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Object displays for identifying multidimensional outliers within a crowded visual periphery

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ABSTRACT

This article discusses the human ability to detect, locate, or identify objects and their features using peripheral vision. The potential of peripheral vision is underused with user interfaces probably due to the limits of visual acuity. Peripheral preview can guide focused attention to informative locations, if the visual objects are large enough and otherwise within the limits of discrimination. Our experiments focused on the task of identifying an outlier and implicated another limiting factor, crowding, for integration of object features. The target object and the corresponding data dimension were located from an object display representation used for integrating multidimensional data. We measured performance on a peripheral vision task in terms of reaction times and eye movements. Subjects identified the target item from 480 alternatives within 100 ms. Therefore, the identification process would not slow down the natural gaze sequence and focused attention during monitoring and data mining tasks.

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1. Introduction

The size of an average computer display has increased, providing more opportunities to present visual items and functionalities. However, usability is compromised if the user cannot discriminate relevant items and direct focused attention appropriately. For instance, spatially focused attention is needed when writing a document such as this one. The process can be constantly interrupted if the word processing tools (such as 'print preview') are difficult to locate (by eye movements in [1]). These problems are emphasized with large displays because users must rely more on peripheral vision. This article identifies two general limiting factors for peripheral information design. First, visual acuity decreases exponentially with increased distance from central vision (eccentricity). Second, visual *crowding* harms the integration of object features.

These influencing factors are common to most tasks, but other task-specific issues are also involved. This article will focus on identifying outliers, when monitoring and analyzing multidimensional data from object displays. Object displays have been especially helpful for integrating object-specific features from multidimensional data. For instance, a car dealer might use bar

or sector diagrams to represent different features (dimensions) for different cars (object) [2: 160–163]. The task could be identifying 'Cadillac' as having an exceptionally low value on the 'mileage' dimension. The findings from the experimental psychology paradigm of visual search are briefly discussed here, and the task-specific design factors for locating and identifying relevant information are distinguished. Visual searching has been studied extensively [3] and visual discrimination is important for efficient searching [4,5].

However, these basic research experiments have focused on perceptual processes *per se* and not on visualizations as representations of data. Some researchers of visualizations [6,7] have even argued that the implications of vision research have not been recognized. The basic research experiments can distinguish the relevant parameters, but their interactions in real applications are more challenging to predict ([8] provides a starting point). We apply the basic research methods of visual search to diagrams and measure gaze direction and reaction times. Search efficiency or parallel processing is examined by increasing the number of alternative diagrams.

The ability to evaluate additional peripheral alternatives with the same effort indicates increased capacities. Using the terms of Gibson's [9] ecological optics, the interface provides more *affordances* when the user can move gaze direction (high-acuity vision) or a pointing device towards peripherally presented objects. Ergonomics of driving provides comparative examples. There is an

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important difference between the perception of road signs that requires high visual acuity and eye movements [10], and the ability to keep a car in a lane by relying on peripheral vision alone [11]. Similarly, visualizations should facilitate peripheral processing and reduce the load from central vision. Furthermore, the goal is for the user to be able to find the relevant information without disruption.

2. Information through peripheral vision

2.1. What are the benefits of peripheral vision?

Vision is the most frequently used perceptual modality for representing scientific information because it provides the highest *information bandwidth* for humans [12]. This article encourages increasing the use of this bandwidth through peripheral vision. The bandwidth is especially needed with large data quantities and multidimensionality. Multidimensionality here refers to different types of information needed for decisions or understanding. These two factors determine when peripheral representations are most wanted, and the importance of peripheral processing is analyzed briefly in the following.

To begin with, the perceptual processing of peripheral information can reduce later cognitive loading by limiting the extent of required attentive searching. The idea that peripheral information directs gaze to informative locations is supported by experiments with gaze-contingent displays [13–15], related modeling [16] and by observed deficits related to tunnel vision [17]. A gaze-contingent display system concurrently measures the gaze point and removes or degrades the information at peripheral parts of the display.

