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Effects of set-size and lateral masking in visual search

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Abstract—In the present research, the roles of lateral masking and central processing limitations in visual search were studied. Two search conditions were used: (1) target differed from distractors by presence/absence of a simple feature; (2) target differed by relative position of the same components only. The number of displayed stimuli (set-size) and the distance between neighbouring stimuli were varied as independently as possible in order to measure the effect of both. The effect of distance between stimuli (lateral masking) was found to be similar in both conditions. The effect of set-size was much larger for relative position stimuli. The results support the view that perception of relative position of stimulus components is limited mainly by the capacity of central processing.

Keywords: Visual search; capacity limitations; lateral masking; signal detection theory; modeling.

INTRODUCTION

Most commonly, visual search studies base their conclusions on the magnitude of the effect of set-size (number of to-be-processed stimuli) on performance. Dependent on the set-size effect, a search may be judged to be either parallel or serial, or either unlimited or limited in processing capacity.

Many recent studies have found that set-size effects in visual search for simple feature targets are consistent with Signal Detection Theory based models with unlimited processing capacity (Palmer *et al.*, 1993; Palmer, 1994; Foley and Schwarz, 1998; Baldassi and Verghese, 2002). Essentially the same models have successfully predicted set-size effects even in the search for conjunctions of simple features (Eckstein, 1998; Eckstein *et al.*, 2000).

Still it seems that there do exist quite simple stimuli that do not conform to these models. In an earlier study (Põder, 1999), I used a difference threshold method similar to that of Palmer *et al.* (1993) and simple stimuli defined by relative position of their elements, and found large set-size effects inconsistent with unlimited

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capacity. These results are in accordance with several other visual search studies arguing that a limited capacity attentional mechanism is required for perception of relative position of elements within visual stimulus (Bergen and Julesz, 1983; Wolfe and Bennett, 1997; Logan, 1994).

However, in my study as well as these other studies, set-size has been at least partially confounded with density of stimulus objects. Consequently, observed set-size effect may not necessarily be the result of central (global) processing limitations, but may be explained by local interactions between adjacent objects (or 'sensory factors') instead.

Adverse interactions between adjacent stimuli have been studied under different names, most frequently 'lateral masking' and 'crowding'; in this article, I shall use 'lateral masking'.

Several studies have reported very large effects of lateral masking in eccentric vision. The spatial extent of lateral masking is approximately proportional to the eccentricity of target stimulus and reaches to 0.5 E (E — eccentricity of target). (Bouma, 1970; Toet and Levi, 1992; Chung *et al.*, 2001; Levi *et al.*, 2002b).

There is some evidence from visual search studies indicating that local interactions may be more extensive for stimuli that are more complex. In comparison of conditions, when either displayed or relevant (pre-cued) set-size was varied, Palmer (1994) found that sensory factors had negligible effect in visual search for simple features, at least with set-sizes up to 8. However, these factors were more influential with more complex stimuli, and the use of more than 4 letter-like objects per display was not possible in order to avoid 'sensory' effects. Cohen and Ivry (1991) have found large density effects in visual search for conjunctive targets and no effect in simple feature search.

On the other hand, several authors have found no effect of distance between stimuli in visual search experiments with letter targets (Hoffmann, 1979; Bennett and Jaye, 1995). Morgan *et al.* (1998), however, report on a large effect of distance with quite simple stimuli — a search for tilted target among vertical distractors.

Lateral masking studies also do not provide a clear answer as to whether the more complex stimuli are more affected by lateral masking than the simple ones. The extent of the lateral masking has been found to be almost the same for letter identification and orientation, spatial frequency, and contrast discrimination (Bouma, 1970; Andriessen and Bouma, 1976; Wilkinson *et al.*, 1997). However, two recent studies (Levi *et al.*, 2002b; Pelli *et al.*, 2003) report much less lateral masking for simple detection tasks as compared with identification or (fine) discrimination.

