Attentional spread in the statistical processing of visual displays

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Abstract

We tested the hypothesis that when attention is distributed over an array of similar items its statistical properties may automatically become available. We found that extracting the mean size of sets of circles was easier to combine with tasks requiring distributed or global attention than with tasks requiring focused attention. One explanation may be that extracting the statistical descriptors requires parallel access to all the information in the array. Consistent with this claim, we found an advantage to simultaneous over successive presentation when the total time available was matched. Evidence that statistical processing is automatic when attention is distributed over the display came from the finding that there was no decrement in accuracy relative to single task performance when mean judgments were made concurrently with another task that required distributed or global attention.

As we navigate through our environment, we sometimes focus attention on a single object like a tree and sometimes spread it over a wider area to see the forest. The forest in turn can yield two different kinds of information. It may have global properties of its own, such as a shape, a color, an orientation, and a density, and it also comprises the aggregate properties of its individual elements which can be statistically summarized. The individual trees have a mean size with a particular variance and range, a mean separation, a mean leafiness, and so on. Most environments are hierarchically structured, as shown in this example. It seems likely, therefore, that perceptual mechanisms have evolved to form representations that connect objects hierarchically to give properties of the wholes as well as properties of their component parts. We perceive the global features that emerge from the arrangement of elements, the individual properties of particular local elements, and the statistical properties of the ensemble. How do we extract these three kinds of information – global, local and statistical?

Our hypothesis is that there are different modes of processing, and that each is favored by a particular distribution of attention. At one extreme, when attention is focused on one object at a time, we bind its features, determine its structure, and perhaps identify it. At the other extreme, we may attend globally to the scene as a whole. When attention is also set to the global scale, this allows access to the gist or semantic interpretation of the scene (for example “a beach in Summer”, “a modern kitchen”), and to its global layout. When attention is distributed over a set of items, but the scale is set to that of individual elements, we have access to their statistical properties. Between these extremes, we may attend to pairs or triplets of objects to determine the relations between them – for example, the book is *under* the table, Mary is *stroking* the cat. The apparently complete and veridical representation of the surrounding scene that we normally experience may be an illusion generated from occasional detailed samples together with statistical summaries of remaining areas and an overall interpretation of the meaning or gist. This sampling and summarizing at different levels of representation may help account for the striking change blindness recently explored by Rensink (2002), Simons (Simons & Levin, 1997), and others.

Global versus local properties

Research pioneered by Navon (1977) has compared global and local processing of shape, using large shapes made of smaller shapes. These paradigms varied both the size of the attended area and the scale of the attended object. An early issue concerned the order of processing: Is the overall structure identified earlier in time than the component parts? Navon reported evidence supporting 'global precedence'. Global precedence, in a different sense, is also reflected in the asymmetry of interference between global and local forms: a global form typically creates greater interference in processing a local form than the converse (Hoffman, 1980; Miller, 1981; Pomerantz, 1983).

A second issue was whether there are separate systems for global and local processing, and how these systems are distributed in the two cerebral hemispheres. Hemispheric specialization suggesting global processing in the right brain and local processing in the left was found in unilateral brain-damaged patients (Delis, Robertson, and Efron (1986), and in normal participants with fMRI (Fink, Halligan, Marshall, Frith, Frackowiak, and Dolan, 1996) and with ERPs (Heinze, Hinrichs, Scholz, Burchert, & Mangun, 1998). Significant increases in relative rCBF were seen in the right lingual gyrus when participants attended to global forms, and in the left inferior occipital cortex when they attended to local forms. The N2 component of ERPs (260 to 360 ms) elicited by a hierarchical letter showed a larger response with attention to the local letters in the left hemisphere and to the global letter in the right, but earlier components showed no lateral asymmetries.

A final question considered in this line of research was whether it is possible to access both global and local information at the same time? Here the results are more complex and may depend on the nature of the task. Using alphanumeric stimuli, Farell and Pelli (1993) found no effect on the accuracy of identifying a target letter or digit when they mixed scales within the same display. On the other hand, Ward (1982) found a delay when participants had to switch the level to which they were attending within a hierarchical stimulus. Similarly, Robertson, Egly, Lamb, and Kerth (1993) showed that a target letter was found more quickly when the level at which it would appear was cued in advance. Using a stimulus containing many different local directions of motion, Watamaniuk and McKee (1998) found that participants could either form a unified global percept of motion in the direction of the mean or focus on one local direction of motion. Direction discrimination thresholds in the post-cued condition were not significantly higher than those obtained in the pre-cued condition, suggesting that direction information for both global and local motion is encoded in parallel.

Statistical versus individual processing of local elements

Studies with hierarchical stimuli confound two senses of the term “global” attention: - the spatial spread of attention over a wide area, and the selection of elements defined at a large rather than a small spatial scale. These two aspects usually go together in tests with hierarchical stimuli, but they need not do so. It might be possible to distribute attention over an ensemble of local elements and to process those individual local items in parallel over a broad spatial area. This is the perceptual mode in which we suggest that statistical properties are coded. To distinguish it from processing of global properties, we will use the term "distributed attention". The environment is full of sets like the trees in a forest, the grass in a field, a flock of birds, the cars in a parking lot, about which we are unlikely to store individuating information. We can perceive them both as global ensembles with global properties of shape and layout, and as sets of local elements, with a mean value and a variance on a number of different dimensions. Other statistical properties of the elements, such as their homogeneity or heterogeneity, may also be perceptually available. Our interest in this paper is to explore the statistical processing of sets of elements rather than the global processing of the ensemble, and to relate this processing to the optimal deployment of attention.

Statistical processing of visual displays has been studied in the context of natural images (Field, 1997; Geisler, Perry, Super, & Gallogly, 2001) and of texture perception (Haralick, Shanmugam, & Dinstein, 1973; Julesz, 1981), but not much research has directly compared the coding of individual elements with the coding of sets. Treisman & Gormican (1988; Treisman, 1991) used the idea of statistical coding in the context of visual search, suggesting that popout performance depends on distributed attention to the display as a whole. The idea was that preattentive processes pool feature information within each of a set of coarsely coded feature maps, giving an average measure of the degree to which each of these feature values is present in the display. A unique target is detected if it generates activity in a set of detectors that are not also activated by the distractors. When the target has no unique feature and activates the same detectors as the distractors, but to a lesser degree, an attention window of adjustable size is narrowed sufficiently to isolate pooled samples whose averaged signal differs detectably when the target is present in the sample and when it is not. Thus a continuum from serial to parallel search functions can be generated by varying the size of the attention windows to match the statistical properties of the display.

Experiments on motion perception also illustrate some effects of different attentional modes. When attention is broadly spread over the display, globally coherent motion is perceived (group motion for the Ternus stimulus), whereas when attention is focused on a small area of the display, local motion is perceived (oscillatory motion, or element motion for the Ternus stimulus. Hock, Park, & Schöner, 2002). Watamaniuk and Sekuler (1992) found that global motion discrimination improved as the area of the display increased, suggesting that simultaneously accessing more information helps us to process the statistical properties of the moving elements.

Ariely (2001; Ariely & Burbeck, 1995) published one of the first studies that explicitly explored the ability to extract the statistics of a display. They showed that the mean size is perceived more accurately than the individual sizes in a display of disks of varied sizes, and that there is little effect of the number of disks. Chong & Treisman (2003) used their paradigm to show that judgments of the mean size are almost as accurate as judgments of single items presented alone, and that they are little affected either by exposure duration or by delay, suggesting an automatic and parallel process. We also confirmed that the judgments involved computing the mean size of an array by showing that they were almost as accurate when the distributions differed as when they were the same.

In the present paper, we use dual task paradigms to test the idea that distributed attention facilitates statistical processing. We ask participants to combine statistical judgments of the mean size of circles with a second concurrent task that has been shown either to encourage a global deployment of attention or to require focused attention to one element at a time. We contrasted two different pairs of tasks, one of each pair requiring distributed or global attention and one focused attention. The first pair involved visual search for a target that either pops out or does not. The second required participants to judge the orientation either of a large or of a small rectangle.