Second, before the first eye movements (within 100 ms) after stimulus onset, a gist or semantic categories about the context (e.g. picnic) can be constructed [18,19]. That is, peripheral processing alone can be enough for some tasks. The peripheral information can also facilitate recognition of objects or facts on the same time scale [20–22]. Accordingly, neurophysiological studies indicate earlier processing of coarse outlines than can prepare processing of details [23]. This can be observed in psychophysical experiments when perceptual groups guide perception of details [24–26]. Thus, peripheral vision generally creates a context in which high-acuity details are interpreted.

Third, global patterns are often important to visual inferences with graphs, and without the support of peripheral vision they need to be constructed from details. The founder of scientific visualization, William Playfair (1786), stated that “Men of great rank, or active business, can only pay attention to general outlines ... And it is hoped that with assistance of these charts, such information will be got, without fatigue and trouble of studying the particulars of which it is composed” [27]. Similarly, modern cognitive psychologists have argued that spatial integration of details from graphs is difficult, time-consuming, and more essential for users than discrimination of details [28–30]. Spatial separation, especially, increases cognitive load and disturbs learning [31]. Object displays have been proposed for integration of multi-feature data, but they will be discussed later (Section 2.4).

2.2. How to represent peripheral information?

The objective of this article is to understand how peripheral vision could be utilized more efficiently. The two constraints specific to peripheral visual representations are size and spacing. The size constraint results from lower visual acuity farther in the periphery [32–34]. For instance, reading this article depends on the perception of small differences in shape and requires central (foveal) vi-

sion. The resolution diminishes exponentially with eccentricity and at about 3° of visual angle the acuity is already much lower (for simulations see: <http://svi.cps.utexas.edu/>). The measure of visual angle and eccentricity depends on the size of the object on the computer display and the distance between the display and the viewer. The width of the thumb when held at arm’s length is approximately 2° [35]. The acuity of central vision is limited by optics, but the acuity of peripheral vision is limited by the number of receptors [36] and neural sampling [37].

The perceptual quality of peripheral vision is not in anyway worse, when the size is scaled according to eccentricity (exp. ~ -0.8 in [32,38,39]). Experiments have confirmed this in many different kinds of tasks. For most experiments discussed in this article, the same is true for visual searching [40] of relevant details. Thus, normal-sized desktop displays serve as good models for large peripheral displays, if the size is radially scaled. The problem is that eccentricity is a distance from the point of fixation to the viewed object (cf. gaze-contingent displays). The distance changes every time the eyes move. As a result, scaling is a sufficient compensation only for the first eye saccade, but this is enough for the following experiments. This is also true for many real applications, because user is likely to fixate at the button that initiates the display.

Scaling, however, is not enough if the visual task involves integration of features corresponding to each object and not detection of a feature. In that case, large enough spacing is required to eliminate peripheral *crowding* [41,42]. The sufficient spacing is half the eccentricity [43]. In some applications, it might be beneficial to emphasize the similarities between neighboring objects at the expense of discriminating them. For instance, features of textures can effectively represent large datasets [44–46]. Therefore, the optimal distance between the objects representing data depends on the task requirements as well.

The third discussed design parameter, the degree of interruption, should also be selected according to the nature of the task. So-called *peripheral displays* are contrasted with *interruption displays* that draw the user’s attention. Initiated movement or a suddenly appearing object can effectively draw attention to the visual [47,48] (in realistic tasks: [49,50]). Unfortunately, the user is often distracted [51–53]. If attention is drawn elsewhere, even salient events might not be noticed [54–56]. Furthermore, the disturbance is more pronounced in cases of fast and stimulus-driven search tasks [57]. The problem of guiding attention is often that users’ interests vary and are not obvious to the designer. By contrast, the idea of peripheral displays is to increase self-controlled attention and improve timesharing between the tasks [58] (see also [59]).

2.3. How to locate relevant details?

In visual “pop-out”, an object with a deviant feature (target) can be detected independent of the number of other objects present [44,60,61]. In fact, adding non-targets can even speed up detection [62,63]. Nevertheless, the irregularity does not draw focused attention in the way that interruption displays do [64]. Since the 1980s, it has been debated whether this search process is truly parallel for different locations [63,65–67]. The alternative is rapid and covert (without eye movements) shifting of attention between the locations [60,68]. However, in natural conditions, covert attention is observed only preceding eye movements [69], and it cannot be directed elsewhere while a saccadic eye movement is being programmed (e.g., [70]). The debate on neural processing is mostly irrelevant for application purposes. Therefore, we use the term “parallel processing” for performance that is independent of the number of visually processed objects. This property is important for visualizations of large quantities of data.

