Partitioning Visual Displays Aids Task-Directed Visual Search

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We reduced time to detect target symbols in mock radar screens by adding perceptual boundaries that partitioned displays in accordance with task instructions. Targets appeared among distractor symbols either close to or far from the display center, and participants were instructed to find the target closest to the center. Search time increased with both number of distractors and distance of target from center. However, when close and far regions were delineated by a centrally-presented “range ring”, the distractor effect was substantially reduced. In addition, eye-movement patterns more closely resembled a task-efficient spiral when displays contained a range ring. Results suggest that the addition of perceptual boundaries to visual displays can help to guide search in accordance with task-directed constraints. Actual or potential applications of this research include the incorporation of perceptual boundaries into display designs in order to encourage task-efficient scanpaths (as identified via task analysis and/or empirical testing).

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PARTITIONING VISUAL DISPLAYS AIDS TASK-DIRECTED VISUAL SEARCH

INTRODUCTION

Processing a visual display often requires a search for a target symbol embedded within a field of distractor symbols. There is still considerable disagreement as to why the difficulty of visual search increases as the similarity of targets and distractors increases (e.g., Duncan & Humphreys, 1989; Treisman, 1993; Wolfe, 1996). However, there is some consensus that only a limited amount of information can be fully analyzed at a given time in displays with relatively low signal-to-noise ratios. Finding a target symbol in such a display generally requires some amount of item-by-item or region-by-region processing, with observers repeatedly shifting the location of eye fixation and attentional focus to different locations in the display until the currently analyzed region contains the target and the perceptual representation of this signal surpasses some threshold level of activation.

Laboratory visual search paradigms generally entail the presentation of targets in random locations within experimental displays that may be searched in whatever manner the observer chooses. Of course, the perceptual organization of such displays may encourage a certain pattern in the sequence of ocular/attentional fixations or “scanpath” (e.g., circular displays encourage circular sequences, blocks of text encourage left-to-right horizontal sequences, etc.). However, there is generally no principled reason for choosing a starting point such tasks, and observers may often follow a roughly random scanpath for such searches (Scinto, Pillalamarri, & Karsh, 1986). In contrast, real-world visual search tasks often impose additional constraints on the scanning process. Locating a target symbol on a radar screen is one instance of a real-world search in which observers generally adopt a non-random scanning procedure; operators generally assess the composition of tracks in the display with specific information-seeking goals in mind

(e.g., “how close is the target symbol to position X?”). Finding a target in one region of the display may be more important than finding it in another region. It is this form of strategic “task-directed” search that we sought to understand better in the current set of experiments.

Following a prescribed scanpath shares many similarities with spatial precuing. Pre-existing knowledge about the probable spatial locations in which target information will appear greatly aids visual processing. Numerous studies have demonstrated that participants are quicker and more accurate to respond to probe stimuli presented at or near cued locations (e.g., Posner, Snyder, & Davidson, 1980). This “cue validity effect” (so-called because enhancement occurs when cues validly predict target location) is generally attributed to the allocation of spatial attention to the cued area (Posner et al., 1980). Providing observers with a pre-specified order in which to attend to different regions in a display should, therefore, have the same consequences as indicating those areas with spatial precues.

If following a prescribed scanpath (“find target closest to point X”) encourages a sequence of ocular/attentional fixations that mimics precuing, then its effects may be enhanced by the addition of perceptual boundaries that delineate to-be-attended regions in the display. Although observers may be capable of confining their attention to an area of less than a visual degree under the right conditions (Nakayama & Mackeben, 1989), they typically experience considerable difficulty restricting attention to an unbounded region in a display. For example, observers generally find it challenging to respond to target stimuli flanked by distractors associated with different responses (Eriksen & Eriksen, 1974). This difficulty may arise partially because observers tend to focus their attention on entire perceptual objects (Duncan, 1984), and similar-looking target and distractor stimuli can appear to form a single perceptual group that encourages the allocation of such “object-based” attention (Baylis & Driver, 1992).

Consequently, these effects of distractor interference may be reduced to a considerable extent when targets appear within perceptually delineated regions of the display (e.g., by drawing a circle around the target), causing the region to appear as a distinct perceptual object on which to focus attention (e.g., Kramer & Jacobson, 1991).

The addition of perceptual boundaries to a display may also help searchers to maintain a better sense of where they have already looked. It has recently been suggested that observers fail to maintain a representation of the distractors that they have rejected in the course of search (Horowitz & Wolfe, 1998; Horowitz & Wolfe, 2000). While other studies have refuted the notion of a fully “amnesic” visual search process (e.g., Peterson, Kramer, Wang, Irwin, & McCarley, 2001), it remains a reasonable assumption that searchers maintain a less than perfect memory for their search history. Perceptual boundaries may serve as landmarks according to which searchers may more easily assess the spatial relationships between the locations they have visited. Moreover, the mere presence of perceptual boundaries may encourage searchers to adopt a task-efficient scanpath, that is, one that appropriately reflects task constraints (e.g., visiting more important locations in the display before less important locations). The sensitivity of observers’ scanpaths to the properties of the visual patterns they are assessing has been clearly demonstrated through the recording of eye movements (e.g., Noton & Stark, 1971).

