

The Adaptation of Visual Search Strategy to Expected Information Gain

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ABSTRACT

An important question for Human-Computer Interaction is to understand how and why visual search strategy is adapted to the demands imposed by the task of searching the results of a search engine. There is emerging evidence that a key part of the answer concerns the expected information gain of each of the set of available information gathering actions. We build on previous research to show that people are acutely sensitive to differences in the density and in the number of items returned by the search engine. These factors cause shifts in the efficiency of the available information gathering actions. We focus on an image browsing task, and show that, as a consequence of changes to the efficiency of available actions, people make small but significant changes to eye-movement strategy.

Author Keywords

Visual Search, Visual Exploration, Strategy, Cognitive Models, Decision Making, Image Search Results, Thumbnails, Eye Movement, Density, Spacing

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: User Interfaces – Theory and methods; H.1.2 Models and Principles: User/Machine Systems – Human Information Processing; H.3.3 Information Storage and Retrieval: Information Search and Retrieval – Selection process

INTRODUCTION

An important question for Human-Computer Interaction (HCI) is how to design the presentation of search results to facilitate visual search behaviour [9,20,35]. Researchers have proposed many alternatives to the standard list of results. They include Space-filling thumbnails of text [7], Tabular interface [36], Faceted category interface [42], and Textually-enhanced thumbnails [41].

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The number of proposals is, in part, a reflection of the scale of the design space. Identifying which of the potentially hundreds of interesting points in this space is best might be informed by a theory of how people choose to search through results, e.g. an ACT-R or EPIC theory of the cognitive, motor, and perceptual processing required to achieve the task [2,18,22,23]. Recent efforts to understand, what Payne, Howes and Reader [28] call interactive search tasks, have included [5,6,8,13,31]. However, it is sometimes difficult to ascertain which interface will be best when the details of the strategy that people will use given a particular task environment are unclear [10,14,17,19]. In this paper we are interested in the strategy choices that people make about visual search, i.e. how they choose to look at search results. Our focus is on the assumption that people attempt to maximise expected utility given the constraints of the human visual system [8,39] and that design changes which change the efficiency of information gathering actions will lead to changes in observed behaviour.

There is some evidence in the visual perception and cognition literature that visual search strategy is adapted to the demands imposed by particular task environments [4,26,40]. It appears that people seek to maximise the efficiency of visual search in the context of the particular display layout. For example, longer fixations enable more information to be gathered from fovea and peripheral vision, although longer fixations can only be effective if the information is available within the *perceptual span* [26]. Moreover, people need to manage the trade-off between the increased information gain of longer fixations and the effort and time cost of holding a fixation.

Some evidence that people adapt their strategy to the task can also be found in the HCI literature. For example, trade-offs in the use of wide versus narrow spacing between icons [11], in more but smaller text versus fewer but bigger text in the same space [15] and in the use of Hyperbolic browser versus standard browser [30]. Even in a standard results layout, such as a simple list of links, there is evidence that search strategy is affected by the context in which the relevance of items is assessed [5,6,8,13]. The position of a target item in a list and relationship between the relevance of this target and distractor items affects search behaviour

[5,6,13]. These findings support the view that search and selection is guided by maximising the expected information gain [8]. Strikingly there is evidence that maximising expected gain can involve fixating on every other item in a list, rather than fixating on contiguous items [5,6], particularly in contexts where good results have already been encountered.

In a number of respects people appear to be sensitive to the expected information gain of information gathering actions. In the following section we review in more detail the literature on the trade-offs that contribute toward the efficiency of information gathering actions during visual search. We are interested in the broad class of *interactive search tasks* [28] but our particular focus is on the visual search strategies and decision-making processes that people use when looking through items returned by an image search engine such as Flickr or Google. Further, we are interested in everyday tasks with somewhat underspecified target criteria, e.g. look for attractive images of the city Florence. In what follows we consider the relevance of the visual search and HCI literature to understanding these kinds of task.

RELATED WORK

Visual Search in HCI

Researchers in HCI have suggested that the details of interface design affect visual search strategy (e.g., [11,15,30]). Everett and Byrne [11], for example, suggested a small difference of 1.6 degrees of visual angle between items can result in participants either fixating on an icon or not. Similarly, Halverson and Hornof [15] provided evidence that low density, task-meaningless large words could lead participants to use fewer and shorter fixations and so shorter overall search time than when given high density, small, task-meaningless, words. Similarly, Pirolli, Card, and Van Der Wege [30] found that participants used more but shorter fixations when using a Hyperbolic browser than when using a standard browser, especially in areas of the Hyperbolic browser in which small, low information scent items, were grouped closely together.

Visual Search in Experimental Psychology

In the visual search literature, there is compelling evidence that the density of items on the display has consequences for search strategy. Ojanpää, Näsänen and Kojo [26] found that decreased spacing in a vertical list of words (common Finnish verbs, nouns and adjectives) resulted in longer but fewer numerous fixations. Vlaskamp, Over and Hooge [40] found that the fixation duration, number of fixation and search time increased dramatically with decreasing item spacing, as the range of spacing smaller than 1.5° visual angle. On the other hand, their data showed that at wide spacing range between 1.5° to 7.1° fixation duration, number of fixations and search time increased slightly as the spacing increased. Bertera and Rayner [4] found that as the item spacing increased the number of fixations and fixation duration increased.

