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The effect of visual complexity and task difficulty on human cognitive load of small screen devices

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With the popularity of smart phones, the design of mobile interface has gained more and more attention from researchers, due to the increasing need to utilize all aspects of design knowledge. However, only few studies have focused on the cognitive aspects of designing mobile phone interfaces, especially the interaction between visual complexity and task difficulty. Therefore, the purpose of this study is to investigate the effect of visual complexity and task difficulty on human cognitive load with mobile-sized interfaces. This study presented 36 college students with mobile pages of three levels of complexity on desktop in a mobile sized screen and collected their eye-movement data by eye-tracking apparatus while they performed tasks of varying difficulties. We found that user satisfaction was more related to extraneous cognitive load (visual complexity), while task completion time, fixation count and fixation duration was more related to internal cognitive load (task difficulty). We also found that the optimal complexity level varies according to different tasks and users achieved the highest efficiency when interacting with moderate visual complexity in difficult tasks. This was the first study to explore the relationship between visual complexity and task difficulty of mobile size interface by using eye-tracking technique. Our results obtained could providing a scientific basis for interface design of small screen devices.

Keywords: *visual complexity; task difficulty; cognitive load; eye-tracking technique; mobile-sized interface*.

1 Introduction

Nowadays, Internet media has gradually replaced traditional paper media and become the first channel for the public to obtain news information. Mobile news, as a form of knowledge presentation[1], is the media to shape ones' attitudes, beliefs, and behaviours[2]. According to iiMedia Research, the number of mobile news users in China has increased to 646 million in the first quarter of 2018 [3]. Besides, the usability research on mobile interface design has gradually gained the attention of academia and business fields. However, very little research has attempted to measure how much and how efficient users comprehend the news. Due to the limitation of the mobile-size screen, the content of the mobile interfaces must be more concise and effective, which requires designers to organize information effectively in a reasonable layout. Therefore, designing effective and logical layout and content to accommodate to the visual behaviour of human has become the focus of designers and researchers of human-computer interface (HCI). Excellent interface layout and suitable amount of information can provide users with good user experience and reduce their cognitive load, which make the process of knowledge acquisition much easier.

2 Theoretical background

2.1 Visual complexity and its outcomes

Visual complexity is an important factor leading to high cognitive load, which can be defined as “the amount of variety in a stimulus pattern” [4]. Geissler et al. [5] believed that stimulus complexity should consist of the number of elements, the level of dissimilarity between elements, and the level of unity between elements. The definition of webpage complexity is developed based on stimulus complexity, which refers to the amount of information that a site is offering [6]. Deng and Poole further divided visual complexity into two dimensions [7]: (1) visual diversity, which refers to the number of different elements (e.g., text, graphics); (2) visual richness, which refers to the amount of each element. Previous studies showed that website complexity affects user outcome, however, researchers have not reached an agreement on their relationship. On one hand, many experimental studies support the point that users prefer interfaces with low visual complexity. Pandir and Knight [8] found a negative relationship between complexity and pleasure in website perception. Deng & Poole [8] found that perceived visual complexity was negatively related to aesthetic perception. Choi & Lee [9] suggested a simplified interface design of visual display attributes contributes to positive satisfaction evaluations when users engage in communication, information search, and entertainment activities. On the other hand, Berlyne [4] first proposed that the relationship between website complexity and user outcomes could be described as an inverted U-shaped curve which users achieved the highest efficiency when interacting with moderate visual complexity compared with low and high level visual complexity. Recently, Spiekermann and Korunovska [10] suggested that users become more creative and thoughtful until visual complexity reached certain point, but after that point, creativity significantly reduced. Lin et al. [11] found that visual complexity of e-commerce websites had a significant effect on users’ pleasure, and the effect could also be described as an inverted U curve.

2.2 Task difficulty from cognitive perspective

There is no clear definition of task difficulty. In resource requirement viewpoint, task difficulty is defined as resources requirement of human information processing [12]. Resource could be referred as cognitive demands [13,14], physical and mental demands [15,16], and short-term memory requirements[17]. In other words, users would invest more resources during more complex task because of limited human information processing resources. Task difficulty is an important factor that influences task performers’ mental workload and predicts human performance and behaviour [12,17]. In the field of human-computer interaction, Wang et al. [18]showed that for simple tasks, the simpler the interface, the better their performance would be; for difficult tasks, their task completion time (TCT), fixation count, and fixation duration were all at the highest level with webpages of medium visual complexity. Huang & Zhou [19]found that TCT and perceived cognitive workload increased more for difficult tasks than in simple tasks as the number of links on the mobile websites increased.

2.3 Cognitive load theory

Sweller [20] proposed cognitive load theory to describe the limited capacity of working memory. According to this theory, people would feel overwhelmed when the amount of information exceeds a limit. He believed that there are three types of cognitive load: intrinsic cognitive load links to the stimuli’s content or the task itself can not be altered by users; extraneous cognitive load depends on the presentation forms, and germane cognitive load that involves information consolidation can be decreased by appropriate structure and layout design. Hence, we can infer that visual complexity relates to extraneous cognitive load, while task difficulty relates to intrinsic load.

