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# Strategy Shifts in Mixed Density Search

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**Abstract**

Visual search in an important aspect of many tasks, but it is not well understood how many aspects of layout design affect visual search. This research investigates, with reaction time and eye movement data, the effect of local density on the visual search of structured layouts of words. Layouts were all-sparse, all-dense, or mixed. Participants found targets in sparse groups faster even after numerosity effects were factored out, and searched sparse groups before dense groups. Participants made slightly more fixations per word in sparse groups, but these were much shorter fixations. Perhaps most interesting, roughly halfway through searching each mixed layout, participants appeared to switch search strategies with respect to the number of fixations per group of words and fixation duration. When dense groups were searched early in a trial, search strategies were more similar to search strategies in the all-sparse layouts. When searched later in a trial, search strategies were more similar to search strategies of all-dense groups. When combining densities in a layout, it may be beneficial to place important information in sparse groups.

## Introduction

It is through visual search that people locate the content and controls for many tasks. Yet, it is not well understood how many layout design practices affect visual search. A large body of basic research on visual search exists in psychology (for example, Greene & Rayner, 2001; Hayhoe, Lachter, & Moeller, 1992; Shen, Reingold, & Pomplun, 2000; Treisman, 1998). Many phenomena have been observed and many theories have been proposed to explain them. However, there has been comparably little research on how to apply basic psychological phenomena in a practical setting. A good applied theory of visual search is needed.

Previous research has investigated the extent to which theories from basic research apply to more ecologically valid tasks in human-computer interaction. One such line of research investigated the visual search of hierarchical layouts with experimentation and cognitive modeling (Hornof, 2001, in press; Hornof & Halverson, 2003). In these experiments, participants searched for a precued target item in labeled or unlabeled layouts. In the labeled layouts, groups had headings and the participant was precued with the target group heading as well as the target item. In the unlabeled layouts, the groups had no headings. It was found that a useful visual hierarchy motivated fundamentally different search strategies. That is, when useful group headings are present, people will first search the headings and then the group content.

The current study extends the work in Hornof (2001) and Hornof and Halverson (2003) by investigating the visual search of more complex non-hierarchical layouts. The purpose of this research is to (a) further inform the development of a predictive tool for evaluation of visual layouts, and (b) contribute to the theories of applied visual search in human-computer interaction.

Varying the density of text and objects is one common design practice used to establish grouping and hierarchy in visual displays (Mullet & Sano, 1995). This paper reports a study that investigates the effect of varying local density on visual search strategies of two-dimensional menu-like lists of words.

The density of items in a display is one factor that has been shown in effective field of view (EFV) studies to affect the number of items that can be perceived in a single fixation. EFV, also referred to as the useful field of view or perceptual span, is the region from which the visual perceptual system processes information in a single fixation. There have been many studies on EFV for various tasks (for example, Bertera & Rayner, 2000; Mackworth, 1976; Rayner & Fisher, 1987; Reingold, Charness, Pomplun, & Stampe, 2001). These studies have found a limited region in the visual field that is sufficient for normal perception of static scenes. This region can be centered on the point of fixation or can be asymmetric with respect to the point of fixation. In addition, these studies have found that the EFV varies in size by type of stimuli, type of task, and task difficulty.

Bertera and Rayner (2000) varied the spacing (density) between a fixed number of randomly placed characters in a search task. They found that search time decreased and the estimated number of letters processed per fixation increased as the density increased. Mackworth (1976) showed similar results in a study in which participants searched for a square among uniformly distributed circles on a scrolling vertical strip. Ojanpää, Näsänen, and Kojo (2002) studied the effect of spacing on the visual search of word lists, and found that as the vertical spacing between words increased (i.e. as density decreased), search time also increased. In general, research examining the interaction between EFV and density has found that the visual search of more dense stimuli is faster per object, with the decrease in the number