Although allowing a high degree of experimental control the tasks [4,26,40] lack ecological validity. For example, Vlaskamp, Over and Hooge [40] used abstract shapes (e.g., squares) in their search task, and, Bertera and Rayner [4] used an unstructured alphanumeric array. Ojanpää, Näsänen and Kojo [26]) used common-words, which reduced the task to a simple visual pattern match, rather than a match of information scent but it is known that search behaviour is contingent on label relevance [5,6]. The different materials may account for the different effects. Both tasks are far from the real HCI task in which the stimuli are more heterogeneous and complicated.

Strategy Change during Search

Visual search strategies are also known to change during the course of a search [27,33]. Over, Hooge, Vlaskamp and Erkelens [27] found that fixation duration increased and the amplitude of saccade decreased gradually as search progressed. They called this is a coarse-to-fine strategy. Rao, Zelinsky, Hayhoe and Ballard [33] used a coarse-to-fine matching mechanism to model the skipping saccades because it could increase the probability of an early match. In contrast, Brumby and Howes [6] found a fine-to-coarse search strategy. People increased saccade amplitude once they had found, but not committed to, a highly relevant target suggesting that although it is known that strategy can change, the reasons for change are not always clear.

Also, it is known that people spend more time examining items that are presented nearer to the top of the returned search results [9,13], presumably, and in part, because search engines tend to rank order results. However, what is not clear is whether people change visual search strategy as they examine links further from the top of the results list. For example, they may be more likely to *skip* i.e. fixate alternate, non-adjacent, items once a potential hit has been found, as was observed in [6].

THEORY

We assume that people make strategic adaptations in order to improve the efficiency of visual search, that is that they rationally adapt the strategy, given cognitive, perceptual, and motor constraints, to maximise benefits while minimising costs [1,8,17,28,29]. More specifically, people adapt their eye movement strategy to maximise the expected gain of task-relevant information and minimise the neural resources devoted to memory [25] and cognitive and attentional load [3]. In this paper, we take an “active vision” approach [12] to understanding the complex interactive behaviours that people exhibit when searching for information. Understanding these behaviours requires bridging between theories of visual search, visual exploration, and decision-making.

Following Cox and Young [8] we assumed that people are sensitive to the prior probabilities that any particular item will be the target item. Cox and Young operationalised this assumption by assuming that prior probabilities were

normalized over the set of potential targets. More search items implies lower initial priors.

Following Ojanpää, Näsänen and Kojo [26] we assumed that the information that can be gathered given the perceptual span is (1) contingent on the item density, (2) contingent on the duration of fixation.

Combining the theories of Cox and Young [8] and Ojanpää, Näsänen and Kojo [26] we assume that the visual search strategy is rationally adapted to the information that can be gained from the perceptual span. On this basis we made two predictions:

(1) that packing items together more closely (high density) would allow more information to be harvested from the perceptual span given sufficient time. We predicate that people would therefore increase the duration spent looking at any one item, and reduce the number of items directly fixated. That is, they would take advantage of the fact that more information was available for each fixation.

(2) if there are more search items then the gaze durations and the rate of number of items directly fixated in a trial should decrease because the prior probability of any one item being the target item is decreased [8]. In other words, when there are more results returned we expect people to give each result less time, presumably reducing the quality of each evaluation in order to conduct more evaluations. The eye movement strategy should switch to a lower cost strategy, involving more item skipping [6].

EXPERIMENT

Method

This study investigates the consequences of expected information gain for the visual search strategy that people use given pages of thumbnails returned by a search engine. Participants were asked to imagine that they were choosing where to go on holiday, and that they were using the web to gather information about various places that they could visit. In particular, their goal was to use a particular image search engine site to find an image of a visually attractive destination.

Stimuli and Design

There were 180 unique sets of images. Each set included image thumbnails about a place, such as a resort, city or country. These image thumbnails were selected from the search results responding to keywords or search phrases input in an image search engine of Flickr, a photo sharing website. Moreover, each set at least contains 1,000 photo results matching the name of the place. For example, Flickr found 423,166 up-to-date results for photos matching Florence. We filtered out the tourists' poor quality self-portrait, maps and pictures with special effect, such as High Dynamic Range (HDR) images which is not clear in the task thumbnail size. Finally, we selected 180 photo thumbnails for each set. So, totally, we had unique 32,400 thumbnails (180 sets \times 180 thumbnails). At the eye-to-

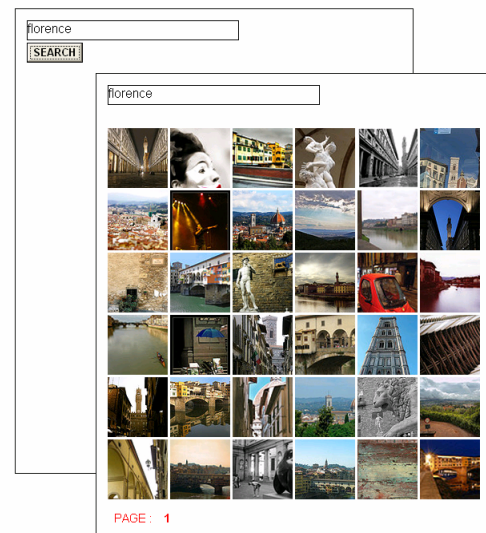


Figure 1: an example of search task with high density layout and one number of pages condition.