With these points in mind, we reasoned that displays may be easier to search with the addition of perceptual cues that direct attention in accordance with task constraints. Such boundaries can help to define the regions that should be attended and ignored, allowing for the construction of a more efficient scanpath. It has previously been shown that partitioning search displays into quadrants provides little to no benefit to a non-task-directed visual search (Scinto et al., 1986). In fact, such boundaries may actually hinder performance by imposing a scanpath that

counteracts the effects of bottom-up attentional guidance on the search process (Eriksen, 1955). However, if task requirements already constrain the path that search takes, perceptual boundaries that are consistent with this path could facilitate scanning along it.

In the current study, we sought to improve the efficiency with which observers searched for airtrack symbols within mock radar screens of the type presented in the Georgia Tech Aegis Simulation Platform (GT-ASP – Hodge, Rothrock, Kirlik, Walker, Fisk, Phipps, & Gay, 1995), a task that simulates the duties of an Anti-Air Warfare Coordinator (AAWC) on a naval Aegis cruiser. A user operating the GT-ASP is required to consider several sources of information in order to identify unknown aircraft flying within the surveyed airspace displayed on a radarscope. A large part of this process involves simply scanning the radarscope for specific airtracks whose identities are indicated by the shapes of their symbols.

Global task constraints influence the pattern in which user should scan the screen. AAWCs are instructed to identify unknown airtracks before they reach a 50 nautical mile (NM) range from the ownship, which is generally represented at the center of the radarscope. As a result, all other track characteristics being equal, closer tracks receive greater priority than farther tracks. This distance-specific prioritization heuristic encourages users to search for targets in an inside-outside direction, first ensuring that targets are absent from regions close to the center before considering regions that lie farther away.

It is this inside-to-outside scanning process that we explored in the current set of experiments. In particular, we were interested in how this process might be facilitated by the addition of a range ring to the radarscope. A range ring is a centrally-presented circle that delineates the region contained within a certain range from the ownship at the center of the scope. The most obvious benefit provided by the range ring is that it quickly indicates where

range-specific boundaries lie, helping operators to determine how close an airtrack is to a given region. Many GT-ASP tasks do require range-specific decisions (e.g., “has a track passed the 50 NM boundary?”), and range rings serve as crucial decision-making tools in these instances.

However, when range-specific decisions are not required, participants can generally follow the simple heuristic that “closer is more important”. They need not know exactly where the 50 NM lies in order to identify potentially dangerous airtracks appearing at a currently safe range; rather, they can rely on raw distance from the center and simply pursue tracks in an inside-to-outside pattern. Indeed, we have found that our participants only occasionally opt to view the radarscope with a range ring visible, suggesting that its value with respect to the main goals of the task is limited (at least under the set of task constraints employed in our laboratory simulations).

Nevertheless, we felt that the range ring might have other uses beyond simply identifying the critical range boundary. In particular, we felt that it might serve to facilitate the inside-to-outside scanning process, itself, by partitioning the display into meaningful regions. To evaluate its use, we conducted an inside-to-outside visual search study using simplified versions of the GT-ASP radar screens that contained only two types of symbols, one of which was designated “target” and the other “distractor”. The radarscope was partitioned into “Close” and “Far” regions by a range ring with a radius half that of the full display. A target could appear within each region of the display, but participants were instructed to click on the one closer to the center. The range ring was invisible in the “No Ring” condition but visible in the “Ring” condition. We predicted that the range ring would facilitate the search process, resulting in faster search times in the Ring condition than the No Ring condition.

EXPERIMENT 1

Methods

Participants. A total of 30 undergraduates from Carnegie Mellon University participated in Experiment 1 for course credit.

Apparatus. A Dell OptiPlex Gx1 computer was used to display stimuli and record responses. Stimuli were presented on an 16-inch monitor with a resolution of 640 x 480 pixels.

Stimuli and Experimental Design. A sample search display is shown in Figure 1 with its different components labeled. A large circle with a diameter of 19° of visual angle served as the outline of the radarscope (a). A small circle (.48° diameter) with a dot in its center served as the central fixation point (the ownship) (b). In the Ring condition, an additional circle with a diameter half that of the radarscope (9.5°) appeared centered around the fixation point, serving as the range ring that delineated Close and Far regions (c); this ring was invisible in the No Ring condition. With the exception of the presence/absence of the range ring, displays were identical in both Ring and No Ring conditions.

Half-circle track symbols served as targets (d), while half-rectangle track symbols served as distractors (e) (each subtended an area of .48° x .24°). Lines (.72°) emanated from each track symbol at one of eight orientations (in a full-scale GT-ASP experiment, these serve to indicate speed and course). The mouse arrow that participants positioned over target symbols measured approximately .95° x .48°.

There were two target conditions: “Close target” and “Far target”. In Close target displays, one target appeared in the Close region and one target appeared in the Far region (in Figure 1, the Close target appears near letter ‘d’ and the Far target appears near letter ‘f’); in Far target displays, only one target appeared in the Far region (the target appearing near letter ‘d’ in

Figure 1 would be replaced by a distractor symbol with the same vector). Targets appeared in each quadrant an equal number of times in each condition, and target locations were randomly generated with these constraints and one additional constraint that the Far target always appear at least 1.5° farther from the center of the displays than the Close target.

