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Measuring Visual Attention Processing of Virtual Environment Using Eye-Fixation Information

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Abstract Numerous scholars have explored the modeling, control, and optimization of energy systems in buildings, offering new insights about technology and environments that can advance industry innovation. Eye trackers deliver objective eye-gaze data about visual and attentional processes. Due to its flexibility, accuracy, and efficiency in research, eye tracking has a control scheme that makes measuring rapid eye movement in three-dimensional space possible (e.g., virtual reality, augmented reality). Because eye movement is an effective modality for digital interaction with a virtual environment, tracking how users scan a visual field and fix on various digital objects can help designers optimize building environments and materials. Although several scholars have conducted Virtual Reality studies in three-dimensional space, scholars have not agreed on a consistent way to analyze eye tracking data. We conducted eye tracking experiments using objects in three-dimensional space to find an objective way to process quantitative visual data. By applying a 12 × 12 grid framework for eye tracking analysis, we investigated how people gazed at objects in a virtual space wearing a head-mounted display. The findings provide an empirical base for a standardized protocol for analyzing eye tracking data in the context of virtual environments.

Keywords: virtual environment, three-dimensional space, eye-fixation, visual attention

1. INTRODUCTION

Due to rapid technological development in recent years, a number of new devices (e.g., virtual reality with head mounted display, eye tracking) have the ability to create virtual spaces in which people can move about freely and interact with digital objects. These devices can also track eye-fixation on those virtual objects. Information acquisition through human eye movement and focus is becoming more important as new technologies emerge. Willetts reported that people gather nearly 80% of the external information available in their immediate environments by means of sight(Willetts, 1997). As the perceptual channel with the highest bandwidth into our cognitive systems, vision is our dominant sense (Reda et al., 2013). Nevertheless, few scholars have explored the types of visual information that individuals use more frequently or how they gather such information using vision. Eye tracking research could illuminate differences in gaze patterns and attention, revealing where people look, which objects they focus on, and how long they keep their gaze on a particular spot. To this end, eye tracking technology offers a well-founded method for explaining the process behind information acquisition through human eyes (Carbon, Hutzler, & Minge, 2006; Clement, Kristensen, & Grønhaug, 2013; Holmqvist et al., 2011)

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(1) Eye Tracking Technology

Surveys are a common and cost-effective way to consolidate gaze data via self-reported perceptions (e.g., personal attitudes, thoughts, and feelings). However, survey respondents might not be aware of their actual thoughts or their reasons for a given answer due to memory loss or distortion. They also might not feel encouraged to provide accurate answers when disclosing sensitive information. In contrast, eye tracking quantifies visual attention as it objectively captures when, where, and at what people look. It can also track blink frequency. This technique enables researchers to overcome the barriers and obstacles to reliable survey data. Eye tracking devices can collect data unaffected by subjective judgement or memory distortion(Jacob & Karn, 2003).

However, coding the enormous amount of quantitative data generated by eye trackers requires much effort and time. Moreover, because no standardized protocol yet exists for eye tracking data analysis, results depend on the analytical frame that a researcher decides to use. The primary components of human eye movement are saccades and fixations(Duchowski, 2007). Saccades are the quick eye movements used to find a target of interest in a visual image, while fixations occur when the eyes stop scanning and hold in one place for a time, allowing the viewer to process visual details. People repeatedly and alternately use saccades and fixations to acquire visual information. The length of a fixation is critical to acquisition. A shorter duration makes visual information acquisition less likely; a longer duration increases the chance that the information will become meaningful. In general, eye-fixation duration indicates processing difficulty and amount of attention.

(2) Eye Tracking Research for Visual Attention

Scholars have shown that eye tracking technology is a useful tool for understanding what people see and how people look at particular objects. The eye tracking method has helped scholars in various fields, including human-computer interaction (Jacob & Karn, 2003; Majaranta & Bulling, 2014), information processing(Glöckner & Herbold, 2011; Mele & Federici, 2012), journalism(Holsanova, Rahm, & Holmqvist, 2006; Leckner, 2012), and indoor design (Schrom-Feiertag, Settgast, & Seer, 2017; Zou & Ergan, 2019). Eye tracking research typically rests on the eye-mind assumption (Babcock, 2002; Gamito & Rosa, 2014), which posits that what people are looking at (i.e., visual concentration) and what they are thinking about (i.e., mental attention) tend to overlap.