The present study directly measures the effect of lateral masking in visual search for feature and for relative position stimuli in order to determine the possible contribution of lateral masking in large set-size effects observed with relative position stimuli. Several studies have attempted to measure set-size effects while controlling sensory effects. Here I try to measure and model both effects simultaneously in the same study. The target and distractor objects were similar to that of my previous study (Põder, 1999). Both variables of interest — set-size and distance between stimuli — were varied as independently as possible within a simple circular configuration.

METHODS

Stimuli

Targets and distractors were either symmetrically or asymmetrically bisected squares with sides of 12 pixels (approximately 0.5 degrees from a viewing distance 60 cm) (Fig. 1). In the feature search condition, the target was asymmetric and distractors were symmetric. Thus, the target had unique simple components (rectangles of certain width) that were not present in distractors. In the relative position search condition, both the target and distractors were asymmetric, distractors being mirror images of the target. Here the target differed from distractors only in the relative position of the same components. The target–distractor similarity (shift of bisector, from square center) was adjusted (based on pilot experiments with one observer) for slightly less than 100 percent correct performance with set-size one in the both search conditions. Factually, the asymmetry was set at two pixels for feature and three pixels for relative position stimuli.

A search display consisted of 1 to 12 stimuli presented in an imaginary circle at 2.5 deg from fixation point (Fig. 2). Nearest neighbour distance (NND) (along the perimeter) was varied from a minimum 1/12 of perimeter up to half of the perimeter (two objects in the opposite ends of the diameter). Thus, center-to-center distance between objects in terms of visual angle was varied from 1.3 to 5 deg. Only a subset of the set-size × NND combinations was applicable in this configuration (e.g. only minimal NND was used with set-sizes 8 and 12). Selection of the location (beginning position) of a group of stimuli on the perimeter of the circle as well as the position of the target (if present) was random. Target was present on half of the trials.

Procedure

Observers initiated a trial by pressing the enter key on the keyboard. After a delay of 0.5 s a search display was presented for 68 ms. Subjects then had to respond by pressing key 1 for target present or key 2 for target absent. A display

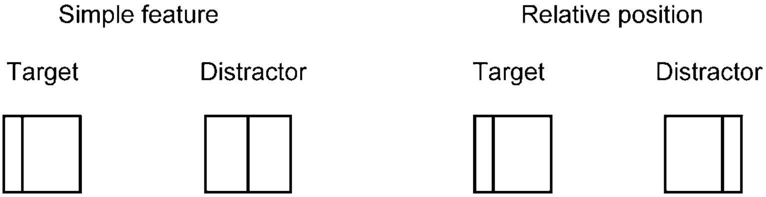


Figure 1. Sketch of targets and distractors used in two search conditions of the present study.