Parallel processing is typically interpreted from reaction times and more recently from eye movement measures. We used the reaction time measure in the first two experiments and eye movement selectivity in the third and fourth experiments. Processing is parallel if reaction times do not increase with added non-targets. Alternatively, subjects should be able to move their eyes immediately to the target location and not elsewhere. The eye movement measures are discussed in more detail before the related experiments. The task and context of visualization naturally affect both eye movements and reaction times [71]. In addition, the mentioned peripheral visibility factors are relevant for detecting deviant features [4,5], especially eccentricity [40].

There are many visualization tasks for which detecting and identifying an outlier is important. With large quantities of data, this might be problematic. Monitoring tasks in the context of a stock exchange, ICT (Information and Communication Technology) traffic, or industrial processes provide examples of such situations. Especially in the event of an accident, sources need to be identified fast. Notice, that the task differs from general attempts to understand patterns of data (data mining). However, identifying an outlier might give an important insight into the structures of data.

2.4. Sector diagram as an example

Peripheral detection and identification of outliers from visualizations are examined with sector diagram. A sector diagram is an object display type originally developed by Florence Nightingale in the mid 19th century to represent causes of wartime mortality. We have successfully used it to represent multidimensional data in several political elections for first-time users [72]. (Its success was indicated by the popularity of the service.) The task of understanding data structures was later analyzed in controlled [73]. According to the results, the performance levels in both integration and discrimination of details were high. By contrast, object displays typically support integration tasks at the expense of discrimination [74,75:p. 126,76]. Performance with sector diagrams was consistently better than with bar diagrams.

The integration with object displays is easier because the different features or dimensions are represented by a single object and not multiple objects [77]. For instance, the shape of a triangle was superior to the length of three bars [74]. Furthermore, performing two tasks simultaneously on one object rather than two different objects is easier [78], even if they are overlaid [79]. Thus, our hypothesis is that users can easily perform two tasks concurrently with sector diagrams: (i) to locate the diagram with a deviant feature and (ii) to identify the deviating dimension. The benefits of focusing on only one object have been explained by *object-based attention*, as opposed to *spatial attention* [80].

The sector diagrams in our earlier experiments were presented in pairs or groups of three. The following experiments focus on peripheral detection and identification from much larger groups (up to 60 diagrams). Another difference is that this time simplified data are used. Otherwise, the task of identification could be masked by problems of discriminability. Especially, target/non-target similarity and non-target heterogeneity have been shown to deteriorate performance [66,68,81] related to target saliency [68]. Real data can also be simplified by first normalizing it and then expanding the extremes. The first experiment replicates the findings from the experimental psychology paradigm of visual search. We expect to find pop-out of a feature in diagrams that can represent multidimensional data. The visual search experiments have typically been conducted to understand perceptual processes. We are more interested in decision making and understanding related to different forms of visualization.

We predict that users will easily locate a sector diagram from a group of similar representations because (i) they can be perceptually

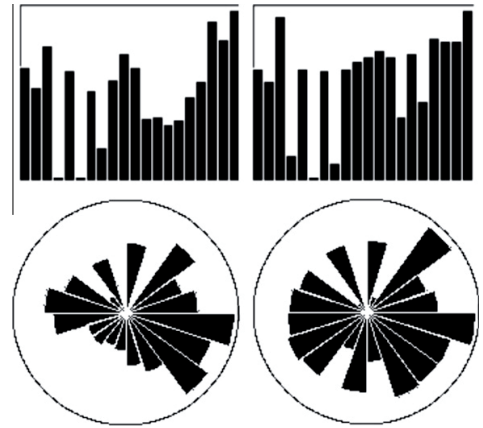


Fig. 1. Sector vs. bar diagram. The two columns of diagrams represent the same 20 data values using both bar diagrams (at top) and sector diagrams (at the bottom). On the sector diagrams, the values are mapped counter-clockwise from the right. Notice how the gap between two sector diagrams is more conspicuous than the gap between two bar diagrams when there is equal horizontal spacing.

ally segmented using the conspicuous gap between them (see example in Fig. 1). Furthermore, (ii) the identities of dimensions are redundantly represented by orientations of each sector in a polar coordinate system. Orientation is a fundamental visual feature for which there are specially tuned cells in the brain [82], and its use could distribute the perceptual neural representation more. As shown in previous visual search experiments, 6–12 non-target orientations begin to provide a relative reference frame that affects perception of the target's orientation [68,83]. By contrast, data values themselves should not be mapped to orientation differences [8]. Our hypothesis is that both of the mentioned design features aid the task of locating deviants from large quantities of data.

