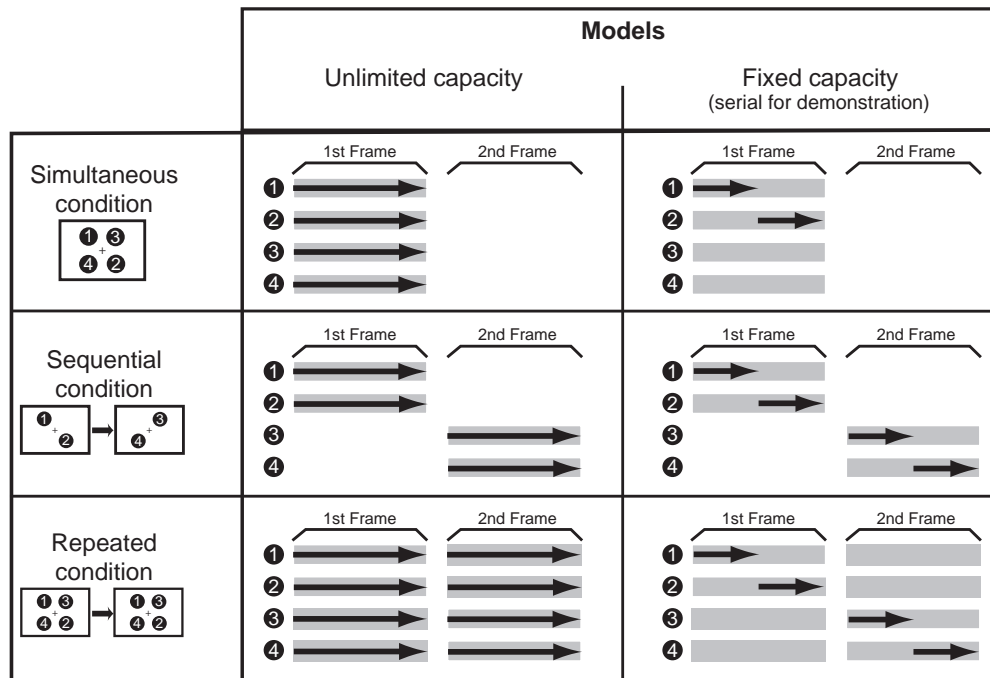


Figure 4. Demonstration of the logic of the extended simultaneous-sequential paradigm. Columns correspond to the two models, rows correspond to the three conditions, so that each cell depicts the performance of each model in each condition. A grey bar represents the presence of a stimulus. Stimuli appear in four locations, indicated by the numbers 1 through 4 arranged vertically. Depending on the condition, stimuli can occur in the first and/or the second frame. The black arrows represent the hypothesized course of perceptual analysis for each model. Overall, the unlimited-capacity model predicts the pattern of performance simultaneous = sequential < repeated, while the fixed-capacity model predicts simultaneous < sequential = repeated.

increase the precision of internal representations of each stimulus. By *independent decisions*, the observer does not integrate the two displays, but instead has two chances to make a decision. In our models, integration predicts a somewhat larger effect of repeating the display than independent decisions. These two models are detailed in the Appendix A.

Fixed-capacity model predictions. Under fixed-capacity models, performance is limited by a fixed-capacity mechanism. For illustration, consider a standard serial model that assumes that for each brief display, the observer analyzes two stimuli to a given extent. The number of analyzed stimuli and the extent of analysis are assumed to be independent of conditions. The right-hand column of Figure 4 illustrates predictions of such a model. In the simultaneous condition, the observer analyzes only two stimuli, leaving the observer no information about the others. In both the sequential and repeated conditions, the observer analyzes all four stimuli. Thus, overall performance is equivalent in the sequential and repeated conditions, and performance in the simultaneous condition is worse than in the other two.

This pattern of predictions applies to many serial models in which two or fewer stimuli can be analyzed per display. The key assumption is that the time course of individual stimulus processing is independent of the number of stimuli in a display. For serial models that can analyze more than two stimuli per display, the equality prediction depends on a further assumption regarding how processing is allocated over multiple displays. The simple case is

to assume that all of the presented stimuli are processed in the same way with no "reallocation." Potentially, such reallocation can benefit the repeated displays differently than the sequential displays (see Townsend, 1972, 1981). Some properties of serial processing that are critical for time-based models of serial processing do not affect the predictions of accuracy-based model. For example, the amount of time necessary for serial switching does not require additional consideration, because it factors into the number of stimuli that can be processed in a brief display. Similarly, neither the distinction between exhaustive and self-terminating search nor the particular distributions of processing times bear on the predictions.

This pattern of predictions (simultaneous < sequential = repeated) can also be made by fixed-capacity, parallel models. In Appendix A, we demonstrate how these predictions can be made from a parallel sampling model (Shaw, 1980).

Generality of equivalence predictions. We emphasize the generality of the two predicted equalities: the simultaneous-sequential equality predicted by unlimited-capacity models and the sequential-repeated equality predicted by fixed-capacity models. As described above, the equivalence predictions are general to many specific models within the broader classes of unlimited- and fixed-capacity models. They are also general in another important way: they apply regardless of the specific evidence distribution associated with each stimulus (see Appendix A).

With additional assumptions, one can quantify the magnitude of the predicted inequalities. For example, the magnitude of the advantage of repeated over simultaneous can be predicted. The required assumptions concern the distribution of internal responses to stimuli and the integration mechanism for the repeated condition. Thus, these magnitude predictions are less general than the equivalence predictions. In Appendix A, we model the predicted magnitude of the nonequivalences by assuming Gaussian evidence distributions.

Experiment 1: Contrast Discrimination Task

In Experiment 1, we use the extended simultaneous-sequential paradigm to measure the effect of divided attention on a contrast discrimination task. It is a good test case for unlimited-capacity processing because a variety of prior studies support unlimited-capacity, parallel processing of simple features.

Method

Observers. Six observers participated in each experiment. All were volunteers from within the laboratory or were paid to participate. All observers had normal or corrected-to-normal acuity and had previous experience with psychophysical tasks. One of the authors (AS) participated in the experiment.

Apparatus. The stimuli were displayed on a flat-screen cathode ray tube monitor (19-inch View Sonic PF790) controlled by a Macintosh G4 (733 MHz, Mac OS 9.2) with an NVIDIA GeForce2 graphics card (832 × 624 pixels, viewing distance of 60 cm, subtending 32 × 24° with 25.5 pixel/deg at screen center; refresh rate of 74.5 Hz). The monitor had a peak luminance of 119 cd/m², and a black level of 4.1 cd/m², most of which was because of room illumination. Stimuli were generated using the Psychophysics Toolbox Version 2.44 (Brainard, 1997; Pelli, 1997) for MATLAB (Version 5.2.1, Mathworks, MA). Observers were seated in an adjustable height chair in front of the display and used a chin rest to maintain a constant the distance from the monitor.

Procedure. Stimuli were displayed in three primary conditions: a simultaneous condition, a sequential condition, and a repeated condition. Each of the three conditions is shown schematically in Figure 3. In the simultaneous condition, four stimuli appeared in a single 100 ms frame. In the sequential condition, four stimuli were shown two-at-a-time, in separate 100 ms frames separated by an interval of 1,000 ms. In the repeated condition, four stimuli appear twice, in 100 ms frames separated by an interval of 1,000 ms. The trials from the three conditions were randomly mixed within each session.

On all trials, observers searched for a single target among three distractors. Stimuli appeared at four corners of an imaginary square surrounding a small fixation cross. After viewing each presentation sequence, the observer indicated the location of the target by pressing one of four keys corresponding to the four stimulus locations: '4,' '5,' '1,' or '2' on the numeric keypad. In the sequential condition, two stimuli shown in the same frame always appeared at opposite corners of the square. The each target location occurred equally often in each condition. In the sequential condition, the pair of locations shown in the first frame was randomized.

Each session comprised 96 trials per condition. Observers trained by completing at least two practice sessions. After prac-

ticing, observers completed 10 sessions in each task, for a total of 960 trials in each display condition for each task.

Stimuli. The stimuli were 0.5° diameter discs that had a higher luminance than the surround. Distractors had a contrast of 20% and targets had a contrast between 28 and 35%, adjusted for each observer to achieve a desired performance level of approximately 75-85% correct responses. Stimuli appeared an average of 6° away from fixation, but were independently jittered up to 1.5° horizontally and vertically.

Each stimulus was centered in a circular dynamic noise field that subtended 2.75° of visual angle. Each pixel of the noise varied in luminance according to a Gaussian function, with a mean luminance equal to the grey background and a standard deviation of 35% contrast. The noise was changed with each refresh of the monitor (75 Hz). We suggest that these noise fields have a similar purpose to using postmasks in making performance more sensitive to the duration of the stimulus.