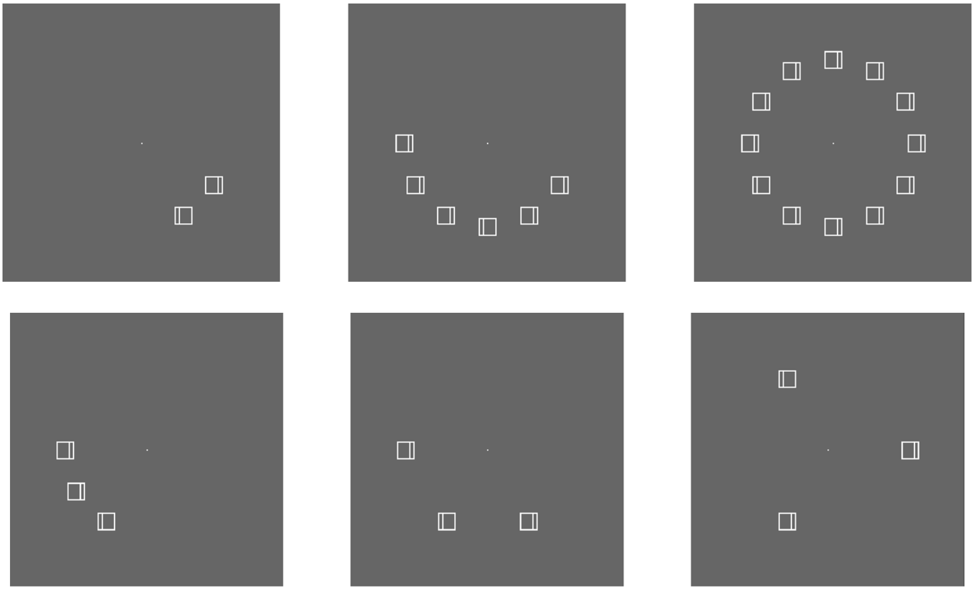


Figure 2. Examples of stimulus configurations. Variation of set-size with fixed NND (top row), and variation of NND with fixed set-size (bottom row).

of correct answers provided feedback after each trial. Experiment was run in blocks of 50 trials. Set-size and NND were held constant within blocks (in order to facilitate optimal criterion setting for each condition). Blocks with different values of independent variables were counterbalanced for order. The search condition (feature or relative position) was varied between observers.

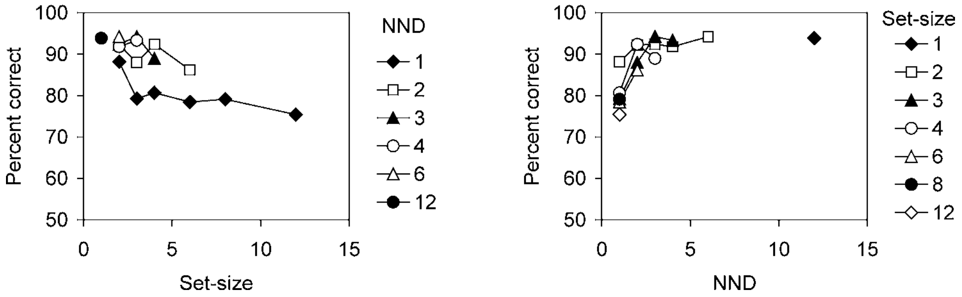
Observers

In total, 9 observers took part in the experiment. All had normal or corrected-to-normal vision. One observer, EP (the author), had previous experience in similar search experiments; others had very little or no experience with this type of tasks and were uninformed in regard to the theoretical background of the experiment. 5 observers participated in the feature and 5 in the relative position condition. One observer (EP) ran both conditions; others were assigned randomly to only one of the two conditions. Each observer completed 100 trials per data-point.

RESULTS AND MODELLING

Percentages correct, as dependent on set-size and NND for the two search conditions are presented in Fig. 3. It is clear that the effect of set-size is much larger for the relative position search while the effect of NND seems to be approximately similar for both feature and relative position conditions.

Feature search



Relative position search

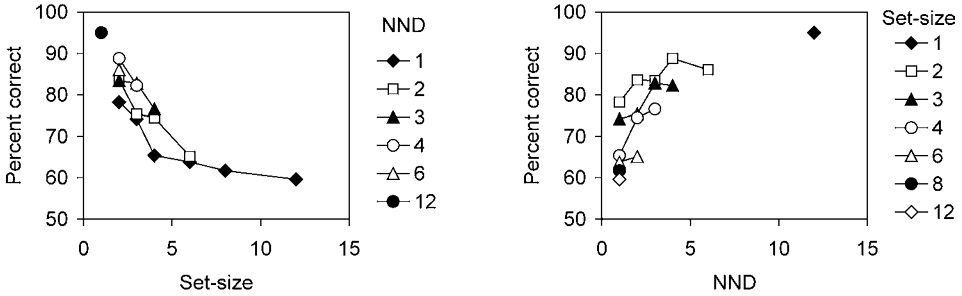


Figure 3. Results of the experiment. Percentages correct as dependent on set-size (left) and NND (right) for two search conditions: simple feature (top) and relative position (bottom). NND is measured in $1/12$ steps of the perimeter of stimulus configuration. For set-size one, NND was arbitrarily assigned to the full perimeter (12). Note that left and right graphs are two views of the same data.