The two target conditions were crossed with three distractor conditions: “No distractors”, “Low distractors”, and “High distractors”. Only target symbols appeared in the No distractors condition. In the Low distractors condition, Close target displays contained three distractors in the Close region and three distractors in the Far region, while Far target displays contained four distractors in the Close region and three distractors in the Far region (thus, every display contained a total of eight symbols). The Low distractors displays were created by adding distractors to the No distractors displays. Finally, in the High distractors condition, both Close and Far target displays contained an additional four distractors in the Far region. High distractors displays were created by adding additional distractors to the Far region in Low distractor displays. This manipulation permitted an assessment of the extent to which peripheral distractors interfered with the processing of targets appearing in the Close region. If the addition of distractors outside the ring created minimal interference, then this would indicate that participants effectively restricted their attention to the Close region initially.

For Low and High distractors displays, symbols were distributed equally among all four quadrants, and locations were randomly generated within a quadrant with the constraint that each symbol never appear superimposed over any other symbol. Furthermore, the additional distractors that were added to Low distractor displays to create High distractor displays appeared only within the region enclosed by the range ring and the dotted line circle (g), which had a

diameter equal to three-quarters that of the radarscope (14.25°); this constraint was adopted in order to increase the density of symbols near to the Close/Far boundary.

A total of 64 displays were generated for each of the six conditions created by the crossing of target x distractor conditions. Participants were randomly assigned to either the Ring or No Ring condition. The experiment was divided into four blocks of trials, each of which contained four miniblocks composed of 24 trials each. Four displays from each of the six target x distractor conditions were randomly presented within each miniblock.

Procedure. Participants viewed displays from a distance of approximately 60 cm. The radarscope was always present on the center of the monitor throughout the course of the experiment (i.e., it was not erased between trials). For participants in the Ring condition, the range ring also remained present throughout the course of the experiment. To begin a trial, participants clicked the central fixation symbol with the mouse arrow. Target and distractor symbols appeared 300 msec later. Participants were instructed to click on the target symbol closest to the center as quickly and accurately as they could. Each trial ended as soon as the mouse was clicked, at which point target and distractor symbols were erased. The experimental session lasted approximately 30 minutes.

Results

Error Results. Any click within 10 pixels of the target symbol (a region subtending $1.91^\circ \times 1.43^\circ$) was scored as correct. The mean error rate across conditions was 2.7%. Close target trials were separated into “wrong target” errors (in which participants clicked on the target in the Far region) and “other” errors (clicking on a distractor or blank space within the display). Only Close “wrong target” errors were subjected to analysis due to the low error rate ($< 1\%$) for all other error measures.

A 2 (No Ring vs Ring) x 3 (No distractors vs Low distractors vs High distractors) mixed analysis of variance (ANOVA) yielded a significant two-way interaction [$F(2,56) = 3.34, p = .043$]; to explore this interaction further, the simple effect of distractor number was analyzed separately for Ring and No Ring conditions. The simple effect of distractor number (No distractors vs Low distractors vs High distractors) was significant for Close wrong target errors in the No Ring condition [0.31% vs 1.46% vs 1.88%; $F(2,28) = 6.048, p = .007$]. In comparison, the simple effect of distractor number was non-significant for the Ring condition [0.21% vs 0.73% vs 0.52%; $F(2,28) = 1.393, p = .265$]. In addition, there were fewer Close wrong target errors for Ring than No Ring participants, as evidenced by a significant difference between error rates in the High distractor condition [$t(14) = 2.578, p = .022$].

This pattern of errors suggests that participants were more likely to miss the target in the Close region when displays contained distractors, indicating that distractors were effective at interfering with target detection even in the Close region. Moreover, the presence of the range ring reduced this effect, suggesting that it helped to prevent participants from missing Close targets by focusing their attention more effectively. All other error effects were non-significant.

Reaction Time Results – Initial Comparisons. For each participant, mean reaction time (RT) scores for correct trials were calculated for each of the six conditions. From these values, mean RTs for each condition were then determined. To eliminate outlying data points, those trials with RTs more than two standard deviations above or below the condition mean were also removed from analysis (an average of 4% of the trials were removed from each condition as either errors or outliers). Condition means were then recalculated. These are displayed in Figure 2.

A 2 (No Ring vs Ring) x 2 (Close vs Far target) x 3 (No distractors vs Low distractors vs High distractors) mixed ANOVA yielded a significant three-way interaction [$F(2,56) = 27.410, p < .0005$]; to explore this interaction further, the simple effects of distractor number and target location were analyzed separately for Ring and No Ring conditions. The effect of distractors was much greater for Far than Close targets, indicated by the interaction of target location (Close vs Far) and distractor number (No distractors vs Low distractors vs High distractors) [No Ring: $F(2,28) = 248.38, p < .0005$; Ring: $F(2,28) = 187.94, p < .0005$]. This difference reflects a combination of factors, including decreasing visual acuity with distance from fixation, increased masking from peripheral distractors, mouse movement time, and scanning pattern (i.e., searching the display from the inside to the outside). As a result, Close and Far target conditions were further analyzed separately under No Ring and Ring conditions.