An eye tracker records a value that corresponds to the position of a gaze each second. Metrics for converting eye tracking data into feasible description vary by analytical technique. For example, heat maps are dynamic aggregations of gaze positions and fixations that show the distribution of visual attention. Areas of Interest (AOI)(Blascheck et al., 2016; Hessels, Kemner, van den Boomen, & Hooge, 2016) are user-defined subregions of a displayed stimulus. Scan Paths indicate trajectories of eye movement when an individual scans a visual field.

Grid Analysis is the most common and relevant technique for interpreting eye movement(Walker, Bucker, Anderson, Schreij, & Theeuwes, 2017; Young & Sheena, 1975). Visual attention can differ across different levels of intentionality. Kim analyzed eye-fixation patterns on purposeful phrases in terms of intentionality and target object. By determining how long an observer focuses on a particular location, eye tracking can measure the sensitivity of a space(J.-Y. Kim, 2016).

(3) Purpose of the Study

Most eye tracking studies have used monitors in labs to analyze two-dimensional (2D) pictures of three-dimensional (3D) spaces. This experimental method is convenient, and researchers have developed innovative techniques to link eye tracking data to the human visual experience. However, eye tracking with 2D images has limitations. Given advancements in instructional technology (IT) that have expanded space construction and simulation, including virtual reality (VR), augmented reality (AR), and mixed reality (MR), eye tracking research must adapt to 3D space. Although several scholars have conducted VR studies in 3D space (J. Y. Kim & M. J. Kim, 2020), this type of eye tracking research is still nascent. Furthermore, scholars have not agreed on a consistent way to analyze eye tracking data. Thus, in the current study, we conducted eye tracking experiments using objects in 3D space to find an objective way to process quantitative visual data. Humans extract visual information from bio-signals stored in the brain using perception and recognition. Some of that information becomes useful after re-recognition during the selection process. Reliable measurement of information recognition based on eye movement and fixation data(J. J. Kim & J. Y. Kim, 2020) can help researchers identify the emotional implications of visual information gathered in VR spaces.

2. MATERIALS AND METHOD

(1) Stimuli and Participants

We selected an open public library space as the visual stimulus for a VR eye tracking experiment. Byeolmadang Library, a large cultural space for reading, exhibition, and cultural activities, opened to the public in 2017. Its spacious atmosphere is visually stunning. We used a 360-degree camera to capture multiple frames of the indoor space.

The participants were recruited 24 undergraduate male students enrolled in a private university in Seoul, Korea in exchange for extra credit. When the participants arrived, we explained the overall goal of the study and the purpose of the experiment. We invited them to take a seat in the lab and helped them put on and calibrate individual HMD headsets. Participants then read the following instructions on the screen: "You are visiting Byeolmadang Library, which has been newly constructed. You will see 3D images taken in the center of the library on VR. This space is also for exhibition. After watching the VR content, please share your opinion or comment on how much you feel like you were in a real space." Then we instructed them to spend 130 seconds look around the virtual space. We set the rate of recording and storage to 250 Hz (i.e., 250 data per second). The experimental setup is shown in Figure 1.

(2) Extraction of Valid Data

We extracted valid data (i.e., fixations and saccades) by coding raw data stored at 250 Hz. Data from subjects with more than 85–90% tracking ratio, indicating good accuracy, are typically regarded as usable, but we a tracking ratio of more than 80% due to limitations in the device we used for this 3D VR experiment. We selected 12 subjects based on effective ratio but subsequently excluded one due to defective data generated during the data extraction. The valid data ratio was 59.51%, which was relatively

Figure 1. Experimental visual stimuli

low. The useless data ratio (e.g., blinking and defective data) was 40.49%. The average tracking ratio was 92.34%, which was considerably high (see Table 1).