ANOVA with accuracy as the dependent variable, set-size and NND as independent variables, and observer as random factor confirmed reliable effect of both independent variables in both (feature and relative position) conditions (set-size effect: $F(5, 20) = 5.2$, $p < 0.01$ for feature search, and $F(5, 20) = 18.1$, $p < 0.001$ for relative position search; NND effect: $F(4, 16) = 3.0$, $p < 0.05$ for feature search, and $F(4, 16) = 3.1$, $p < 0.05$ for relative position search. The effect of interaction was significant for feature search condition only ($F(6, 24) = 4.1$, $p < 0.01$ for feature search, and $F(6, 24) = 1.5$, $p > 0.05$ for relative position search).

In order to measure the effects of set-size and NND quantitatively, two models were tried. In the first model, simple linear regression was applied to the log-transformed data (percentages correct were transformed into d' assuming equal noise and signal variances and unbiased observer). The fitted models were as follows.

Feature search:

$$\log d' = 0.27 \log D - 0.17 \log N + 0.45. \tag{1}$$

Relative position search:

$$\log d' = 0.28 \log D - 0.64 \log N + 0.46, \tag{2}$$

where N is set-size and D is straight center-to-center distance between nearest neighbour stimuli in display.

The fit was very good for relative position condition ($R^2 = 0.95$) and not so good for feature condition ($R^2 = 0.77$). The estimated effects of NND are remarkably similar across conditions (0.27 ± 0.08 for feature, and 0.28 ± 0.07 for relative position search) while the effects of set-size are different (0.17 ± 0.08 for feature, and 0.64 ± 0.07 for relative position). The results seem to support the involvement of limited capacity in relative position discrimination. Note that with set-size one, performance was roughly equal for both search conditions; therefore, the different slopes can hardly be explained by different levels of performance. Also, it is important to mention that the maximum performance of near 95% correct observed in the experiment is not an absolute ‘ceiling’ on performance. In the pilot experiment, nearly perfect (99–100%) accuracy was observed with a larger target–distractor difference. Thus, a ceiling effect is unlikely to hide part of the set-size or NND effect.

In order to compare the empirical set-size effects with the predictions of limited and unlimited capacity models (e.g. Shaw, 1980; Palmer *et al.*, 1993, 2000; Eckstein, 1998) based on Signal Detection Theory (SDT), I calculated theoretical $\log d'$ *vs.* $\log N$ slopes for these models at the points corresponding to the average d' and N of the experimental data (see Appendix A). The theoretical slopes, based on unlimited capacity assumption, were −0.19 for feature search data, and −0.30 for relative position data. Empirical slope −0.17 ± 0.08 of feature search data matches the prediction very well, but slope −0.64 ± 0.07 of relative position data is significantly different from unlimited capacity prediction. At the same time, it is also different from limited capacity (sample size model) prediction −0.96. Figure 4 depicts the empirical data as $\log d'$ *vs.* log set-size, and theoretical graphs based on unlimited and limited capacity models. Note that the unlimited capacity model predicts different slopes for different performance levels. This may explain, at least in part, the effect of interaction of set-size and NND found with the feature search data.

An obvious problem with the first model is the assumption of a linear relationship between d' and NND in log–log coordinates. Actually, the present data as well as several previous studies indicate that lateral masking effect virtually disappears when the target–distractor distance exceeds some critical value.

Several attempts have been made to express this relationship mathematically. The present study uses a slightly modified version of the model proposed by Levi *et al.* (2002a). I removed their built-in constraint on the amplitude of masking effect (in their model, lateral masking had to cause the un-masked threshold to at least double), and selected another spatial parameter that is not related to the point of doubling the threshold. According to this model, additional noise in observer