Reaction Time Results – Close Targets. There was a main effect of distractor number in both No Ring [$F(2,28) = 91.218, p < .0005$] and Ring [$F(2,28) = 92.147, p < .0005$] conditions. This indicates a general increase in RT as distractor number increased. However, although the RT increase between Low and High distractors conditions was significant in both No Ring [$t(14) = 3.26, p = .006$] and Ring conditions [$t(14) = 3.20, p = .006$], the increase between No and Low distractors conditions was much greater [No Ring: $t(14) = 5.83, p < .0005$; Ring: $t(14) = 8.02, p < .0005$], indicating that adding additional distractors to the Far region in the High distractors condition had a relatively small effect on search time for Close targets. This, along with the dramatic differences in RT between Close and Far target trials with distractors, suggests that participants did begin their searches in the Close region of the display and were fairly successful at filtering out distractors appearing in the periphery.

The increase in RT between Low and High distractors conditions may reflect the capturing of attention by distractors appearing in locations in the Far region that lie near to the Close/Far boundary; that is, the span of attention might “spill over” the division even when the boundary is delineated by the range ring. Additional Far distractors in the High distractors condition might increase the difficulty of figure/ground separation for the range ring, as well, increasing the time required to discern it from the field of distractors. Given the small size of this effect and considering the entire pattern of results in this experiment, it is unlikely that it represents instances of scanning from the outside in.

Moreover, note that the High-Low distractors RT difference was greater in the No Ring condition (52 msec vs 23 msec); although non-significant, this trend suggests that such spill-over may have been reduced when the range ring was present. Indeed, the range ring did effectively reduce the effect of distractors. Comparisons between No distractors conditions and High distractors conditions for No Ring and Ring participants illustrate this point. There was no difference between the RTs for No distractors conditions, but the High distractors RT was lower for Ring than No Ring participants [$t(28) = 2.531, p = .017$]. This difference may be attributed to more effective filtering of peripheral distractors and enhanced processing of symbols in the Close region.

Reaction Time Results – Far Targets. There was a main effect of distractor number for both No Ring [$F(2,28) = 265.30, p < .0005$] and Ring [$F(2,28) = 178.96, p < .0005$] conditions. This reflects the large increase in RT with increasing distractor number. The RT increase between Low and High distractors conditions was significant for both No Ring [$t(14) = 13.20, p < .0005$] and Ring [$t(14) = 12.14, p < .0005$] participants, indicating that the additional Far distractors interfered with target detection in both conditions. Moreover, for No Ring

participants, the High-Low distractors RT difference was no smaller than the Low-No distractors RT difference [$t(14) = 1.718, p = .108$], suggesting that the effect of adding distractors was comparable in both Low and High distractors conditions.

However, the High-Low distractors RT difference was significantly smaller than the Low – No distractors difference for Ring participants [$t(14) = 11.57, p < .0005$]. Moreover, the High-distractors RT was faster for Ring than No Ring participants by almost a second [$t(28) = 4.59, p < .0005$]. These results indicate that the addition of distractors to the Far region had less of an effect on target detection when displays contained the range ring. While search time essentially doubled from Low to High distractors conditions for No Ring participants, there was much less of an increase for Ring participants. Thus, the benefits of the range ring for Far target detection increased as the number of distractors increased.

Discussion

Experiment 1 demonstrated that partitioning displays into task-relevant regions with a range ring facilitated search for the closest target to the center. We suggest that the range ring helped observers to allocate attention to different positions within the display (either inside or outside the range ring) with more precision, facilitating both the processing of symbols within the attended region and also the filtering out of peripheral distraction. The range ring may also have helped participants to remember where they had already searched, preventing the revisiting of previously rejected distractors. Finally, the circular range ring may have encouraged observers to search the display in a more task-efficient pattern (e.g., spiraling out from the Close region to the Far region). Any or all of these factors could have combined to speed up search time by around a second in the Far target High distractor condition.

EXPERIMENT 2

The influence of the range ring on the scan-path could only be inferred indirectly from response times in Experiment 1. In order to measure the characteristics of Ring and No Ring scanpaths more directly, we reran the inside-to-outside search task while recording observers' eye movements in Experiment 2. The sequence of fixations obtained during the interval beginning with the onset of the track symbols and ending with a mouse click on a target symbol was assumed to approximate the scanpath for a given trial. While there may have been covert movements of attention, the difficult nature of target/distractor discrimination (i.e., the lack of pop-out in the presence of multiple distractors) should have ensured that participants rarely detected the target unless they were fixating near it, allowing for the sequence of fixations to approximate the actual attentional scanpath. We predicted that the sequence of fixations participants produced in searching for the target in displays with range rings should have more "spiral-like" qualities (i.e., circling around the Close region and then circling around the Far region, moving in a path that does not cross itself, etc.) if the range ring prevented participants from revisiting previously-analyzed regions of the displays and/or encouraged them to follow a more task-efficient inside-to-outside scanpath.

Experiment 2 also contained two different range ring conditions. In the On/Off Ring condition, the range ring appeared with the onset of the search symbols and was erased along with the search symbols as soon as participants clicked on the display. In contrast, the range ring remained on the screen the whole time in the On Ring condition, thus allowing participants to use the range ring to prepare their focus of attention prior to the onset of the search display (as in Experiment 1). We thought that benefits of the range ring might be especially strong when

participants viewed the range ring prior to the onset of the search array (On Ring), allowing to them time to prepare their focus of attention (e.g., Murphy & Eriksen, 1987).

Methods

Participants. A total of 18 undergraduate and graduate students from Carnegie Mellon University participated in Experiment 2 for monetary compensation (\$20).