2.4 Studies on different devices

Several studies explored differences in user behaviour on different devices. Jones et al. [21,22] conducted a behavioural experiment and found that user performance dropped as screen size reduced because it would be more difficult for users to make good judgements or to gain a general overview effectively on smaller screens. Kim et al. [23] found that users had more difficulty extracting information from search results pages on smaller screens although they exhibited less eye movement as a result of infrequent use of the scroll function. However, there were no significant difference between the 2 screens in terms of TCT on search results pages and the accuracy of finding answers. Sohn et al. [24] conducted an online shopping experiment on mobile phones and tablets, and found that participants were more likely to feel spatially crowded in visually complex surroundings on mobile phones than tablets, which leaded to lower satisfaction.

However, no study has explored the influence of visual complexity and task difficulty on mobile users' cognitive load. Therefore, in the present study, we systematically investigated the effects of visual complexity and task difficulty on human cognitive load and performance with mobile size interface indexed by eye-tracking technique.

3 Research methods

3.1 Participants

36 college students (15 male) were recruited from Zhejiang University. All participants had normal colour vision and normal or corrected-to-normal visual acuity. Participants were 22.28 (SD=1.86) years old on average and were all right-handed. This research complied with the American Psychological Association Code of Ethics and was approved by the Research Ethics Board of the Department of Design, Zhejiang University. Written informed consent was obtained from each participant.

3.2 Experimental materials

We used Eyelink-1000 produced by SR research to collect the eye movement data of the right eye. The sampling rate was 1000 Hz. The experimental stimuli was presented on the 19-inch Dell display, of which the screen resolution was 1024*768. The distance between participants' eye and the display was 60cm. We produced three types of news interfaces with different visual complexity levels through Axure RP8 by manipulating the number of pictures per news (as shown in Fig.1, the interfaces from left to right correspond to low complexity, moderate complexity, and high complexity respectively).

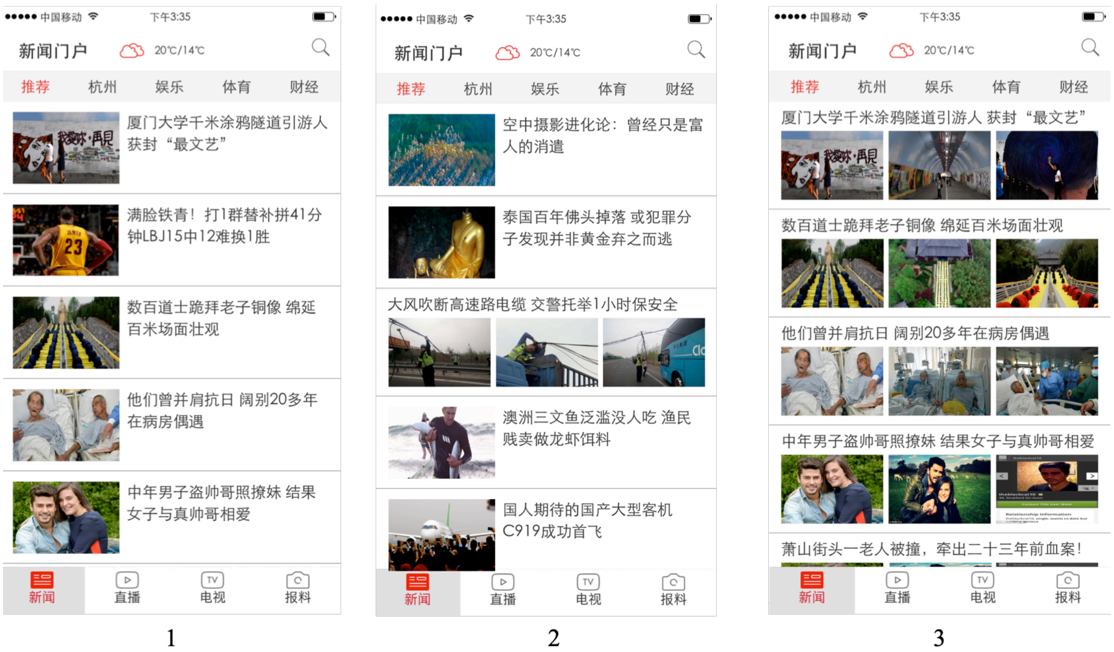

Figure 1. Three types of interface with different visual complexity levels.

3.3 Experimental task

In this study, we manipulated three difficulty levels of tasks based on the information processing model from the perspective of resources [12,25] that users usually performed on mobile phones. Browse task: Participants were required to browse the interfaces like how they usually do on the mobile phone, and they can end the trials as they like by pressing space. This is the simplest task in our study, which was similar with the study of Tuch et al. [26]. Search task: Participants were required to find an asterisk in the given stimuli, and press space as quickly as possible. This task simulates searching for a particular target of interest on an interface. This procedure requires visual resources to detect and psychomotor resources to make a quick response, which is more difficult than the *browse* tasks. Answer task: Each trial started with a question (the question was "to find news that took place abroad"). Participants could then proceed to the first page and look for the answer. Participants needed to press space first and then announce the desired information loudly once they find the answer. This process requires not only cognitive resources to process textual information, but also short-term memory resources to recall the key words, which makes the task the most difficult one.