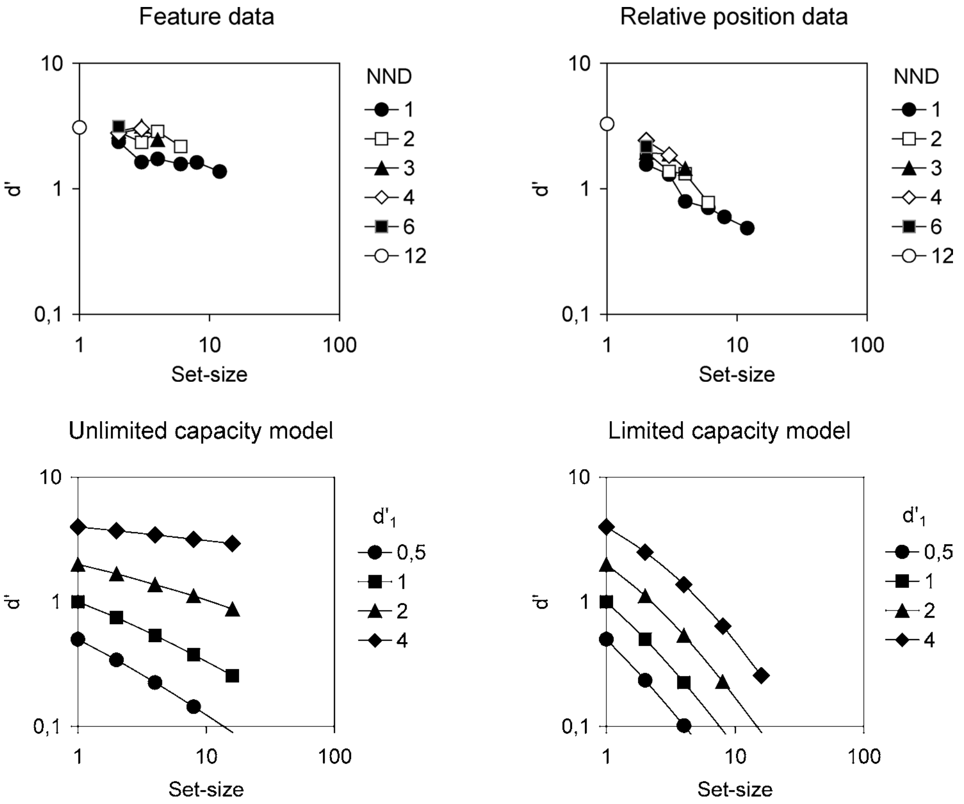


Figure 4. Results of the experiment depicted as log d' *vs.* log set-size for two search conditions (top), and theoretical log d' *vs.* log set-size graphs predicted by unlimited and limited capacity models based on SDT (bottom).

created by distractor, decreases following Gaussian function of the target–distractor distance. The detectability of target with a distractor at distance D is given as follows:

$$d' = \frac{d'_0}{1 + (a-1)(a+1)^{-(\frac{D}{s})^2}}, \tag{3}$$

where d'_0 is d' without distractor, a is the maximum effect of lateral masking (number of times d' decreases with overlapping (zero distance) distractor); s is the distance where decrease of d' reaches half of the maximum decrease.

This model, combined with multiplicative (linear in logarithmic scale) set-size effect, accounted for 0.90 and 0.97 of variance of log d' for feature and for relative position search, respectively. Figure 5 depicts the empirical data (log d' *vs.* log NND) after the removal of log set-size effect, together with fitted Gaussian curves. The estimates of the spatial parameter s (with bootstrap estimates of standard error) were 0.62±0.14 deg and 0.90±0.40 deg for feature and for relative position conditions, respectively. However, the difference was not reliable (single-tailed