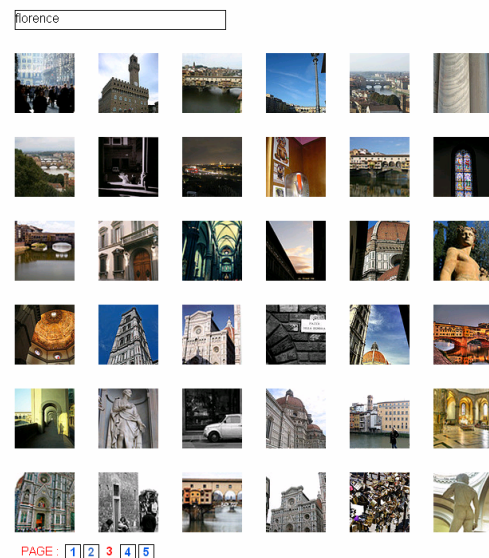


Figure 2: A sample trial of low density layout and 5 pages set size. This shows the thumbnails on page 3.

screen distance of 60 centimeters used in the experiment, the size of thumbnails (75 \times 75 pixels) subtended a visual angle of 2.15°.

The experiment was a within-subjects design and had two independent variables. These were thumbnail density and number of pages (set size). Density had two levels with narrow or wide spacing between items displayed in the search task. Figure 1 shows a sample display from one high density trial. The edge-to-edge item spacings were 3 pixels (visual angle = 0.085°) in high density layout. Figure 2

shows one low density trial. The edge-to-edge item spacings were 30 pixels (visual angle = 0.85°) in low density display. Unlike in Halverson and Hornof [15] and Pirolli, Card, and Van Der Wege [30] the size of thumbnails was held constant, so that density was manipulated by changing proximity only.

Number of pages had three levels: 1-page, 2-pages and 5-pages. Each page consisted of exactly 36 thumbnails (6×6 square layout). In the 1-page condition, there were 36 thumbnails in total and the first 36 of 180 thumbnails of sets were used. In 2-pages condition, 1st to 36th thumbnails were used in the first page; 37th to 72nd thumbnails were used in the second page and there were 72 thumbnails in total. In the 5-pages condition, all 180 thumbnails were used sequentially. There were page links below thumbnails in any page. It appeared all the time (see figure 1 and 2). Participants could click these links to switch between pages during a trial. So, when Participants searched in the first page, they also gained the information about how many pages in this task.

In total, there were 6 conditions (2 densities \times 3 number of pages). Each condition had 30 trials. The total number of trials was 180. Each set of thumbnails could be arranged into one of six conditions. The presentations of each set of thumbnails were counterbalanced across subjects.

Apparatus

The experiment was performed with a Tobii 1750 eye tracker. The eyetracker is embodied in a 17" monitor. The eye tracker has a tracking rate or the frame rate of 50 Hz. The temporal resolution of 20 ms is sufficient for monitoring long fixation and eye movements in our task. Although low temporal resolution could cause noise in signal sampling, noise was reduced by averaging several gazes per page and by testing 30 trials per condition. The screen resolutions were set at 1024×768 pixels.

Participants

Participants were twenty four students from University of Manchester who received 5-10 pounds depending on their time for their volunteer. All participants were between 18 and 28 years old and have normal vision or corrected-to-normal vision.

Procedure

Participants were presented with instructions and then a practice block allowed them to become familiar with the task. After the practice block, the eye tracker system was calibrated. And then participants completed all 180 trials.

The whole Experiment took between 40 minutes and 70 minutes depending on different participants. The variation in time was because we didn't give our participants any time limitation. Some participants were faster than others.

The participant looked at a place label then clicked on the search button to make thumbnail search results appear. The participant was instructed to move the cursor to a thumbnail

of a visually attractive destination and click on it to finish a trial. The trial process and interface are shown in Figure 1.

Results

Normally, eye movement studies analysed participants' search time, number of fixations and fixation duration. When we observed the participants' search behaviour, we also found the gaze transitions were not always from one item to the next adjacent item; instead, participants skipped one or more items during their saccade. We calculated how many gaze transitions were not between spatially adjacent thumbnails. Therefore, in this study, we were interested in visual search performance, particularly in how (1) search time and (2) number of item gazes (all contiguous fixations on an item were combined to be a single gaze), (3) gaze duration (the sum of all fixation durations on a thumbnail prior to moving to another thumbnail), and (4) the proportion of skipping gaze transitions (the total number of gaze transitions divided by the number of skipping gaze transitions), are affected by the thumbnails density and number of pages. The data in the revisited page were not included. These four measures might reveal the adaptation of search strategy while participants interact with different item densities and number of items.