To measure the accuracy of statistical processing in the context of these concurrent tasks, we adapted the paradigm first developed by Ariely (2001). On each trial participants responded to one of the concurrent tasks and then decided either which of two test circles matched the mean size of the circles in the previous display, or which of two test circles had been presented as an individual element in the previous array. We used a staircase procedure, varying the size difference of the two probes to achieve 80% accuracy. Our hypothesis was that distributed attention would be more effective than focused attention for extracting the mean size of the circles, but not for judging the individual sizes. The suggestion is that the mean is a statistical property of the display as a whole and that it is directly accessed as such, rather than by summing the individual sizes and dividing by their number.

In the last two experiments, we tested whether the statistical processing mode requires simultaneous presentation of the set to be judged. Statistical processing has previously been tested with successive presentation. For example, Helson (1947) showed that the scale of weight judgments was centered on a weighted logarithmic mean of the successively presented weights. In a different context, Posner and Keele (1968) explored the extraction of prototype shapes from sequential presentations and found that the prototypical shape comes to represent the set in visual memory. These experiments studied learning across trials and representations in memory. We were interested in seeing whether the perceptual processing mode that we studied with simultaneous displays can also be applied to a sequence of elements. We asked for mean judgments with 8 circles presented either simultaneously or successively in different display locations. The simultaneous displays were presented for two different durations, one matching the duration of the whole sequence of successive presentations, and the other matching the duration of a single circle in the successive presentation.

Experiment 1

The purpose of Experiment 1 was to explore what deployment of attention would be most compatible with extracting statistical properties like the mean size. We hypothesized that statistical properties might be best represented when attention was distributed over the scene as a whole, whereas individual elements might be better discriminated with attention focused on each in turn. To control the deployment of attention we used a dual task paradigm in which the concurrent task would encourage either focused or distributed attention.

Search for a closed circle among circles with gaps has been found to require focused attention to each item in turn, whereas a circle with a gap among closed circles 'pops out' of the display (Treisman & Souther, 1985). If distributed attention facilitates extracting the mean size of a set and focused attention facilitates recognizing individual items, concurrent search for a circle with a gap should lead to better performance in discriminating the mean size, whereas concurrent search for a closed circle should lead to better performance in identifying the size of a randomly selected individual item. To check that our manipulation did control the deployment of attention, we varied the number of elements in the display between 4 and 12. If focused attention is required to detect the closed circle, the search time should increase between displays of four and 12 items, whereas if distributed attention is used to detect the circle with a gap among closed circles, the number of elements should have no effect.

Method

Participants

Twelve participants including the first author took part in the experiment. All were members of Princeton University. All had normal or corrected-to-normal vision.

Apparatus and Stimuli

The stimuli were created with the Psychophysics Toolbox (Brainard, 1997) and presented on the screen of an Apple 17" Monitor, which was driven by a Macintosh G3. Participants were seated approximately 45 cm from the screen. At this distance, a pixel was approximately 0.06° of visual angle. Each display consisted of a gray background and white outline circles or circles with gaps that deleted 12.5% of the circumference. The luminance of the circles was 49.9 cd/m^2 and the luminance of the gray background was 25.0 cd/m^2. Half the displays had a target and half did not. In the focused attention condition, the target was a closed circle and the nontarget elements were circles with gaps. In the distributed attention condition, the target was a circle with a gap and the nontargets were closed circles. The locations of the gaps were randomly chosen among four positions (80º, 170º, 260º, and 350º).

The circles in both conditions were of four different sizes, equally spaced on a log scale separated by a factor of 1.15. The mean circle diameter was 5.9°, and the diameters ranged from 4.8° to 7.3°. Sets with 4 and 12 circles were used, with 1 or 3 circles in each of the four sizes. The sets with 4 and 12 circles were presented in randomly chosen locations in an imaginary 3 x 3 matrix, and 5 x 5 matrix, respectively. The 5 x 5 matrix was centered at fixation and the 3 x 3 matrix was randomly located within the 5 x 5 matrix. The length and width of a cell was 12°. An example of a display is shown in Figure 1 together with two sample-test circles.

The participants' response to the visual search task was immediately followed by two test circles presented 15º to the left and right of fixation. One of the test circles matched either the mean size of the set or the size of one member of the set. The other test circle was either slightly larger or slightly smaller in size than the first test circle. The difference in size was determined by a staircase procedure depending on the performance of the previous trials. The initial size difference was 50% diameter difference. If participants were correct three trials in a row, the difference decreased by 3%. If they were incorrect in the previous trial, the difference increased by 3%. In each trial all of the circles shown were randomly scaled by a small multiplicative factor to discourage the observer from basing his judgments on previously seen stimuli. Four multiplicative factors (1, 1.1, 1.2, 1.3) were used and the same factor scaled all the circles in any given trial.

···Figure 1···

Design

There were four independent variables, which were all varied within participants. The first variable was the type of visual search – target closed or open circle; the second was the type of size judgment – either mean or member. Both these were blocked. The third variable was target presence – either present or absent; and the fourth was set size – either 4 or 12 items. Both these factors were randomly mixed within blocks. Each participant served in four experimental blocks (2 types of visual search x 2 types of size judgment) as well as four practice blocks. The order of the experimental blocks was counterbalanced between subjects. The order of trials within each block (target present or absent x display size 4 or 12) was randomly selected under the constraint that each condition was presented once before any condition was repeated. There were 50 trials in the practice blocks and the experimental blocks continued until 17 reversals had occurred in the staircase procedure. The initial diameter difference in the experimental block was the last diameter difference in the practice block.

Procedure

A timeline of the procedure is shown in Figure 1. Each trial started with a fixation cross for 500ms, followed by a search display which remained present until the participant responded. Participants' first task was to search for either an open or a closed circle (the target). They pressed '1', when the target was present, and '2', when it was not. When their decision was incorrect, they heard a brief high tone.

After they responded to the search task, two circles appeared in the center of screen. The second task was to decide which of the two test circles matched the mean size of the circles in the previous display, or which of the two test circles had been presented as an individual element at the location indicated by a marker on the screen. The marker was a small white square which appeared at the same time as the two test circles. In the member identification task when the target was present, the target was always presented as one of the two test circles. Participants pressed '1', when they thought that the left circle was the answer and '2', when they thought that the right circle was the answer. They received feedback, as they had in the first task.

We used a staircase procedure to determine the size judgment threshold, varying the diameter difference of the two test circles to achieve 80% accuracy. The step size was 3% diameter difference between the two test circles. We used the mean of the last 12 reversals as the threshold for size discrimination.

Results and Discussion

The results of Experiment 1 are shown in Figure 2. Figure 2(a) shows the results of the visual search. Participants were faster when they searched for a popout target (a circle with a gap) than when they searched for a non popout target (a closed circle; $F_{(1, 11)} = 60.4$, $p < .01$), and they were faster when the set size was 4 than when the set size was 12 ($F_{(1, 11)}$

= 114.9, $p < .01$). The interaction between the type of visual search and the set size was significant ($F_{(2,32)} = 72.3$, $p<.01$). The mean slope relating search times to the set size for present and absent target was relatively shallow for the popout target (averaging 24 ms/item). Unlike the results of Treisman & Souther (1985), this slope was significant ($t_{(11)} = 3.2$, $p<.01$), suggesting that there may have been some interference from the competing dual task. However, the slope for a non popout target was much steeper, (126 ms/item, $t_{(11)} = 11.99$, $p<.01$), indicating that our attempt to modulate attention was successful. No other two-way or three-way interactions were significant. The error rates in the search task with focused attention were 7% and 6% for the concurrent mean and member judgments respectively; with distributed attention the corresponding rates were 2% and 3%. An ANOVA showed that participants were more accurate when they searched for a popout target than when they searched for a non popout target ($F_{(1, 11)} = 26.2$, $p < .01$). Accuracy in visual search was not affected by which of the two size judgment tasks it was combined with (mean or member, $p = .78$), and the two-way interaction was not significant.