Results

The results of Experiment 1 are plotted in Figure 5. Percent correct is plotted for each of the three conditions. Simultaneous performance was 77% with a standard error of the mean of ±3%, sequential performance was 75 ± 2%, and repeated performance was 85 ± 2%. The mean within-subject difference between simultaneous and sequential was 2 ± 1%, $t(5) = 1.48$, $p > .1$. Individually, five of the six observers were consistent with the overall result (Observer SY: $p < .01$, all other observers: $p > .1$).

Repeated performance was reliably better than sequential performance. The mean within-subject difference between repeated and sequential conditions was 10 ± 1%, $t(5) = 6.86$, $p < .001$. Individually, all six observers showed a reliable advantage in the repeated performance ($p < .01$).

Effect of target frame in the sequential condition. A critical assumption for the logic of this paradigm is that the conditions differ only in when the stimuli are processed. In particular, we assume that whether a stimulus in the first or second frame has no

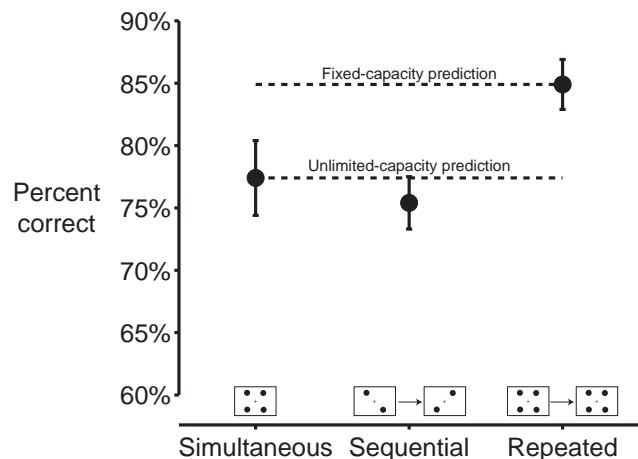


Figure 5. Results of Experiment 1: contrast discrimination task. Percent correct performance is plotted for each of the three conditions. Results are consistent with the unlimited-capacity model, which predicts equivalence between the simultaneous and sequential conditions.

effect on stimulus processing. An example of how this assumption might fail is that stimuli that appear in the first frame might be subject to more memory loss than stimuli that appear in the second frame. On the other hand, maintaining memory for stimuli that appear in the first frame may interfere with processing of stimuli that appear in the second frame. To test the assumption of equivalent processing, we compared performance between sequential trials with first-frame targets and sequential trials with second-frame targets. A reliable difference would signify a violation of a key assumption of the paradigm. We found that on average, performance was similar for first-frame and second-frame targets, and this difference of $1 \pm 2\%$ was not reliable, $t(5) = 0.33$, $p > .7$. Individually, only 2 of the 6 subjects showed a reliable advantage for one frame over the other. These two subjects showed the effects in opposite directions. Thus, there was no consistent evidence for an effect of first versus second frame.

Interpretation of Experiment 1

For a contrast discrimination task, sequential performance was not reliably different from the simultaneous, and was reliably worse than repeated performance. These data are consistent with an unlimited-capacity model and reject the fixed-capacity model.

Experiment 2: Word Categorization

In Experiment 2, we use the extended simultaneous-sequential paradigm to measure the effect of divided attention on word categorization. Our subjective experience of reading is that it is a serial process, which is consistent with fixed-capacity processing.

Method

Observers, apparatus, and procedure were identical to Experiment 1. The observer's task was to localize a target word belonging to a prespecified semantic category (e.g., localize the animal word in the display).

Stimuli were English words, presented in mono-spaced Courier 18-point font. The words were written in lower-case letters, centered 2° eccentric from fixation, and were not jittered. The contrast of the stimuli was between 40 and 50%, adjusted for each observer. As in Experiment 1, stimuli were presented within dynamic Gaussian noise fields. The words used in the experiment are listed in Appendix B. There were six word categories, each containing eight words. Each category had 2 three-letter words, 3 four-letter words, and 3 five-letter words. Categories were roughly equated for average word frequency (Kucera & Francis, 1967). Three reviewers independently checked the word lists to ensure that each word fit its category unambiguously and did not fit in any other category.

Preceding each trial, a 500 ms cue displayed the target category for that trial (e.g., "animal"). The trial included one word from the target category (e.g., "dog") and three randomly selected words from distractor categories (e.g., "poet," "hat," and "car"). All words were targets equally often, and each word was a target equally often in each condition.

Results

The results of Experiment 2 are plotted in Figure 6. Percent correct is plotted for each of the three conditions. Simultaneous

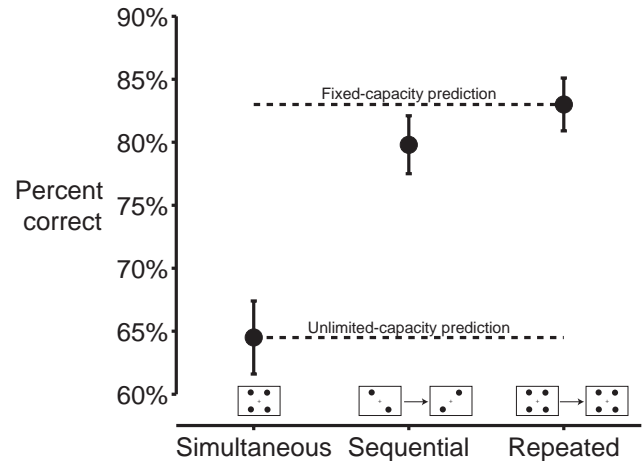


Figure 6. Results of Experiment 2: word categorization task. Percent correct performance is plotted for each of the three conditions. Results are nearly consistent with the fixed-capacity model, which predicts equivalence between the sequential and repeated conditions.

performance was $64 \pm 3\%$, sequential performance was $80 \pm 2\%$, and repeated performance was $83 \pm 2\%$. The mean within-subject difference between the sequential and simultaneous performance was a $15 \pm 1\%$ advantage for sequential, $t(5) = 23.47$, $p < .0001$. Individually, all six observers performed reliably better in the sequential condition ($p < .01$).

The mean within-subject difference in performance between repeated and the sequential conditions was $3 \pm 1\%$. This is a modest but reliable advantage for repeated performance, $t(5) = 4.36$, $p < .01$. This 3% effect is much smaller than the comparable effect in the contrast discrimination task (3 vs. 10%). Individually, only two of the six observers showed reliable differences between repeated and sequential ($p < .01$ for each). The four other observers showed no reliable difference between the conditions ($p > .1$).

Effect of target frame in the sequential condition. We again compared performance in sequential trials with first-frame targets with sequential trials with second-frame targets. The mean within-subject difference between frames was $0.1 \pm 2.0\%$, $t(5) = .07$, $p > .85$, indicating that there was no effect of target frame. Individually, no subjects showed a reliable advantage for either target frame ($p > .05$). Thus, there was no evidence for an effect of first versus second frame.

Interpretation of Experiment 2

For a word categorization task, there was a large, reliable advantage for sequential condition over the simultaneous condition. This result allows one to reject the unlimited-capacity model for word categorization. However, there was also a small, reliable advantage for the repeated condition over sequential. That the effect was very small, and reliable in only 2 of 6 observers, suggests that word categorization had nearly fixed capacity. However, that it was reliable indicates that word categorization was not completely consistent with fixed capacity. The small deviation from fixed-capacity might be explained by a model proposed by Rayner, Balota, and Pollatsek (1986), in which physical word-shape information is extracted in parallel, but semantic word

information is extracted serially. Consistent with this line of thinking, several observers reported that they could sometimes identify targets on the basis of a word's shape alone. Another possibility is that processing was serial but not as independent as assumed in the standard serial model. Specifically, perhaps observers can profitably reallocate processing in the repeated display but cannot in the sequential display because of the reduced number of stimuli (Townsend, 1981).

In comparison with Experiment 1, the simultaneous-repeated effect in Experiment 2 is relatively large. The difference between simultaneous and repeated in Experiment 2 was $20 \pm 1\%$, while in Experiment 1 the difference was only $8 \pm 2\%$. This difference in effect size is consistent with our quantitative predictions (presented in Appendix A): parallel processing yields a smaller simultaneous-repeated effect than does serial processing.

General Discussion

In this study, we measured the capacity limitations in perception for two visual search tasks. For contrast discrimination, the results were consistent with unlimited capacity. For word categorization, the results were consistent with nearly fixed capacity. And for both experiments, the observed equality in accuracy for the first and second frames supported a key assumption of the simultaneous-sequential paradigm.