3. Experiment 1 – detecting a deviant diagram

In Experiment 1 (Fig. 3), we tested whether a sector diagram with a deviant sector (Fig. 2C) stood out among distracting diagrams without a deviant sector (Fig. 2B). In serial search, items must be analyzed one at a time; this means that reaction times will increase as a function of the number of items. When the search is parallel, the target can be detected without directing gaze at it, and the search time can be independent of set size.

3.1. Subjects

There were two subjects with normal or corrected to normal vision: one author and one individual naïve to the purpose of the experiment. Notice that psychophysical experiments typically test

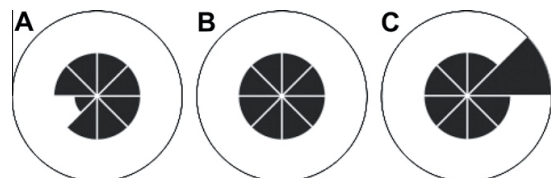


Fig. 2. Sector diagrams used in Experiment 1. Diagram A has one sector with a value of 0.25, in diagram B all sectors have value of 0.5, and in diagram C one sector has a value of 1.0. In the experiments, the target was always a diagram in which one randomly selected sector had a value of 1.0. The distractors were the same as those in diagram B.

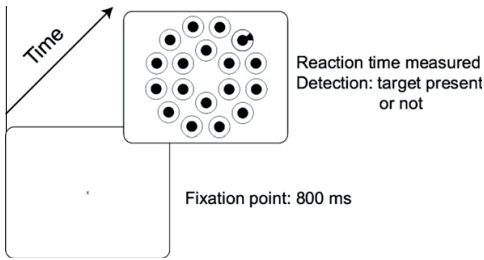


Fig. 3. Experiment 1 illustrated. The experiment tested whether the detection of a target diagram occurs in a serial or parallel fashion.

fewer subjects than experimental psychology in general because simpler visual features (in easy tasks) are assumed to be processed with qualitatively more similar neural mechanisms than more natural scenes [84]. In a metastudy of 330 independently-rated psychophysical experiments on simple visual or auditory features (published in 2007 by J. Vis., Vision Res., Perception, and Percept. Psychophys.) 60% had 6 or fewer subjects and 42% included non-naïve subjects. From the reviewed 38 eye movement studies with simple visual features, 71% had had 6 or fewer subjects (the mode was 2), and 36% included non-naïve subjects.

3.2. Stimuli, apparatus and procedure

In the detection task, subjects searched for a target among 0–59 non-targets. At a viewing distance of 50 cm, the center circle of each diagram subtended 1° and the whole plot subtended 1.4°. Items were randomly distributed on four evenly spaced imaginary circles (diameters 5.5°, 10.8°, 16.2°, and 20.6°). Their locations were randomly varied by ±0.2°. The whole stimulus area had a diameter of 22°. Subjects reported whether a target was present or not. A target was present in half of the 64 trials of a stimulus block. Each subject performed 1024 trials per experiment. Stimuli were presented on a 17" monitor with 75 Hz frame rate and 1024 × 768 pixel resolution.

3.3. Results and discussion

Search times were almost independent of the number of non-targets when the target was present, and the search was very efficient for both observers (Fig. 4). When the target was absent, RTs (reaction times) increased by, on average 5 ms for each of the added non-target. The slope is very shallow compared to most par-

allel searches (e.g., [3] or [68]). Thus, a sector diagram with a deviant sector was preattentively detected among distracting diagrams with no deviant sector.

4. Experiment 2 – detecting deviant sector

In the previous experiment detection of the target diagram was parallel. Experiment 2 was similar to the previous experiment, but instead we tested whether the orientation of the deviant sector (up or down) could be identified equally efficiently. In addition, the subjects and apparatus were the same.