···Figure 2···

Figure 2(b) shows the results of the size judgment task. Neither the type of search nor the type of size judgment had a significant effect on the size thresholds. However the interaction between them was significant ($F_{(1, 11)} = 9.6$, $p < .05$). In the mean size judgment participants had lower size thresholds with the popout search (22% for target C) than with the serial search (25% for target O), whereas in the member size judgments, they had lower thresholds with serial search (24%) than with popout search (28%).

In the member identification task when the target was present, the target was always presented as one of the two test circles. In order to see whether size judgments differed between target present and absent trials, we reanalyzed the member identification performance depending on the presence of the target, using percent correct rather than thresholds. Member size judgments were better when the target was present (90%) than when the target was not present (76%) ($t_{(11)}$ = -6.5, p < .01). Remembering detailed information, like the size of an individual element, may benefit from focal attention to that particular element.

The critical question we tested in Experiment 1 was whether the type of search task would differentially affect the two types of size judgment. We predicted that judgments of mean size would benefit more from the parallel search condition because it induced more distributed attention. Indeed, we found the predicted interaction between the type of search task and the type of size judgment. Even though there was unlimited time to search for a target in both search conditions, and the resulting exposure durations were much longer for the O targets, search for the C was actually more accurate. This allows the possibility that participants might have had more spare capacity for the mean size judgments when concurrently doing the parallel search than the serial search. However, this alternative is ruled out, because in the member judgment task participants were better with the serial search (O target) than with the parallel search. Differences in leftover capacity cannot therefore explain the differences between the two types of size judgments. Our explanation for the interaction is that judgments of the mean size benefited more from the parallel search because it led participants to see the display as a whole, whereas judgments of member size benefited more from the serial search because it led participants to individuate each item in the display. The result makes it very unlikely that the mean size is judged by serially perceiving and summing each individual size and dividing by the total number.

Experiment 2

The concurrent tasks in Experiment 1 contrasted focused and distributed attention. To generalize the results, in Experiment 2, we used a different concurrent task to modulate the deployment of attention, requiring participants to judge either a global or a local orientation while again judging the mean size of the circles in the display. The concurrent tasks differed from those in Experiment 1 by requiring attention to different perceptual units, other than the circles on which the size judgments were to be made. Participants were to say whether a rectangle was horizontally or vertically oriented. The rectangle was either a small one at the fovea or a large one surrounding the circles. Thus the tasks required attention to be divided between different stimuli (rectangles and circles), as well as between different tasks (orientation judgment and size judgment).

Methods

Participants

Ten Princeton undergraduate students participated in the experiment for the option of course credit. All had normal or corrected-to-normal vision.

Apparatus and Stimuli

The apparatus for Experiment 2 was the same as for Experiment 1. The displays were the same as in Experiment 1, with the following exceptions: All the circles were closed ones and there was no target. The sizes were equally spaced on a log scale separated by a factor of 1.15. The mean circle diameter was 2.5°, and the diameters ranged from 2° to 3.04°. Participants were seated approximately 79 cm from the screen. All displays consisted of 16 circles, presented in an imaginary 5 x 5 matrix located in the center of the screen. The length and width of a cell was 6°. The positions of the circles were randomly chosen among the matrix cells, except the cell in the center. The method of choosing test circles was same as in Experiment 1. The luminance of both the stimuli and the background was the same as in Experiment 1.

A small rectangle was always presented in the center cell and a large rectangle surrounded the display of circles. An example of a display is shown in Figure 3. The initial size of the large rectangle was either 35.6° x 30.3° or 30.3° x 35.6° and the initial size of the small rectangle was either 2.4° x 2.04° or 2.04° x 2.4°. Thus the aspect ratios were matched. To equate the difficulty of the orientation judgment between the large and small rectangle, the aspect ratio was determined by a staircase procedure depending on the participant's performance in the previous trials. A single staircase was used for both of the rectangles. A step size was a change of 1% in the aspect ratio. If participants were correct three trials in a row, the difference decreased by 1%. If they were incorrect in the previous trial, the difference increased by 1%. The aspect ratio was varied between 6% and 17%.

···Figure 3···

Design

In this experiment, only the mean size judgment was tested in addition to the orientation judgment, so there was just one independent variable, either global or focused attention. This was varied within participants by selecting whether the concurrent task was to judge the orientation of the large or of the small rectangle. Each participant served in four blocks (2 for each type of attention) as well as four practice blocks. The practice blocks had 50 trials and the experimental blocks ended after thirteen reversals of the staircase. The two attention conditions were tested in separate blocks, with their order counterbalanced across and within subjects.

The staircase procedure for the size judgment was the same as in Experiment 1 except that we collected 13 reversals rather than 17 reversals during each of the two experimental blocks. We used the average of the two means of the last 12 reversals as the threshold of size discrimination.

Procedure

A timeline of the procedure is shown in Figure 3. Each trial started with a fixation cross for 500ms, followed by a display (200ms), which in turn was followed by the two test circles. Unlike in Experiment 1 where the search task preceded the mean size judgment, participants' first task here was to decide which of the two test circles matched the mean size of the circles in the previous display. They pressed '1', when they thought that the left circle was the answer and '2', when they thought that the right circle was the answer. When their decision was incorrect, they heard a brief high tone. After they had responded to the size task, key instructions for the orientation task appeared. A relevant rectangle was designated at the beginning of each block and the relevant rectangle was varied across blocks. Participants pressed '1', when the designated rectangle was aligned horizontally and '2', when it was aligned horizontally. A constant reminder of key mapping was always present on the screen. Participants received feedback as they had in the first task.

Results and Discussion

The results of Experiment 2 are shown in Figure 4. Figure 4(a) indicates the results of the orientation judgment task. There was no significant difference in accuracy between the two orientation judgments ($t_{(9)} = -1.2$, $p = .25$), suggesting that performance on the global and local orientation judgments was closely matched in difficulty, as we had hoped.

Figure 4(b) shows the results of the size judgment task. Thresholds for the mean size were lower when the large rectangle was relevant than when the small rectangle was relevant in the concurrent orientation task, ($t_{(9)} = -2.7$, $p < .05$). We found the same effect in a pilot experiment with set size of 4 rather than set size of 16 ($t_{(7)} = -3.2$, $p < .05$). Thus we found the predicted advantage of global attention for judging the mean size of an array. In both conditions in this experiment, attention was directed to a rectangle as well as to the circles. However, discriminating the orientation of the large rectangle required that global attention be spread across the display, allowing easier concurrent processing of the array as a whole, which in turn seems to have favored easier extraction of its statistical properties.

The fact that the scale was different for the large rectangle does not seem to have prevented statistical processing of the circles to determine their mean size.

···Figure 4···

In order to see whether set size affects the accuracy of statistical processing, we compared the pilot experiment (set size of 4) and this experiment (set size of 16). The threshold difference in size judgments between global and focused attention did not differ significantly across the two experiments ($t_{(16)}$ = -1.35, p = .20). The overall thresholds did not differ significantly across the two experiments ($t_{(34)}$ = -2.0, p = .053), nor did the thresholds from global attention ($t_{(16)}$ = -1.3, p = .21), or the thresholds from focused attention ($t_{(16)}$ = -1.5, p = .16). This result is consistent with Ariely's finding (2001) that there was no set size effect in judging the mean size of a set.