In the following discussion, we compare the extended simultaneous-sequential paradigm to other paradigms that measure perceptual capacity. Our review is organized by the three general approaches of accuracy search, dual tasks and response-time search. **The review is focused on studies that measure capacity under relatively idealized conditions. By idealized, we mean the use of brief displays or other methods that avoid eye movements and mimic a single eye fixation (e.g., Palmer & Ames, 1992; Palmer et al., 2000).** In addition, we mean the use of sparse displays in peripheral vision that control crowding and eccentricity effects (e.g., Palmer, 1995; Rosenholtz, 2001). Needless to say, there is much relevant research on simple features and words beyond our narrow focus and we briefly mention three examples. For simple features, Geisler and others (Geisler & Chou, 1995; Najemnik & Geisler, 2005) have made the case for parallel processing of simple feature information for the guidance of eye movements in visual search. For words, Rayner and colleagues (Starr & Rayner, 2001; Rayner et al., 1986) have used preview paradigms in reading-like experiments to argue for nearly serial processing of words. Similarly, Lachter, Forster, and Ruthruff (2004) and Risko, Stolz, and Besner (2005) among others have made the case that the Stroop effect and related phenomena are because of failures of selective attention and need not imply parallel processing of words. In the following discussion, we maintain a narrow focus on divided attention tasks mimicking a single fixation.

Capacity in Accuracy Search

Set-size effects. One approach to addressing questions of processing capacity is to measure the accuracy of visual search as a function of the number of stimuli in a display. A major issue for this method is how to separate effects of set size on perception from its effects on decision. Since Tanner (1961), it is clear that

most theories of decision predict effects of set size on decision. This is typically addressed using quantitative models of the decision component of the set-size effect (e.g., Shaw, 1980; Palmer, 1994). For example, Palmer (1994) manipulates both set size and target-distractor discriminability, and then predicts the effects of set size on decision for a given level of performance (e.g., at a 75% correct difference threshold). These predictions can be made for both unlimited and a fixed capacity assumptions.

Set-size effects in accuracy search have been measured for a variety of simple features including contrast, color, orientation, motion, and shape. Under the ideal conditions that minimize crowding and other sensory effects, the results are generally consistent with an unlimited-capacity, parallel model (Palmer, 1995; Monnier & Nagy, 2001; Dobkins & Bosworth, 2001; Baldassi & Verghese, 2002). These results contradict the notion that all perceptual processes are subject to capacity limitations (e.g., Posner, 1980) and support the view that many low-level perceptual processes are parallel and have unlimited capacity (e.g., Gardner, 1973). Although there are several accuracy search experiments that have tested more complex tasks and shown exceptions to unlimited capacity (e.g., Palmer, 1994), we know of none that have used these methods to test word categorization.

An interesting extension of accuracy search deserves a brief mention. Doshier, Han, and Lu (2004) used a response signal paradigm to manipulate the time allowed before a response. This allows one to begin to address the dynamics of processing using an accuracy paradigm. The initial cases examined in this article were consistent with an unlimited capacity, parallel model. We look forward to studies that use this method to reveal instances of serial processing.

The set-size, accuracy paradigm for measuring capacity effects tests specific predictions of unlimited and fixed capacity models. However, the downside of this approach is that it relies on relatively elaborate assumptions to predict specific magnitudes of set-size effects. In particular, one must assume a specific family of noise distributions and how they vary with target-distractor discriminability. While these elaborated models are interesting for understanding visual search, a paradigm that requires fewer assumptions is also desirable.

The simultaneous-sequential paradigm. The simultaneous-sequential paradigm, which is extended in this article, is an instance of accuracy search. Its special feature is to distinguish the number of stimuli relevant to the decision from the number that are simultaneously displayed. This allows one to eliminate the differential effects of decision and instead measure the perceptual effect of the number of simultaneously displayed stimuli. In other words, this is a modified set-size manipulation that provides an experimental approach to the problem of accounting for the contribution of decision to set-size effects.

Several simultaneous-sequential experiments have addressed capacity for simple features. For example, Huang and Pashler (2005) found evidence for unlimited-capacity processing in searches that relied on size judgments and for searches that relied on size-orientation conjunction judgments. Other studies have found that searches for alphanumeric characters also yield evidence for unlimited-capacity processing (e.g., Shiffrin & Gardner, 1972; Pashler & Badgio, 1987). In a study of multimodal perception, Shiffrin and Grantham (1974) observed no simultaneous-sequential differences in a task that required processing of simple

auditory, tactile, and visual signals, indicating that simple stimuli from these three modalities can be processed independently and with unlimited capacity.

Other studies using the simultaneous-sequential paradigm have addressed word identification. Harris, Pashler, and Coburn (2004) had observers search for specific words among other words. In one experiment, they compared searching for the observer's own name to search for other names. In another experiment, they examined searches for emotional words among neutral words. In all cases, they found an advantage of sequential presentations over simultaneous that rejects unlimited-capacity processing of words. Similarly, Patterson (2006) had observers indicated which number-word (e.g., "one," "two," etc.) in a display had the highest value. She found an advantage for sequential over simultaneous presentations. When she used single digits in place of the words, this advantage went away. Thus, there is evidence from several tasks that reject unlimited capacity for word search. The current results further specify that this limitation is fixed capacity or nearly so.

We have already discussed the advantage of the simultaneous-sequential paradigm over other accuracy search paradigms. It provides a relatively simple way to isolate capacity limitations in perception from limitations because of decision. The disadvantage of the simultaneous-sequential paradigm arises from the use of sequential displays. One must assume that each of the two frames from the sequential displays is processed equivalently. There can be no differences in perception or memory for the two displays. This assumption is easy to check and is typically satisfied. In our sequential conditions, we found no reliable differences between performance in the two displays. A more challenging issue that arises in the context of the extended simultaneous-sequential paradigm is that the repeated display condition requires assumptions about how information is pooled over the two displays. In Appendix A, we discuss alternative models of how information might be combined for repeated displays. The quantitative modeling reveals one way in which our equivalence prediction could fail—a parallel sampling model with independent decisions does not predict the equivalence of the sequential and repeated conditions. However, even if it doesn't match a fixed-capacity prediction for all assumptions, the repeated condition still provides a benchmark for the maximum improvement one expects for the sequential condition relative to a single simultaneous display.

To summarize, the simultaneous-sequential paradigm has an important advantage over a direct manipulation of set size in accuracy search. It controls for decision contributions with minimal assumptions. In addition, equivalent performance is predicted between the sequential and repeated condition for many fixed-capacity models. Together, these advantages make the extended simultaneous-sequential paradigm an attractive refinement over other accuracy search paradigms. With respect to the test cases of simple features and words, the simultaneous-sequential paradigm provides several results for simple features that are consistent with unlimited capacity and for words that are consistent with fixed capacity.

Capacity in Dual-Task Paradigms

Speeded dual tasks. Dual tasks performed under time pressure have long been studied in what is usually called the *psychological refractory period* (PRP) paradigm. In it, one presents two

stimuli, requires two speeded responses in a particular sequence and varies the stimulus onset asynchrony (SOA) between the stimuli. The typical result is that reducing the SOA between the tasks increases the response time to the second task. In the extreme, this increase in response time is equal to the reduction in the SOA. Such a one-for-one reduction is consistent with a bottleneck that allows the processing of only one task at a time (serial processing). This paradigm has been applied to a variety of tasks across perception, decision, memory, and motor control (for reviews see Johnston & McCann, 2006; Lien & Proctor, 2002; Pashler, 1994, 1998). Much of the focus is on a particular instance of serial processing in which there is a bottleneck that allows only one response selection process to be executed at a time. Pursuing this hypothesis, many studies contrast potential dependencies in response selection to other processes that might cause the bottleneck. In the context of perception, one must use more indirect arguments to address whether a given aspect of perception has the kind of fixed capacity implied by a bottleneck model. The primary approach is called the *locus of slack logic* (Schweickert, 1978; Pashler & Johnston, 1989). The key prediction arises for manipulations of the second task. If such manipulations affect processes before the bottleneck, smaller effects are predicted for the short SOAs compared to long SOAs (subadditive effects). Alternatively, if such manipulations affect processes at or after the bottleneck, equal effects are predicted for short and long SOAs (additive effects).

