Effect of Illumination on Reading Performance and Affect in a Virtual Environment

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Abstract. The development of virtual reality (VR) technology facilitates reading in a virtual environment. However, how the virtual environmental factors influence users' reading performance has not been studied. Researchers need to compare reading in a virtual environment to the real world situation and to normal digital displays. This paper examined the effect of illumination (dim vs. glaring) in a virtual environment on Chinese text understanding performance, long-term recall performance and affect. The effect of gender is also discussed. The results reveal that in a brightly lit environment, people show better text understanding and logic reasoning performance. However, in a dim environment, people concentrate more and have better long-term memory performance. These findings can be used in guidelines for designers and virtual environment developers. A brightly lit environment is more suitable for understanding and for logical reasoning tasks and a dim environment is suggested for tasks regarding memory and concentration.

Keywords: Virtual environment · Reading performance · Illumination

1 Introduction

Virtual reality technology has developed quickly in recent years. The application of head-mounted display (HMD) dramatically increased users' immersion in a virtual environment. This technology is now applied in many different fields and researchers have investigated people's performance in different virtual environments [1]. However, the existing work mainly focuses on the performance influenced by the display technology or the rendering software. Few studies have focused on how a virtual environment influences the cognition performance of people working or playing in it. Environmental psychologists have conducted a significant body of research about the effect of real environmental factors on people's cognition and affect. However, these studies are all cases in the real world. Whether the case would be the same in a virtual environment remains to be discovered. In most situations, a virtual environment is formed by an HMD and the device offers mainly visual information. The difference between an HMD and other self-luminous displays need to be examined.

Nowadays, many researchers show an interest in knowing how people read in a virtual environment, and thus the effect of virtual environmental factors on people's reading performance is worth investigating. In reading tasks, text understanding and memory are two important cognition processes. In our study, the effect of light

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illumination in a virtual environment on readers' understanding performance and memory were measured. The mood change induced by the light was also studied. This study aims to supply guidelines for designers on how to build virtual environments for a reading activity and other similar cognition tasks.

2 Literature Review

Many environmental psychologists have investigated the influence of environmental factors on mood and cognition performance in the real world. Some of these works produced valuable findings. Light illumination in real environments was found to have a significant influence on mood and cognition performance, and the influence differed greatly by gender [2–4]. There are also some other works regarding how ambient illumination affects the performance of a digital display such as on a lap-top or a tablet computer. The head-mounted display, as a new type of display device, should also be contrasted with lap-tops and tablets.

2.1 Mood

In an environmental system, many factors influence people's mood, and light is an important factor. A study contrasted the effect of light in several different places in the world where the cultural style and the latitude varied. The result of this research showed that the effect was significantly similar in different places [3]. Knez and his colleagues conducted research on exploring the effect of light on mood and cognition performance [2, 5, 6]. In the experiment performed by Knez, mood change was measured by the difference between the affect before and the affect after the experiment. This had not been measured by earlier researchers [2]. This study showed a significant interaction effect between illumination and light temperature. It also illustrated that a positive mood is preserved best in warm white light with low illumination level and in cool white light with high illumination level. McCloughan et al. discussed the effect of light from two aspects, namely initial effect and long-term effect. They found that many factors change the effect of light, including the light color temperature, the illumination, and gender [4]. Their findings about the interaction between mood and gender are also in accordance with the work by Knez and Enmarker that males are more positive than females [5].

2.2 Performance

Daurat et al. compared the different effects of bright light and dim light. They found that, unlike dim light, bright light stimulates subjects' alertness and improves their performance [7]. Another experiment investigated people's cognition performance under different environmental conditions of noise (38 and 58 dB), illumination (300 lx and 1500 lx) and air temperature (21 °C and 27 °C), and the results indicated that subjects have better long-term recall performance in environments with a high illumination level [8]. As for the performance of long-term recall, Knez stated that people perform better in the condition which induces the least negative mood, but he did not

establish the relationship between long-term recall performance and objective illumination conditions [2]. However, in a later work examining light and cognition performance, no significant results regarding memory were found [5].