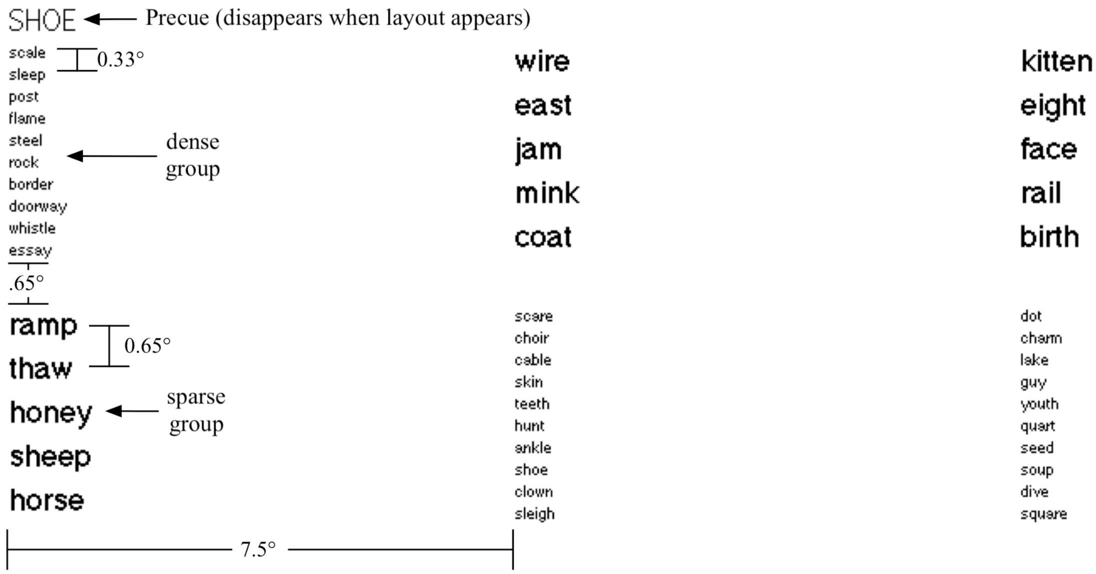


Figure 1: A mixed-density layout. All angle measurements are in degrees of visual angle.

of fixations required to find the target being the largest factor.

Density may be measured as *overall density* or *local density*. Overall density is the number of items per degree of visual angle over an entire layout. Local density is the number of items per degree of visual angle within a visually distinct group.

Besides affecting the search time and number of items inspected per fixation, local density may also affect the *order* of inspection. Several studies have found that visual attention is drawn to "more informative" stimuli (for example, Berlyne, 1958; Mackworth & Morandi, 1967). "More informative" is often defined as regions having greater contour in pictorial stimuli. For example, with geometric shapes, angles are considered more informative than straight lines. Yet, it is not readily known how to predict *a priori* which of two stimuli are more informative. One plausible factor of "informativeness" is local density. It may be that regions with a higher local density are more informative since they are more likely to contain more angles.

The following hypotheses were tested in this study:

**H1:** The search time per word is greater in sparse layouts than in dense layouts.

**H2:** Dense regions will be searched before sparse regions.

The following experiment builds on previous research by investigating the extent to which previous findings hold in tasks that are more ecologically valid than those used in Bertera and Rayner (2000) and Mackworth (1976). While these previous studies are very informative, the stimuli are single characters or simple shapes. It is unclear whether the same phenomena will be seen with stimuli in which the items are more complex, such as words, or when density changes within a visual layout. One spatial property – local density – was manipulated in this study.

## Method

### Participants

Twenty-four people, 10 female and 14 male, ranging in age from 18 to 55 years of age (mean = 24.5) from the University of Oregon and surrounding communities participated in the experiment. The participants were screened as follows: 18 years of age and older; experienced using graphical user interfaces (such as Microsoft Windows or Macintosh); no learning disability; normal use of both hands; and normal or corrected-to-normal vision. Participants were paid $10, plus a bonus that ranged from $0 to $4.54 based on their performance.

### Apparatus

Visual stimuli were presented on a ViewSonic VE170 LCD display set to 1280 by 1024 resolution at a distance of 61 cm that resulted in 40 pixels per degree of visual angle. The experimental software ran on a 733Mhz Apple Power Macintosh G4 running OS X 10.2.6. The mouse was an Apple optical Pro Mouse, and the mouse tracking speed was set to the fourth highest in the mouse control panel.

Eye movements were recorded using an LC Technologies Eyegaze System, a 60 Hz pupil-center/corneal-reflection eye tracker. A chinrest was used to maintain a consistent eye-to-screen distance.