Of relevance here, we can compare manipulations of simple feature discriminations (e.g., stimulus contrast) and manipulations of word judgments (e.g., word frequency). First consider a simple feature experiment. Pashler (1984) examined effects of stimulus contrast on a visual search task. The manipulations of contrast and dual-versus-single task were subadditive. This is consistent with the perceptual processes being before the bottleneck and hence not limited by it. In contrast, the effects of manipulations presumed to be on response selection (presence vs. absence) were additive. Next consider a pair of word experiments. Carrier and Pashler (1995) manipulated the retrieval difficulty in an episodic memory word recognition task. Here, the manipulations of retrieval difficulty and SOA were additive, consistent with word recognition occurring at or beyond the bottleneck (but see Logan & Delheimer, 2001). Similarly, McCann, Remington, and van Selst (2000) manipulated word frequency in a word naming task. The frequency and SOA effects were again additive consistent with the word frequency effect being at or beyond the bottleneck (but see Cleland, Gaskell, Quinlan, & Tamminen, 2006). Thus, there are several results using speeded dual tasks suggesting that some aspect of word recognition is at or beyond the response selection bottleneck. In the terms of this article, this is an example of a fixed-capacity limitation.

These experiments and the theory that allows one to consider a wide variety of tasks involving perceptual, memory, decision, and response factors is very valuable. However, limitations in nonperceptual processes, such as decision or memory, can contribute to the effects in these speeded tasks. Distinguishing limitations in perceptual capacity from limitations in other processes involves a number of assumptions and fairly specific modeling. We next turn to variations of the dual-task paradigm that aim to minimize the role of memory, decision and response by the use of dual tasks involving accuracy search or detection.

Unspeeded dual tasks. One can also measure capacity limitations using a dual-task paradigm with accuracy (e.g., Sperling & Melcher, 1978; Bonnel, Stein, & Bertucci, 1992; Bonnel & Hafter, 1998). In this dual-task paradigm, two tasks are performed at the same time in a dual-task condition or separately in single-task conditions. Accuracy on each task in the dual-task condition is compared with performance in the corresponding single-task condition. If the two tasks have unlimited capacity, performance is predicted to be identical in dual- and single-task conditions. If the two tasks have limited capacity, then performance is predicted to be worse in the dual-task condition compared to the single-task condition. Furthermore, if one makes assumptions about the relationship between capacity and performance, then one can predict specific decrements for the dual-task condition relative to the single-task condition (see a review in Sperling & Doshier, 1986). In addition, serial processing also predicts that performance between the two tasks is inversely correlated from trial to trial. An example of this analysis can be found in Bonnel and Prinzmetal (1998). We highlight the equality predictions for the case with unlimited capacity, because this is likely to be a robust prediction relative to the other cases in which one must predict the magnitude of differences.

Bonnel and colleagues (1992) found no dual-task decrement in an experiment that required simultaneously detecting two luminance increments. Similarly, Bonnel and Hafter (1998) found no performance decrement in a study that required simultaneously detecting a visual luminance increment and an auditory intensity increment. However, in both studies they found that dual-task effects emerged when the task was to *identify* whether the signal change was a decrement or increment. They initially concluded that the task difference—identification rather than detection—was responsible for difference. Later, however, they found that memory was the real culprit: capacity limitations emerged because the identification task required that each stimulus be compared to a standard in long-term memory (Hafter, Bonnel, Gallun, & Cohen, 1998). When they altered the tasks so that they instead relied on a comparison to a standard that was persisting in sensory memory, the dual-task effects disappeared.

This unspeeded dual task paradigm minimizes the role of response processes relative to the speeded dual tasks. A remaining disadvantage, however, is that the paradigm still requires two responses. This still allows for potential intrusions from memory-, decision-, and response-related capacity limitations (Duncan, 1980; Hafter et al., 1998). This possibility is usually minimized by careful choice of task and response. However, as illustrated by a sequence of studies by Bonnel and Hafter reviewed above, one must check for unanticipated capacity limitations that are not related to perception.

A different limitation of the unspeeded dual task paradigm is emphasized in reviews by Pashler (1998). He raises the possibility that one might miss capacity limitations in perception if one allows the observer to defer processing in one task relative to another. He cites the example of estimating the capacity limits of memory retrieval as a case in which unspeeded dual tasks miss the dependency. Instead, he advocates the use of speeded dual tasks. Of particular interest, he combines a speeded first task and an unspeeded second task. This eliminates the potential interference between the response selection of the first and response selection in the second task. Pashler (1989) used this method to test for

capacity limits between simple perceptual tasks and response selection and found no such limits (see also Pashler, 1991; Giesbrecht, Dixon, & Kingstone, 2001).

To summarize, the speeded dual tasks have wide generality in their potential application in exchange for requiring additional assumptions to separate perceptual capacity limitations from other possibilities. By comparison, the unspeeded dual tasks or the hybrid speeded-unspeeded combination give up generality but show promise in minimizing nonperceptual contributions. In particular the predicted equality of dual and single task conditions are likely to be a robust indicator of unlimited capacity. With respect to the test cases of simple features and words, the speeded dual-task paradigm provides several examples for simple features that are consistent with unlimited capacity and for words that are consistent with fixed capacity. For the unspeeded variations, the existing studies show that simple features are consistent with unlimited capacity. For unspeeded dual tasks, we know of no studies addressing word recognition.

Capacity in Response-Time Search

Set-size effects. Response time paradigms are perhaps the most popular and most misunderstood approach to capacity issues. The most common example of this paradigm is to manipulate the display set size and measure the effect on response time (e.g., Neisser, 1967; Treisman & Gelade, 1980; Wolfe, 1998). Typically, the observer's task is to indicate whether or not a target is present or absent in a display with multiple distractors. Generally, the mean response time increases as a function of set size, but the magnitude of this increase varies with the task. In prior work, the emphasis is on identifying which tasks yield small set-size effects and which yield large set-size effects. In early interpretations of these experiments, the magnitude of set-size effects were regarded as indicative of serial or parallel processing. Small set-size effects were deemed consistent with parallel processing, while large set-size effects were deemed consistent with serial processing. It is now clear that this interpretation is problematic.

The direct interpretation of set-size effects on response time fails for at least two reasons. First consider limited-capacity, parallel models. Townsend and colleagues have demonstrated that such models can generate any magnitude of set-size effect and in fact mimic serial models in detail (e.g., Townsend, 1971, 1974, 1990; Townsend & Ashby 1983; Townsend & Wenger, 2004). Townsend and colleagues have gone on and developed methods to separate the estimation of capacity from the parallel-serial distinction, some of which we review below.

Second, consider the possibility of error. By error, we mean that observers can mistake a distractor for a target, or vice versa. Assume that an observer identifies a single stimulus, target, or distractor, with imperfect accuracy. Assume further that the probability of correct identification is independent between stimuli. Using independence, one can calculate how the probability of error increases with set size. For example, suppose the accuracy for set size 1 is accuracy 95%. For set size 10, the accuracy of identifying all stimuli correctly is predicted to drop to about 60% ($.95^{10}$). With errors, set size inevitably affects accuracy, even for unlimited-capacity, parallel models (e.g., Shaw, 1980; Palmer et al., 2000). This increase in errors with set size also has implications for response time. At best, one might expect errors to increase with set

size independently of the response time increasing with set size (Schweickert, 1985, 1989). However, it might be worse than this. As the set size increases, observers are likely to adjust their speed-accuracy tradeoff to avoid making more errors at the cost of increasing their response time (Palmer & McLean, 1995). For example, Palmer (1998) found that with instruction and feedback, observers can adjust their speed-accuracy tradeoff to maintain equal errors for all set sizes. This presumably increased the effect of set size on response time. If such speed-accuracy tradeoffs occur, even large-set size effects on response time do not to rule out unlimited-capacity, parallel processing. **In summary, depending on the assumptions about error, unlimited and fixed capacity models can generate any magnitude of set-size effect. Thus, the magnitude of set-size effects on response time cannot distinguish capacity limitations.**

Factorial methods. Another approach involves separately manipulating the processing rate of stimuli by degrading visual quality. This can be achieved by reducing contrast or adding visual noise to some or all stimuli (e.g., Egeth & Dagenbach, 1991; Townsend & Nozawa, 1995). If one assumes that this manipulation selectively influences the processing rate for the affected stimuli, unique response time predictions can be made for parallel and serial models and capacity limitations can be estimated. This method has been called the *double factorial paradigm* (Townsend & Wenger, 2004; Fific, Nosofsky, & Townsend, 2008). For example, Townsend and Nozawa (1995) had observers detect a flash of light that could occur at one or both of two widely separated locations. They also manipulated the intensity of the flash separately at the two locations. This application of the method to detection is particularly promising because the concerns about speed-accuracy tradeoffs are much reduced in a detection experiment compared to a search experiment in which the set size is clearly visible to the observer. From the cumulative distribution functions for sets of conditions, they estimated a capacity index that is 1 for unlimited capacity and is 0.5 for fixed capacity. Their analysis takes into account the stochastic processing that allows the completion time for the first of two processes to be less than the completion time for a single process. In this article, they found a range of capacity estimates from greater than 1 (supercapacity) to fixed capacity. More recently, Townsend and colleagues (Townsend & Honey, 2007; Townsend & Eidels, under review) have presented a further analysis that helps narrow these capacity estimates. Specifically, if one estimates the contribution of the base response time that is unaffected by stimulus quality and decision (sometimes called the residual time), the estimated capacity index is reduced as the base time contribution increases. Another unresolved issue is that the capacity estimates from different parts of the response time distribution tend to differ (lower capacity for longer times). In summary, this work has formalized a very general treatment of capacity in the context of response time distributions. However, its applications have yet to make clear-cut estimates. In particular, it would be reassuring if this method yielded the same results for the detection of light flashes that is found with other methods (e.g., Graham, Kramer, & Haber, 1985; Bonnel et al., 1992).