Experiment 2 differed from Experiment 1 in that the concurrent tasks in Experiment 2 required attention to different elements, (the rectangle and the circles), whereas in Experiment 1 attention was paid to different properties of the same stimuli, (the shape and size of the circles). Thresholds with focused attention were lower in Experiment 1 than in Experiment 2 (25% vs. 37%, $t_{(20)}$ = -2.3, p<.05), suggesting that attention is more easily divided between attributes of the same objects than between different objects. The two experiments also differed in that Experiment 1 required attention to local elements both in the popout search task and in the mean judgment task, both using distributed attention. In the corresponding conditions of Experiment 2, on the other hand, attention was divided between a global rectangle at a large scale and local circles at a smaller scale, requiring global attention to the rectangle and distributed attention to the circles. Mean size thresholds in Experiment 1, where both tasks required distributed attention, were significantly lower than mean size thresholds in Experiment 2 where one task required global attention and the other distributed attention (22% vs. 31%, $t_{(20)} = -2.1$, $p<.05$). The interpretations need to be confirmed by further research, since there were other differences between the tasks and the experiments, but they are suggestive.

Experiment 3

In both experiments, focused attention proved less compatible than global or distributed attention with judging the mean size of the circles. We have proposed that there is a special perceptual mode of statistical processing that requires parallel attention to a set of simultaneously presented stimuli. On the other hand, previous research has shown that participants can also form a memory representation of the mean when stimuli are presented successively over longer intervals (Helson, 1947). Experiment 3 compares simultaneous with successive presentation using the same stimuli to compare the efficiency of statistical processing in the parallel mode and in the successive memory integration mode.

Methods

Participants

Ten Princeton Undergraduate students participated in the experiment for the option of course credit. All had normal or corrected-to-normal vision.

Apparatus and Stimuli

The apparatus for Experiment 3 was the same as for Experiment 1. Each display consisted of white outline circles. An example of a display is shown in Figure 5. The sizes were equally spaced on a power function with an exponent of 0.76 (the psychological scale for size, Teghtsoonian, 1965). Since participants were seated approximately 79 cm from the screen, a pixel was approximately 0.04° of visual angle. The mean circle diameter was 2.74°, and the diameters ranged from 2° to 3.39°. Sets with 8 circles were used, comprising two of each of four sizes. The circles in both the simultaneous and the successive conditions were presented in randomly chosen positions in an imaginary 3 x 3 matrix located in the center of the screen. In each trial the circles were randomly scaled by a small multiplicative factor to discourage the observers from basing their judgments on previously seen stimuli. Four multiplicative factors (1, 1.1, 1.2, 1.3) were used and the same factor scaled all circles in any one trial. The method of choosing test circles and the luminance of both the stimuli and the background were the same as in Experiment 1.

···Figure 5···

Design

There were two independent variables in the experiment, which were both varied within participants. The first variable was the type of size judgment task – either mean or member identification. These were presented in separate blocks, counterbalanced across subjects. The second was the type of presentation – either successive or simultaneous. With simultaneous presentations, 2 durations were tested, 250 ms and 2 sec. These three types of presentation were randomly mixed within blocks under the constraint that each condition was presented once before any condition was repeated.

Each participant served in two blocks (2 types of task) as well as two practice blocks. The practice blocks ended when four reversals of the staircase procedure had occurred, and the experimental blocks ended after thirteen reversals. The staircase procedure for the dependent measurement was same as in Experiment 1 except that we collected 13 reversals rather than 17 reversals during each experimental block.

Procedure

A timeline of the procedure is shown in Figure 5. Each trial started with a fixation cross for 500ms, followed by a display. The duration of the display was 250ms in the short simultaneous presentation and 2 sec in the long simultaneous presentation. It was 250 ms for each circle in the successive presentation, making a total of 2 sec. After the display, two circles appeared in the center of screen. Participants' task was to decide which of the two test circles matched the mean size of the circles in the previous display, or which of the two test circles had been presented as an individual element at the location indicated by a marker on the screen. The marker was a white square which appeared at the same time as the two test circles. Participants pressed '1', when they thought that the left circle was the answer, and '2', when they thought that the right circle was the answer. When their decision was incorrect, they heard a brief high tone.

Results and Discussion

The results of Experiment 3 are shown in Figure 6. Thresholds were lower for the mean identification task than for the member identification task ($F_{(1,9)}$ = 259.177, p<.01). There were significant threshold differences depending on presentation types ($F_{(2,18)}$ = 6.245, p<.01). t-tests showed that the simultaneous-long presentation gave a significantly lower threshold than the simultaneous-short presentation, both for the mean identification task ($t_{(9)}$ = -2.316, p<.05), and for the member identification task ($t_{(9)}$ = -2.744, p<.05). The successive presentation condition did not differ significantly from either of the simultaneous conditions. The interaction between the type of task and the type of presentation was not significant ($F_{(2,18)}$ = .415, p=.67).

···Figure 6···

These results seem inconsistent with our hypothesis that extracting statistical descriptors requires parallel access to all the information in the array. They show that participants can also extract the mean by accumulating representations of successive items, and that this may be as efficient as processing a simultaneous display. The small (3%) benefit of the longer exposure with the simultaneous presentation suggests that statistical processing is not instantaneous. This benefit is comparable to the finding by Chong and Treisman (2003) that mean discrimination thresholds decreased by 2% when the duration of the stimulus increased from 50ms to 1sec. However, the three presentation modes may have given similar results simply because the four different sizes appeared equally often in each trial, allowing participants to attend to just one of each. This might be a particularly attractive strategy with the successive presentation, where full attention could be devoted to each circle, making the structure of the sequence clearly apparent. We tested this possibility in Experiment 4.

Experiment 4

In this experiment, we used only two sizes but varied their relative frequency in different displays, making it impossible to store just one of each size. By varying the proportions of each size, we ensured that the whole set would have to be processed to ensure accurate judgments.

Methods

Participants

Eight Princeton undergraduate students and two experienced participants (including the first author) served in the experiment. All had normal or corrected-to-normal vision. The eight undergraduate students participated for the option of course credit.

Apparatus and Stimuli

The apparatus, the stimuli, and the luminance were same as in Experiment 3 with the following exceptions: Only the smallest and the largest size were used in 5 different frequency distributions – 2 instances of the smallest with 6 instances of the largest circle, 3 instances of the smallest with 5 instances of the largest circle, four instances of each of the two sizes, 5 instances of the smallest with 3 instances of the largest circle, and 6 instances of the smallest with 2 instances of the largest circle.

Design and Procedure

The design of Experiment 4 was the same as that of Experiment 3 with the following exceptions: The member identification task was not included, and instead participants did the mean identification task twice. Consequently, the threshold was defined as the average of the two means of the last 12 reversals.

The two experienced participants did this whole experiment one additional time with the positions of the 8 circles fixed at the center of the screen (with a small jitter to prevent identical circles from exactly overlapping each other), instead of appearing successively in a series of different locations. We compared performance in this fixed location condition with performance in the successive presentation conditions in which the circles were presented in different locations in a randomized order.

Results and Discussion

The results of Experiment 4 are shown in Figure 7. There were significant threshold differences depending on presentation types ($F_{(2,18)} = 7.33$, $p<.01$). *t*-tests showed that the simultaneous-long presentation gave significantly lower thresholds than both the simultaneous-short presentation ($t_{(9)} = -3.355$, $p<.01$) and the successive presentation ($t_{(9)} = 4.684$, $p<.01$). The thresholds in the simultaneous-short presentation did not differ from those in the successive presentation ($t_{(9)} = -1.432$, $p=.19$).

The average threshold of the two experienced participants in the successive presentation with fixed position (20%) was exactly the same as that with the random positions (20%), suggesting that the random versus fixed positions in the successive presentation made no difference to accuracy in extracting the mean size.

···Figure 7···

Given the same total exposure time, the results show that the mean size can be extracted somewhat better with simultaneous displays than through the accumulation across time of serially presented items. These results are consistent with our hypothesis that extracting statistical descriptors benefits from parallel access to all the information in the array. However the difference is quite small and the simultaneous brief exposure is only slightly worse, despite the eightfold reduction in exposure time. The thresholds are also very similar to those in Experiment 3, suggesting that participants were extracting the mean in both cases rather than using a few exemplars when the frequencies were matched.