3.4 Experimental procedure

In the present experiment, we adopted a within-participant design to investigate the effects of two main variables: task difficulty (3) × visual complexity (3). The present experiment was composed of 3 blocks (one task difficulty for one block), and each block included 3 trials (visual complexity). To minimize the carry-over effect, the order of the presentation of 3 trials was randomized for the participants while the order of blocks was counterbalanced across participants. At the beginning of each block session, participants performed two practice trials for around 30s to familiarize themselves with the procedure, followed by experimental tasks with 3 different levels of visual complexity trial. The block interval was 60s. After each block, participants were required to rate the subjective evaluation, including perceived task difficulty, perceived visual complexity and satisfaction with the interfaces by using a 7-point Likert scale. At the end of the experiment, participants were required to fill out a post-experiment questionnaire, which include basic information, such as age, background, familiarity with news applications and using mobile devices, and rank the difficulty of the given three tasks. The entire experiment took approximately 20 minutes for each participant to complete.

3.5 Eye-tracking metrics and data analysis

This study adopts eye-tracking technique to observe users' fixation behaviour for different tasks on mobile-sized interfaces. We chose fixation duration, fixation count, and pupil size as fixation metrics. Among them, fixation duration and fixation count are the most commonly used metrics to measure visual attention [27]. Fixation duration can reflect how much effort is required for information processing. Longer fixation duration implies that information is more difficult to extract or from another perspective, more attractive [27]. The fixation count shows the total number of fixations on a given object [28], which reveals the interests of attention. Pupil size is often considered to be associated with cognitive load [29–31], and the greater the pupil size is, the higher the human cognitive load in the task [32,33]. We employed this metric to measure the difficulty of tasks. TCT, which reflects users' task performance was also taken into account. Less TCT usually indicates more efficient decision-making and better design interface[18]. We employed analysis of variance (ANOVA) for TCT and fixation duration, with a log-transformation *log(x+1)* to maintain the normality assumption because TCT and fixation duration did not meet the normal distribution[34]. We adopted generalized linear mixed models (GLMMs) with a Poisson distribution and logarithm link function for fixation count. For the case of factors that did not satisfy Mauchly's test of sphericity before repeated measurement ANOVA, we applied Greenhouse-Geisser correction. The significance level in this study was set at 0.05.

4 Results

4.1 Background information

At the end of the experiment, we asked participants to evaluate their familiarity with mobile phones and news applications by using 7 points Likert scale. The average familiarity with the mobile phone was 5.18 (SD=0.93), that is, all users were familiar with the usage of mobile phones. For news APP, the degree of familiarity was 4.65(SD=1.28), which means that most users were familiar with news APP.

4.2 Manipulation check

At the end of each task, we conducted a subjective evaluation of visual complexity and task difficulty using 7 points Likert scale. We found a significant main effect on visual complexity ($F(2, 70) = 49.608$, $p<0.001$), participants rated higher scores when visual complexity increased ($p<0.001$). We also found a significant main effect on task difficulty ($F(2, 70) = 22.879$, $p<0.001$), participants rated higher scores when task difficulty increased ($p<0.001$). These results confirm that we have successfully manipulated visual complexity and task difficulty.

4.3 Task completion time(TCT)

Before conducting repeated ANOVA, we used *log(x+1)* to transform the data of TCT to maintain the normality assumption which is the same as the study of Kim et al.[27]. A significant main effect of task difficulty was noted in TCT ($F(2, 70) = 52.096$, $p<0.001$). Generally, TCT of *search* task was shorter than that of the other two tasks (search vs. browse: $p<0.001$; search vs. answer: $p<0.001$), while there was no significant difference between browse and answer ($p>0.05$). No significant main effect of visual complexity in TCT was found ($F(2, 70) = 2.428$, $p>0.05$).

The interaction with task difficulty and visual complexity reached significance (F (2.717, 95.080) =4.679, $p<0.01$, Fig.2). TCT obtained after high visual complexity was significantly longer than that produced after low visual complexity for search tasks ($p<0.05$). For answer tasks, TCT obtained after medium complexity was relatively shorter than that of low visual complexity and high visual complexity (medium vs. low: $p<0.001$; medium vs high: $p<0.05$), and TCT produced after low complexity was marginally longer than that of high complexity ($p=0.05$), which showed a nearly U-shaped curve.