Table 1. Eye tracking data for participants

Participants (N=12)	Tracking Ratio (%)	Valid data			Useless data	
		Fixation	Saccade	Ratio (%)	Frequency	Ratio (%)
Average	92.3	9,017.8	8,663.5	59.5	12,091.5	40.5

(3) 3D Data in VR Space and Analytic Frame

As shown in Figure 2, a 3D space is comprised of a horizontal x-axis and y-axis and a vertical z-axis. However, eye tracking data for VR space stores the x-axis × y-axis as an x-value and the z-axis as a y-value. Eye level is the central y-value. In the experiment, we set the viewing duration at 130 seconds. Therefore, we analyzed 32,500 (130 seconds × 250 Hz) fixation data for each participant. Then we extracted the number of fixations and saccades every five seconds from the valid data we generated during the initial coding process. We calculated fixation times by summing each time section (i.e., number of fixations × 1/250 = fixation time). Then based on 24 time sections, we calculated fixation frequency to estimate the characteristics of eye- fixation. We used grid distribution to analyze the characteristics of eye-fixation Ahn and Kim used 6 × 6 grids(Ahn & Kim, 2018), while Kim and Kim suggested using 12 × 12 grids for eye tracking analysis(J. H. Kim & Kim, 2012). Though numerous scholars have used 12 × 12 grids, no study has indicated which grid system is optimal for analyzing eye-fixation in VR space. We used a 12 (x-axis: uppercase letter) × 12 (y-axis: lowercase letter) grid, where fixation time for each grid section was the target of analysis. In order to obtain fixation time for each grid section, we coded only the remaining fixation data.

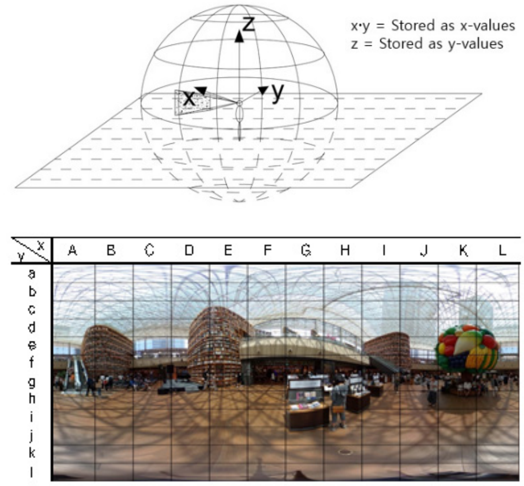

Figure 2. Diagram of data store in VR space (upper) and 12x12 grids for eye tracking analysis (lower).

3. RESULTS

(1) Analysis of eye-fixation in 3D space

In the following section, we detail our analytical process for one subject (i.e., participant #1). As shown in Table 2, out of the 30,000 raw data, we extracted 6,575 valid fixation data (21.9%) and 8,790 valid saccade data (29.3%). The total unusable data was 14,635 (48.8%).

Table 2. Eye tracking data for participant # 1.

	Valid data		Useless data
	Fixation	Saccade	
Frequency	6,575	8,790	14,635
Ratio	21.9	29.3	48.8

We obtained 250 eye-fixation data per second from the eye tracking VR experiment. Calculating the number of fixations for each grid section yielded the fixation time for each grid section. High fixation frequency in a section means that a subject looked at that section for a long time, meaning that the subject fixed his eyes on one point in that section for a long time and that the subject observed that section often. At the beginning of the experiment, the subject's initial fixation point was the center of the image (i.e., the boundary between columns F and G in Figure 3). Across the total fixation time, the number of sections on which the subjects fixed their eyes for more than 0.5 seconds was 25, the number of sections on which the subjects fixed their eyes for more than 1.0 second was 7. The latter indicates that the eyes were fixed on the section between rows d and f. Considering that eye level was the boundary between rows f and g, the subjects demonstrated the highest fixation frequencies with their heads lowered. Interestingly, a frequency of 62 occurred in section i-G (i.e., an area underfoot), indicating that the participants were curious about the lower part of their stance during a VR experiment.

y \ x	A	B	C	D	E	F	G	H	I	J	K	L
a	0	0	0	0	0	0	0	0	0	0	0	0
b	0	0	0	0	45	0	0	0	0	20	0	0
c	0	33	0	0	13	0	0	0	0	57	33	31
d	215	352	41	143	0	63	28	132	251	149	0	112
e	156	442	143	24	285	31	130	329	151	34	75	217
f	88	242	212	142	132	308	118	36	261	199	188	40
g	0	39	19	159	113	96	128	55	0	0	163	40
h	0	0	0	0	0	0	0	0	0	0	0	0
i	0	0	0	0	0	0	62	0	0	0	0	0
j	0	0	0	0	0	0	0	0	0	0	0	0
k	0	0	0	0	0	0	0	0	0	0	0	0
l	0	0	0	0	0	0	0	0	0	0	0	0

: Sections with eye-fixation for more than 1.0 second

Figure 3. Frequency distribution of eye-fixations.