Comparisons across the four experiments can throw some light on the second question that interested us – whether the mean size is registered automatically or requires some limited capacity resources. Experiments 1, 2, and the pilot experiment measured thresholds for judging the mean while carrying out a concurrent task whereas Experiments 3 and 4 tested the mean identification task on its own, using the same method across all four experiments. The mean identification thresholds (27.7%) from the dual tasks overall were significantly higher than those (24.4%) from the single tasks ($t_{(118)}$ = 2.01, p<.05). However, if we take only those with a concurrent global attention task and compare them only to those with circles presented simultaneously, the thresholds did not differ (25.9% versus 23.7%; $t_{(58)}$ = .986, p=.33). Providing that attention is distributed over the whole display, extraction of the mean appears not to require any additional resources. Statistical processing seems to be automatic.

General Discussion

Attention is used in two different senses, both of which could be relevant to statistical processing in perception: 1) attention can refer to the selection of items in a particular spatial area for enhanced processing, and 2) it can refer to the allocation of resources from a limited capacity pool to one task at the expense of another. The research described here may throw some light on both. Our hypotheses were 1) that statistical processing is a distinct mode of perceptual analysis that accompanies distributed attention to sets of similar objects; 2) that given this distributed deployment of attention, statistical processing is automatic, occurring without additional effort or resources.

Spatial attention and statistical processing

The first two experiments used a dual task paradigm to vary the spatial deployment of attention. Either statistical judgments of the mean size or judgments of the size of specific individual items were made while participants also worked on a concurrent task designed to encourage attention either to the array as a whole or to local elements. The prediction was that performance would be better on judgments of the mean size when the concurrent task encouraged distributed or global attention, and on judgments of individual size when the concurrent task required focused attention to each element in turn. The results generally supported the hypothesis. We found such an interaction in both of the experiments.

In Experiment 1, participants searched either for a target that pops out when attention is distributed over the set as a whole (C among Os), or for a target that requires focused attention to each item in turn (O among Cs). The threshold for judging the mean size was lower with the popout target, even though the exposure duration was only half as long. (The exposure was terminated when the participant responded, and search times were considerably slower with the target O among Cs). If anything the reverse was the case when size judgments were required on an individual item; here thresholds were lower with focused attention (search for O among Cs). Size judgments on individual items presumably require the relevant circle to be individuated, which we believe needs focused attention. Consistent with this hypothesis, thresholds were also lower in target present than in target absent trials. When the target was present, the probed size was always that of the target. Presumably this received more attention than the distractors, although the total exposure time was longer on target absent trials.

Experiment 2 used orientation judgments as the concurrent task and varied the scale of the shape to be judged. Focused attention was induced by making the orientation judgment on a small local rectangle in the center of the display, whereas global attention was induced by asking for the orientation of a large rectangle that framed the display. The threshold for the mean size was lower when the concurrent orientation judgment was made on the global shape.

Searching for C among Os in Experiment 1 required distributed attention to the same display elements at the same scale as the size judgments, whereas judging the orientation of the large rectangle in Experiment 2 required global attention to a different display element at a different scale. Searching for O among Cs in Experiment 1 required focused attention to the same elements as the size judgments, whereas judging the orientation of a center rectangle in Experiment 2 required focused attention to a different local element from the size stimuli. These contrasts might contribute to explaining threshold differences between the two experiments. Thresholds were lower in Experiment 1 (22% and 25% for distributed and focused attention respectively) than in Experiment 2 (31% and 37% for global and focused attention respectively). The advantage of Experiment 1 was obtained despite the fact that the size judgments were made after the response to the search task, whereas in Experiment 2 they were made before the orientation judgments. This increases the weight of the evidence that distributed attention to the same elements is more efficient for statistical processing than global attention to a surrounding element. However, the result cannot be taken as conclusive evidence for the effects of different deployments of attention since the tasks were also different. It could be the case that there is greater competition between orientation and size judgments than between search and size judgments. Further research will be needed to sort out the contributions of these different factors.

We tested a further prediction from the idea that statistical properties become available through parallel processing of global sets: If there is a special processing mode for statistical properties, it might depend on simultaneous exposure to a whole set of items. We compared judgments of the mean size when the items were presented sequentially, one at a time, and when the whole display was available at once. Experiment 3 showed no difference in accuracy with simultaneous and with successive presentation, but may have allowed participants to base their responses only on a subset of items. Experiment 4 blocked this strategy and forced participants to respond more specifically to the mean size. Here we did find an advantage to simultaneous over successive presentation when the total time available was matched.

Automaticity of statistical processing?

A comparison of performance across selected conditions in dual task and single task conditions that were otherwise matched allows a test of the automaticity of statistical judgments. If there is no decrement with the dual tasks, the hypothesis that statistical processing is automatic is supported. We compared performance in Experiments 1 and 2 with performance in the corresponding conditions of Experiments 3 and 4, which were performed with no concurrent task. The dual task conditions that required global or distributed attentions showed no decrement in thresholds for judging the mean relative to the same statistical judgment tasks performed alone. Thus as long as attention is directed to the display as a whole, the mean size seems to be extracted automatically without any demand for limited resources.

Comparison with earlier findings

The mean size thresholds without a concurrent task reported by Chong & Treisman (2003) averaged about 5 to 10%, whereas in the present experiments they were around 25%. When we compare the thresholds for the same two participants (including the first author) in both sets of experiments the threshold was still considerable lower in the earlier experiments (by 12%), suggesting that it is most likely due to differences in methods between the studies. One difference is that the earlier experiments measured relative thresholds by asking which of the two displays had the larger mean size, whereas the present tests measured absolute thresholds by asking which of the two test circles was the mean size of the previous display. The other difference is that Chong & Treisman (2003) used the method of constant stimuli and defined the thresholds as the diameter difference that gave 75% accuracy, whereas in the present experiments we used a staircase method and aimed for 80% accuracy. Woods and Thomson (1993) found that the method of constant stimuli generated lower thresholds than the staircase method even under the same experimental conditions.

Judgments of an individual size in our experiments were generally less accurate than statistical judgment of the mean size, confirming the earlier finding by Ariely (2001; Ariely & Burbeck, 1995). Our method of measuring the threshold for individual items differed from Ariely's. He picked a random item to test, without indicating to the participant which one, whereas we used a location cue to indicate which item was being probed. We wanted to force participants to focus on individual items. Our method decreases the processing load in one way, but it may have increased it in another by requiring memory for the locations. Ariely did not specify the location of the test item, and may therefore have tested recognition of types rather than individual tokens.

In conclusion, we showed that it is easier to recognize the mean size of an array when attention is shared with a concurrent global task than with a concurrent local task. Recognizing individual elements requires focused attention, but there may be a separate visual mechanism, enabled by a distributed or global deployment of attention, that directly extracts statistical properties without having to identify each individual item.

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Figure Captions

Figure 1. The stimuli and the timeline for Experiment 1. Participants first did one of two search tasks and then did one of the size judgments tasks.

Figure 2. The results of Experiment 1. The error bars indicate the standard errors. (a) DISTRIBUTED indicates searching for a circle with a gap among circles without a gap and FOCUSED indicates searching for a circle without a gap among circles with a gap. (b) MEAN indicates mean discrimination task and MEMBER indicates member identification task.

Figure 3. The stimuli and the timeline for Experiment 2. Participants first did the mean discrimination task and then did one of the orientation judgments tasks.

Figure 4. The results of Experiment 2. GLOBAL indicates deciding the orientation of the large rectangle surrounding circles and FOCUSED indicates deciding the orientation of small rectangle at the center of the screen.

Figure 5. The stimuli and the timeline for Experiment 3. In the simultaneous presentation, there were two different durations (250ms and 2sec). In the successive presentation, each item was presented at a randomly chosen position for 250ms and it never appeared at the same location.

Figure 6. The results of Experiment 3. SUC indicates the successive presentation, SIML stands for the simultaneous long presentation, and SIMS stands for the simultaneous short presentation.