2.3 Gender

Some researchers discovered that the degree of illumination of light has an interactive effect with gender. Belcher and Kluczny found that the positive mood of males increases in a bright light environment (2175 lx) while it remains stable in a dim light environment (215 lx). For females, the change is in the opposite direction [9]. Even though gender plays a significant role in affecting mood, the influence of gender on cognition performance such as long-term recall and attention has not been examined. However, for cognition tasks like short-term recall, females performed better than males in a bright illumination condition [8]. In line with former studies, Knez and Enmarker found that, compared to females, males perform much better in decision making tasks [5]. People's perception also differs by gender so that females generally perceive the environment as being more glaring than males do.

2.4 Ambient Environment

In recent years, HMD becomes a widely used VR device. To some extent, HMD is more like a display device with a special appearance and it works in a close proximity to the users. It has many characteristics in common with other traditional self-luminous display devices such as tablet computers. In a real indoor environment, the ambient illumination is the light source. However, in the virtual environment, the reading material is self-luminous. In this case, the virtual reading task is similar to the reading activity on a tablet computer in a real environment, especially considering that tablet computers also have backlit displays.

Some researchers focused on the performance on tablet computers used in different ambient illumination environments and they arrived at some conclusions. J.-G. Chen, Wu, Chiu, Tu, and Liu chose 200 lx and 500 lx as their experiment conditions to investigate the influence of ambient illumination when using tablet computers [10]. Their results showed that the ambient illumination had no significant effect on performance, which is in line with previous research [11]. In this case, researchers also found no significant difference when the illumination conditions were respectively 200 lx, 450 lx, and 700 lx. However, Kim et al. stated that the ambient illumination actually impairs the display effect as the illumination level increases [12]. However, all of these research studies focused mainly on the display and the visual expression, when assessing the users' performance. They ignored the influence of the environment on people's cognition performance. On the other hand, the illumination levels they chose were too similar. Therefore the results might not reflect the real case.

3 Research Hypothesis

Compared to a desktop, an HMD increases a user's immersion in a virtual environment [13]. People wearing a HMD feel more natural about the virtual environment and are assumed to act in a similar manner to how they would act in the real world. The main hypothesis is that, although virtual environments mainly provide information of visual modality, the effect of visual factors like illumination on mood and cognition of users is similar to its effect in the real world. Based on the main hypothesis, we formulated the following sub-hypotheses.

Hypothesis 1. For reading tasks in a virtual environment, the text understanding performance in a condition with high illumination level (glaring) will be better than that in a condition with low illumination level (dim).

Hypothesis 2. Content displayed in a condition with a high illumination level (glaring) leaves readers with a deeper impression than content in a condition with a low illumination level. (i.e., people can recall more things that they read in a glaring environment).

Hypothesis 3. The mood induced by the environment differs by gender. Males tend to have more a positive mood than females in a glaring reading environment.

4 Methods

4.1 Experiment Design

A two-parameter mixed-design experiment was designed. Illumination with two levels (dim and glaring), and gender, were chosen as the independent factors. Participants' mood, understanding of the reading materials and their long-term recall performance were chosen as the dependent variables. The mood was measured three times using PANAS scales (before the experiment, after experiment 1 and after experiment 2) [14]. The effect of illumination on mood change was mainly investigated. Participants' understanding of the reading materials was measured by the accuracy of subjects' answers to the reading questions. The long-term recall performance was measured by the number of the topics that subjects recalled after the experiment.

The reading materials were based on the reading questions of the HSK test, which is a standard Chinese language test for foreign language learners similar to the TOFEL/IELTS in English. Two sets of reading material were prepared (The two sets contained respectively 2,872 and 2,893 Chinese characters). Each set of reading material contained eight reading topics and each reading topic was followed by one or two questions. Each set of reading material contained 14 questions in total. The length of each reading topic ranged from 201 Chinese characters to 486 Chinese characters.

Illumination was a within-subject variable and participants of different gender were equally and randomly divided into four different experiment groups (illumination by content). Participants in each group were tested both in the glaring and in the dim illumination conditions.

4.2 Subjects

Sixteen participants were recruited for the experiment (eight females and eight males). They were all undergraduate and graduate students in Tsinghua University. The ages of these participants ranged from 20 to 27 (mean = 23.32 and SD = 1.49). All the participants were native Chinese speakers and they all had used VR equipment more than twice and less than ten times. No participant had reading problems.