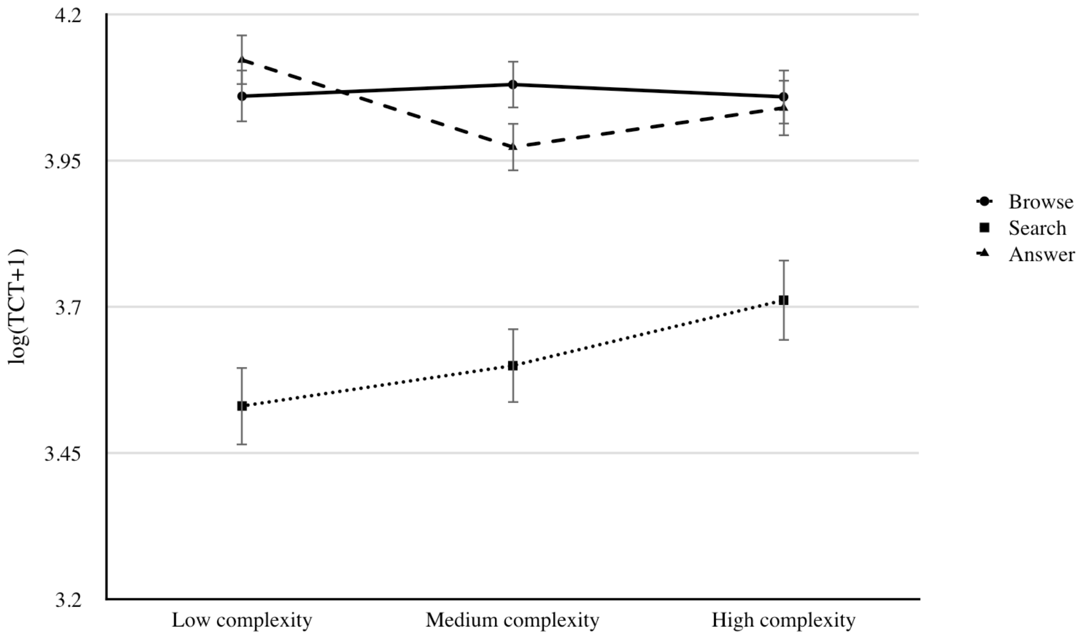

Fig. 2. TCT of three complexity levels in each task.

4.4 Fixation count

We found significant main effects of task difficulty and visual complexity on fixation count (χ^2=1475.060, df=2, p<.001; χ^2=41.397, df=2, $p<0.001$). Generally, fixation count of search task was significantly lower than that of browse and answer tasks (search vs. browse: $p<0.001$; search vs. answer: $p<0.001$). From perspective of visual complexity, fixation count obtained after high visual complexity was significantly higher than that of low and medium complexity (high vs. medium: $p<0.05$; high vs. low: $p<0.001$), fixation count obtained after low visual complexity was significantly higher than that of medium complexity ($p<0.001$).

The interaction between task difficulty and visual complexity in fixation count was also significant (χ^2=83.935, df=4, $p<0.001$). A post hoc test showed that fixation count obtained after higher visual complexity level was more than that of others in search tasks ($p<0.001$), and fixation count obtained after medium complexity level was obviously less than that of low and high answer tasks ($p<0.001$) which showed an obvious U-shaped curve (see Fig. 3).

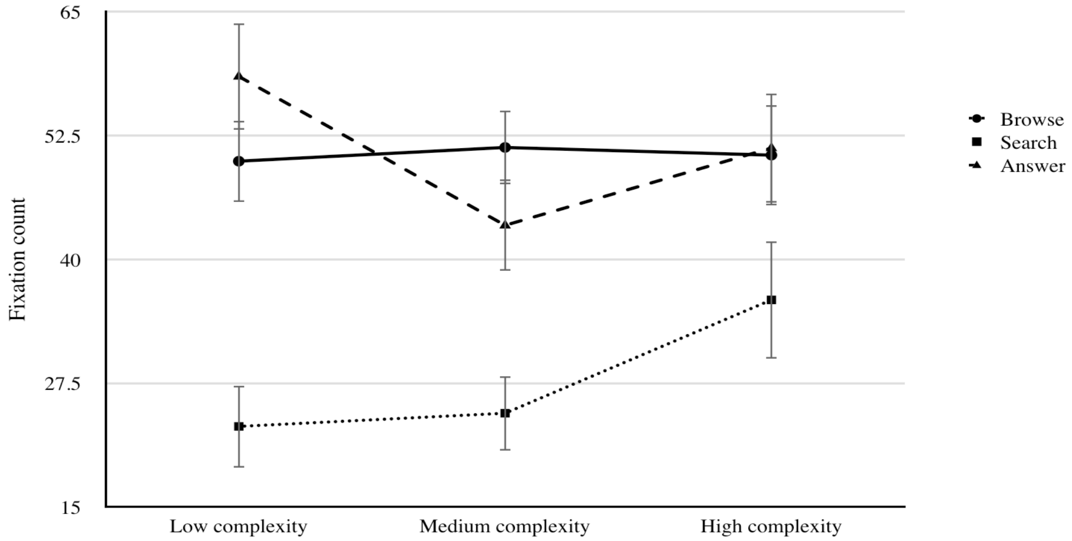

Fig. 3. Fixation count of different visual complexity in each task.