At the beginning of the VR experiment, each participant stood at the center, observing the middle section between columns F and G (i.e., front). The dominant eye-fixation sections were the left side of column B and the right side of column I in Figure 4. It represents that same diagram applied to 3D space. Because the horizontal angle of eye-fixation was 30° and the vertical angle of eye-fixation was 15°, the subjects are thought to have observed the part with the center of 240° range of 8 sections. The range of up-and-down eye-fixation was 45°. The participants primarily observed areas within a 240° horizontal range and a 45° vertical range.

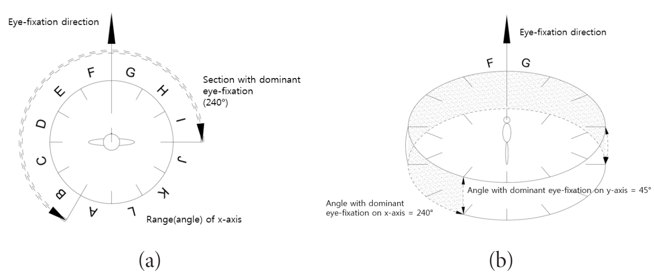

Figure 4. (a) Horizontal angle (x-axis) of eye-fixation angle with dominant. (b) eye-fixation on x-axis and y-axis.

(2) Difference of dominant sections by difference of eye-fixation time

Figure 5 summarizes fixation times for sections characterized by "Visual Appreciation" (i.e., > 0.3 seconds). Based on a threshold of 0.3 seconds rather than 1.0 second, the dominant eye-fixation sections on row g distinctively increased. That is, adopting different standard times (1.0 second vs. 0.3 seconds) produced a different distribution of dominant eye-fixation sections.

y \ x	A	B	C	D	E	F	G	H	I	J	K	L
a	0	0	0	0	0	0	0	0	0	0	0	0
b	0	0	0	0	0.2	0	0	0	0	0.1	0	0
c	0	0.1	0	0	0.1	0	0	0	0	0.2	0.1	0.1
d	0.9	1.4	0.2	0.6	0	0.3	0.1	0.5	1	0.6	0	0.4
e	0.6	1.8	0.6	0.1	1.1	0.1	0.5	1.3	0.6	0.1	0.3	0.9
f	0.4	1	0.8	0.6	0.6	12	0.5	0.1	1	0.8	0.8	0.2
g	0	0.2	0.1	0.6	0.6	0.4	0.5	0.2	0	0	0.7	0.2
h	0	0	0	0	0	0	0	0	0	0	0	0
i	0	0	0	0	0	0	0.2	0	0	0	0	0
j	0	0	0	0	0	0	0	0	0	0	0	0
k	0	0	0	0	0	0	0	0	0	0	0	0
l	0	0	0	0	0	0	0	0	0	0	0	0

: Sections with eye-fixation for more than 0.3 second

Figure 5. Sections with eye-fixation for more than 0.3 second.

Eye-fixation in a VR space occurs over time. In this study, we segmented fixation time into five-second units to identify dominant eye-fixation sections by time. We used the following procedure:

i) For each subject, we segmented eye-fixation into five-second units (total 1,250) to extract 24 sections data.
ii) From the valid data in those 24 sections, we selected only the eye-fixation data.
iii) We applied the 12 × 12 Grid Distribution Program to extract the data by time range.
iv) The frequency distributed on 12 × 12 Grid is converted into time.

