Characteristics of Space Search Determined by Tracking Scanning Paths

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Abstract

We tracked scanning paths to determine what visual activities subjects performed while observing the lobby of a public space. Extracting the observation pattern and establishing the scanning attributes in 10-second blocks enabled us to evaluate the characteristics of continuous space search. First, we analyzed scanpath characteristics in six time frame ranges and found that more scanpaths overlapped when the time frame was longer, and they were too fragmentary when it was shorter. Consequently, 10 seconds was determined to be the best time frame for analyzing scanning features. Second, during 2 minutes of observation, subjects used a combination of mixed scanning (41.3-seconds), horizontal scanning (35.4-seconds), and circular scanning (28.8-seconds). Subjects focused on one spot for only 12.1 seconds, and spent most of the observation time engaged in space search. Third, mixed scanning made up 45%–50% of all the scanning patterns, indicating that a significant proportion of space search was accomplished through mixed scanning. Fourth, horizontal search was prominent during the early stage of observation, indicating that subjects tended to use horizontal search at the initial stage of space observation. Fifth, subjects initially searched the space horizontally and then repeated mixed search in 20–30 second intervals after circular search.

Keywords: public space; eye-tracking; visual memory; fixation; scanning path

1. Introduction

Humans' dependence on space perception is so significant that as much as 80%–90% of their five senses are dedicated to it. Even though it is very hard to clearly differentiate perception from recognition, how spatial traits are assessed through vision and what information is acquired are very important for decisions about shapes in a space. Users can appreciate the purpose and pattern of any space based on visual information. Primary effect is a psychological term meaning that the information that is acquired first has a more powerful effect on overall image formation than information that is acquired later; the information acquired during the first observation of a space is significant. During space search, the eyes continuously search the object under observation to acquire information. When visual information is acquired, it may affect space estimation and the process of space search.

During space search, dependence on vision is considerably high, but the acquired visual information has rarely been analyzed systematically. Information obtained through visual perception is expected to act as a catalyst for the way in which the visitor perceives a given space in a building, triggering spatial judgment and, subsequently, his/her next action. In addition, determining the characteristics of the visual information that is stored and utilized in memory could, in turn, form the basis for understanding the characteristics of the visitor's spatial perception. This could play an essential role in the adoption of not only construction plans that include signs and colors, but also evacuation plans. In addition, using objective measures of visual attention to appreciate subjects' experience of space may provide tips for enhancing communication with users during space planning. Characteristics of spatial information acquisition include quantity and order. The amount of information can be considered to be the accumulation of the information acquired in order. Therefore, the order in which information is acquired provides a critical lead for understanding spatial traits.

Information acquired through vision is used to judge the next behavior, and the information acquired about a space can vary depending on the time and situation. The information and the order in which it is

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acquired play a mechanistic role for judging situations and searching activities. Although the order in which information is acquired seems to play a significant role in judging situations, and existing studies show that conclusions are drawn from observed traits, no study has sought to organize searching features using scanpath tracking. When any space is visited, there may be differences in acquired information or visual appreciation depending on the subjects' sight-line position and the attributes of their space search process.

Scanpath can be used to analyze the characteristics of searching, information acquisition, and way finding for different kinds of spaces. However, differences in space perception between subjects may lead to subtle differences in the way in which they search visual information.

In this study, we examined general observation patterns using a common space as the experimental environment. Specifically, the experiment space was the lobby of a public building. Subjects were asked to observe the space, and their observations were recorded and analyzed. Based on the analysis of this visual data, we found that the features of space search can be derived from scanpath tracking.

2. Study Content and Observation Data

2.1 Previous Studies and Definition of Scanning Time

1) Previous Studies

In the process of observing a space, the eyes perform intermittent saccades to search the space for information, and receive information through fixation, where the eyes are focused on one place. The visual information acquired during fixation can be analyzed. The acquired information is connected by scanpaths, and the development of IT has enabled tracking of sight-line movement. An eye-tracker is used for tracking sight line, and it has enabled an appreciation of subconscious processes that were not easily analyzed with any previous methods.

Most previous studies combined observation characteristics (Kim, 2011) and the observations of the subject to analyze the relation between observation tendency and space medium (Yoo *et al.*, 2011) in an observation area. Some studies have analyzed the relationships between the factors that constitute space structure and space, confirming the interaction between space cues (Kim *et al.*, 2007). Other studies have analyzed observation traits based on assumptions about changes in observation time (Ban and Kim, 2012).

However, these studies analyzed observation traits

using frequency analysis or the characteristics of the observation area. No studies have examined the order of observation information acquisition.

2) Observation and Scanning Time

Most observation theories of scanning time have described scanning time according to an understanding of first impressions or visual information. It is well known that different researchers use various interpretations and definitions of observation time. The definition of observation time described in previous research is being used in the present study. In contrast, scanpath is a term meaning "the technique of repeated fixations and movements when eyes are looking at a scene." Subjects use different scanpaths, and scanpaths for different pictures are independent (Solso, 2000). Since no information is stored while the sight line is moving, a definition of eye fixation is needed to analyze scanpaths. Different interpretations of observation features can be drawn from eye fixation duration. Observation time is defined in either seconds or milliseconds, depending on the researchers. Table 1. shows continuous observation times and observation data recorded by the devices used in this study.