We predicted that when the thumbnails were displayed close together, participants would spend longer in a gaze, and be more likely to skip thumbnails during search in the display, than when thumbnails were displayed further apart. In addition, page links below the thumbnails indicated that the number of pages and total items in the task. We predicted that when there are more pages and thumbnails, people would adopt a different strategy which would be revealed by these four measures.

Overall Performance

Figure 3 illustrates the overall performance. There were significant main density effect on total search time ($F(1,23) = 23.43$, $p < 0.001$), number of gazes ($F(1,23) = 15.87$, $p=0.001$), gaze duration ($F(1,23) = 17.34$, $p < 0.001$), and proportion of skipping gaze transitions ($F(1,23) = 35.04$, $p<0.001$). The results showed that participant spent less time ($M = 12,709$ ms vs $14,044$ ms, figure 3a), fewer gazes ($M = 8.16$ vs 9.28 , figure 3b), longer gaze ($M = 407$ ms vs 387 ms, figure 3c) and skipped more often ($M = 72.4\%$ vs 67.7% , figure 3d) in high versus low density.

There were significant main number of pages effects on total search time ($F(2,46) = 136.54$, $p < 0.001$), number of gazes ($F(2,46) = 73.18$, $p < 0.001$), gaze duration ($F(2,46) = 10.16$, $p < 0.001$), and proportion of skipping gaze transitions ($F(2,46) = 8.37$, $p=0.001$). A Bonferroni test revealed that every pairwise comparison was significantly different ($p < 0.05$). According to the pairwise comparison, participants spent significantly less time (1-page: $M = 7,514$ ms, 2-pages: $M = 11,482$ ms and 5-pages: $M = 21,132$ ms), gazed less (1-page: $M = 10.96$, 2-pages: $M = 15.8$ and 5-pages: $M = 28.02$), and skipped less often (1-page: $M = 66.5\%$, 2-pages: $M = 70.7\%$ and 5-pages: $M = 72.9\%$), in

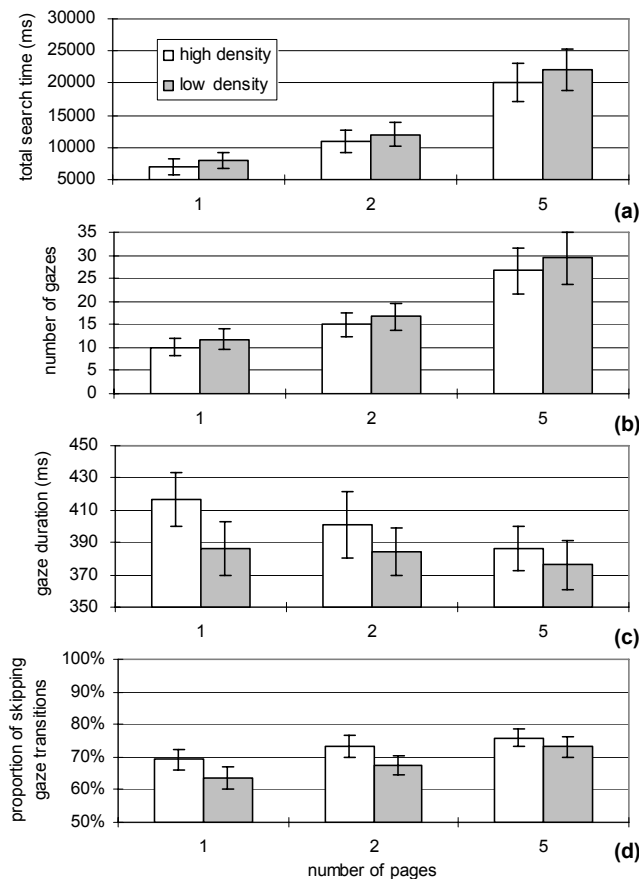


Figure 3: four measures of overall search performance per density and number of page condition. (a) mean response times; (b) mean number of gazes; (c) mean gaze duration and (d) proportion of skipping gaze transitions for high density (white bars) and low density (grey bars) in each page set size. Error bars indicate 95% confidence intervals and also in all figures below.

the fewer page condition. Also, pairwise comparison showed that they spent longer gaze duration in the 1-page condition ($M = 401$ ms) than 5-page condition ($M = 369$ ms), although 2-pages is not significant different to 1-page and 5-pages condition. There were no significant interactions on total search time, number of gazes and gaze duration, except proportion of skipping gaze transitions, $F(2,46) = 3.73$, $p < 0.05$.