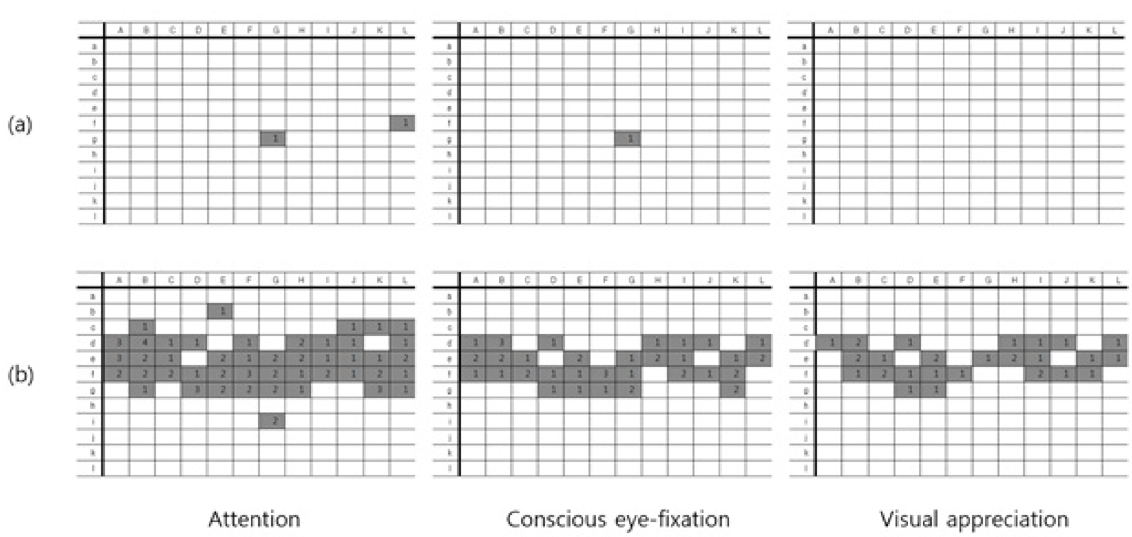

Figure 6. Eye-fixation frequency. (a) The time range of 0-5 seconds. (b) The entire time rage

v) Based on 24-sections data by time range, the frequency of data for more than 0.1, 0.2 and 0.3 second on the standard of time are extracted.

(3) Standardizing eye-fixation types

People perceive and recognize spatial information according to the length of time they fix their eyes on a particular spot. Thus, scholars have conceptualized eye-fixation times to describe and analyze eye-fixation variation across the visual grid: attention (0.1 seconds), conscious eye-fixation (0.2 seconds), and visual appreciation (0.3 seconds or more). In previous studies, scholars standardized eye-fixation durations to analyze visual perception of VR space. Accordingly, we used the frequency of eye-fixation times to calculate the total amount of eye-fixation in each section of the grid. Analyzing the range of eye-fixation time by individual and the total eye-fixation time by section not only reveals the most dominant sections but also permits comparison of perceptual characteristics between individuals and sections. Given a total viewing time of 0-5 seconds, two sections (Gg and Lf) reached the level of attention (0.1 seconds), one section (Gg) reached the level of conscious eye-fixation (0.2 seconds), and no sections reached the level of visual appreciation (0.3 seconds or more). In other words, longer eye-fixation times were less frequent than shorter eye-fixation times (see Figure 6a). Figure 6b also shows the accumulated frequency of eye-fixation times by section within a total viewing time of 5 seconds. The sections with higher frequencies are places where subjects repeatedly looked, suggesting greater interest.

(4) Analyzing eye-fixation frequency

In the current study, we analyzed the distribution of eye-fixation frequency across the visual grid. We found 76 instances of attention (0.1 seconds) across 46 sections (see Figure 7). Section Bd had four instances, and the other 22 sections had one instance.

y \ x	A	B	C	D	E	F	G	H	I	J	K	L
a												
b					1							
c		1								1	1	1
d	3	4	1	1		1		2	1	1		1
e	3	2	1		2	1	2	2	1	1	1	2
f	2	2	2	1	2	3	2	1	2	1	2	1
g		1		3	2	2	2	1			3	1
h												
i							2					
j												
k												
l												

Figure 7. The cumulative total of eye-fixation frequency in the section of "Attention".

(5) Dominant eye-fixation frequency

Table 3 indicates which eye-fixation times were most frequent and which sections reached the different eye-fixation levels. We identified 46 sections that reached attention, 31.9% of the entire space. Conscious eye-fixation occurred in 21.5% of the space, visual appreciation occurred in 17.4% of the space. The sections on which most subjects fixed their eyes are likely to have similar spatial characteristics. The ratio of sections with multiple types of eye-fixation to sections with only one type of eye-fixation is called the "overlapping ratio." A high overlapping ratio means that subjects repeatedly fixed on more sections in many time ranges. For instance, attention occurred in 46 sections, and because overlapping eye-fixation occurred in 23 of those sections, the overlapping ratio is 50%. Moving from attention to conscious eye-fixation to visual appreciation, the overlapping ratio dropped. Analyzing the overlapping ratio by eye-fixation time sheds light on which eye-fixation types are most dominant in a VR Space.

Table 3. The frequency by sections.