The results of post hoc test from the perspective visual complexity were shown in Fig.4. In condition of low visual complexity, fixation count of search task was significantly lower than that of browse and answer tasks ($p<0.001$), and fixation count of browse tasks was lower than that of answer tasks ($p<0.001$). In condition of medium visual complexity, fixation count of search task was significantly lower than that of browse and answer tasks ($p<0.001$). However, fixation count of interfaces with medium complexity in browse task was higher than answer task ($p<0.001$), which was different from low level. In condition of high visual complexity, fixation count of search tasks was also the lowest ($p<0.001$), but fixation count between browse and answer had no significant difference ($p>0.05$).

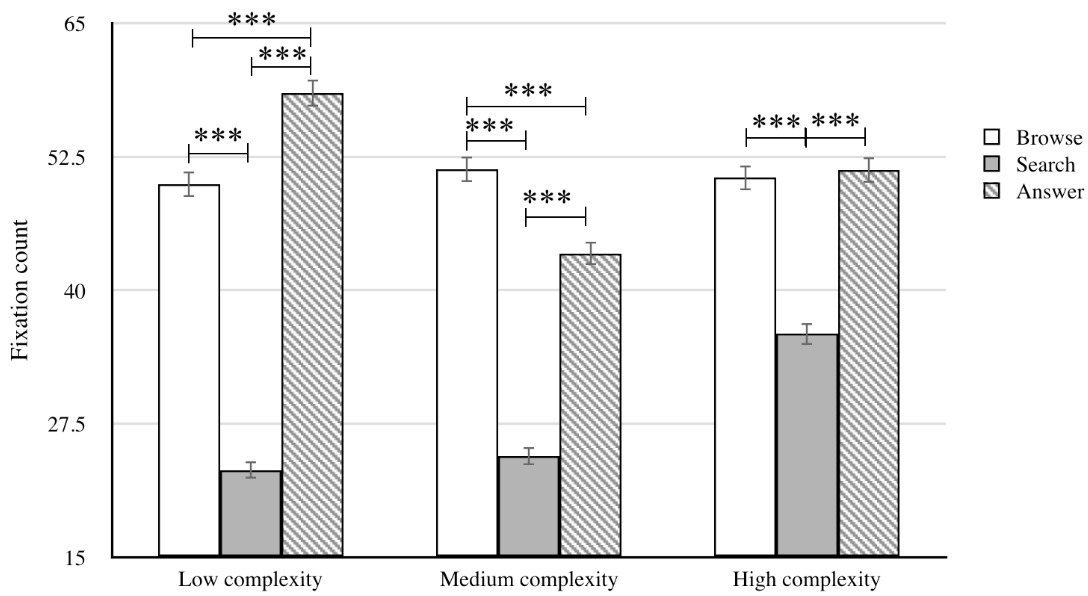

Fig.4. Fixation count of each task with different visual complexity.

4.5 Fixation duration

A significant main effect of task difficulty was found (F(2, 70)=57.286, p<0.001), whereas no significant main effect of visual complexity was found on fixation duration (F(2, 70)=1.442, p>0.05). Generally, fixation duration of search tasks was shorter than that of browse and answer (search vs. browse: p<0.001; search vs. answer: p<0.001), however the difference of fixation duration between browse and answer tasks was not significant (p>0.05).

The interaction with task difficulty and visual complexity in fixation duration reached significance (F(2.922, 102.280)=3.942, p<0.05). The post hoc test showed that fixation duration obtained after high complexity was significantly longer than that of low one in search task (p<0.05); however, the fixation duration produced after low visual complexity was significantly longer than that of medium and high one in answer tasks (low vs. medium: p<0.001; low vs. high: p<0.05) (see Fig.5).

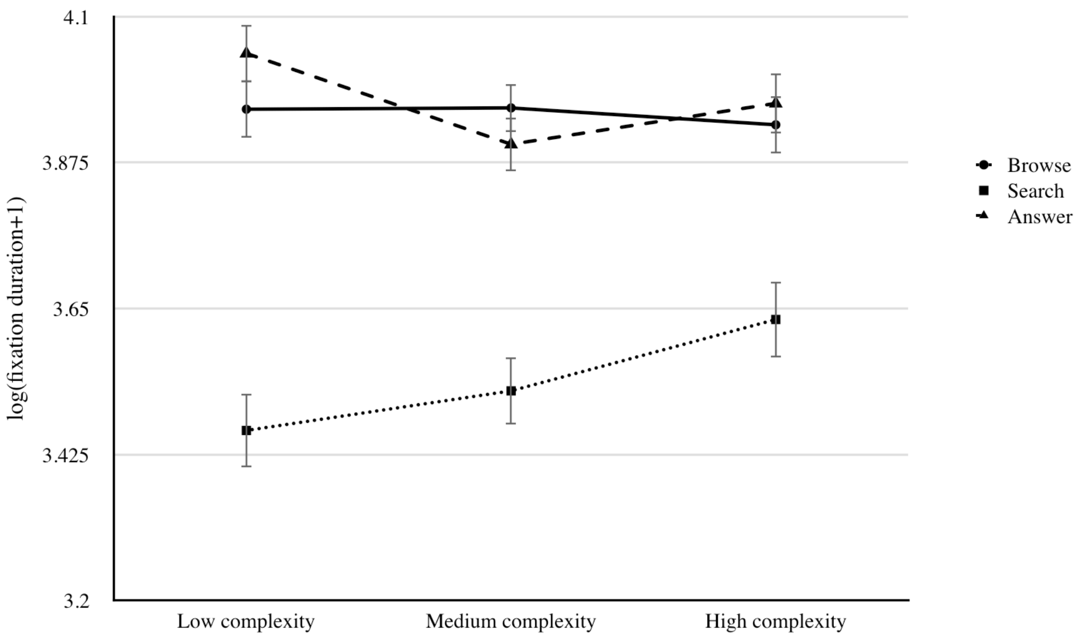

Fig.5. Fixation duration of each task and visual complexity.