Moreover, following Reiman, Young and Howes [34], we analysed the revisiting. Figure 4a shows the number of items that were visited at least once and revisited (i.e. visited at least twice) for each experimental condition. Participant revisited around 22% to 27% of visited items for each condition. Density and number of pages had similar effects on the number of visited and the number of revisited items. Participants visited and revisited more items in low density (all p 's < 0.01) and when there were more pages (a Bonferroni test for analysing three page levels showed every pair was significantly different, $p < 0.001$). In

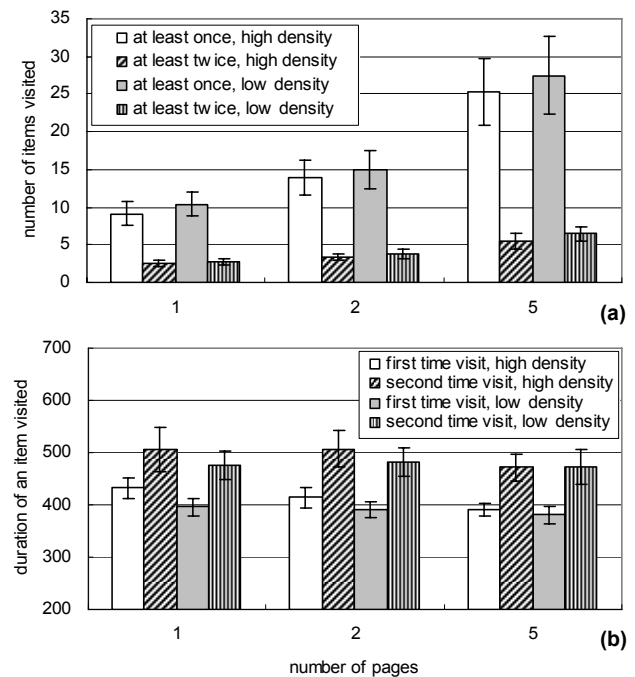


Figure 4: (a) mean number of items visited at least once (bars with solid pattern) and items visited at least twice (bars with line pattern) and (b) mean duration of an item visited at the first time visit (bars with solid pattern) and at the second time visit (bars with line pattern).

addition, figure 4b shows that our participants spent more time on an item when they revisited it than when they visited it the first time, $F(1,20) = 99.788$, $P < 0.001$.

Performance in the First Page

We analysed data in more detail. In this section we contrast performance in the first page of each condition. (Not all conditions had subsequent pages so the first page provides the critical test. In addition, it is the first page behaviour that should be affected by information about the number of pages, rather than by the quality of the additional items.) We analysed our four measures (search time, number of gazes, gaze duration and skipping rate) taken from the first page of search results. We conducted a 2×3 (density \times number of pages) repeated-measure ANOVA for each measure separately.

Duration on a page was defined as the total time from the display onset to the time leaving the first page by click a page number link, or from the onset to the start of participants' last fixation on the clicked target.

As expected, there was a main effect of density on mean search time in the first page, $F(1,23) = 28.27$, $p < 0.001$. The search performance in the first page was quicker in high density ($M = 6082.24$ ms) than low density ($M = 6742.9$ ms). There was also a main effect of number of pages on search time of the first page, $F(2,46) = 15.82$, $p < 0.001$.

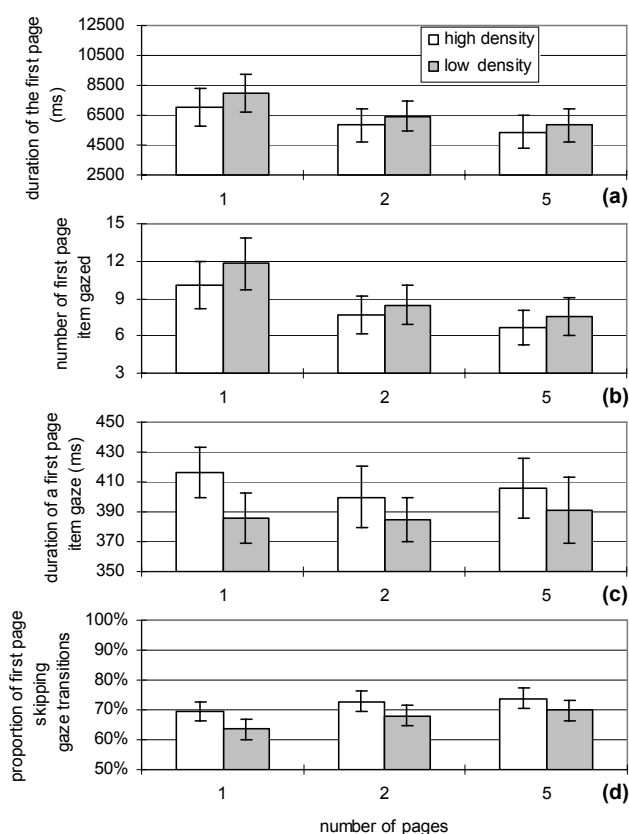


Figure 5: the four measures of mean search performance in the first page per density condition and number of page condition. (a) mean duration of first page; (b) mean number of first page gazes; (c) mean first page gaze duration and (d) mean proportion of first page skipping gaze transitions.