Figure 7. The results of Experiment 4.

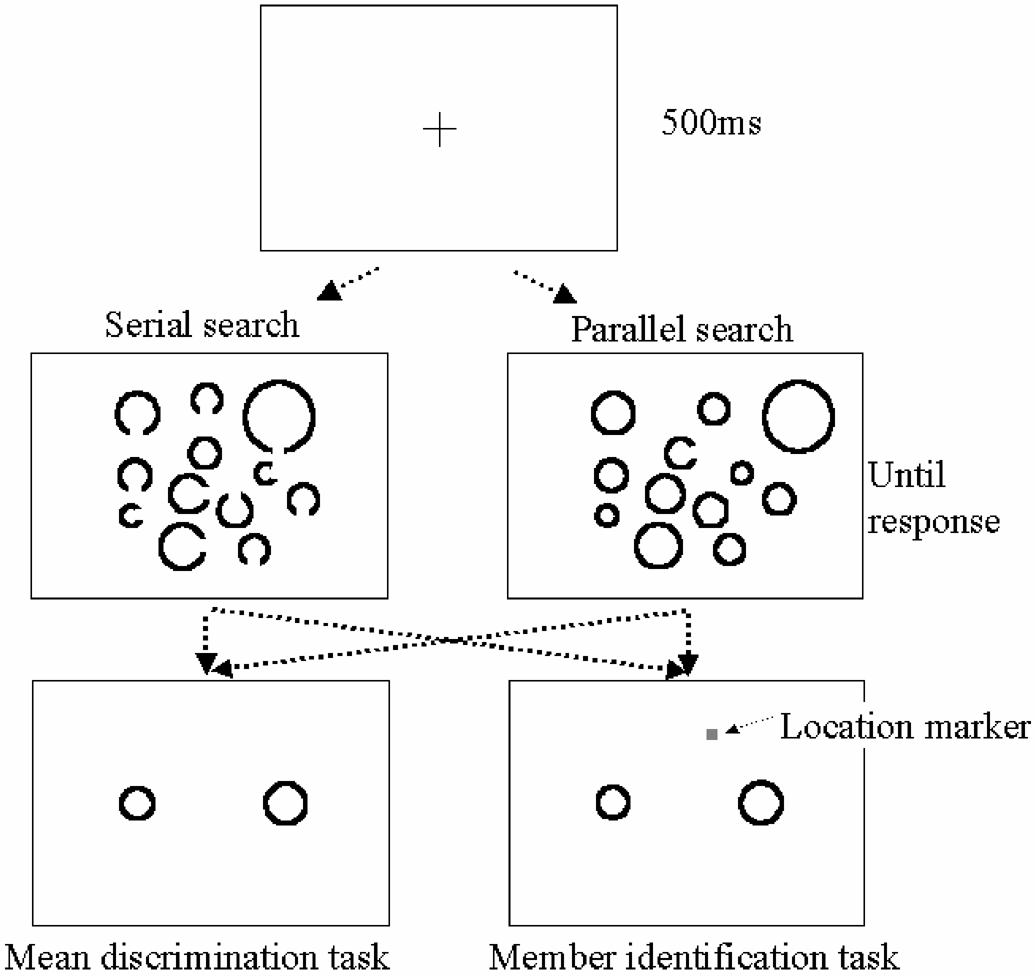

500ms
Serial search
Parallel search
Until response
Location marker
Mean discrimination task
Member identification task

Figure 1

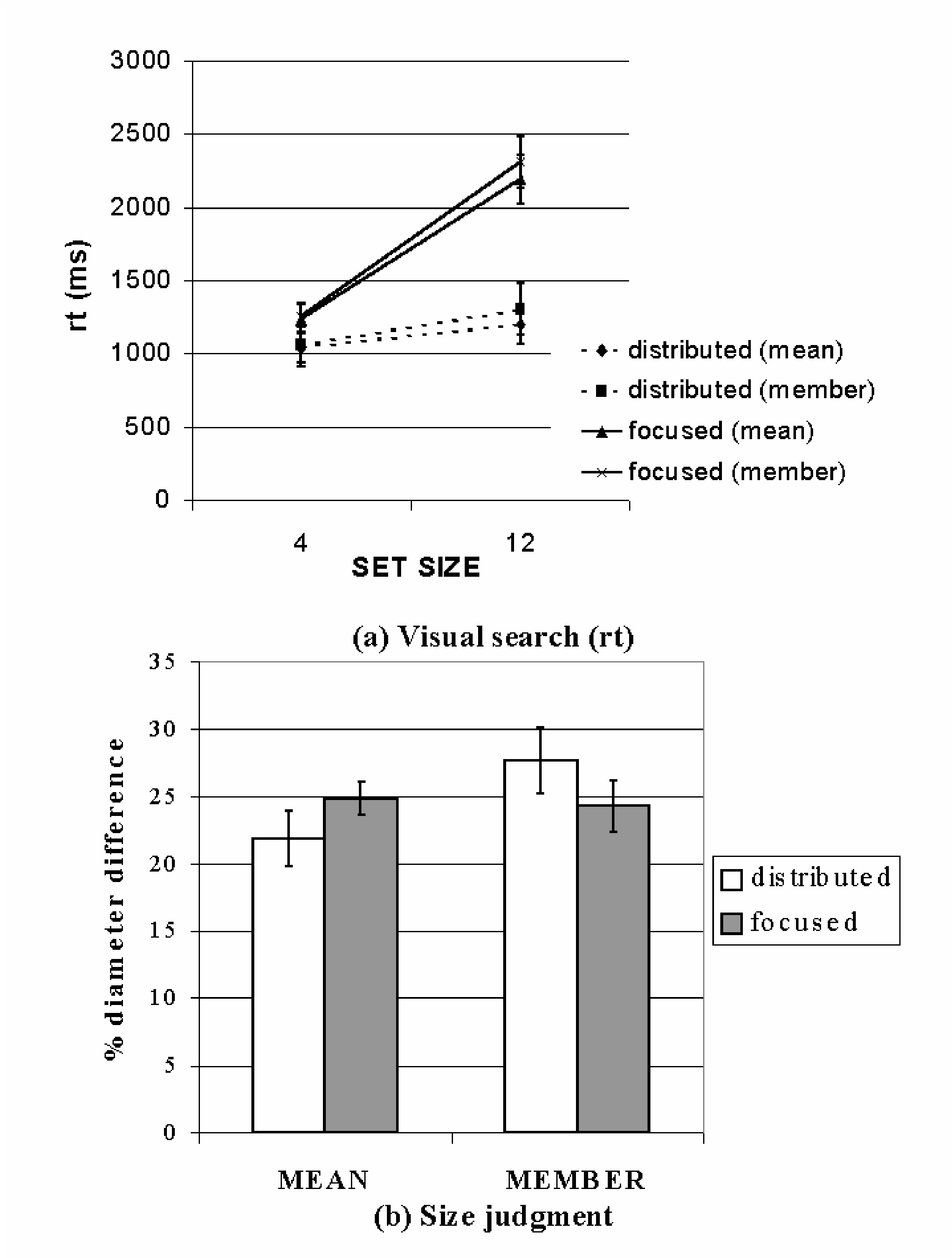

3000
2500
2000
1500
1000
500
0
rt (ms)
4
12
SET SIZE
distributed (mean)
distributed (member)
focused (mean)
focused (member)
(a) Visual search (rt)
35
30
25
20
15
10
5
0
% diameter difference
distributed
focused
MEAN
MEMBER
(b) Size judgment