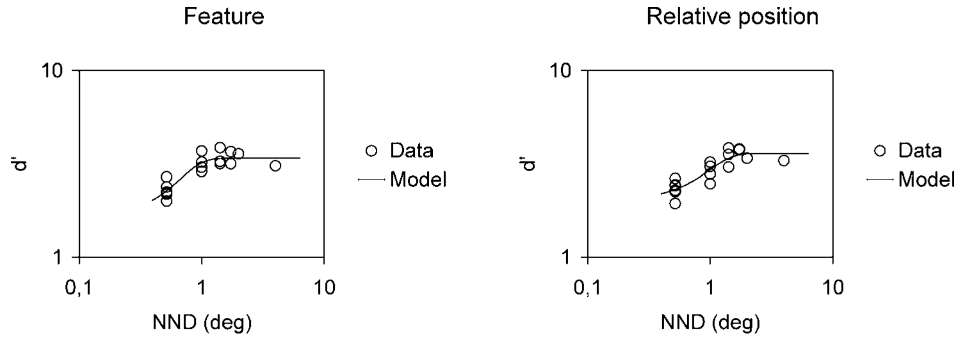


Figure 5. Effect of NND on d' for feature (left) and relative position (right) conditions. Both variables are in logarithmic coordinates. Linear effect of log set-size has been subtracted from empirical log d' data. Curves represent the predictions of best-fitted Gaussian model (equation (3)).

t-test, $p > 0.05$). Estimation of maximum masking effect (parameter a) was very unreliable (because there were no data points at very small NNDs), but the fitted values were nearly equal for the two search conditions (2.1 ± 9.4 and 1.8 ± 1.3 for feature and relative position, respectively). Estimated effects of set-size remained virtually the same as in the first model (-0.19 ± 0.06 for feature, and -0.65 ± 0.06 for relative position data).

Up to this point, it was assumed that the effect of lateral masking is determined by the nearest neighbour only, thereby ignoring the number of stimuli at the same nearest distance, as well as all other stimuli further away. However, there is evidence from several studies that the effect of lateral masking depends on the number of flanking stimuli (Bouma, 1970; Kröse and Burbeck, 1989); in some cases, lateral masking was not found at all with a single distractor (Toet and Levi, 1992).

Therefore, I attempted to estimate the effect of the number of neighbours from the present data. For this purpose, I compared the percentages for correct detection of target when it was located either at the end or in the middle of a group of simultaneously presented stimuli and, consequently, had either one or two neighbours at the nearest distance. Calculations were performed for each set-size × NND combination where segregation of 'end' and 'middle' stimuli was possible. From 14 comparisons, 4 revealed statistically significant ($p < 0.05$) differences according to χ^2 test. All significant differences were in the expected direction: targets at the ends of a group were detected more frequently than targets in the middle of a group. However, the effect was rather small, on average, 6.4 and 5.7 percentage points for feature and relative position conditions, respectively. Since the effect was very similar in both conditions, it cannot contribute significantly to the observed differences in the set-size effect.

Interestingly, a significant effect of 'end' positions was found for the same particular set-size × NND combinations in the both search conditions. These were set-size 3, NND 3 steps, and set-size 6, NND 1 step. The common property of these configurations is the location of the 'end' stimuli approximately at the ends of a diameter of the imaginary circle centered at fixation point. Rather speculatively, this strange finding may reflect either a slit-shaped attentional window, or processing that starts from the farthest ends of the stimulus configuration.

DISCUSSION

The present results indicate that local (distance-dependent) interactions are nearly equal for simple (feature) and complex (relative position) search, and accounted for by a simple lateral masking model. The set-size effects in two search conditions are very different even after elimination of lateral masking effects, and must reflect central capacity limitations of relative position discrimination.

This conclusion is well in accordance with the results of a recent study by Davis *et al.* (2003). These researchers used a pre-cueing procedure designed to eliminate all sensory effects, and confirmed the capacity limitations for different examples of relative position stimuli.

In the present study, lateral masking was considered the main ‘sensory factor’, and the data appear to support this assumption. However, things may be different with different stimuli. A closer look at Palmer’s (1994) results reveals that the ‘sensory factors’ he attempted to eliminate were probably not related to lateral masking. In lateral masking conditions, thresholds for small set-size, cued from a larger set of displayed objects, should be higher than with the same set-size displayed without additional irrelevant objects. ‘Sensory’ effects observed in Palmer (1994) with complex stimuli do not conform to this pattern, and their exact nature remains unclear.