4.1. Stimuli and procedure

The entire setup was similar, except for the subjects' task. In this experiment, the target was always present and subjects reported whether the sector of the target diagram was directed upwards or downwards.

4.2. Results and discussion

Reaction times were the same irrespective of whether the deviant sector was oriented upwards or downwards (Fig. 5). Even though there was a slight increase in reaction times when the set size was increased from 1 to 4, the slope was quite flat. Therefore, not only did the sector diagram with a deviant sector stand out among other diagrams, but subjects could also preattentively identify whether the direction was upwards or downwards.

5. Locating with gaze

Experiments 1 and 2 showed parallel processing with regard to the latency of keyboard actions for detecting diagram or data dimensions. However, identification from a user interface typically requires directing spatial attention to that detail. For instance, the user might need to select an item with the mouse cursor. Such motor actions are typically preceded or accompanied by an eye movement (e.g. [85]). Thus, eye movements are likely to be an ecologically more valid measure of efficient peripheral processing than keyboard reactions. These tasks can involve different cognitive and neural processes [86,87], especially in the case of peripheral vision [88]. More specifically, eye movements might not require consciousness of object recognition. Sometimes eye saccades remain accurate when the conscious perception is not veridical [89]. These differences have also been observed in speed of visual searching when the response modality is changed [90].

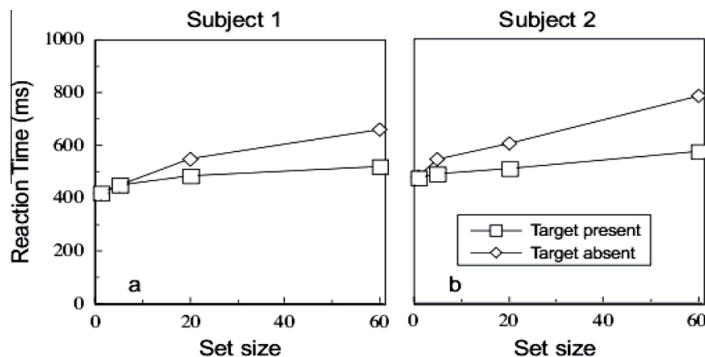


Fig. 4. Results of Experiment 1. Reaction times did not increase as a function of set size when the target was present but did so when the target was absent.

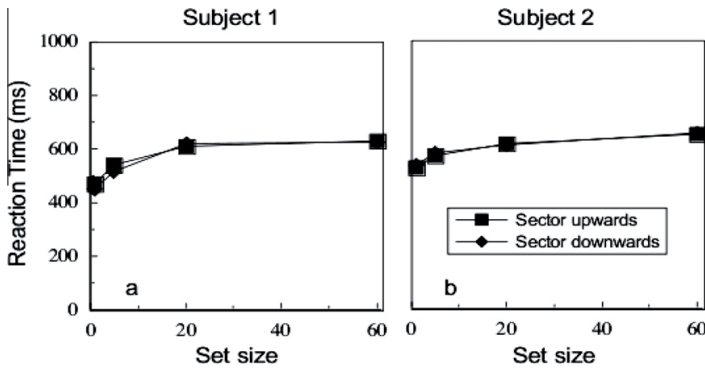


Fig. 5. Results of Experiment 2. Reaction times did not increase as a function of set size when the target was oriented upwards or downwards. This indicates that the orientation of a sector does not influence the result of a search task. Overall, RT/set size functions were relatively flat.

In visual search experiments, gaze direction is a good indicator of search efficiency because it is highly correlated with focus of spatial attention [91]. Typically eye movements have been recorded to reveal the serial search path (for review, see [92]). In addition, eye movement selectivity can measure the ability to discriminate a feature from the visual periphery. Furthermore, even an efficient design might include serial subtasks, such as locating a numeric index [13]. Second, searching can be parallel only for a limited eccentricity range. In that case, eye movements are relevant for more eccentric targets (e.g., over 8.26° in [93]). Eye movements have a large effect on search efficiency when peripheral visibility is poor. As a result, more saccades are made without awareness [94].