4.3 Apparatus

The experiment in our study was carried out in a laboratory where the noise, the temperature and the humidity were kept stable. The VR equipment used in this experiment was HTC Vive and the virtual experiment environment was developed via Unity 3D. The experiment environment was a virtual indoor environment with two different illumination conditions (dim vs. glaring) shown as Fig. 1. We built the two different illumination conditions by setting the light intensity in Unity 3D (glaring: light intensity = .3, dim: light intensity = 1.6).

In the virtual environment, there was a sofa for the subjects to sit on when answering the reading questions (Fig. 2). A real sofa was placed in the real laboratory and it matched the virtual sofa. This was intended to increase users' immersion during the experiment process. All the reading materials were displayed on a screen in the virtual environment and the readers interacted with the virtual environment via the trigger button of the controller (see Fig. 3). After every test, the program automatically recorded the accuracy and the time remaining (total time for every reading test was 20 min). The experiment set-up is also shown in Fig. 3.

Fig. 1. Experimental virtual indoor environment with different illumination levels (dim vs. glaring)

Fig. 2. Equipment used to increase participants' immersion in the virtual environment

Fig. 3. Experiment set-up (above) and interaction interfaces in the virtual environment (below)

4.4 Procedures

The experiment took place in the following stages: (1) Before the first stage of the reading test, the subjects were asked to fill in a PANAS scale to measure their mood at the time. (2) Subjects took part in the first stage of the reading test. Before the test began, every participant was shown around the virtual environment and was asked to walk to the sofa and to sit on it. The total test time was 20 min. (3) Subjects were asked to fill in the PANAS scale for a second time. After that, they were invited to close their eyes and to take a rest for five minutes. (4) Subjects took part in the second stage of the reading test. The total test time was also 20 min. (5) Subjects filled in the PANAS scale for the third time. (6) Subjects were required to recall as much as possible of the reading topics (14 in total) within five minutes (After five minutes, participants could choose to continue or not). (7) A semi-structured post experiment interview was conducted and it consisted of four questions ("Which stage was more suitable for reading and why?" "During which stage did you have a more positive mood, and why?" "During which stage were you more able to concentrative, and why?" "Which stage would be your preference for a reading environment?").

The average time for the whole experiment for all subjects was around 55 min.

5 Results

5.1 Understanding

The result of a mixed ANOVA test showed that participants' understanding of the reading materials in a dim environment and in a glaring environment was different. The main effect of illumination on participants' accuracy in answering reading questions was significant ($F(1,14) = 6.07$, $p < .05$, Cohen's $d = 0.95$). As shown in Fig. 4, participants' accuracy in a glaring environment (Mean = .77, SD = .11) is higher than that in a dim environment (Mean = .87, SD = .09). However, the main effect of gender ($F(1,14) = .067$, $p > .79$) and the interaction effect between illumination and gender ($F(1,14) = .8$, $p > .38$) are not significant.

As for the time spent in each reading stage, the time use of each subject remained similar in each stage of the reading task. The result of a mixed ANOVA test suggested that the main effects of illumination and gender on the use of time were not significant (Illumination: $F(1,14) = .68$, $p > .42$; Gender: $F(1,14) = 1.68$, $p > .22$). The interaction effect was also not significant ($F(1,14) = .44$, $p > .51$). This result meant that, in the different stages, the time used was almost the same and it also partially supported the results for accuracy by excluding the possible influence of reading speed. The results of understanding are similar to previous research showing that cognition performance is better in a glaring environment, thus hypothesis 1 was proved.