Apparatus. Eye-movements were recorded by means of an ISCAN ETL-500 tracker (60hz temporal resolution and less than 1° spatial resolution). Head movement was constrained by means of a chin-rest positioned 60 cm away from the monitor.

Stimuli and Experimental Design. Experiment 2 utilized a within-participant design; thus, participants viewed displays from all three display conditions (i.e., No Ring, On/Off Ring, and On Ring). Display condition varied with block, and the order in which display conditions were assigned to different blocks was counterbalanced across participants. There were four blocks for each display condition within the experiment. As in Experiment 1, each block contained four miniblocks composed of 24 trials each (four trials from each of the six target x distractor conditions).

Procedure. Experiment 2 employed the same basic procedure as Experiment 1. The eye tracker was recalibrated before each block of trials. Each experimental session lasted 1.5 hours.

Results

Error Results. As in Experiment 1, any click within the 1.91° x 1.43° region surrounding the target was scored as correct. The mean error rate across conditions was 0.75%. Close target trials were again separated into “wrong target” errors (in which participants clicked on the Far target instead of the Close target) and “other” errors. As in Experiment 1, only Close “wrong target” errors were analyzed.

A 3 (No Ring vs On/Off Ring vs Off Ring) x 3 (No distractors vs Low distractors vs High distractors) repeated measures ANOVA yielded a significant two-way interaction [$F(4,68) = 3.10, p = .021$]; to explore this interaction further, the simple effect of distractor number was analyzed separately for No Ring, On/Off Ring, and Ring conditions. The simple effect of distractor number (No distractors vs Low distractors vs High distractors) was significant for Close wrong target errors in the No Ring condition [0.26% vs 1.22% vs 3.13%; $F(2,34) = 15.400, p < .0005$], On/Off Ring condition [0.17% vs 2.0% vs 1.82%; $F(2,34) = 7.830, p = .002$], and On Ring condition [0.26% vs 1.22% vs 1.74%; $F(2,34) = 5.186, p = .011$]. This pattern of errors again suggests that participants were more likely to miss the target in the Close region when displays contained distractors, indicating that distractors were effective at interfering with target detection even in the Close region. In addition, Close wrong target errors in the High distractors condition were greater in the No Ring condition than in the On Ring condition [$t(17) = 2.600, p = .019$], suggesting that the presence of the range ring did help to prevent observers from missing Close targets. There were no significant differences between Close wrong target errors in the High distractors condition for No Ring vs On/Off ring conditions [$t(17) = 1.736, p = 1.01$] or On/Off Ring vs On Ring conditions [$t(17) = 0.160, p = 0.875$]. All other error effects were non-significant.

Reaction Time Results – Initial Comparisons. For each participant, mean reaction time (RT) scores for correct trials were calculated for each of the six conditions. From these values, mean RTs for each condition were then determined. To eliminate outlying data points, those trials with RTs more than two standard deviations above or below the condition mean were also removed from analysis (an average of 4.57% of the trials were removed from each condition as either errors or outliers). Condition means were then recalculated. Means from On/Off Ring and

On Ring conditions were first compared. There was no difference between these two display conditions [$F(1,17) = .459, p = .507$], and there were no significant interactions of these display conditions with any other factors. Thus, means from On/Off Ring and On Ring conditions were averaged together to form a combined Ring condition. These Ring means are displayed along with No Ring means in Figure 3.

A 2 (Close vs Far target) x 2 (No Ring vs Ring) x 3 (No distractors vs Low distractors vs High distractors) repeated measures ANOVA yielded a significant three-way interaction [$F(2,34) = 4.84, p = .014$]; to explore this interaction further, the simple effect of distractor number was analyzed separately for No Ring and Ring conditions. As is evident in Figure 3, the effect of distractors was again much greater for Far than Close targets, indicated by the interaction of target location (Close vs Far) and distractor number (No distractors vs Low distractors vs High distractors) [No Ring: $F(2,34) = 96.52, p < .0005$; Ring: $F(2,34) = 149.95, p < .0005$]. As a result, Close and Far target conditions were again analyzed separately under Ring and No Ring conditions.

Reaction Time Results – Close Targets. There was a main effect of distractor number in both No Ring [$F(2,34) = 31.248, p < .0005$] and Ring [$F(2,34) = 34.59, p < .0005$] conditions. This indicates a general increase in RT as distractor number increased. However, although the RT increase between Low and High distractor conditions was significant in both No Ring [$t(17) = 2.81, p = .012$] and Ring conditions [$t(17) = 2.47, p = .024$], the increase between No and Low distractors conditions was again much greater [No Ring: $t(17) = 3.34, p = .004$; Ring: $t(17) = 4.95, p < .0005$].

The range ring appeared to facilitate Close target detection to a much lesser extent in this experiment, and the difference between High distractors RTs for Ring than No Ring conditions

was not significant [$t(17) = 1.03, p = .319$]. The within-participant design of Experiment 2 may be responsible for the reduced effect of the range ring compared with that in Experiment 1. Participants had considerable practice searching for targets in On/Off Ring and On Ring displays, and they may have been able to transfer this experience to search in the No Ring conditions. This proposal will be considered further below.