		Attention	Conscious Eye-fixation	Visual Appreciation
Valid	Frequency	46	31	25
	Ratio (%)	31.9	21.5	17.4
Dominant	Frequency of overlapped area	23	12	6
	Overlapped ratio (%)	50	38.7	24

(6) Eye-fixation type ratios in valid sections

Eye-fixation time indicates how much information subjects acquire from a particular section and how valuable that information might be to them. The average number of sections in which attention occurred was 43.0 (29.9%), followed by 31.3 (21.7%, a decrease of 27.3%) for conscious eye-fixation and 23.7 (16.5%, a decrease of 24.1%) for visual appreciations. The standard deviation by subject was 4.5–5.2% (see Table 4).

Table 4. Dominant eye-fixation information with valid data.

Participants' ID \ Section		Attention	Conscious Eye-fixation	Visual Appreciation
1	Frequency	46	31	25
	Ratio (%)	31.9	21.5	17.4
2	Frequency	48	33	25
	Ratio (%)	33.3	22.9	17.4
ellipsis				
24	Frequency	47	35	19
	Ratio (%)	32.6	24.3	13.2
Mean	Frequency	43.0	31.3	23.7
	Ratio (%)	29.9	21.7	16.5
Standard Deviation	Frequency	6.4	6.7	7.5
	Ratio (%)	4.5	4.6	5.2

(7) Overlapping eye-fixation types

Overlapping eye-fixation in a particular section indicates repeated interest. The average frequencies of attention, conscious eye-fixation, and visual appreciation in sections with overlapping eye-fixation were 22.5 (52.0%), 14.9 (46.6%), and

9.5 (39.7%), respectively. Taken together, the three eye-fixation types overlapped in more than 40% of the sections, indicating a high ratio of repeated observation. The standard deviation by subject was 7.7–11.2%. Moving from attention to conscious eye-fixation and from conscious eye-fixation to visual appreciation, the percentage of sections with eye-fixation overlap decreased 33.9% and 36.0%, respectively (see Table 5).

Table 5. Overlapped eye-fixation information with valid data.

Participants' ID \ Section		Attention	Conscious Eye-fixation	Visual Appreciation
1	Frequency	46	31	25
	Ratio (%)	31.9	21.5	17.4
2	Frequency	48	33	25
	Ratio (%)	33.3	22.9	17.4
		ellipsis		
24	Frequency	47	35	19
	Ratio (%)	32.6	24.3	13.2
Mean	Frequency	43.0	31.3	23.7
	Ratio (%)	29.9	21.7	16.5
Standard Deviation	Frequency	6.4	6.7	7.5
	Ratio (%)	4.5	4.6	5.2

4. FEATURES OF PERCEPTION AND RECOGNITION IN VR SPACE

(1) Attention

We analyzed the eye-fixation characteristics of all subjects. Figure 8a summarizes the occurrence of attention. Figure 8a shows that based on data from 11 subjects, attention occurred 11 times in 8 different sections. We defined any section with more than 8 eye-fixations as "dominant." Based on this definition, 27 sections (18.8%) were dominant, observed by more than 72% of the subjects. Some of these sections were on row e, while most were on rows f and g. The horizontal angle of eye-fixation was 360°, meaning that the subjects observed the entire row, and the vertical angle of eye-fixation was 30° upward from row g (see Figure 8a).

(2) Conscious eye-fixation

Moving from attention to visual appreciation, the number of sections with eye-fixation decreased. As shown in Figure 8b, sections with conscious eye-fixation were more to the right than sections with attention. On both sides of the grid, conscious eye-fixation occurred mostly within 90° of columns J and K (Area III) and columns C and D (Area I) in the direction of. Subjects observed Area II at the beginning of the experiment and then moved to Areas I and III, which helped create a sense of depth in the VR space. Comparing sections where attention occurred to sections where conscious eye-fixation occurred helped us infer the following facts about eye-fixation in the VR space:

i) Eye-fixation on the right was stronger than eye-fixation on the left.
ii) The base line occurred just below eye level.
iii) Subjects tended to return to sections on which they first fixed their eyes.
iv) Subjects tended to fix their eyes most on sections that generated a sense of depth.