4.6 Pupil size change

Because the individual difference of pupil size varies widely, we adopted the change of pupil size (the change of pupil size = pupil size- average pupil size of each participant) for analysis. A negative value indicates myosis, and a positive number indicates mydriasis. After two-factor repeated measures ANOVA, we found significant main effects of task difficulty and visual complexity on the change of pupil size (F (2, 70) =29.345, p<0.001; F (2, 70) =12.063, p<0.001), the interaction between task difficulty and visual complexity in the change of pupil size was not significant (F (4, 140)=.633, p>0.05). A post hoc test showed that there were significant differences among the three tasks (see Fig.): the change of pupil size of task answer was significantly bigger than that of task browse task (p<0.001), and the change of pupil size of search was significantly bigger than that of browse task (p<0.001).

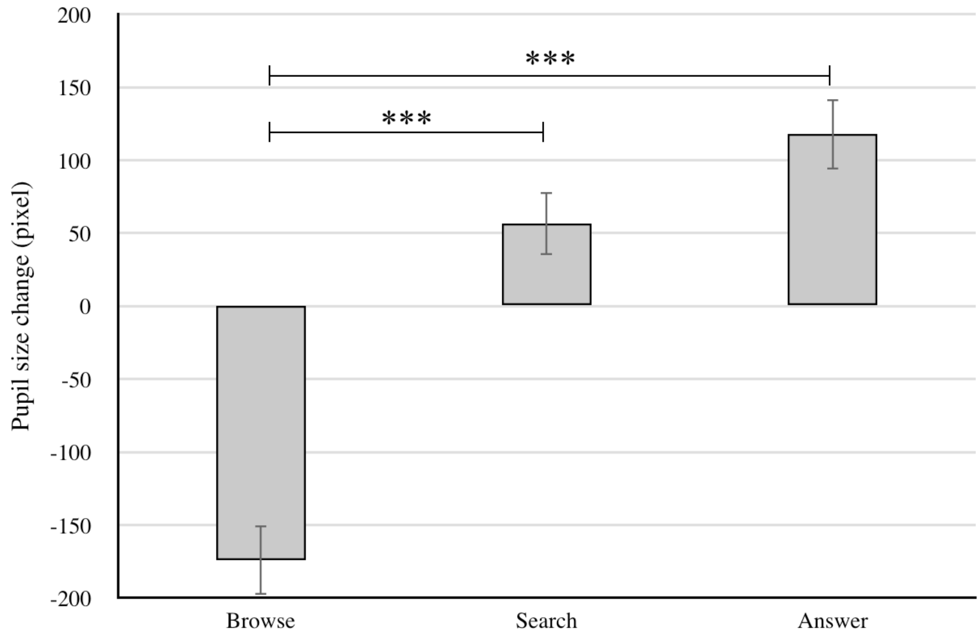

Fig. 6. The change of pupil size of each task.

Fig.7 showed that the change of pupil size obtained after high complexity was significantly bigger than that of medium and low one (low vs. high: $p<0.001$; medium vs. high: $p<0.01$).