Figure 2

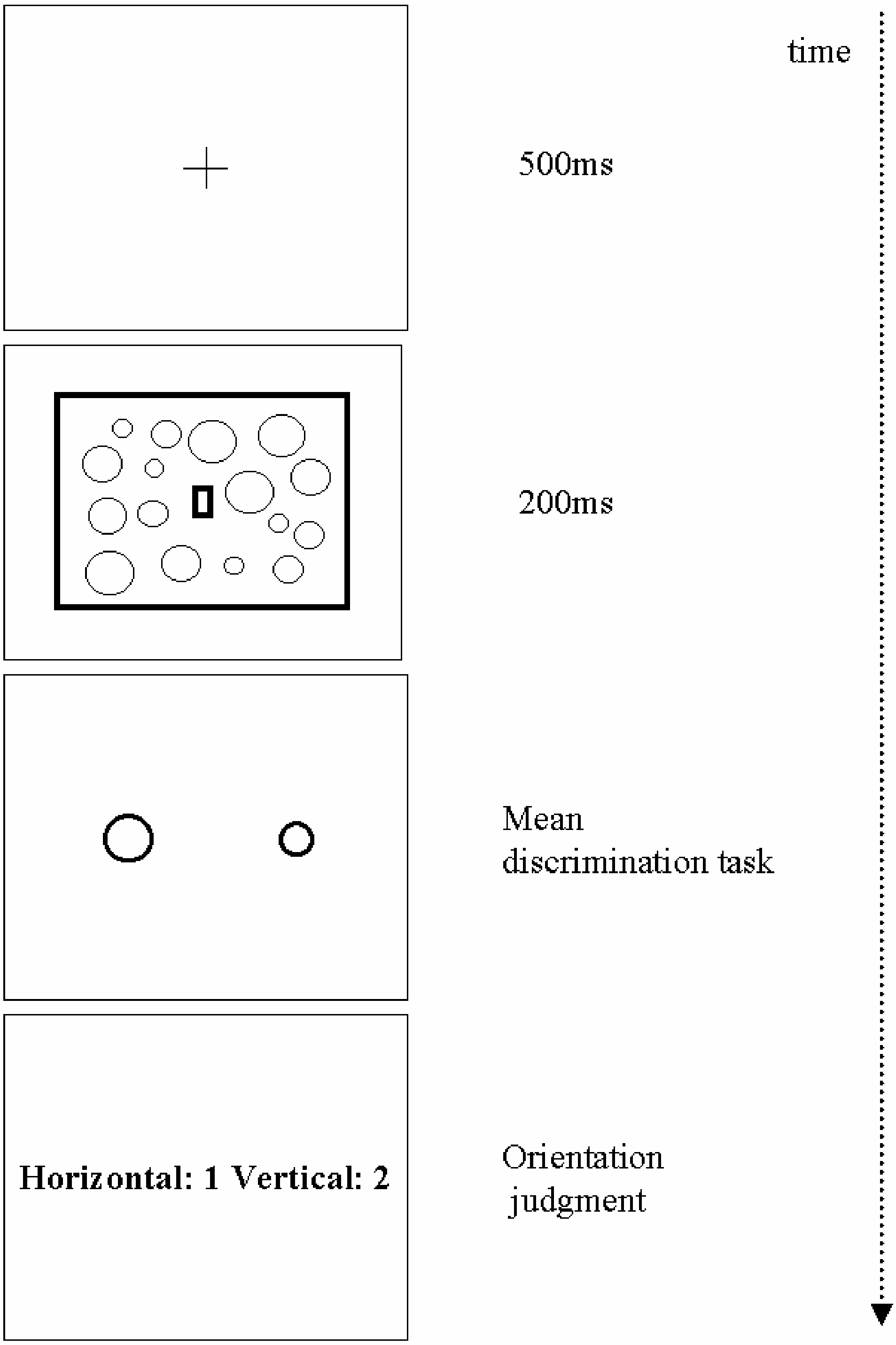
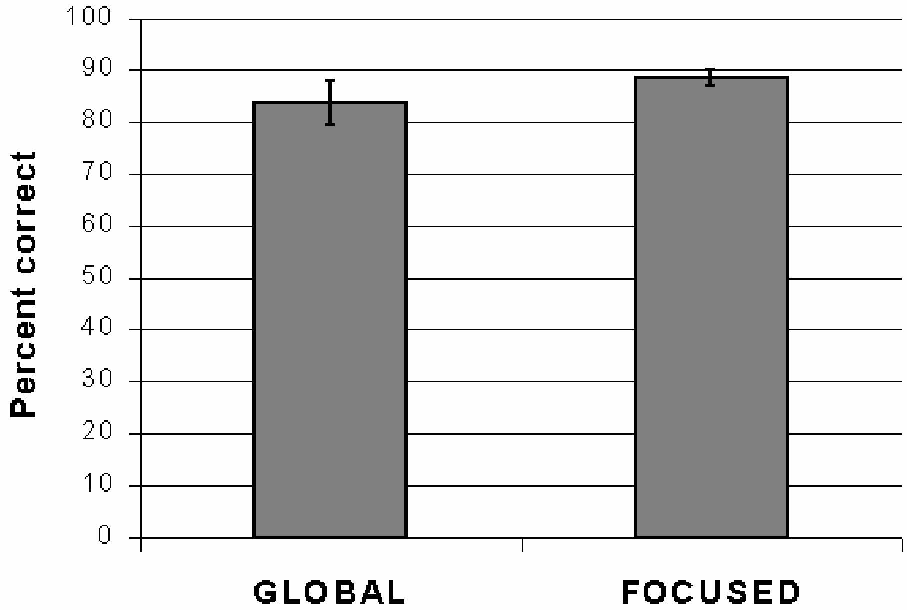
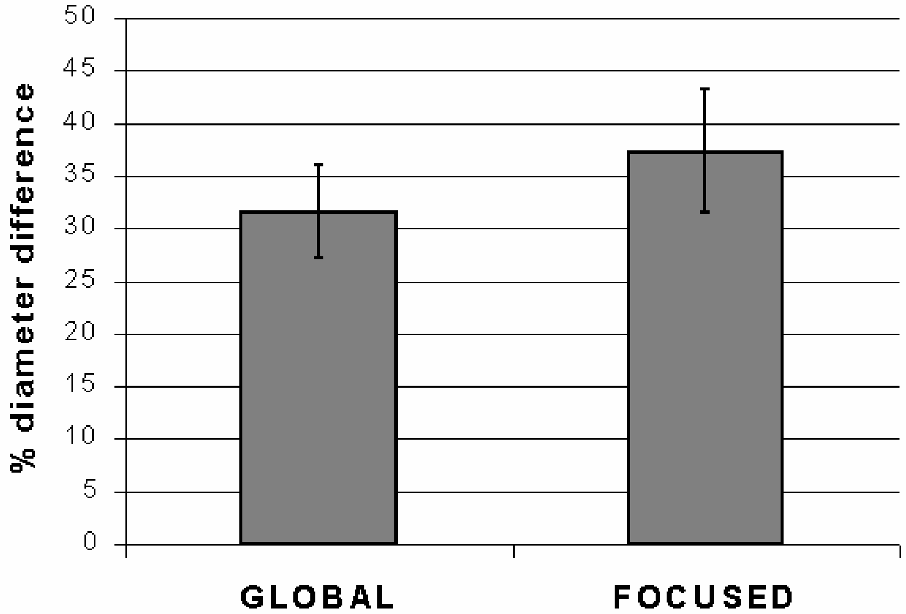

time
500ms
200ms
Mean
discrimination task
Horizontal: 1 Vertical: 2
Orientation
judgment