(3) Visual appreciation

The time required for visual appreciation (0.3 seconds or more) indicates strong interest. The area where visual appreciation occurred was 90° to the left of columns F and G. Similar to the left side, where the VR experiment started, subjects fixed their eyes intensively on Cf and Cg, when they fixed their eyes on the right side. Subjects moved their eyes from the starting location in the experiment to the left 120° and to the right 180° for intensive observation, allowing us to conclude that subjects were more interested in objects on the right than on the left (see Figure 8c).

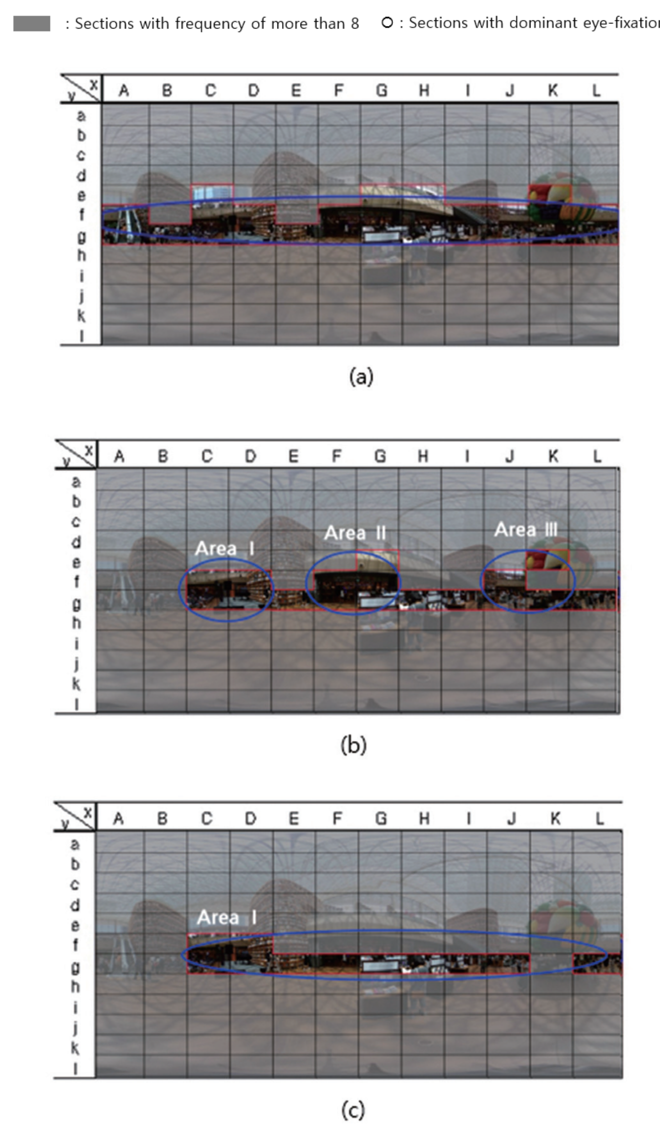

Figure 8. Area of dominant eye-fixation. (a) attention. (b) conscious eye-fixation. (c) visual appreciation.

5. CONCLUSION

In this study, we conducted eye tracking experiment to investigate eye-fixation on a VR representation of the Byeol-Madang Library. Our findings describe how subjects gazed at objects in the virtual space. First, subjects fixed their eyes in all the directions horizontally from the base line, which was a little lower than eye level. Eye-fixation on the right side was stronger than the left side. Second, to analyze eye-fixation distribution in VR space, we used 12×12 Grid System, which enabled us to gather visual-perceptive information based on dominant eye-fixation. This approach made the characteristics of space and eye-fixation clearer, particularly conscious eye-fixation, which requires at least 0.2 seconds to occur. Third, subjects tended to return their eyes to the respective points they first observed in the VR space and to fix their eyes where they felt a sense of depth. Fourth, the direction and angle of eye-fixation differed depending on the type of eye-fixation we were analyzing. The eye-fixation scopes of horizontal attention, conscious eye-fixation, and visual appreciation were 360°, 300°, and 270°, respectively. The vertical scope was 30°~60° above the base line.

Though techniques for VR space are rapidly developing, our understanding of the ways in which people perceive VR space is primitive. We conducted an eye tracking experiment to figure out how subjects fixed their eyes on a VR space representing the Byeol-Madang Library and how their eye-fixations might be analyzed. Because our study and our findings are somewhat exploratory, scholars should continue investigating how humans acquire visual-perceptive information from VR spaces and continue developing analytical techniques to clarify the relationship between spatial characteristics and eye-fixation types.

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