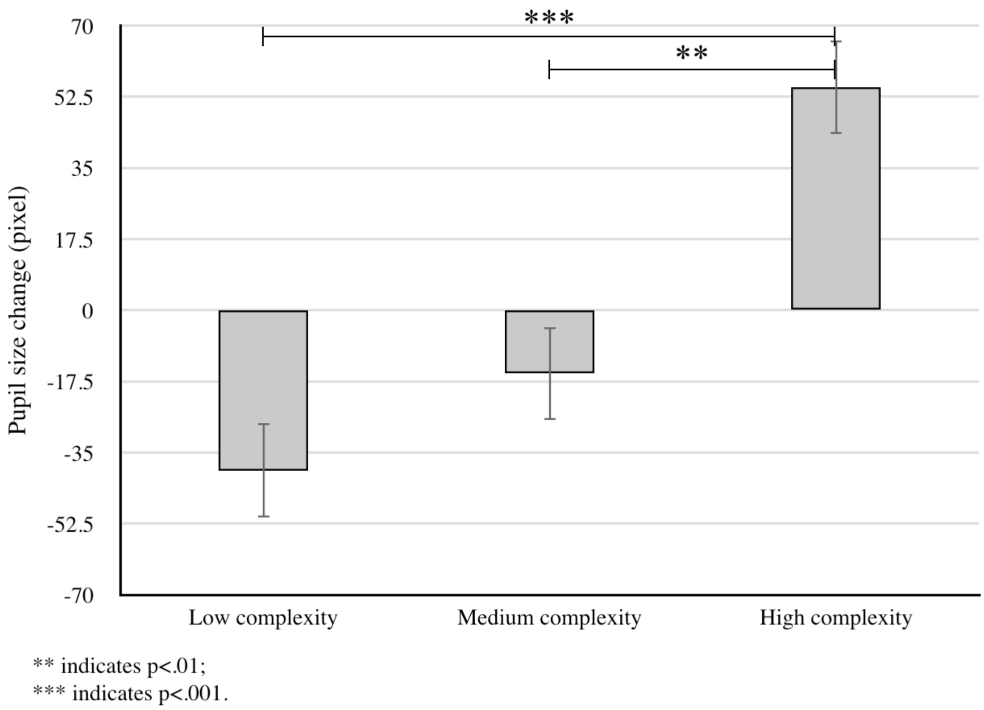

Fig. 7. Pupil size change of visual complexity levels.

4.7 User satisfaction

At the end of the experiment, participants were required to rate their satisfaction after each task using a 7-point Likert scale. We found that only visual complexity had main effect on satisfaction ($F(2, 70) = 22.879$, $p<0.001$). Post hoc test showed that participants were more satisfied with lower complexity level (low vs. medium: $p<0.01$; medium vs high: $p<0.001$; low vs. high: $p<0.01$) (see Fig.).

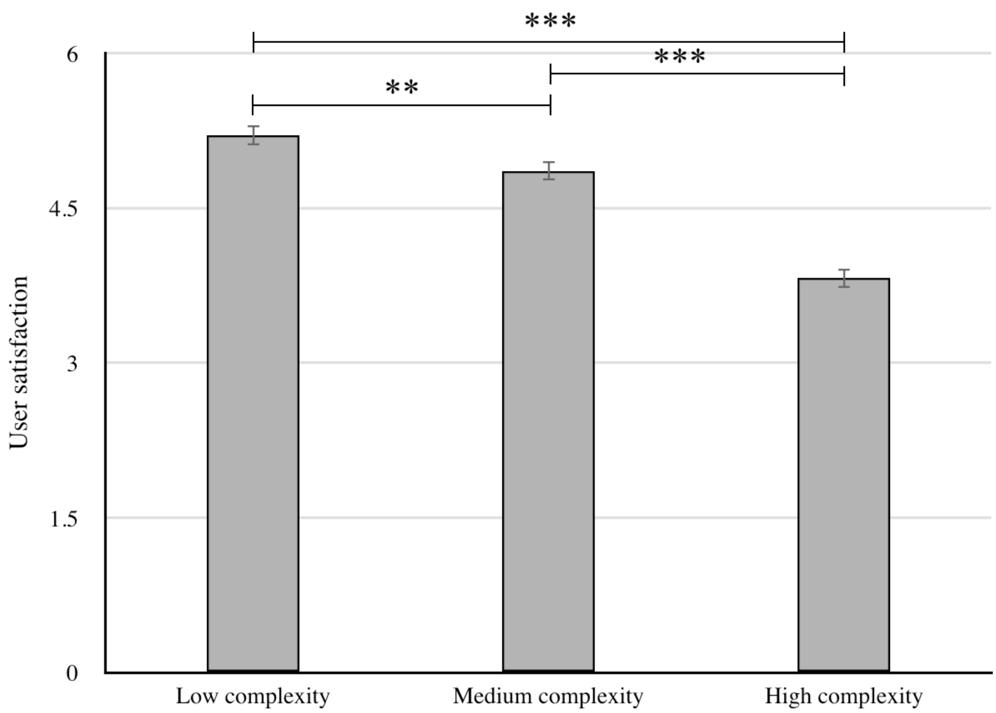

Fig. 8. User preference of three complexity degrees.

4.8 Correlation Test

In the correlation test, we excluded the data of browse, because this task had no clear goal that made the values higher than other tasks. Table 1 showed the results of correlation test. There was a significant positive correlation between TCT and the change of pupil size (r=.990, $p<0.01$), between fixation count and the change of pupil size (r=1.000, $p<0.01$), and between fixation duration and the change of pupil size (r=.880, $p<0.01$). High positive correlations were found between TCT and fixation count (r=.990, $p<0.01$), between fixation count and fixation duration (r=.880, $p<0.01$), TCT and fixation duration (r=.867, $p<0.01$).