### Stimuli

Figure 1 shows a sample layout from one mixed-density trial. All trials contained six groups of left-justified, vertically-listed black words on a white background. The groups were arranged in three columns and two rows. Columns were 7.5 degrees of visual angle from left edge to left edge. Rows were separated by 0.65 degrees of visual angle.

There were two types of groups with different local densities: *Sparse* groups contained five words of 18 point Helvetica font with 0.65 degrees of vertical angle between the centers of adjacent words (0.45° for word height, and 0.2° for blank space). *Dense* groups contained 10 words of 9 point Helvetica font with 0.33 degrees of vertical angle between the centers of adjacent words (0.23° for word height, and 0.1° for blank space). Both types of groups subtended the same vertical visual angle.

There were three types of layouts: *sparse*, *dense*, and *mixed-density*. Sparse layouts contained six sparse groups. Dense layouts contained six dense groups. Mixed-density layouts contained three sparse groups and three dense groups. The arrangement of the groups in the mixed-density layouts was randomly determined for each trial. Sparse and dense layouts were identical to the mixed-density layout, with the exception of group densities.

This experiment was designed, in part, to determine the effect of combining multiple local densities in a single layout. Combining multiple local densities necessitated maintaining the number, size (in degrees of visual angle), and spacing of groups between layouts. Therefore, text size and number of words per group were varied to produce different local densities. Text size often covaries with local density in real-world tasks.

The words used in each trial were selected randomly from a list of 765 nouns generated from the MRC Psycholinguistic Database (Wilson, 1988). No word appeared more than once per trial. The words in the list were selected as follows: three to eight letters, two to four phonemes, above-average printed familiarity, and above-average imagability. Five names of colors and thirteen emotionally charged words were removed.

The target word was randomly chosen from the list of words used in each trial. The participant was precued with the target word before each layout appeared. The precue appeared at the same location every time, directly above the top left word in the layout, in 14 point Geneva font.

### Procedure

Each trial proceeded as follows: The participant studied the precue; clicked on the precue to make the precue disappear and the layout appear; found the target word; moved the cursor to the target word; and clicked on it.

The trials were blocked by layout type. Each block contained 30 trials, preceded by five practice trials. The blocks were fully counterbalanced.

At the start of each experiment, the eye tracker was calibrated to the user. The calibration procedure required the participant to fixate a series of nine points until the average error between the predicted point of gaze and the actual location of the points fell below an error threshold (approximately 6.35 mm). During the execution of the experiment, an objective measure of the eye tracker's calibration was taken during each trial as described in Hornof and Halverson (2002). In short, if the calibration had deteriorated below a threshold (2.13 cm), a calibration was automatically initiated before the next trial. In addition, the trial in which the error was found was not analyzed, and a new trial was added to the block.

To separate visual search time from mouse pointing time, the point completion deadline was used (Hornof, 2001). In short, participants were instructed to not move the mouse until the target was found. Once the mouse was moved more than five pixels in any direction, they had a small amount of time (determined by Fitts' law) to click on the target. If this time was exceeded, a buzzer sounded and the trial was recorded as an error. The trial in which the error occurred was not analyzed, and a new trial was added to the block.

## Results

Since dense groups contained more words, the following analyses were conducted after normalizing for the number of words per layout. This was accomplished by dividing the search time and number of fixations per trial by half of the number of words in the layout.[1] Table 1 shows the mean search time per word, the mean number of fixations per word, and the mean fixation duration for each layout type. The mean search time per word, mean fixations per word, and mean fixation duration for each of the twenty-four

[1] Measures were divided by half based on the assumption that participants, on average, searched half of the items. This assumption is not consequential for analysis purposes.

Table 1: Search time per word, fixations per word, and fixation duration for sparse, mixed-density, and dense layouts.

| | Search Time per Word (ms) | | Fixations per Word | | Fixation Duration (ms) | |
|---|---|---|---|---|---|---|
| Layout | Mean | SD | Mean | SD | Mean | SD |
| Sparse | 208.25 | 49.10 | .69 | .16 | 250.44 | 33.21 |
| Mixed | 253.58 | 61.78 | .70 | .14 | 306.97 | 48.81 |
| Dense | 265.11 | 54.52 | .62 | .14 | 369.65 | 67.89 |

n=24

participants were analyzed using repeated-measures ANOVAs. Eye movements that started before the precue was clicked and after the target was clicked are excluded from all eye movement analysis. An alpha level of .05 was used for all statistical tests.