Models of response time and error. Perhaps the most obvious but also the most difficult approach is to build models of response time that incorporate error. While these models have been developed for a variety of decision tasks (e.g., Palmer, Huk, &

Shadlen, 2005; Ratcliff & Smith, 2004; Roe, Bussemeyer, & Townsend, 2001; for a general review see Luce, 1986), they have only just begun to be applied to visual search. The most developed model relevant to visual search is by Thornton and Gilden (2007). They defined models of multiple-target search tasks, in which both the number of stimuli and the number of targets varied. The models allowed for a range of capacity limitations and for both parallel and serial processing. Thornton and Gilden compared the fits of their model to results of 29 different search tasks. A few tasks were best fit by their serial model, including searches for specific direction of rotating motion (e.g., clockwise among counterclockwise). Most of their tasks were fit best by parallel models. Capacity limits were assessed by fitting a free parameter that placed each task on a continuum from unlimited capacity to fixed capacity. On the unlimited-capacity side of this continuum were simple feature tasks such as size, color, and orientation discriminations. On the fixed-capacity side of the spectrum were spatial configuration tasks, such as a mirror-image discrimination of whether a left-facing C-like figure was present among rightward facing C-like figures. They did not test any word stimuli. The limitation of this approach is the quantitative models required relatively specific assumptions about the nature of the search. The alternatives to such assumptions is an open research question.

Redundant target effects. Redundant targets experiments manipulate the number of targets in a search display. Two of the paradigms just discussed incorporated such manipulations into a larger methodology. In this section, we focus on the specific predictions of the redundant target paradigm. In this paradigm, the targets are redundant in the sense that identifying any target is sufficient for responding correctly (e.g., van der Heijden, 1975; Snodgrass & Townsend, 1980; Egeth, Folk, & Mullin, 1988; Mullin & Egeth, 1989; Townsend & Wenger, 2004). The critical trials are those in which all stimuli are targets or all are distractors. In all-target trials, the unlimited-capacity, parallel model predicts that response time decreases as set size increases. This is because the fastest of n processes becomes faster as n increases. This effect is termed *redundancy gain*. In contrast, the standard serial model predicts that response time is constant regardless of the number of targets. This is because a response is always made following the first stimulus identification and all stimuli are either targets or distractors so that any one stimulus provides enough information to make a response (Snodgrass & Townsend, 1980).

Redundant target experiments have been conducted for both simple features and words. For simple features, Egeth and colleagues (1988; Experiment 6) conducted a study of line-orientation judgments. The targets were horizontal or vertical line segments against a background of diagonal line segments. Response time decreased as the number of targets increased, consistent with unlimited-capacity, parallel processing. For words, Mullin and Egeth (1989) conducted an experiment in which observers responded to words drawn from a specific semantic category. They observed no redundancy gain, a result consistent with serial processing and inconsistent with unlimited-capacity, parallel processing. Such a standard serial model implies fixed capacity processing.

The advantage of the redundant targets paradigm is that it provides an equality prediction for the standard serial model that does not depend on the details of the model such as the particular response time distributions. Moreover, for this equality prediction,

the assumptions about error are not likely to be important. This is because the standard serial model predicts equality in both response time and errors for these particular conditions with only target-only or distractor-only displays. Thus, there is no incentive for observers to adjust their speed-accuracy tradeoff. Parallel models that predict the magnitude of the redundancy gain are not so general. Instead, the predicted redundancy gains depend on what specific assumptions are made about errors. An additional concern is that redundancy gains can occur even with a serial model if increasing the number of targets increases the probability that a target will appear at a "favored position" (Mordkoff & Miller, 1993). Thus, one must take care to minimize differences in performance across the possible target locations and check for such effects. In summary, the redundant target paradigm holds promise for the particular purpose of identifying cases of the standard serial model because of the generality of the predicted equality in response time and error.

We have reviewed a number of approaches to measuring capacity using response time. In some cases, we are critical of these methods because they are not general to different assumptions about error. While progress is being made in developing more general models, they are still in their infancy. On the other hand, the redundant target paradigm shows specific potential for identifying serial models because of its robust prediction of equality in response times and errors.

Comparing Paradigms of Divided Attention

Our review was organized into the three approaches of accuracy search, dual tasks, and response time search. It highlighted three paradigms that make equality predictions for particular models that are likely to be robust for a variety of assumptions. These three paradigms are:

- a. The extended simultaneous-sequential paradigm: It predicts equality of simultaneous and sequential for both unlimited capacity and equality of sequential and repeated for fixed capacity,
- b. The unspeeded dual-task paradigm: It predicts equality of dual-task and single-task performance for unlimited capacity,
- c. The redundant target paradigm: It predicts equivalent performance across set-sizes for the standard serial model.

No paradigm is completely general. We suggest the best path ahead is to build consensus for a subset of paradigms by seeking agreement in the interpretation of test cases, as done here for contrast discrimination and word categorization. In our review of the three most robust paradigms, the results currently available are all consistent with unlimited capacity for simple features and fixed (or nearly fixed) capacity for words.

Conclusion

The simultaneous-sequential paradigm has been used to distinguish unlimited-capacity models from other possibilities. In this article, we added the repeated condition that distinguishes the fixed

capacity model. The extended simultaneous-sequential paradigm compares favorably to others that measure capacity because its predictions depend on relatively minimal assumptions. We investigated two test cases that showed distinctive results. For contrast discrimination, the results are consistent with unlimited-capacity and reject fixed capacity. This is consistent with previous proposals that the perception of simple visual features depends upon unlimited-capacity, parallel processing. For word categorization, the results are consistent with nearly fixed capacity and reject unlimited-capacity processing. This is consistent with previous proposals that reading words depends upon a serial process.

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Appendix A

Signal Detection Models of the Extended Simultaneous-Sequential Paradigm

In this appendix, we use models based on signal detection theory to derive predictions for the localization tasks described in this article. We define three models and for each derive predictions for simultaneous, sequential, and repeated conditions. The primary purpose of this theory is to derive the three critical *equality predictions*:

- The simultaneous-sequential equality for the unlimited-capacity, parallel model,
- The repeated-sequential equality for the standard serial model, and
- The repeated-sequential equality for the fixed-capacity, parallel model with integration.

The secondary purpose is to estimate the magnitude of the predicted inequalities for models that do not predict an equality. For example, the fixed-capacity, parallel model predicts an particular difference in performance for the simultaneous and sequential conditions. These *magnitude predictions* can be compared to the equality predictions to provide a sense of the power of the equality predictions. For example, is an observed deviation from the equality between the simultaneous and sequential conditions as large as predicted by a fixed-capacity model or some small fraction of that prediction? However, we emphasize that the magnitude predictions rely on additional assumptions while the equality predictions are more general.

Notation and Common Assumptions

Following previous models of accuracy visual search (e.g., Shaw, 1980; Busey & Palmer, 2008), we make two assumptions based on the ideas of signal detection theory (Green & Swets, 1966) that are common to all models considered here. Throughout, consider localization search experiments with n stimuli of which 1 is a target and $n-1$ are distractors.

Single random variable for each stimulus. The task-relevant internal representations for each stimulus is assumed to correspond to a real-valued random variable. These variables represent the relative evidence that a particular stimulus is a target rather than a distractor. For targets and distractors, these random variables are designated T and D , respectively. Random variables for the $n-1$ distractors are subscripted $D_1 \dots D_{n-1}$. The corresponding density distributions are denoted $f_T(x)$, $f_{D1}(x)$, \dots , $f_{D_{n-1}}(x)$. The corresponding cumulative distributions are denoted $F_T(x)$, $F_{D1}(x)$, \dots , $F_{D_{n-1}}(x)$.