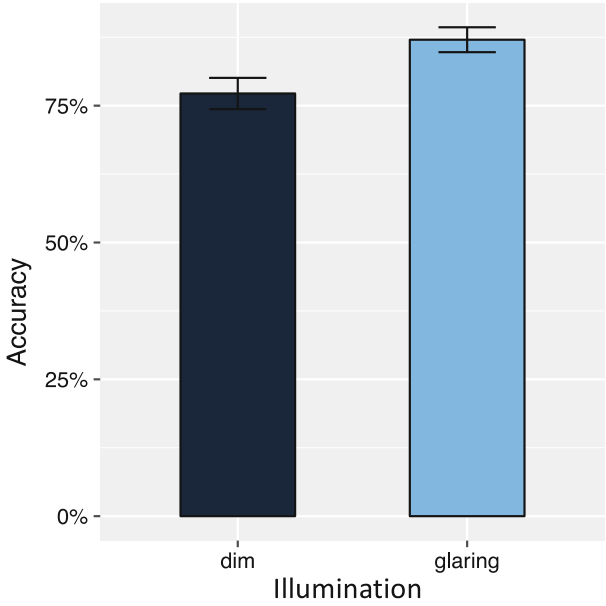

Fig. 4. The mean accuracy and standard error in a dim environment and a glaring environment

5.2 Long-Term Memory

The total number of reading topics was sixteen and, within each reading stage, the quantity of reading topics was eight. The long-term recall result is shown in Fig. 5. As for the quantity of topics, participants recalled more topics that were displayed in the dim environment (mean = 4.4, SD = 1.26) than topics displayed in the brightly lit environment (mean = 3.5, SD = 1.26). This indicated that long-term memory in a dim environment might be better than that in a bright environment.

A mixed ANOVA test was conducted with gender as a between-subject variable and illumination as a within-subject variable. The result indicated that the main effect of gender was not significant ($F(1,14) = .093$, $p > .76$). However, we can assume the illumination has a relatively significant inclination to influence participants' recall performance ($F(1,14) = 3.77$, $p < .073$, Cohen's $d = .69$).

The result for long-term memory was quite opposite to hypothesis 2, which meant that people had a deeper impression of items displayed in an environment with dim light. Therefore, the reverse of hypothesis 2 was proved.

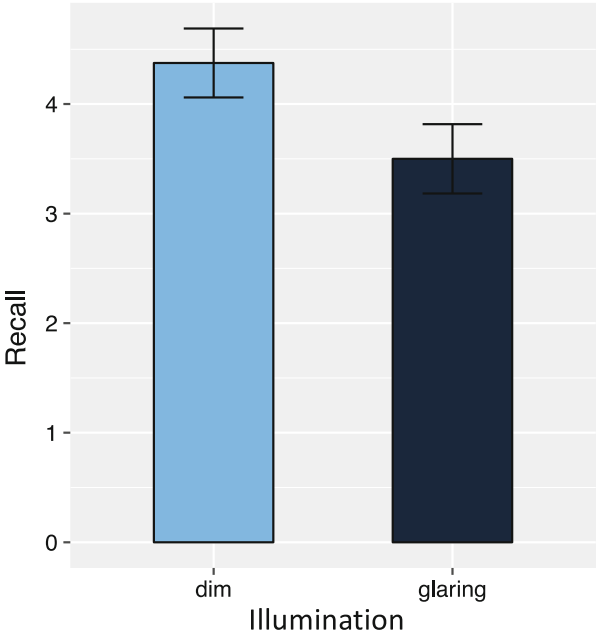

Fig. 5. The quantity of topics recalled by participants in different illumination conditions

5.3 Mood

We firstly examined the scores for positive and negative affect in test environments with different illumination conditions. The results of a mixed ANOVA test showed that both illumination and gender had no significant influence on the participants' affect as measured after finishing each reading test (For both positive and negative affect, all ps > .5).

We also examined the change in participants' affect. The mood change was defined by the positive state (or negative stage) after the experiment minus the positive state in the beginning. The results showed that, for positive affect, the effect of illumination, gender and interaction between illumination and gender are not remarkable (with all ps > .26). As for the negative state, there were also no remarkable results (with all ps > .55). However, when considering whether the affect was strengthened, the result was different. Subjects' affect was marked as strengthened when the mood change was above zero. The result of the Chi square test showed that males' positive mood is more likely to be induced than that of females ($Chi^2(1) = 5.24$, $p < .05$). As for negative affect, the difference between genders was not significant ($Chi^2(1) = .51$, $p = 0.48$). The result was convincing evidence that the positive affect of males was more likely to be induced which is in line with the findings of previous studies in a real world indoor environment.