Participants spent, on average, less time per word in layouts with fewer dense groups, $F(2,46) = 13.94$, $p < .01$. Post-hoc analysis showed that the search time was faster in the sparse than in the mixed layouts ($p < .05$) or dense layouts ($p < .05$); but not different between the mixed and dense layouts ($p > .05$). Participants made slightly fewer fixations per word in layouts with more dense groups, $F(2,46) = 3.25$, $p = .05$. Post-hoc analysis showed that participants used fewer fixations per word in the dense layouts than in the mixed layouts ($p = .01$). Conversely, participants' fixations were longer in layouts with more dense groups, $F(2.46) = 61.82$, $p < .01$. Post-hoc analysis showed that participants made longer fixations in the dense layouts than in the mixed layouts ($p < .05$) and longer fixations in the mixed layouts than in the sparse layouts ($p < .05$).

The search time per trial was analyzed by layout uniformity (all one density vs. mixed density) and target group density. Figure 2 shows the results. Locating a target in dense groups took longer than sparse groups, $F(1, 23) = 83.87$, $p < .01$. The mean search time for all-sparse and all-dense was no different than the mean search time for mixed-density layouts, $F(1,23) = 1.03$, $p = .32$. However, there was an interaction between layout uniformity and target group density, $F(1,23) = 16.87$, $p < .01$. In other words, when the target was in a sparse group, participants found the target faster in all-sparse layouts than in mixed layouts; when the target was in a dense group, participants found the target faster in mixed-density layouts than in all-dense layouts. Further, in mixed density layouts, participants found the target faster when it was in a sparse group, ($p < .01$).

Group visitation data were also analyzed. A group was visited if one or more contiguous fixations fell within 1 degree of visual angle of the group. Group revisits were not included in the analysis presented here. The order of group visitation in mixed density layouts was tested by comparing the percentage of visitations to sparse or dense groups for the first through sixth group visit, regardless of the position of each group in the layout. The results are shown in Figure 3. The data show that participants tended to visit sparse groups before dense groups, $\chi^2(5, N = 24) = 500.04$, $p < .01$.

The mean number of fixations per group and mean fixation duration per group were analyzed. Group revisits were not included in the analysis presented here because it was assumed that the participants' behavior may differ within groups already visited. Additionally, the final groups visited were not included because it was assumed that the participants' behavior may differ within the group in which the target was found. Repeated-measures ANOVAs were conducted to test the effects of group density, layout type (all one density or mixed density), and order of group visit. Figure 4 shows the number of fixations per group as a function of the order in which groups were visited, regardless of the group position in the layout. Each layout type is plotted separately. Mixed layouts are further separated by the visits to dense versus sparse groups. Figure 5 is similar to Figure 4, but shows the mean fixation duration.

The overall number of fixations in all-dense and all-sparse layouts was no different than in mixed-density layouts, $F(1,9) = 2.69$, $p = .14$. The fixations in mixed density layouts are longer than in other layouts, $F(1,9) = 11.22$, $p < .01$. Participants used more fixations per group in dense groups than in sparse groups, $F(1,9) = 112.30$, $p < .01$. Fixation durations were longer in dense groups than in sparse groups, $F(1,9) = 139.36$, $p < .01$.