Table 1: Correlations between variables

	TCT	Fixation count	Fixation duration	Pupil size change	Satisfaction
TCT	1	-	-	-	-
Fixation count	.990**	1	-	-	-
Fixation duration	.867**	.880**	1	-	-
Pupil size change	.990**	1.000**	.880**	1	-
Satisfaction	0.024	.014	.051	.013	1

*** p<.01, * p<.05*

5 General discussions

5.1 User behaviour in each task

Again, as mentioned before: the fixation count shows the total amount of attention on a given object [28]; longer fixation duration implies that information is more difficult to extract or from another perspective, more attractive[27]. Less TCT usually indicates more efficient decision-making and better design interface[18]. In our current study, in browse tasks, we found no significant difference in TCT, fixation count and fixation duration among 3 levels of visual complexity, which suggests that the user's browsing behaviour are independent on visual complexity. Since search tasks only require low HIP resources to match asterisk, we found that TCT, fixation count and fixation duration produced after high visual complexity was significantly longer than that of lower ones. This result is similar to the simple task in the study of Wang et al.[18]. Answer tasks required participants to understand the problem and the content of the news, and then find the right answer, hence requiring more HIP resources and short-term memory. We found that TCT, fixation count and fixation duration obtained after medium complexity was significant shorter than that of other two visual complexities, showing a nearly U-shaped curve. This result supplements the Berlyne's theory that a page must surpass a certain minimal level of complexity but not be too complex to achieve optimal effectiveness[4], and is partly supported by Huang & Zhou [19] who found that TCT increased more for difficult tasks than in simple tasks as the number of links on the mobile websites increased. However, this result is incongruous with the finding of Wang et al. [18], who found that for difficult tasks, TCT, fixation count, and fixation duration were all at the highest level with webpages of medium visual complexity. Previous study showed that users had more difficulty extracting information [23] and making good judgements[21,22] on smaller screens compared with larger screens. Therefore, for interfaces in mobile size, it seems that, appropriate visual complexity (not too high or too low) could help users to achieve best efficiency and performance. Considering the effect of visual complexity on human eye movement, we found that fixation count obtained after search task is lower than that of browse tasks and answer task regardless of visual complexity. As we know that the fixation count shows the interests on a given object, these results indicate that, compared to search task, browse tasks and answer task could attract more of the user's attention in mobile-sized interface. Furthermore, we noted that fixation count of browse tasks was lower than that of answer task in low visual complexity, while it was higher than that of answer task in medium complexity. Considering the browse task as a baseline, interfaces with low visual complexity hinder the completion of answer tasks, while interfaces with medium visual complexity improves user performance. However, interfaces with high visual complexity offering excessive information distracts users while browsing.

5.2 Subject evaluation

Subjective satisfaction scores of mobile-size interfaces were collected by 7 points Likert scale at the end of each task. We found that participants were more satisfied with low complexity level than medium and high visual complexity, whereas no significant main effect was found on task difficulty. In other words, participants preferred low visual complexity, which is independent of task difficulty. This finding is in line with the result of previous study that suggested a simplified interface design contributes to positive satisfaction in webpage[9]. In this study, we found that users were more satisfied with simpler interface regardless of task difficulty, however, the change of user performance were related to different tasks. This indicates that user satisfaction may contradict with user performance in tasks requiring high level of cognitive processing, for example, answer task in this study.

5.3 Cognitive load

Pupil size is considered to be associated with cognitive load, and the greater the pupil size, the higher the user's load in the task [35]. According to Sweller's theory[20], task difficulty is related to intrinsic load, while visual complexity is related to extraneous load.

We found a significant main effect of task difficulty on pupil size change, the pupil size change of answer tasks was significantly bigger than that of search tasks, which means that intrinsic cognitive load of human increased as task difficulty increased. Considering the effect of task difficulty on eye movement and user behaviour, we found that, except the condition of browse tasks, TCT, fixation count and fixation duration with answer tasks were at a higher level than that of search tasks. These results suggest that varying intrinsic cognitive load might be one of the reasons that induced the change of eye movement and user behaviour for answer and search tasks. However, we found that, the pupil size change of browse tasks was significantly smaller than that of task search, while TCT, fixation count and fixation duration in browse tasks were at higher level than that of search task. In the present study, compared with search tasks, participants could end the trial without an obvious goal in browse tasks led to longer TCT, longer fixation duration and more fixation counts. Therefore, we think that these results might be caused by the characteristics of the task itself. We found a significant main effect of visual complexity on pupil size: the pupil size of high complexity was larger than that of low and middle ones, which means that extraneous cognitive load increased when visual complexity increased. With regard to the effect of visual complexity on subjective satisfaction, we found that participants were more satisfied with lower complexity level than medium and high visual complexity. In other words, participants preferred low visual complexity, which is independent of task difficulty. These results suggest that higher extraneous cognitive load of high visual complexity might lead to lower satisfaction, while lower extraneous cognitive load might induce higher satisfaction on mobile-size interface.

6 Conclusion

In conclusion, we found that task difficulty had an effect on behavioural performance (TCT, fixation duration and fixation count), which is caused by intrinsic cognitive load. Furthermore, we also found that user satisfaction is more related to extraneous cognitive load, such as visual complexity. We suggest that interfaces for users to search should be designed as simple as possible in order to maximize user performance, while interfaces requiring users to extract information should be of moderate complexity level.

This was the first study to explore the relationship between visual complexity and task difficulty of mobile size interface by using eye-tracking technique. Our results obtained could provide a scientific basis for interface design of small screen devices.

Further effort would be needed to confirm whether these results could be used in real mobile environment. Because there are many dimensions affecting interface complexity, such as the layout and length of interfaces, we should study the effect of other dimensions on users' outcomes in the future.

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