Reaction Time Results – Far Targets. There was a main effect of distractor number for both No Ring [$F(2,34) = 91.41, p < .0005$] and Ring [$F(2,34) = 130.13, p < .0005$] conditions. This again reflects the large increase in RT with increasing distractor number. The RT increase between Low and High distractors conditions was significant in both the No Ring [$t(17) = 8.32, p < .0005$] and the Ring [$t(17) = 12.43, p < .0005$] conditions, indicating that the additional Far distractors interfered with target detection in both conditions. Moreover, unlike in Experiment 1, the High-Low distractors RT difference was significantly smaller than the Low-No distractors RT difference for both No Ring [$t(17) = 4.01, p = .001$] and Ring conditions [$t(17) = 6.95, p < .0005$], suggesting that the effect of additional distractors decreased between Low and High distractors conditions whether or not displays contained a range ring.

The High distractors RT was still significantly greater for No Ring than Ring conditions by almost 200 msec [$t(17) = 2.24, p < .039$], indicating the presence of the range ring did still facilitate search for a Far target among many distractors. Nevertheless, the effect of the range ring was clearly reduced in Experiment 2 relative to that in Experiment 1. As noted above, the reduced effect of the range ring in Experiment 2 may have resulted from the use of a within-participant design that granted participants repeated exposure to both No Ring and Ring conditions. As shown in Figure 4, differences between No Ring and Ring RTs decreased dramatically over the four repetitions of each condition. From searching Ring displays,

participants may have been able to (1) practice focusing attention using the range ring as a guide, (2) learn to discriminate better the Close/Far boundary, and/or (3) learn to use a more effective search pattern. Any of these could have facilitated subsequent search with No Ring displays. Still, even during the last repetition of the display conditions, there was a marginally significant difference between No Ring and Ring search times [$t(17) = 1.90, p = .075$], suggesting that participants may have continued to rely somewhat on the range ring as a search aid even towards the end of the experiment.

Eye-Movement Results. Results from eye movement analyses are shown in Table 1. Only eye-movement data from correct trials were considered for analysis. In addition, only data from Far target High distractors trials will be reported, as these yielded the greatest number of fixations/trial and provided the closest approximation to the symbol-dense radar screens that generally are presented within the context of the full GT-ASP task. There were no differences between the On/Off Ring and On Ring conditions, so these were again averaged together to form a single Ring condition.

Intervals within the eye-movement record during which velocity was less than 30°/sec for 83 msec or more were identified as fixations. Fixations falling outside the display (1.3%) were excluded from analysis. The average duration for the remaining fixations was 321.21 msec. Participants tended to generate multiple fixations prior to clicking on a target, supporting our assertion that fixation is generally required for detecting targets among distractors in these displays; the indirect patterns of eye movements that we recorded also suggest that participants were not simply moving their eyes to targets that they had already detected with covert movements of attention. These observations validate our use of eye movements as indicators of scanpaths. Unfortunately, the small size of the track symbols and lack of tracker precision made

it difficult to determine whether participants revisited specific distractors; however, the data did reveal a number of important characteristics about the scanpaths in No Ring and Ring conditions.

Representative scanpaths for No Ring and Ring conditions are shown in Figures 5 and 6. These figures depict the sequence of fixations that a single participant produced while searching through two displays that were identical except for the absence (Figure 5 - No Ring) or presence (Figure 6 - Ring) of the range ring. Each circle corresponds to a single fixation, and circle diameter varies with fixation duration. The No Ring scanpath contains one more fixation than the Ring scanpath (7 vs 6); in fact, mean scanpath lengths for the entire set of data mirrored those in this example (see Table 1). As is evident in comparing the two scanpaths, the Ring scanpath appears to resemble more closely the “ideal” task-efficient scanpath, i.e., one that spirals outwards from Close to Far. In contrast, the No Ring scanpath moves between Close and Far regions several times, suggesting a less organized search.

To examine differences between eye movements in No Ring and Ring conditions in more detail, fixations were identified as falling within either the Close or Far region. To compensate for a lack of precision in the eye-tracker, fixations lying within 1° of the Close/Far boundary were not associated with either region (an average of 20.9% of fixations/trial for the No Ring condition and 19.5% of fixations/trial for the Ring condition). Total time spent fixating the Close region was equivalent in the No Ring and Ring conditions, but total time spent fixating the Far region was significantly longer for No Ring than Ring displays. Similarly, the total number of fixations in the Close region was equivalent in the No Ring and Ring conditions, while the total number of fixations in the Far region was significantly longer in the No Ring condition.

Properties of the scanpath were further explored by grouping fixations in “gazes”, sequences of consecutive fixations within the same region. The mean duration for initial Close

“gazes” (i.e., the period of time prior to fixating outside of the Close region at the start of the trial) was greater for Ring than No Ring conditions, as was the mean number of initial fixations in the Close region. This suggests that participants initially searched the Close region more thoroughly before looking farther away from the center of the display. In addition, the total number of gazes was greater for No Ring than Ring displays, suggesting that participants moved between Close and Far regions more often when displays did not contain a range ring. This result may partially reflect the longer scanpath for No Ring than Ring displays. However, it is important to note that total fixation time per gaze was shorter in both Close and Far regions for No Ring displays, as well; similarly, total number of fixations per gaze was smaller in the Close regions for No Ring displays. This suggests that participants did transition between regions more frequently in the No Ring condition, suggesting a less organized search pattern.