Statistical independence. Statistical independence is assumed between all of the random variables. On a particular trial,

the value of any one random variable, say D_1 , is independent of any other representation on the same trial, say D_2 .

Unlimited-Capacity, Parallel Model

Definition. By parallel processing, the random variables are assumed to develop at the same time without any temporal dependence. By unlimited capacity, the random variables for each stimuli are assumed to be independent of the number of stimuli. To further define a “standard” unlimited-capacity, parallel model for localization, we follow the analysis of the n -alternative localization task described by Shaw (1980). For the decision rule, the observer is assumed to choose the stimulus with the largest value in the relevant representation (e.g., the highest contrast representation). This is equivalent to a maximum rule on an appropriately signed and normalized evidence variable. With this rule, the probability of choosing the correct location is

$$p(\text{correct}) = p[T > \max(D_1, \dots, D_{n-1})]. \quad (1)$$

For localization with these assumptions, this decision rule is optimal (Green & Swets, 1966). The assumptions can be summarized as follows:

- Single random variable for each stimulus,
- Statistical independence,
- Parallel processing,
- Unlimited capacity,
- Maximum decision rule.

Derivation. To make predictions, Equation 1 can be rewritten as

$$p(\text{correct}) = \int_{-\infty}^{\infty} f_T(x) F_{D1}(x) F_{D2}(x) \dots F_{D_{n-1}}(x) dx. \quad (2)$$

This equation integrates the product the density function representing the target multiplied by the cumulative distributions representing the distractors.

Fixed-Capacity, Parallel Model

Definition. We following the sample size model of Shaw (1980) in defining a fixed-capacity, the parallel model. It is similar to the unlimited-capacity, parallel model, but with the variance of each random variable proportional to the number of stimuli present in each frame. Thus, the variance of each random variable is doubled in the simultaneous condition compared to the sequential condition. The other assumptions remain unchanged.

(Appendices continue)

Standard Serial Model

Definition. To describe serial processing, we follow the approach of Davis, Shikano, Peterson, and Michel (2003) and assume that in a given display, some stimuli are scanned, while others are not. The number of stimuli that can be scanned in each display is designated m . The observer has information about m stimuli and has no information about $n - m$ stimuli. When a stimulus is scanned, it can still be misidentified, thus the overlap of the target and distractor distributions remains relevant. This is somewhat different than often assumed in the response time literature for the “standard” serial model (e.g., Townsend & Ashby, 1983). A further assumption of the standard serial model defined here is that the values of m and the random variables are independent of the number of stimuli being processed. The parameter m can be a discrete value (e.g., $m = 2$), or a distribution of possible values (e.g., $m = 1, 2$ or 3 with equal probability). This description of a serial model is different than the perhaps more familiar approach of specifying distributions of completion times for each process (but see Schweickert, 1985, 1989 for efforts toward unifying these different approaches). Finding a common “standard” serial model for both accuracy and response time is a problem for the future.

While one can use the same maximum decision rule as described above, we consider a rule customized for the serial model. We call it the *maximum decision rule with sophisticated guessing*. If all stimuli are scanned ($m = n$), the observer chooses the stimulus with the largest value, as with the parallel model. In this case, the standard serial model makes the same predictions as the unlimited-capacity, parallel model. In other words, when the observer can scan all the stimuli in the time allowed, the standard serial model is not distinct from the corresponding parallel model for the tasks considered here. The interesting case when only some of the stimuli are scanned ($m < n$). In this case, the observer chooses the scanned stimulus with the largest value, unless that value falls short of criterion c . If the highest of the m scanned stimuli does not exceed c , the observer randomly guesses that the target was one of the $n - m$ stimuli that were not scanned.

Given these definitions, the probability of choosing the correct location is:

$$p(\text{correct}) = \frac{m}{n} p[T > \max(D_1, \dots, D_{m-1}) \text{ and } T > c] + g \left(1 - \frac{m}{n} \right) p[c > \max(D_1, \dots, D_m)] \quad (3)$$

where $g = 1/(n - m)$. The first line of Equation 3 considers the case in which the target is among the m scanned stimuli. This occurs with probability m/n . If any scanned stimulus yields a value greater than c , the observer chooses the stimulus corresponding to the largest value. If no scanned stimulus yields a value greater than c , the observer randomly chooses among the $n - m$ remaining stimuli that were not scanned. If this happens, the response is always incorrect, because the target was among the m scanned stimuli. Thus, in this case for the observer to respond correctly, the target

random variable must take a value that exceeds the criterion and also the values taken by all three distractor random variables.

The second line of Equation 3 considers the case in which the target is not scanned. These cases occur with probability $1/(n - m)$. If any of the m scanned distractors take a value greater than the criterion c , the observer will incorrectly choose that the distractor as the target. If the observer correctly rejects all the scanned distractors, she guesses the location from the remaining $n - m$ unscanned stimuli, guessing correctly with probability $g = 1/(n - m)$.

For this model, the assumptions can be summarized as follows:

- Single random variable for each stimulus,
- Statistical independence,
- Serial processing in the sense that some stimuli are processed and others not,
- The number of processed stimuli are independent of the number of stimuli,
- The random variables for the processed stimuli are independent of the number of stimuli,
- Maximum decision rule with sophisticated guessing.

Derivation. Equation 3 describing the standard serial model is equivalent to:

$$p(\text{correct}) = \frac{m}{n} \int_c^\infty f_T(x) F_{D_1}(x) F_{D_2}(x) \dots F_{D_{m-1}}(x) dx + \left(1 - \frac{m}{n} \right) \left(\frac{1}{n - m} \right) F_{D_1}(c) F_{D_2}(c) \dots F_{D_m}(c). \quad (4)$$

The first line of Equation 4 considers the cases in which the target is scanned. The probability of correct response in this case is the integral of the product of the density function of the target and the cumulative function of all identified distractors from c to infinity. The second line of the equation considers the case in which the target is not scanned. The cumulative functions of the distractor evaluated at c gives the probability that a given scanned distractor does not exceed c . The product of m such cumulative functions gives the joint probability that none of m scanned distractors exceed c . If the observer correctly rejects all of the scanned distractors, she has a chance to correctly guess among the remaining unscanned stimuli.

Predictions for the Simultaneous-Sequential Comparison

Equality predictions for the unlimited-capacity, parallel model. For the unlimited-capacity, parallel model, we have assumed that the quality of information about each stimulus is equivalent for all stimuli that are presented for an equivalent duration (unlimited capacity). Thus, both the simultaneous and

sequential conditions are modeled according to Equation 2 and hence must be identical. Thus, this prediction is general to any evidence distribution and changes in the decision rule that remain consistent with unlimited capacity.

Assumptions for estimating magnitudes of nonequivalences.

To make more specific predictions, we constrain random variables to be from the same family of distributions. Specifically, all distractors D_i are identically distributed with the density function designated $f(x)$. The target random variable is assumed to have the same distribution shifted by a target-distractor discriminability parameter w and designated $f(x - w)$. The corresponding cumulative distributions are $F(x)$ and $F(x - w)$, respectively.

The target-distractor discriminability parameter w is closely related to d' . It represents the difference between the expected values of a target and distractor distribution. For a simple yes-no task with a single stimulus and unit-variance Gaussian distributions, the parameter w is d' .

With these further assumptions about common distributions for targets and distractors the predicted performance of the unlimited-capacity, parallel model in Equation (2), can be rewritten as:

$$p(\text{correct}) = \int_{-\infty}^{\infty} f(x - w) F_1(x)^{n-1} dx. \quad (5)$$

Similarly, the prediction of the standard serial model in Equation (4), can be rewritten as:

$$p(\text{correct}) = \frac{m}{n} \int_c^{\infty} f(x - w) F(x)^{m-1} dx +$$

$$\left(1 - \frac{m}{n}\right) \left(\frac{1}{n - m}\right) F(c)^m. \quad (6)$$

For magnitude predictions, we further assume that all random variables are Gaussian and that they have unit variance, except where otherwise specified. Without loss of generality, we can set the mean of the distractor density function $f(x)$ to zero. This implies that the target density function $f(x - w)$ has expected value w . For all predictions given below, w varies from 0 to 6 and the number of stimuli n is set equal to 4.

Panel A of Figure A1 shows the predictions of the unlimited-capacity, parallel model in the simultaneous and sequential conditions. Difficulty is represented on the abscissa as the difference in means of the target and distractor random variables normalized by the standard deviation (d'). The predicted percent correct in each condition is represented on the ordinate. For the unlimited-capacity, parallel model, the curves representing performance in the simultaneous and sequential conditions were generated from identical equations, signifying that the model predicts that at any level of difficulty, performance is equivalent in the two conditions.