Furthermore, typical presentation time limits (e.g. 100 ms to exclude eye saccades) are artificial and might not represent real use. Excluding eye movements might not always slow down the detection performance [90], but it still affects the ability to shift attention or select an item with a pointing device (cf. Fitts' law; [95,96]) (predicted by [4]). Fortunately, the visual parameters relevant for keyboard reactions (e.g., [40,44,68,81,97]) are similar to the parameters influencing eye movement selectivity (e.g., [67,94,97,98,100,102]). Those parameters are grouping, redundancy (in several features), spacing, eccentricity, target/non-target similarity, and non-target heterogeneity. Even though this meta-analytic comparison has been supported by the recent findings [103], it is still rather imprecise. Eye movement selectivity and latencies of keyboard responses might lead to differing efficiency

criteria. Therefore, we extend the findings from Experiments 1 and 2 to eye movement selectivity in Experiments 3 and 4.

6. Experiment 3 – selective eye movements to deviant diagram

In experiment 3 (Fig. 6), we tested the subjects' ability to locate the diagram with a deviant sector. At the beginning of each trial they looked at a fixation point. After stimulus presentation (100 or 300 ms), they made a saccade to the location of the target. Presentation times were chosen so that the shorter (100 ms) was clearly below the saccadic reaction time and the longer (300 ms) clearly above it.

Experiments 3 and 4 measured initial saccadic accuracy (distance to target) which is affected by efficiency of parallel processing of peripheral items [91,104] and their visibility [94]. This is not always true for initial latency [94]. Initial latency is affected by many other factors as well, for instance, non-targets near a fixation point [101] and other peripheral processing [105]. However, initial latency and accuracy interact [99]; longer latencies can increase saccadic accuracy. For that reason, we controlled the latencies with limited display durations.

6.1. Subjects

There were three subjects with normal or corrected to normal vision: one author and two naïve.

6.2. Stimuli and procedure

The stimuli were the same as in previous experiments, but with 60 items (only 18 diagrams are presented here for clarity). Each trial started with the presentation of a fixation cross (X) for 800 ms and was followed by the stimulus for 100 or 300 ms. After the stimulus presentation, circles with crosses inside indicated the places where diagrams were located. The subjects' task was to make a saccade toward the place where they saw the target and fixate it for 1 s. Their eye movements were recorded and analyzed trial-by-trial from video stream with a concurrently overlaid gaze-point.

6.3. Eye movement recordings

Subjects' eye movements were recorded using a head-mounted gaze tracking system (iView from SensoMotoric Instruments GmbH). It has two small video cameras, one monitoring the scene in front of the subject's eyes and the other monitoring the partici-

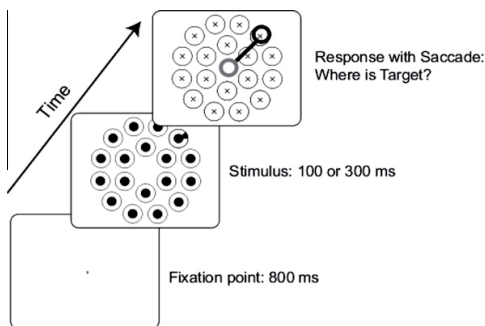


Fig. 6. Experiment 3 illustrated. The same diagrams as in Experiment 1 were used here but with a setup of 60 items only (only 18 diagrams are presented here for clarity).

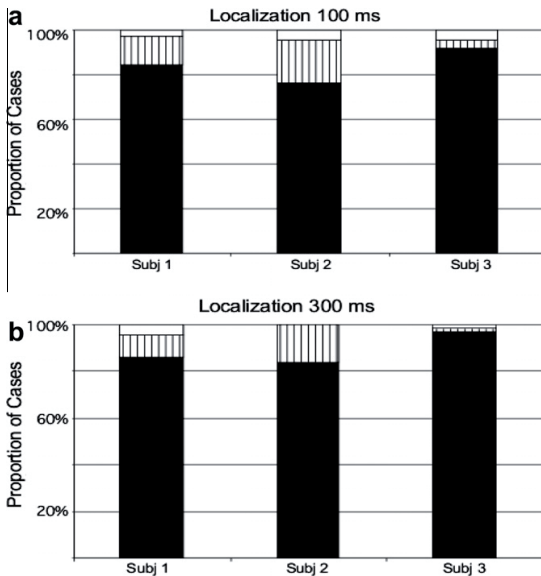


Fig. 7. Results of Experiment 3. The task of this experiment was to locate the target diagram and to direct the gaze to its location. The proportion of the saccades that were located exactly at the target is represented by the black bar and those located in the immediate neighborhood by the hatched bar for each subject.

pant's dominant eye while an infra-red LED illuminated the eye. Video images of the pupil and corneal reflection of the infra-red LED were captured at a rate of 50 Hz by the eye tracker.