As a final measure of scanpath efficiency, the number of intersections between lines formed by connecting all fixations in the scanpath (i.e., including those fixations not classified as Close or Far) was calculated for No Ring and Ring conditions. In an effort to correct for effects of scanpath length, the number of intersections in each trial was divided by the number of fixations in the scanpath. The resulting ratio was greater for No Ring than Ring displays, indicating that scanpaths in the latter conditions crossed themselves fewer times, as would be expected if scanpaths resembled the spiraling “ideal” scanpath.

Discussion

Experiment 2 replicated most of the important effects obtained in Experiment 1. Search time increased with both distance from center and distractor number, and the range ring reduced the effect of distractors, at least in the Far target High distractors condition. However, the effect of the range ring was reduced in comparison with that in Experiment 1. This reduced effect size

is probably a reflection of the within-participant design employed in Experiment 2. As suggested above, participants had considerable practice searching for targets in On/Off Ring and On Ring displays. Participants may have learned to visualize better the Close/Far boundary and to use this knowledge to direct the focus of their attention. More importantly, they may have developed effective search strategies while searching displays with range rings and applied these strategies to No Ring searches. Comparisons of Far target High Distractor RTs for Ring vs No Ring conditions across blocks support these conclusions.

Moreover, the lack of any significant difference between On Ring and On/Off Ring conditions suggests that participants did not require any significant period of preparation time prior to the onset of the display in order to use the range ring effectively. This suggests that the ability to focus attention on the Close region prior to the onset of a display provided little additional benefit to searching. It may be that the ability to focus attention more narrowly on the Close region would have been of more use if the Close region were smaller and distractors looked less similar to the target; as it was, attending to the entire Close region probably spread attention too thinly and provided little benefit for detecting targets that required direct fixation.

Nevertheless, the basic data patterns of Experiment 1 were still replicated despite the fact that trends were weaker in Experiment 2. In addition, although the within-participant design may have created opportunities for participants to transfer their range ring-guided search behavior to No Ring displays, the eye movement analyses described above clearly suggest that participants transitioned between Close and Far regions more often when displays lacked a range ring. Thus, it does appear that the range ring not only helped participants to focus their attention but also directed them to follow a task-efficient spiraling scan-path more closely.

GENERAL DISCUSSION

Experiments 1 and 2 demonstrated that partitioning displays into task-relevant regions with a range ring facilitated inside-to-outside search. Because the ring encircled the Close region in these displays, one might have predicted that its largest effect would be to help participants to focus on the Close region at the start of the trial, facilitating the detection of Close targets appearing there. However, the greater effect of the range ring on RTs for Far rather than Close targets indicates that displaying the close/far boundary did more than simply cue attention initially to the Close region; in fact, the lack of difference between the On/Off and On Ring conditions in Experiment 2 suggests that being able to use the range ring to focus on the Close region at the start of the trial may have provided little overall benefit. Instead, we suggest that participants continually made use of the range ring in the course of searching through the display. Specifically, we propose that the range ring facilitated performance by helping participants to (1) focus attention effectively on fixated locations and (2) allocate attention to different locations within the display in a task efficient scanpath.

Range Ring as an Attention-Focusing Tool

The range ring may have helped observers to allocate attention to different positions within the display with more precision, facilitating both the processing of symbols within the attended region and also the filtering out of peripheral distraction. As described in the Introduction, the influence of perceptual boundaries on the allocation of attention has been well documented (e.g., Baylis & Driver, 1992; Kramer & Jacobson, 1991). Distractors create far more target interference when they appear within the same perceptual group as targets.

Moreover, observers may be able to focus attention more narrowly and more effectively within the confines of prescribed perceptual boundaries even in the absence of distractors (Cave

& Bichot, 1999). Without such boundaries, the spread of attention may be more diffuse and less beneficial, as the efficacy of spatial attention appears to decrease as the size of the attended area increases (Castiello & Umiltá, 1990). Note that the range ring could serve as a boundary for directing attention not only within the Close region but also within the Far region, especially when used in combination with the outer perimeter of the display.

Range Ring as a Scanpath Guide

The range ring could also have helped to encourage an effective path of search through the display. The nature of the “find closest target to center” task constrained the pattern in which displays could be searched most efficiently. To find the closest target to the center, participants should have adopted a scanpath that spiraled outward from the center, allowing them to ensure that the target was absent from locations closer to the center before looking farther away in the periphery.

Why might participants have failed to adopt this ideal scanpath?. To begin with, they may have forgotten precisely which locations they had already visited and which distractors they had previously rejected (Horowitz & Wolfe, 1998, 2001). The range ring could have facilitated performance by serving as a landmark within the display, helping observers to recall previously searched regions of the screen by referencing those locations relative to the range ring.

Secondly, participants’ attention might have been diverted more easily by peripheral distractors in the absence of a range ring (highlighting once again the role of the range ring as an attention focuser and distraction filtering aid). There is evidence that observers find it difficult to follow a prescribed path of saccades through dense arrays of symbols (Hooze & Erkelens, 1998). This difficulty may partially reflect the ease with which attention may be distracted by salient

features in the environment (e.g., Theeuwes, 1994), which can even result in the production of reflexive eye movements to those features (Theeuwes, Kramer, Hahn, & Irwin, 1998).