Larger density effects with search for color-shape conjunctions, as compared with feature search (Cohen and Ivry, 1991), may indicate the use of different mechanisms in different ‘complex’ search tasks. Classical conjunction search and relative position (or spatial configuration) search are different in several aspects (e.g. Wolfe, 1998), and need not be affected equally by density of stimuli. Moreover, in reaction time studies with long exposure durations, eye movements can mediate display density effects.

Set-size effect for relative position search measured in the present study was somewhat less than the prediction of sample size model. In my previous study (Põder, 1999) set-size effects were well consistent with the sample size model for similar stimuli. There are many differences between these studies, and I cannot state exactly what matters. In the present study, stimulus displays were more regular, and regularity was found to be an important factor of search efficiency for some relative position stimuli (Humphreys *et al.*, 1989). However, different methods of data analysis and modeling, or inter-individual differences may also play some role.

Nonetheless, perception of relative position of stimulus components seems to require some sort of processing that is limited in capacity, even if the sample size model is not always the best way to describe this limitation.

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APPENDIX A: CALCULATION OF THEORETICAL SET-SIZE EFFECTS

The present research follows the ideas of Shaw (1980, 1984), Palmer *et al*. (1993, 2000) and Eckstein (1998) applying SDT to visual search. Previous researchers have predicted either percentage correct or target–distractor difference threshold for one set-size from the same performance measure for another set-size. Here, I explore one more version of essentially the same model calculating the predictions of detectability index d' for set-size N from the same index for set-size 1 (notated as d'_1).

Stimuli (target and distractors) are internally represented as independent random variables. Assume that they have Gaussian distributions with equal (unit) variance. Probability densities are $g(x)$ for distractors, and $g(x-d'_1)$ for target. Corresponding cumulative distributions are $G(x)$ and $G(x-d'_1)$.

For an unlimited capacity model, the number of presented stimuli (set-size) does not affect internal variables. Observer is assumed to respond “yes” when maximum of internal variables exceeds criterion c.

With set-size N, the cumulative distribution of maximum value for target-absent (noise) trials is

$$F_n(x) = G^N(x), \tag{A1}$$

and for target-present (signal) trials

$$F_s(x) = G^{N-1}(x) \cdot G(x - d'_1). \tag{A2}$$

Through differentiation, we can find corresponding probability density functions:

$$f_n(x) = \mathrm{d}[F_n(x)]/\mathrm{d}x, \tag{A3}$$

$$f_s(x) = \mathrm{d}[F_s(x)]/\mathrm{d}x. \tag{A4}$$

In order to maximize percentage correct, the criterion c should be selected such that

$$f_n(c) = f_s(c) \tag{A5}$$

(Note that optimal criterion is different for different set-sizes.) From hit and false-alarm rates we can calculate the detectability index d' for a given set-size:

$$d' = G^{-1}[1 - F_s(c)] - G^{-1}[1 - F_n(c)], \tag{A6}$$

where G^{-1} is the inverse of Gaussian distribution.

For limited capacity (sample size) model, signal-to-noise ratio of individual internal variables is assumed to be inversely proportional to square root of set-size N. Thus, in equations d'_1 was replaced with $d'_1/\sqrt{N}$.

Values of d' as dependent on N and d'_1, for unlimited and limited capacity models, were calculated numerically and are plotted in Fig. 4 (bottom). Essentially the same functions (for unlimited capacity case only, with set-size as parameter) have been published in several articles (e.g. Swensson and Judy, 1981; Pelli, 1985; Palmer *et al.*, 2000). The curves are slightly different from straight lines in logarithmic coordinates; however, within limited range of data, linear approximation looks not too bad.

In order to calculate theoretical $\log d'$ *vs.* $\log N$ slopes for the empirical data, I determined the coordinates of the centers (mean $\log d'$ and mean $\log N$) for both feature and relative position data sets. Mean $\log d'$ was 0.367 and 0.129 (corresponding to d' 2.33 and 1.35) for feature and relative position search, respectively. Mean log N was 0.515 ($N = 3.27$) for both conditions. Local slopes of theoretical curves at these points were estimated and the empirical slopes were compared to these estimates.