Every pair comparison of number of pages condition with Bonferroni method was significantly different ($p < 0.01$). It was found that time spent in the first page was more in the fewer page condition (1-page: $M = 7514.54$ ms, 2-pages: $M = 6117.07$ ms and 5-pages: $M = 5606.10$ ms). The interaction between density and number of pages was not significant. Results are summarized in Figure 5a.

Figure 5b shows the data of mean number of gazes in the first page. Number of gazes was approximate one fewer in the high density ($M = 8.16$) than low density ($M = 9.29$), $F(1,23) = 24.65$, $p < 0.001$. There was also a main effect of number of pages, $F(2,46) = 24.9$, $p < 0.001$. Every pair comparison of number of pages condition with Bonferroni method was significantly different ($p < 0.001$). It showed that participants spent greater number of gazes in fewer page conditions (1-page: $M = 10.96$, 2-pages: $M = 8.07$ and 5-pages condition: $M = 7.11$). In addition, the interaction of density and number of pages was also significant, $F(2,46) = 4.48$, $p = 0.017$. The fewest number of gazes were made in the first page of the high density display when there were 5-pages of items.

Figure 5c illustrates mean first page gaze duration. Participants' mean gaze duration in the first page was longer in the high density ($M = 407$ ms) than low density layout ($M = 387.259$ ms), $F(1,23) = 22.414$, $p < 0.001$. The main effect of number of pages was not significant. There was no interaction between density and number of pages.

Figure 5d shows the data of mean proportion of first page skipping gaze transitions. The density had significant effect, $F(1, 23) = 46.72$, $p < 0.001$. It was found that participants were more likely to skip thumbnails in the high density ($M = 72\%$) than in the low density layout ($M = 67.2\%$). The main effect of number of pages was also significant, $F(2, 46) = 15.00$, $p < 0.001$. Every pairwise comparison of number of pages condition was significantly different ($p < 0.01$). It showed that our participants skipped more often in 5-pages condition ($M = 66.5\%$), than they did in 2-pages condition ($M = 70.3\%$), which in turn was more often than in the 1-page condition ($M = 71.8\%$). There was no interaction between density and number of pages.

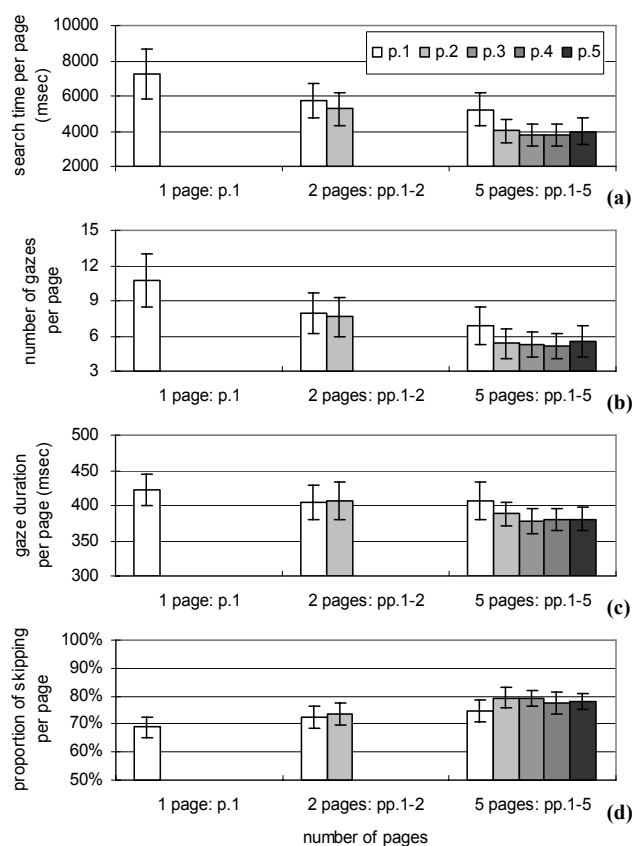


Figure 6: the four measures of mean search performance per page. Page 1, page 1 to 2 and page 1 to 5 of 1-page, 2-pages and 5-pages condition, respectively in high density condition. (a) mean search time per page; (b) mean number of gazes per page; (c) mean gaze duration per page and (d) mean proportion of skipping gaze transitions per page.

Performance per Page

Figure 6 summarises the mean performance of our eighteen participants' eye movement behaviour in the high density condition. (All results of the low density condition has the same trend as in the high density condition) Figure 6a shows mean search duration per page, figure 6b shows mean number of gazes per page, figure 6c shows mean gaze duration per page and figure 6d shows the proportion of skipping gaze transitions in number of pages condition. Each bar within a page condition shows the performance on each page of that condition. For example, the only bar in the 1-page condition shows performance in the 1-page condition, the two bars in 2-pages condition show each performance in page 1 and 2 and the five bars in 5-page condition show each performance from page 1 to page 5, from left to right respectively.

When we examined whether participants adopted different strategies in different pages in a search course, the values of four measures of search performance were taken from each page.

Because there were four participants who didn't have data in all five pages in the 5-page condition, we took out these four participants. Then, we arbitrarily selected and removed another two participants from the analysis to keep the counterbalanced design. Therefore, in this section, the results were from analysing eighteen participants' data. The following analyses were conducted in 2-pages and 5-pages condition separately.