Before each registration, the eye movement system was recalibrated using nine screen locations. During the calibration procedure, the subject's head was stabilized with a chin rest in order to improve the accuracy of calibration. The responses were classified into three categories: (1) within target, (2) immediate neighborhood of target, and (3) all others. The first two categories were considered correct and the third incorrect.

6.4. Results and discussion

In total 88.8% of the saccades were located exactly at the target, and 97.6% of the saccades were correct when the immediate neighborhood was also included (Fig. 7). Different presentation times did not influence the number of correct saccades ($\chi^2(1) = 2.149$, $p > 0.05$): 96.8% (100 ms) and 98.4% (300 ms), respectively. When the target was located on either of the two outer imaginary circles, statistically more ($\chi^2(1) = 6.923$, $p < 0.001$) incorrect saccades were observed (11.2% and 10.0%) compared to the two inner circles (0.3% and 1.1%). Thus, the subjects' accuracy decline somewhere between the eccentricities of 5.4° and 8.1° . Interestingly, above that eccentricity Bouma's crowding limit (half the eccentricity) is exceeded because the spacing between diagrams was almost constant (about 2.8° between midpoints) for all eccentricities. All together, this experiment shows that subjects could not only detect the diagram with a deviant sector in parallel, but they could also locate the target with high accuracy.

7. Experiment 4 – selective eye movements to a deviant sector

The subjects' ability to recognize the orientation of the deviant sector was studied in Experiment 4. Here the subjects' task was more difficult than in the previous experiments; the subject had to (i) locate the diagram having the deviant sector, (ii) analyze

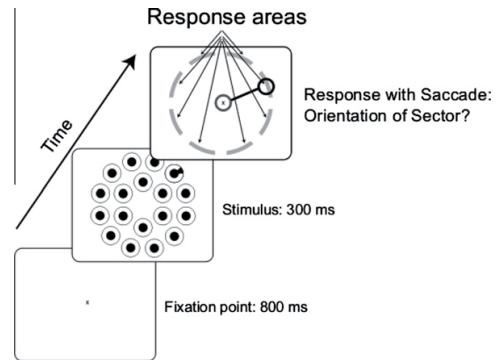


Fig. 8. Experiment 4 illustrated. The setup in Experiment 4 was similar to Experiment 3; only the task was different. The subjects had to detect the orientation of the deviant sector, make a saccade towards an appropriate response area, and then fixate it for about 1 s. Each orientation of the deviant sector had its own response area.

the direction of this sector, (iii) decide on the correct response area (one out of eight areas), and (iv) make a saccade in its direction. The subjects and apparatus were the same as in Experiment 3.

7.1. Stimuli and procedure

The stimuli were the same as in the previous experiments; only the task differed. The subjects had to detect the orientation of the deviant sector, make a saccade toward an appropriate response area (see Fig. 8), and then fixate it for about one second. To be precise, each orientation of the deviant sector had its own response area.

7.2. Results and discussion

In total, 87.6% of the saccades were located exactly in the response area of the target and 97.9% of the saccades were correct when the immediate neighborhood was also included (Fig. 9). None of the orientations (direction of a deviant sector) differed statistically from the others ($\chi^2(21) = 2.358$, $p > 0.05$). One possible reason for this is that there were no strictly horizontal or vertical orientations that are biased in graphs [106]. To sum up, this experiment confirms and extends the result of Experiment 2 and further shows that it is possible to identify the direction of a randomly oriented sector (among at least eight possibilities in a randomly selected diagram) efficiently from among 60 diagrams.

8. General discussion

The researchers interested in human visual processes, as opposed to visual representations, have conducted most of the experiments on visual searching. The results of these experiments have been used in this article to identify the important visual parameters that determine the effectiveness of visual representations. The properties of peripheral vision were argued to be especially important. However, the typically stimuli in such experiments (e.g. Gabor patches) are not representative of object displays or visual representations in general. Therefore, we reported visual search experiments with sector diagram stimuli that we have earlier used to represent multidimensional information.