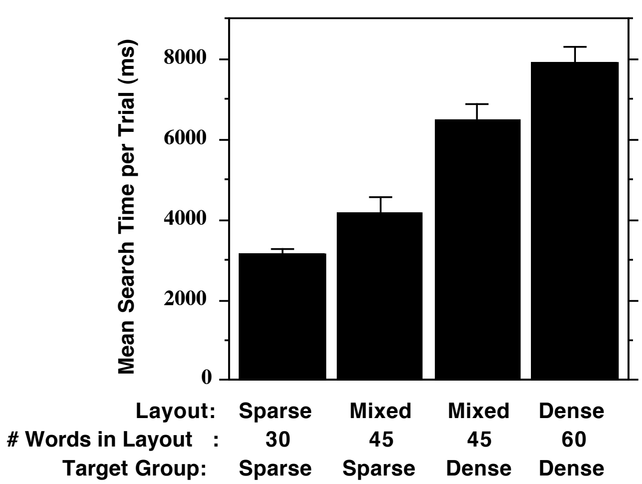


Figure 2: Search time for trials in which the layout was sparse, mixed-density, or dense, and the target was in either a sparse or dense group. Error bars indicate ±1 standard error.

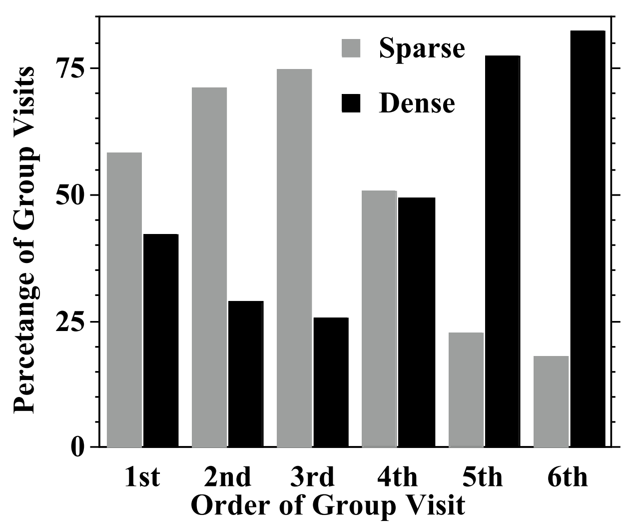


Figure 3: The percentage of visits in mixed density layouts that were to sparse or dense groups, as a function of the order in which groups were visited.

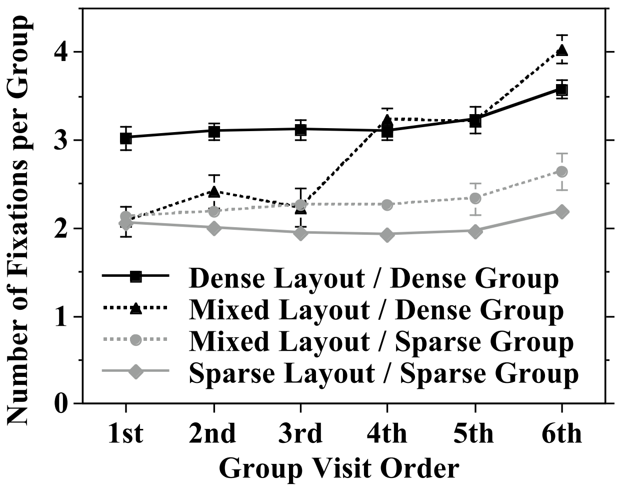


Figure 4: Mean number of fixations per group as a function of layout, the density of the group currently visited, and order of the visit. Error bars indicate ±1 standard error.

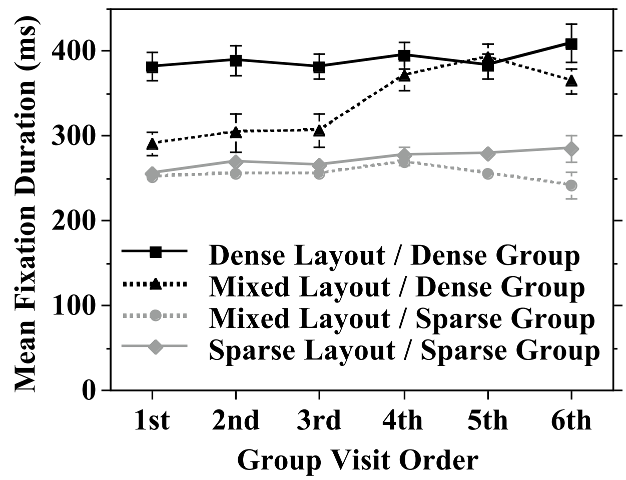


Figure 5: Mean fixation duration by group as a function of layout, the density of the group currently visited, and the order of visit. Error bars indicate ±1 standard error.