In the 2-pages condition, every measure of four search performance of participants was not significantly different in page 1 and page2. it indicated that the search strategy did

not vary in the first and second page, when participants search in a 2-pages display (see Figure 6a, b, c, d, 2-pages condition).

In 5-pages condition, the results of a 5×2 repeated-measure ANOVA (page number: page 1, 2, 3, 4 and 5 × density: high and low) showed there were main effect of page number and density on every measure of search performance our participants' performance (see Figure 6 a, b, c, d, 5-pages condition). The results of search performance per page in the 5-pages condition are summarized in Table 1. In general, search performance was in page number 1 is different to other pages.

pairwise comparisons of page number with Bonferroni method in search duration, number of gazes, and proportion of skipping gaze transitions showed that the measures in page 1 were different from those in page 2 to page 5 (pair between page 1 and any other page was significant, $p < 0.01$ and pair between page 2 to page 5 were not significant different). There was a significant difference between page 1 and page 3 in gaze duration. Although any other pair does not reach significant, there was a trend for people to take longer gaze on page 1 than on pages 2, 3, 4, or 5. This indicated that participants search in the first page more carefully than other pages.

DISCUSSION

The results support the claim that visual search strategy is guided by expected information gain when people search results returned by an image search engine:

1. Participants were observed to adjust the duration that they attended to each item to the item density. When more

		search duration (ms)		number of gazes		gaze duration (ms)		proportion of skipping gaze transitions		
		mean	SD	mean	SD	mean	SD	mean	SD	
page number										
high density	p. 1	5,238.64 ^a	2,048.75	6.83 ^a	3.49	406.81 ^b	55.64	74.64% ^a	0.08	
	p. 2	4,004.51	1,494.82	5.35	2.72	388.18	37.58	79.33%	0.08	
	p. 3	3,796.32	1,295.97	5.27	2.30	377.32 ^c	39.58	79.36%	0.06	
	p. 4	3,781.66	1,359.42	5.13	2.41	380.30	34.42	77.55%	0.08	
	p. 5	3,999.54	1,653.50	5.50	2.88	381.00	36.14	77.86%	0.06	
low density	p. 1	5,810.45 ^a	2,240.65	7.95 ^a	4.01	399.47 ^b	57.47	69.53% ^a	0.08	
	p. 2	4,176.94	1,853.84	5.64	3.20	365.01	37.52	77.33%	0.07	
	p. 3	4,164.26	1,624.12	5.82	2.97	365.20 ^c	38.85	76.84%	0.09	
	p. 4	4,282.31	1,828.08	5.98	3.14	378.27	55.09	74.17%	0.08	
	p. 5	4,346.20	1,540.77	5.91	2.53	381.86	36.53	74.66%	0.06	
repeated-measures ANOVA		<i>F</i>	<i>MSE</i>	<i>p</i>	<i>F</i>	<i>MSE</i>	<i>p</i>	<i>F</i>	<i>MSE</i>	<i>p</i>
	spacing	14.32	4.83E+05	0.001	9.54	1.942	0.007	4.56	757.26	0.048
	page	29.63	5.21E+05	<0.001	17.06	1.397	<0.001	5.4	998.24	0.001

Table 1. Search duration, number of gazes, gaze duration and proportion of skipping gaze transitions across per page in the 5-pages condition and per density condition. (Note. p. = page number. ^asearch performance is significant different to all other pages in the same density condition. ^{b,c}search performance is significant different to each other in the same density condition)

items were available within the perceptual span (higher density), longer item visits were used, and when fewer items were available (lower density), shorter item visits were used. Longer visits were only used when they were efficient, i.e. when expected information gain was high.

2. Longer visits to items were combined with skipping. Participants in the high density conditions skipped items more often, visited fewer items, and spent less time searching overall. In other words, when the potential information gain for longer visits was high, people made more use of longer visits and reduced the number of items that they directly fixated. They made more use of the perceptual span when it was rational given the constraints of the visual system to do so, and gained an overall reduction in the required search time.

3. Participants were observed to reduce the number of items that they visited, i.e. they skipped, when there was a larger number of items (Figure 5d) but without increasing the duration spent attending to each item (Figure 5c). These findings suggest that skipping was sensitive to the prior probability that any one item would be attractive enough to be selected but that gaze duration was not.

4. Participants spent more time on an item, when they revisited it than when they visited it for the first time. This finding indicates that people may use an *iterative deepening of attention* [34]. This strategy may help participants to parse large amounts of information quickly using lower tolerance to rule out poor quality items and then focus effort on a smaller set. The difference between [34] and our study is that our participants didn't sample all items before they started to revisit, especially in conditions with more pages (Figure 4b). This finding suggests that the set size of potential items may be constrained by the capacity limitation in memory. We also observed participants select an item at the first time visit before sampling all items. This indicated that people also picked an item immediately when the value of the item currently visited is beyond their satisficing criteria [38]. Adopting the coarse-to-fine strategy [27,33] and employing satisficing [38] could save lots of visual processing cost for sampling out poor items quickly and gain an item with satisficing value or gain a revisited item with acceptable value.