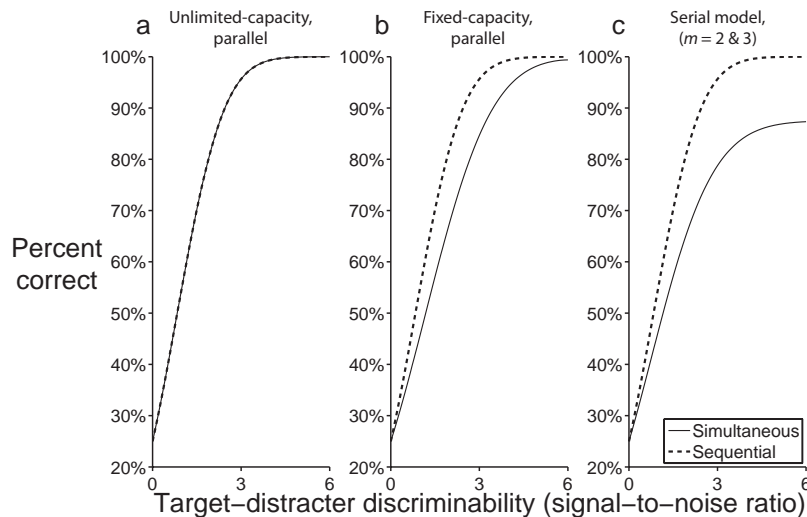


Figure A1. Quantitative predictions for three models in the simultaneous-sequential comparison. Predicted percent correct for each condition is plotted as a function of task difficulty. (a) Predictions of the unlimited-capacity, parallel model. (b) Predictions of the fixed-capacity, parallel model. (c) Predictions of the standard serial model. These predictions were generated using an equal mixture of standard serial models with m values of 2 and 3.

(Appendices continue)

This equality prediction is general to any assumed density function. Only the magnitude predictions depend on the distributions.

Magnitude predictions for the fixed-capacity, parallel model. For the fixed-capacity, parallel model, we adopt the parallel sampling model of Shaw (1980). The number of samples that are obtained from each stimulus is inversely proportional to the number of simultaneously presented stimuli. Thus, the variance of all random variables is proportional to the number of stimuli being processed at once. This assumption has the effect of doubling the variance of the random variables representing each stimulus in the simultaneous condition (4 stimuli), relative to the variance of the random variables in the sequential condition (2 stimuli). The simultaneous and sequential conditions are each modeled using Equation 2, taking into account the difference in variance of the density functions.

Panel B of Figure A1 shows the predictions of the fixed-capacity model for the simultaneous and sequential conditions. The model predicts that performance between the two conditions is similar when the task is very easy or very difficult, but performance is superior for the sequential condition at intermediate difficulties.

Magnitude predictions for the standard serial model. To model the predictions of the standard serial model in the simultaneous and sequential conditions, we assume that observer can scan m stimuli in the simultaneous condition, and can scan $2m$ stimuli in the sequential condition (with the caveat that $2m$ may not exceed n , the total number of stimuli in display sequence). For example, if an observer can scan only one stimulus in the simultaneous condition, she can scan two stimuli in the sequential condition. In summary, there are two independent determinants of performance in this model: the parameter m representing the number of stimuli scanned per frame, and the parameter w representing target-distractor discriminability. For simplicity, we also fix the criterion c to be half of w .

Panel C of Figure A1 shows the predictions of the standard serial model in which $m = 2$ for half of the trials and $m = 3$ for the other half of the trials. This specific model accounts for the data collected in our word categorization experiment. More generally, sequential performance is better than simultaneous performance whenever w exceeds zero.

Discussion. To compare the numerical predictions with our data, we use a parametric plot that is shown in Figure A2. This figure shows performance in the sequential condition plotted against performance in the simultaneous condition. In this figure, difficulty sweeps out a curve so that the bottom left corner represents the most difficult target-distractor discriminations ($w = 0$) and the upper right corner represents very easy discriminations ($w = 6$). The vertical distance of each point on a curve from the diagonal indicates the predicted magnitude of the simultaneous-sequential effect. The results of the two simultaneous-sequential comparisons in this article are plotted as points with error bars representing 1 SEM. The predictions of two standard serial models are plotted: one with $m = 2$ and one with $m = 3$. The data from the word-categorization experiment fall between these predictions.

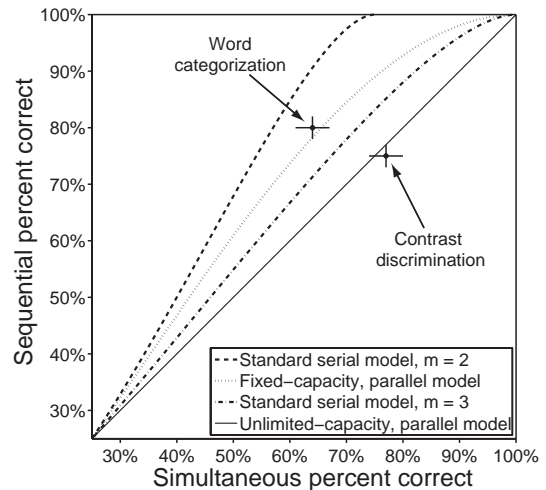


Figure A2. Comparison of the models and data for the simultaneous and sequential conditions. Percent correct in the sequential condition is plotted against percent correct in the simultaneous condition. Data from the contrast increment and word categorization experiments are plotted with error bars representing 1 SEM.

Thus, these experimental results are consistent with observers analyzing between two and three words per brief display, on average.

The figure supports the arguments in the body of this article: the results for word categorization are consistent with either the fixed-capacity parallel model or the standard serial model, but reject the unlimited-capacity model. The results for contrast discriminations are consistent with the unlimited-capacity, parallel model, and reject both the fixed-capacity, parallel model, and the standard serial model.

Additional Assumptions for the Repeated Condition

To model the performance of parallel models in the repeated condition, it is necessary make an assumption about how observers pool information about stimuli that are repeated in two displays. We describe two different information pooling models. The assumptions correspond to the two major models of information pooling in signal detection theory: integration and independent decisions (see Green & Swets, 1966).

Integration. In this model, the observer retains and integrates all information extracted from both displays. The observer then decides on the basis of the integrated representations. To make numerical predictions, we assume that repeating the display doubles the number of samples, consequently reducing the variance of each random variable by a factor of one half.

Independent decisions. In this model, the observer retains memory of only the most likely target from each display. This model is consistent with findings that observers remember little about the identity of items that have been rejected during search

(Appendices continue)

(Beck, Peterson, Boot, Vomela, & Kramer, 2006; Beck, Peterson, & Vomela, 2006). To make numerical predictions, we assume that the observer analyzes each frame of the repeated condition independently, then applies a max rule to pick the most likely target from between the two displays.

Serial models. The repeated conditions presents a different issue for serial models. For such models, one typically assumes the effect of each comparison process is independent of the place in the sequence in which the process occurs. This can be naturally extended to apply to processes in the first or second frame. In addition, one must consider what happens if the serial process exhausts all of the stimuli ($m = n$). The independence assumption states that all stimuli that are processes receive the same degree of processing. This implies that there is no “reallocation” of the processing if it completes while stimuli are still available. This is because such a reallocation would preferentially advantage some stimuli that are ruled out by independence. Thus, for both the sequential and repeated conditions the four stimuli are each processed individually without reallocation. This prevents the repeated condition from gaining an advantage in having more stimuli that can support such reallocation (see Townsend, 1972, 1981). In summary, the independence assumption of the standard serial model rules out reallocation.

Predictions for the Sequential-Repeated Comparison

For each of the parallel models, we generate separate predictions for integration and independent decisions assumptions. Figure A3 shows the parametric plot for this comparison. Panel A shows

predictions with integration and Panel B shows predictions with independent decisions. In each panel, percent correct in the sequential condition is plotted against percent correct in the repeated condition. Difficulty sweeps out a curve such that the bottom left corner represents the most difficult conditions ($w = 0$) and the upper right corner represents the easiest conditions ($w = 6$). The vertical distance from the diagonal to a model prediction is the predicted size of the sequential-repeated effect. The results of the two sequential-repeated comparisons in this article are plotted as points with error bars representing standard error of the mean performance in each of the two conditions.