The main result of these experiments was that subjects were able to concurrently detect (Exp. 1–2) and locate (Exp. 3–4) deviant objects and their dimensions. The concurrent task is comparable to

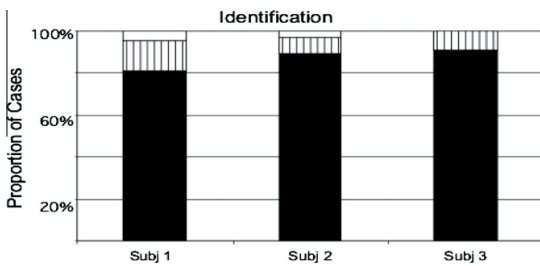


Fig. 9. Results of Experiment 4. The task in this experiment was to detect the orientation of the deviant sector and to make a saccade toward an appropriate response area. The proportion of the saccades that were located exactly at the target is represented by the black bar and those located in the immediate neighborhood by the hatched bar, for each subject.

conjunction search in experimental psychology, because two visual features are used for distinguishing targets from non-targets. However, unlike the typical conjunction search experiment, the response for identity was given in two phases. Length (or size), as visual parameter, represented the identity of a diagram and orientation represented the identity of a dimension. The experimental protocol excluded the possibility that dimensions would also have been identified by location alone. That is, the sectors of Experiment 4 were given new response areas based on the orientations. In previous experiments, consistent surrounding orientations have facilitated the detection of an orientation [68] and its selection with eye saccades [83]. Therefore, we predicted that orientation is an efficient feature for representing identities (but not quantities, see [8]) in large groups of diagrams. The prediction was confirmed because identification performance was relatively independent of the number of diagrams.

One can say that the effectiveness of the sector diagrams in the experiments was noteworthy.

The ability to perceive and interpret sector diagrams was very rapid. The speed of perception is important in context of interactive use of visualizations, because the small differences that might even occur several times per second can accumulate and generate significant usability problems. Thus, the further research on other object displays would be informative to show whether the results reflect special nature of sector diagrams or are the other object displays as effective in locating and identification tasks. We believe that the use of orientation, to differentiate the dimensions, contributes to the effectiveness of sector diagrams. Therefore, we predict that the commonly used bar graphs would not be as effective. Even though this is yet to be directly tested, our earlier experiments with much fewer graphs support such conclusion [73].

The task was made difficult by increasing the number of diagrams, not by decreasing the size of the represented difference in the data. Our earlier experiments with fewer sector or bar diagrams showed that the ability to evaluate the graphs depended linearly on the size of the difference in the represented data [73]. Moreover, the discussed findings (Sections 2.4 and 5) from other visual search experiments provide similar predictions. Further research is needed to confirm these predictions about identification performance by manipulating the levels of target/non-target similarity (how different the deviant is) and non-target variability (how homogenous the background is). When identifying is important, the size of deviance can be increased by scaling at the expense of other differences. In interactive use, however, all of the subtle differences need not be represented at once. Our experiments show that the number of evaluated alternatives can be increased up to 480 (60 diagrams with 8 dimensions) without extra time needed for perception processes. Unlike the stimuli in typical basic

research experiments of visual search, we have used the stimuli for representing multidimensional data in real applications [72].

9. Conclusions

A deviant object and its critical feature can be identified rapidly from crowded object displays. Thus, more information can be provided preattentively and peripheral vision is utilized more efficiently. However, the deviance must be large enough. Perception is limited by visual acuity and the harmful effects of peripheral crowding. Our results also provide indirect support for the importance of crowding. In many monitoring tasks, rapid identification is crucial. Furthermore, the data mining applications that facilitate rapid identification are often more usable. For instance, an identifiable deviant can serve as a reference point. Even very small delays in the gaze sequence can accumulate and cause a critical usability problem because eye movements are typically even more frequent than heart beats. The ability to accurately direct gaze direction is important because direct gaze provides high-acuity information about the target (e.g., label [13]) and makes manual selection with a pointing device possible. This way of representing peripheral information does not interrupt the user by capturing attention, freeing the user to focus on task-related details.

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