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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.

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 that 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) vision. 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.