Figure 3



(a) Orientation judgment



(b) Size judgment

Figure 4

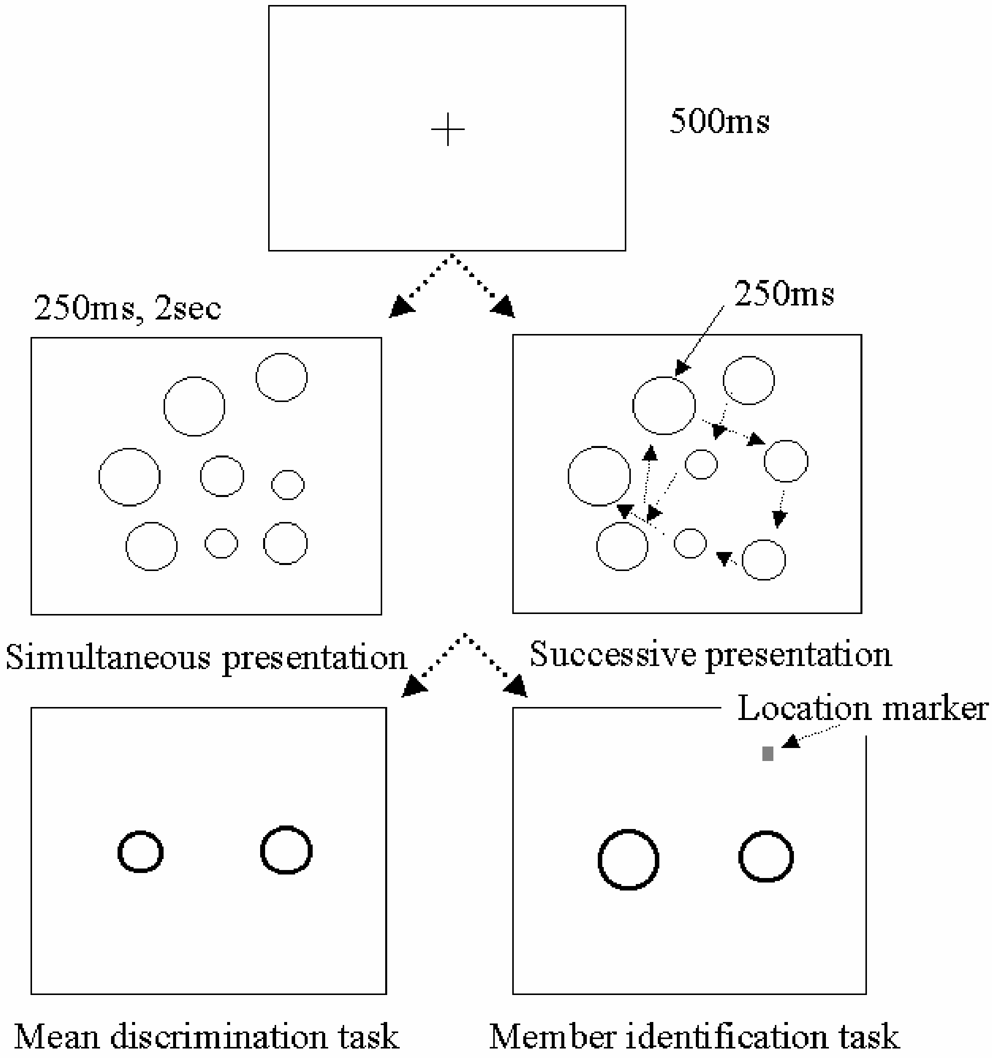

500ms
250ms, 2sec
250ms
Simultaneous presentation
Successive presentation
Location marker
Mean discrimination task
Member identification task

Figure 5

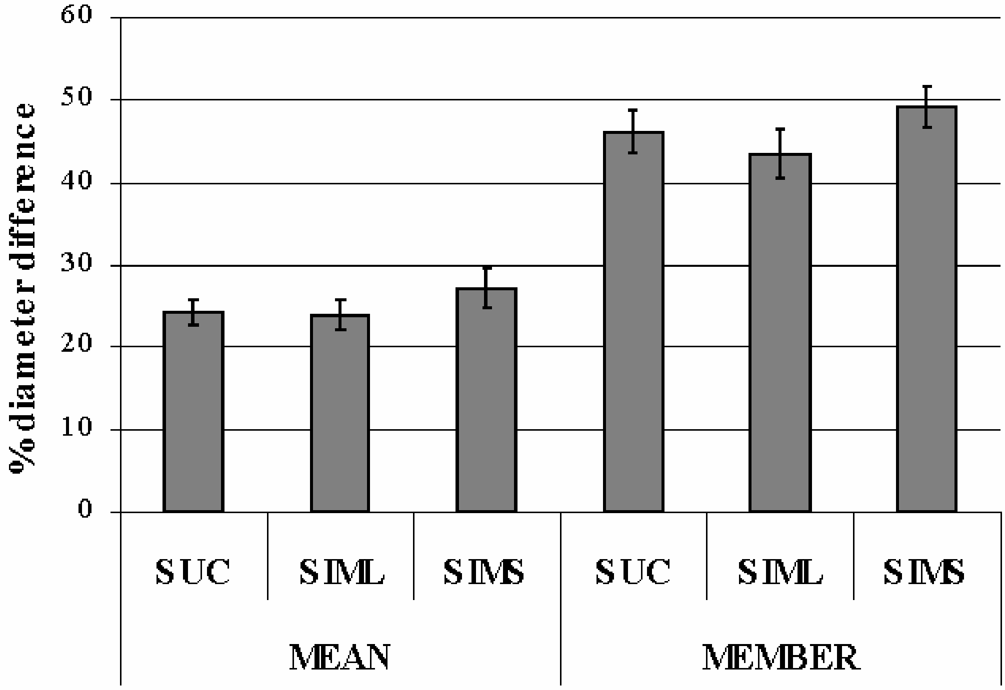

% diameter difference
0
10
20
30
40
50
60
SUC
SIML
SIMS
SUC
SIML
SIMS
MEAN
MEMBER

Figure 6

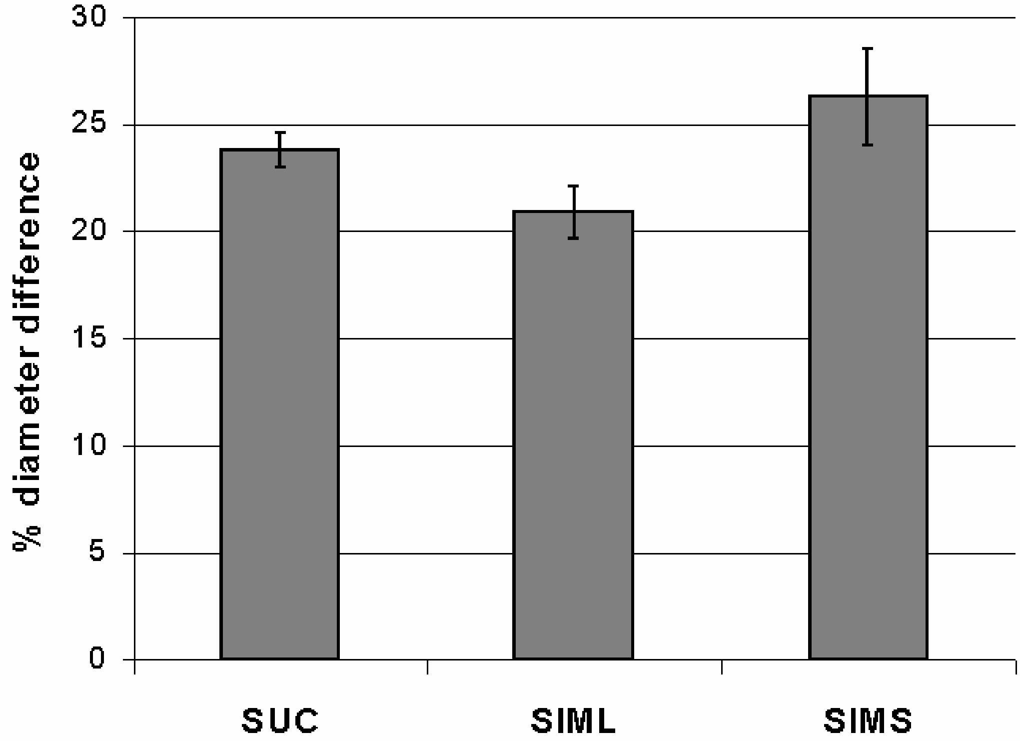


Figure 7