Finally, participants may have chosen to adopt alternative search strategies that were in conflict with the spiraling scanpath. For example, it has been shown that observers sometimes choose to examine stimuli near to the center of their attentional focus irrespective of overriding task constraints (Araujo, Kowler, & Pavel, 2001), possibly reflecting the overall ease of such strategies or the frequency with which they bring good results in every day life. Our participants might have occasionally “wandered” into the Far region to inspect symbols that lay near to the Close border before examining all of the symbols that lay within the Close region. Alternatively, lack of confidence in the adequacy with they processed a display region could have encouraged observers to return to a previously searched area.

The range ring would have worked against the tendencies described above. Using the range ring as a tool for focusing attention and determining relative position within the display may have increased observers’ confidence in the quality of their search. Moreover, the mere presence of the circular range ring may have encouraged participants to adopt a more circular search path, as scanpaths are highly influenced by the geometric properties of stimulus patterns (e.g., Noton & Stark, 1971). It is likely that both of these factors lead to the generation of scanpaths that more closely resembled the ideal spiral in the range ring condition (as indicated by eye movement analyses).

Conclusions and Future Directions

We have demonstrated that when task constraints dictate an effective search pattern, perceptual boundaries that partition displays in accordance with task constraints can help searchers to adopt this pattern. We suggest that the addition of perceptual boundaries to a search

array may serve as a useful technique for designing graphical user interfaces (GUIs). Although our experiments only indicated that the presence of a range ring could reduce search time by around a second, the tendency for such small behavioral differences to have large influences when compounded over time and activity should not be underestimated (consider how frequently a simple visual search for a relevant target symbol might be initiated during an hour of radar monitoring). Moreover, as the complexity of visual displays and the tasks that utilize them (and the scanpaths that reflect this usage) increases, the performance enhancement that results from the addition of perceptual boundaries may increase substantially, as well.

Establishing the benefits of this method in the context of a more applied GUI-driven task will be critical for validating its usefulness as an interaction design procedure (the visual search paradigm employed in these experiments is not an example of real-world task – although it mimics aspects of such tasks). The first step in such an attempt should be identifying the scanpaths traversed during display inspection, possibly through an examination of eye movement transition patterns and/or task analyses (e.g., Morrison, Marshall, Kelly, & Moore, 1997). Key perceptual boundaries should then be designed to meet the scanning demands imposed by the different tasks for which the interface is employed. These boundaries could be permanently incorporated into the GUI, or they could be inserted at key points during the execution of tasks for which they were designed (this process could potentially be automated or semi-automated via mixed-initiative mechanisms). Finally, task performance with standard and enhanced displays should be compared to assess the benefits of the added boundaries. The application of perceptual boundaries to a real-life design problems will yield important information concerning the efficacy of this technique for GUI design, in addition to furthering basic understanding of task-directed visual search.

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Table 1: Eye movement analyses for Experiment 2.

Measure	No Ring	Ring	<i>t</i>(17)	<i>p</i>
Scanpath length	7.83 fixations <i>SE</i> = 0.64	6.72 fixations <i>SE</i> = 0.44	2.50	.023 *
Total time fixating Close	636.2 msec <i>SE</i> = 32.5	613.5 msec <i>SE</i> = 26.4	1.13	.274
Total time fixating Far	819.4 msec <i>SE</i> = 62.9	721.9 msec <i>SE</i> = 55.2	2.13	.048 *
Total number of Close fixations	2.82 msec <i>SE</i> = 0.17	2.69 msec <i>SE</i> = 0.14	1.08	.295
Total number of Far fixations	3.25 msec <i>SE</i> = 0.30	2.64 msec <i>SE</i> = 0.21	2.70	.015 *
Initial Close gaze duration	526.12 msec <i>SE</i> = 17.96	493.14 msec <i>SE</i> = 14.11	2.99	.008 *
Number of initial Close fixations	2.23 fixations <i>SE</i> = 0.10	2.05 fixations <i>SE</i> = 0.10	3.03	.008 *
Total number of gazes	2.82 gazes <i>SE</i> = 0.18	2.51 gazes <i>SE</i> = 0.14	3.01	.008 *
Total time/Close gaze	456.20 msec <i>SE</i> = 12.4	499.52 msec <i>SE</i> = 16.2	3.72	.002 *
Total time/Far gaze	640.05 msec <i>SE</i> = 25.2	697.26 msec <i>SE</i> = 31.4	3.48	.003*
Total # fixations/ Close gaze	2.00 fixations <i>SE</i> = 0.08	2.18 fixations <i>SE</i> = 0.09	2.99	.008 *
Total # fixations/ Far gaze	2.41 fixations <i>SE</i> = 0.09	2.50 fixations <i>SE</i> = 0.12	1.01	.326
Intersections/ length	0.214 <i>SE</i> = 0.03	0.130 <i>SE</i> = 0.01	4.00	.001 *

FIGURE CAPTIONS

Figure 1: Sample Far target High distractor stimulus display. See text for details.

Figure 2: Search time results for Experiment 1.

Figure 3: Search time results for Experiment 2.

Figure 4: Search time results across blocks for the Far Target High Distractor conditions in Experiment 2.

Figure 5: Sample scanpath for a single participant scanning a Far target High distractor display without a range ring. Circle diameter reflects fixation durations.

Figure 6: Sample scanpath for a single participant scanning a Far target High distractor display with a range ring. Circle diameter reflects fixation durations.

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