6 Discussion

6.1 Understanding

The results for text understanding performance are in support of the previous findings arrived at in a real world environment. This is a proof that, in a virtual environment, when performing reading tasks, people tend to perform better in a glaring environment. The result is in line with the findings of Daurat et al. [7].

The results of interviews showed that nine of the 16 subjects felt that the glaring environment was more fruitful for the reading tasks (another five preferred the dim environment and two said they had no preference), as they felt "more active in this environment" and "the reading materials seem more clear". This may result from higher arousal state in a glaring environment [8].

6.2 Long-Term Memory

The results of long-term recall denied hypothesis 2, but in the opposite direction, the result showed that the main effect of illumination on long-term recall in a virtual environment was significant.

In the post-experiment interview, 10 of the 16 subjects said that they could concentrate more in the dim environment, while five others said that the glaring environment made them more dedicated and one said that there was no difference. The multiple resource theory of Wickens might explain the results [15]. In the glaring environment, the aesthetic features of the virtual indoor environment would have occupied some cognition resources, thus the readers would have received more information than in the dim environment in that less memory capacity was used to remember the reading topics.

The number of reading topics that were mentioned was also in line with the information processing capacity theory of Miller [16]. The average number of recalled topics is 7.79 (SD = 1.32), quite close to the number in Miller's theory. To some extent, it could partially validate the experiment result.

As in the previous study, the effect of light on long-term recall could sometimes be non-significant [5]. We assumed that the effect might not only result from the illumination condition, it might be also caused by the illumination contrast between the environment and the screen. A movie shown in the cinema is a good example. Therefore, further studies may focus more on the effect of contrast between the environment and the reading material since, in a virtual environment, the screen is also self-luminous.

6.3 Mood

An analysis of the change of positive mood and negative mood showed no remarkable effect of illumination and gender. However, there is quite possibly a tendency that the positive mood of males will be more likely to be strengthened, which is in line with the findings of Belcher and Kluczny [9]. Considering the definition of arousal, the strengthened positive mood is similar to the arousal state. For the future work, direct

concern about the arousal state influenced by illumination and gender may matter more, referring to the discussion of the arousal model influenced by environmental factors [8].

6.4 Comparison with Tablet Computers

In an HMD based virtual environment, only information of visual modality was offered to the users. However, in the real world, heat and humidity are all influenced by the light which will in turn influence people's cognitive performance. The results of our study showed that, even with only the visual modality, the influence of the virtual environment established by HMD-based VR did have similar effects as those in the real world.

Tablet computers are another kind of widely used display. The illumination condition of tablet computers was studied. Just as in an HMD, the screen of tablet computers is also self-luminous. When considering the performance of tablet computers, the illumination conditions in former research studies are all no more than 750 lx [10–12]. Researchers found that the effect of illumination conditions was not significant. This may result from experiment conditions that are too similar. In the domain of environmental psychology, the difference between illumination conditions is quite large.

When considering the usage of new digital devices, engineers are concerned more about the display performance. Therefore, they ignore the effect of illumination on users' cognition. As an environmental factor in itself, illumination has a direct influence on people's cognition. Some studies considered it instead from an indirect aspect by examining how illumination affected the screen display and then affected the readers. For HMD equipment, the visual influence from the outer environment was isolated, therefore the virtual environment offered the only visual information that should be considered.

7 Conclusion

This study investigated the effect of illumination and gender on reading tasks in a virtual indoor environment. The result showed that in a glaring environment, people had better performance with text understanding and logical reasoning tasks, because they were more aroused in bright conditions. However, while in dim conditions, the subjects felt less interference from the environment, thus they could concentrate more on the items that they would like to keep in mind. Therefore, people recalled more items that they read in dim environment.

This research concentrated mainly on the effect of illumination on reading performance, long-term memory and mood. The other important factor of light environment is color temperature. Considering both illumination and color temperature as well as their interaction effect will be important for future work.

Another important contribution of this study is that it proved the significant effect of a virtual environment established by head-mounted display (HMD) and contrasted its similarity and difference with other self-luminous digital displays. Guidelines can also be given to designers and virtual environment developers that a glaring environment is suitable for arousing users and helping users to deal with understanding and logical

reasoning tasks, while a dim environment with little interference can increase concentration and is more suitable for remembering items.

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