In sum, the results support the view that people adjusted their visual search strategy to their expectations of information gain, and that these expectations were contingent on (a) the density of items, and (b) the prior likelihood that an item is the one that they will want to select. In the remainder of the Discussion we first offer further explanations for the details of the findings, we then discuss some design implications.

Further Explanations

Why, for some designs, is it more efficient to use fewer longer gazes than more, shorter, ones? Essentially, because planning and executing gaze transitions, saccades, is

expensive. Planning and executing a new gaze so as to bring a foveal fixation to a new place requires effort, both mental and physical effort. Neurophysiological evidence indicates that making a saccade involves high cost neural processes to keep the visual scene stable (see [37] review). Therefore, to prolong an old gaze to gain information about an adjacent item can cost less than to plan and execute a new gaze. For example, in our experiment a new item visit took an extra 400 ms, but a longer gaze took only about 20 ms more. Although each longer gaze takes more time, fewer gazes are required, reducing the overall visual search time.

Why was it not possible for participants to increase perceptual span to cover adjacent items in lower density displays? Findings reported by Hooze, Vlaskamp and Over [16] suggest that information can be gathered from a wider area of a display as gaze durations increase, i.e. it is possible that perceptual span is itself contingent on duration of fixation. However, there are clearly limits [4], and it appears as though the reduction in the rate that information can be acquired caused by the lower densities in our experiment pushed participants beyond this limit.

Will the findings generalise to other types of search result items? There is some evidence that the finding would generalise to word items. For example, Pollatsek, Perea and Binder [32] found that fixation duration is longer when a word with more neighbours than few neighbours. Longer fixation duration in a more dense display suggests that more information within the perceptual span is required to be processed serially. In contrast, Motter and Belky [24] showed that fixation duration didn't change as the number of items within a 4° constant area and assumed that this result is because items surrounding a fixation are processed in parallel (number of items surrounded the fixation will not affect the fixation duration). These contrary results could be because of the relative complexities of stimuli in these two tasks are so different. Simple items, e.g. symbols, adjacent to a fixation can be processed in parallel, but complex items such photographic thumbnails in our task have to be processed in series and result in longer durations.

Why do the findings differ from previous research? The importance of ecological validity. The observed density effect on gaze duration and number of gazes are consistent with some previous studies [26], but contrary to others [4,15]. Unlike most of the previous studies, our target was not defined by only one or two visual features (color, shape, and orientation et al.) or non-words (non-words without semantic meaning can be searched by their shape or the order of characters), but was, instead, informed by the semantic description of a place. In contrast to these previous studies, participants in our study had to search a target based on aesthetic judgment. They spent longer gaze duration in our task than normal visual search task. These differences in the task environment may lead to the different results of the effect on search performance. Ecological validity is therefore crucial to understanding the constraints on visual search strategy.

On the other hand, we have chosen to control some variables that are confounded in studies of potential new designs. For example, in studies of hyperbolic browsers [30] item size and item density are confounded, i.e. items that are close together are also smaller than items that are further apart. Although this is perhaps, a natural confound for systems like hyperbolic browsers, failing to isolate what are otherwise independent factors will limit the generality of conclusions drawn from the data.

A downside of our effort to engage our participants in a meaningful task -- looking for attractive images of potential destinations -- was that there was a weak criterion for successful trial completion. The trial was over when participants indicated that they had found an attractive thumbnail but some participants may have used radically different thresholds for 'attractive' than others. In contrast, experiments in which participants were asked to find a particular item have a strong and measurable criterion for trial completion and moreover participants can make errors. Although we claim that our design reflects some part of the natural task ecology, it also reduces the strength of the conclusions that we can draw from the fact that participants took less time, overall, when items were presented with a higher density.

Design Implications

A persistent problem for HCI is that the exploration of new designs in the absence of adequate empirically grounded theory might lead to the rejection of the design on the basis of false negatives. Hyperbolic or other fish-eye view projections have, for example, had no impact on the way that most people use computer systems, despite the huge research investment over many years. It is tempting to take this fact as evidence that hyperbolic browsers are not fit for purpose. However, an alternative reason for their failure to find a role might be that the particular design instances are not tuned to the detailed constraints and adaptive capability of the human visual system. Hyperbolic browsers that fail to let people adapt to the constraints and capabilities imposed by their visual system are unlikely to succeed. Careful empirical investigation in response to well-formed theory and motivated by the ecology of user's real task environments may have the potential to address this problem.

For example, although users might adapt their search strategy to achieve the highest payoff given a particular thumbnail density, some layout designs are better for decreasing of total search time and manual response time. The results reported above suggest the high density (3 pixels gap between thumbnails) can facilitate search.

Interestingly, even higher densities than we have explored in this paper are unlikely to produce further gains. Previous work [21] has suggested that when the spacing between icons is zero pixels search becomes more difficult. Thumbnails require at least some space for visual search, which perhaps reflects common intuitions.

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