Participants used more fixations per group as search progressed, $F(5,45) = 8.14$, $p < .01$. Contrast analysis revealed that the sixth group visited received more fixations than all other groups (all p's < .05), but there were no differences between any other orderings (all p's > .05). Fixation durations tended to be longer for groups visited later than for groups visited earlier, $F(5,45) = 4.89$, $p < .01$. The following interactions were also found in the fixations per group data: The difference between the number of fixations in sparse and dense groups was greater in uniform density layouts than in mixed density layouts, $F(1,9) = 5.20$, $p = .05$. As search progressed (i.e. from left to right in Figure 4), the number of fixations increased faster in mixed-density layouts than in all-dense and all-sparse layouts, $F(5,45) = 6.7$, $p < .01$. The number of fixations increased faster in dense groups than in sparse groups, $F(5,45) = 5.05$, $p < .01$.

## Discussion

The data counter the study's first hypothesis – that the search time per word is greater for sparse layouts than for dense layouts. The search time data reported here demonstrate that people actually spent *less* time per word searching sparse layouts. Participants adopted a more efficient eye movement strategy that used slightly more, but much shorter, fixations in the sparse groups. This result is contrary to the search time results found by Bertera and Rayner (2000) and Ojanpää, et al. (2002) in which the search time decreased as the density increased. This discrepancy may be due to the way in which density is manipulated. In the previous studies, the spacing between items was varied. This could result in a need for more saccades, as both Rayner (2000) and Ojanpää, et al. (2002) found, to move the EFV over the next group of unprocessed stimuli. In the current study, the size of words (i.e. font size) was varied. The smaller words were more tightly packed, which could have made it more difficult for people to fixate directly on the desired words, requiring more saccades as found in this study. It may be that although various factors affect local density, they do not all affect visual search of those densities in the same way.

The data also counter this study's second hypothesis – that participants will search dense groups first. A preference for search order as a function of group density was found. However, it was in the opposite direction than predicted. The search time data show that when the target was in a sparse group, the mean search time was much closer to that of the sparse layouts, and that when the target was in a dense group, the mean search time was much closer to that of the dense layouts. If one density were consistently searched before the other, then we would expect the search time for targets located in groups of a preferred density to be lower than the search time for targets located in the other groups, which is what we observed. The data suggest that the participants tended to search the sparse groups first. This preference was confirmed with analysis of the eye movements in the mixed layouts. As is seen in Figure 3, participants tended to look at sparse groups first.

While the first group visited was quite often a dense group, as seen in Figure 3, this is expected as the top-left group in the layout was equally likely to be either sparse or dense and 89% of all initial fixations were to that group. These are likely *anticipatory fixations*, as predicted and observed by Hornof and Halverson (2003).

A trend that emerged from the data analysis is evidence of a shift in search strategy between the third and fourth group visited in mixed layouts, right around the time that participants tended to switch from sparse groups to dense groups. When a dense group was one of the first three groups visited, the participants tended to search the dense groups in the same manner as sparse groups, with fewer and shorter fixations. Yet, when the participants searched through the all-dense layouts, all-sparse layouts, or sparse groups in the mixed-density layouts, no significant changes in oculomotor programming were found at any point during the search. This suggests that the participants started searching mixed-density layouts with a more eager approach, adopting the search strategy used for the preferred sparse-density groups; then, as the search progressed and the target had not been found, participants reverted to a different strategy for dense groups.

## Conclusion

This research investigates the effect of local density on visual search of structured, two-dimensional layouts. It is shown that sparse groups of words are searched faster and, when presented with dense groups, sparse groups are searched earlier than dense groups. This lends support to the practice of displaying important information in less dense groups.

Further, at least in the mixed density task, people appear to apply local search strategies used for sparse groups to all groups, regardless of density, early in the task. At some point in the unfolding of their visual search, approximately halfway through, the participants made a global strategy shift towards a more thorough search of dense groups. This suggests that care should be taken when combining densities in a visual layout. Performance in a mixed density task cannot be predicted by assuming people will search regions of a given density the same as they will in a layout of uniform density. Additional research will determine how these findings generalize to a variety of mixed-density layouts.

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