Equality predictions for the standard serial model. In the standard serial model, the effect of the repeating the display is equivalent to doubling the value of m , as m stimuli are identified in the first display and an additional m stimuli are processed in the second display. This doubling is equivalent to the effect of the sequential presentation. Thus, standard serial models predict equivalent performance in the sequential and repeated displays, falling along the diagonal in both panels of Figure A3.

Equality predictions for fixed-capacity, parallel models with integration. With integration, observers integrate information from two frames, resulting in a more accurate representation of each stimulus. Predictions of the fixed-capacity, parallel models with integration are shown in Panel A of Figure A3. For the fixed-capacity, parallel model, variance is halved because the display is repeated, but doubled because twice as many stimuli are being sampled in each display; so there is no overall change in variance. Performance in sequential and repeated conditions are

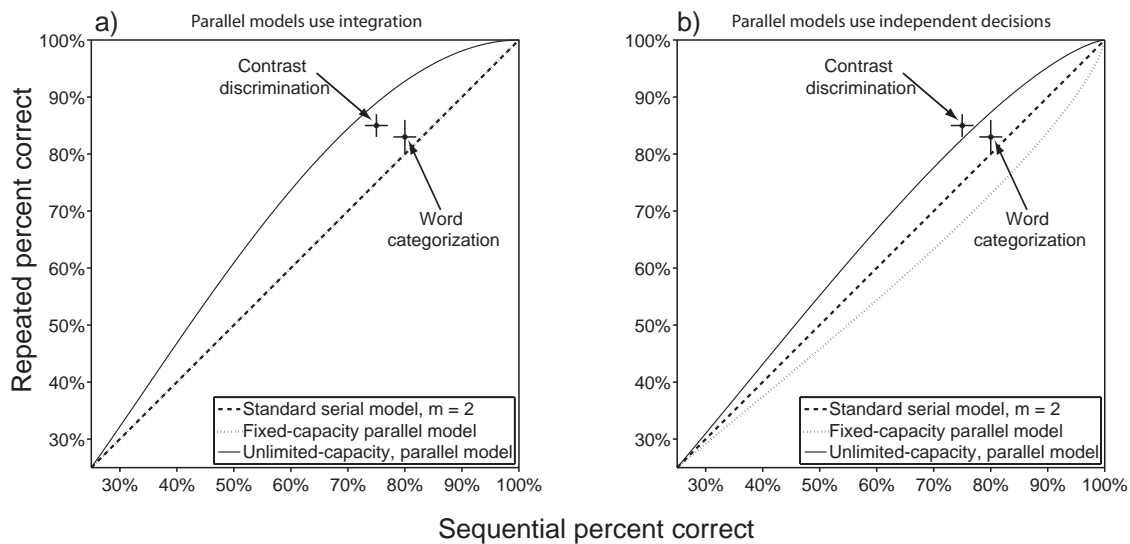


Figure A3. Comparison of the models and data for the sequential and repeated conditions. Percent correct in the repeated condition is plotted against percent correct in the sequential condition. Data from the contrast increment and word categorization experiments are plotted with error bars representing 1 SEM. (a) Predictions assuming integration model of information pooling. (b) Predictions assuming independent-decisions model of information pooling.

(Appendices continue)

equivalent for this fixed-capacity, parallel model and the predictions of this model fall along the diagonal axis in Panel A of Figure A3. This equality prediction is general to any distributional assumption.

Magnitude predictions for unlimited-capacity, parallel models with integration. For the unlimited-capacity, parallel model, viewing each stimulus twice in the repeated display has the effect of halving the variance of each representation in the repeated display, resulting in superior performance in that condition. These predictions are also shown in Panel A of Figure A3.

Magnitude predictions for parallel models with independent decisions. Under independent decisions, observers respond successfully when either view of the target yields a value that is greater than the maximum of all the distractors' values. The independent decisions assumption requires one to consider each frame separately. To do so, use T_1 and T_2 to designate the random variables corresponding to the target in the first and second frame, respectively. Similarly, the random variables for the distractors are designated $D_{1,n}$ and $D_{2,n}$ for the n th distractor in the first or second frame, respectively.

For independent decisions, we assume that the observer responds correctly when the value of either target representation exceeds the all of the other representations:

$$p(\text{correct}) =$$

$$p(T_1)p(T_1 > \max(T_2, D_{1,1}, \dots, D_{1,n-1}, D_{2,1}, \dots, D_{2,n-1})) + \\ p(T_2)p[T_2 > \max(T_2, D_{1,1}, \dots, D_{1,n-1}, D_{2,1}, \dots, D_{2,n-1})] \quad (7)$$

which is equal to:

$$p(\text{correct}) = 2 \int_{-\infty}^{\infty} f_T(x) F_T(x) F_D(x)^{2(n-1)} dx. \quad (8)$$

The integral in Equation 6 counts all cases in which the value of one of the targets exceeds the value of all other stimulus representations (both the distractors and the other target). To count the cases in which one or the other target yields the highest value, the integral is multiplied by two.

Panel B of Figure A3 shows the predictions with independent decisions for the sequential-repeated comparison. For the unlimited-capacity, parallel model, there is a smaller advantage for the repeated condition relative to the same model with integration. For the fixed-capacity, parallel model, independent decisions predicts an advantage for the sequential condition, whereas integration predicts equivalence between the two conditions. Our standard serial model does not require information pooling, so its predictions remains at the diagonal.

Discussion. These models echo the informal predictions in the body of this article: the unlimited-capacity, parallel model predicts better performance in the repeated condition than the sequential condition. This prediction follows from either the integration or independent decisions assumptions. On the other

hand, the predictions from fixed-capacity, parallel model depend on the information pooling assumption. The standard serial model and the fixed-capacity, parallel model with integration predict equivalence between sequential and repeated conditions. The fixed-capacity, parallel model with independent decisions predicts better performance in the sequential condition than the repeated condition.

A comparison of our data to these models reinforces the conclusions in the body of this article. The contrast discrimination results are consistent with unlimited-capacity, parallel processing and can be predicted by either information pooling model. The word categorization data is consistent with the standard serial model, or with the integration version of the fixed-capacity, parallel model.

Predictions for the Simultaneous-Repeated Comparison

Although it is not one of our primary comparisons, it is informative to consider the comparison of the simultaneous and repeated condition. This comparison addresses the information pooling assumptions more directly than our other comparisons. All models predict an advantage for repeated condition, but the magnitude of the benefit differs among the models.

Figure A4 shows the predictions of each model. No model predicts equivalence between the two conditions, but we include a diagonal line in the figure for reference. The unlimited-capacity parallel and fixed-capacity parallel models make identical predictions for this comparison, but the two pooling assumptions make different predictions. Parallel models with independent decisions

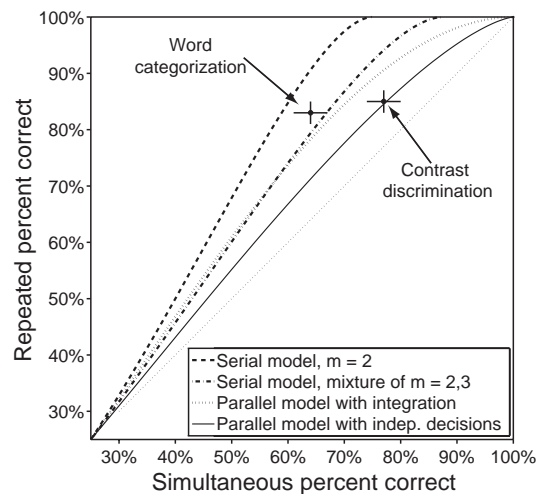


Figure A4. Comparison of the models and data for the simultaneous and repeated conditions. Percent correct in the repeated condition is plotted against percent correct in the simultaneous condition. Results from Experiments 1 are shown for the contrast increment and word categorization tasks with error bars representing 1 SEM.

(Appendices continue)

predict a more modest benefit for the repeated condition than do parallel models with integration. The results for contrast discrimination are consistent with a parallel model with independent decisions. A standard serial model ($m = 2$) predicts a larger

advantage for the repeated condition than predicted by either parallel model. As in the other comparisons, the word categorization results are accounted for by a standard serial model that has an even mixture of $m = 2$ and $m = 3$ trials.

Appendix B

Words Used in Word Categorization Task

Animals: Cat, dog, lion, bear, wolf, snake, mouse, tiger.

Body parts: Lip, ear, chin, neck, face, elbow, thumb, wrist.

Clothing: Tie, hat, belt, coat, vest, scarf, pants, shirt.

Food: Ham, pie, soup, rice, meat, bread, fruit, salad.

Professions: Nun, cop, chef, maid, poet, nurse, actor, judge.

Transportation: Bus, jet, boat, ship, taxi, truck, train, plane.

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