2.2 Method and Scope of Study

1) Experiment Space

The lobby of a public space is a space which is open to everyone, and which is also used as a space for people first entering a building. Visitors can acquire and judge space information by searching the structure space and any information sign in the lobby. That is, the lobby is a landmark representing the architecture of the building, and is a significant point that provides space information to visitors. Therefore, the lobby was selected as the experimental space for tracking scanpaths. The space will be structured in a way that enables a sense of distance due to perspective representation. In addition, a space through which light can be projected diagonally will be assigned to enable the visitor to view the entire space at a glance. By structuring the space this way, vertical and horizontal elements can be prevented from having a strong impact on the space, thereby allowing the space to be used for active visual activities.

The lobby space used for the observation experiment was digitally reproduced. Signs and facilities (Fire-plug, Emergency Exit, Monitor) were included, and to create a sense of reality passers-by were also positioned, but they were silhouetted so that they did not hinder subjects' space search. The subjects were asked to observe the digitally presented space and imagine that they were entering the lobby to visit the relevant space.

Table 1. Definition of Observation Time by Researchers

Researcher	Observation Time		Continuous Observation Numbers	Definition of Observation Time
	Seconds	m/s		
Berger (2011)	0.05	50	1.5	Securing continuity
Solso (2000)	0.3	300	9	Visual understanding
Solso (2000)	0.2~0.25	200~250	6~7.5	Time to focus on the object or scene
Gratzer (1971)	0.2	200	6	The mean time to focus for recognition

2) Experiment Environment

- ① Subjects: 31 males.
- ② Experiment Surroundings: The surroundings were dark so that the subjects could focus on the images on the monitor.
- ③ Subjects: University students with eyesight of more than 0.6.
- ④ The distance between the monitor and the visual apparatus¹ worn on subjects' eyes was 65 cm, and the size of the monitor was 67.7 × 38.1 cm.
- ⑤ Method: Calibration that the monitor was being observed for the measured point and for the eyes to be brought to a focus was performed at 16 Observation Points and the subjects were allowed a 30 second adaptation time wearing visual apparatus in a darkroom. After an overall explanation of the experiment, subjects observed the space for 2 minutes², one at a time.
- ⑥ Data Recording: Thirty eye movements per second were recorded as [x, y] coordinates.

Fig.1. Experimental Space Image and Observation Experiment Set-up

2.3 Adjustment of Observation Data and Setup of Continuity

1) Summary of Visual Perception

When a person observes a space, his eyes are naturally focused on one point. This point is the fovea, and in this area, the optic nerve is concentrated such that only the image included in the fovea is perceived clearly. When any interesting visual information is detected, the head or eyes move so that the new information is focused in the fovea. While searching an object, the eyes move and focus on other detailed features, and they sometimes return to a feature to see the previously perceived details again. However, only the visual information that enters the fovea is considered to be precisely observed and saved in memory.

2) Summary and Adjustment of Observation Data

The observation data from the subjects observing the space is saved as a value between 0 and 1 for the relevant area (X, Y), and if they observe areas other than the relevant space, the data is saved as less than 0 or more than 1. Subjects were allowed 2 minutes to observe the space, and 3600 data points were obtained.

Seven out of the 31 participants exhibited a lot of blinking or observations outside the scope of the image. Since the probability of significance is specified as 95%, we analyzed the data of 24 participants who

had more than 95% of usable data.

3) Observation Scope and Scanpath

During space search, information is acquired in cycles of concentration and discontinuity. The experiment devices used for this study produced 30 observations per second. In order for this data to show that a given position was fixated successively for observation, times of successive observation were estimated. The observation data measures scope [0–1] on [X, Y] axes, but since the width and height of the images used in the experiment were different, the width was corrected. Fig.3. shows the recorded data along with the position and path of eye fixation, where the duration of eye fixation is marked by the size of the □ mark and series number. The time-series tracking of the size and position of the marks indicates the position where the eyes were focused and their movement, allowing for the analysis of space observation traits.

Fig.2. Observation Scope of Fovea and Parafovea

Fig.3. Example of Point Mark by Observation Measurement

3. Data Analysis for Scanpath Analysis

3.1 Characteristics of Observation Time and Scanpath

Since there is no clear definition of what visual traits will occur during space observation, the data were analyzed based on "time when visual understanding occurs," defined as nine successive observations (Table 1.).

The observation data produced during 2 minutes were 1,602 on average. There were 170.8 on average and 9.8 on average were included in each observation point (Table 2.).

Since there are too many observation points and many observation paths overlapped, reproduction of all the observation points and scanpaths for the experiment images cannot be applied effectively for analysis (Fig.4.). Accordingly, we analyzed scanpaths in sections based on the time frame.

Table 2. Observation Data for Each Subject
(Nine Successive Observations)

Subject	Frequency	Number	Average
1	99	1795	18.1
3	180	1493	8.3
4	155	1635	10.5
5	181	1669	9.2
6	186	1799	9.7
7	158	1698	10.7
8	166	1623	9.8
10	153	1300	8.5
11	168	1551	9.2
13	173	1700	9.8
14	167	1701	10.2
16	251	1354	5.4
17	117	2143	18.3
19	192	1396	7.3
20	166	1889	11.4
21	173	977	5.6
23	156	1987	12.7
24	210	1059	5.0
25	173	1908	11.0
26	199	1515	7.6
27	166	1146	6.9
28	168	2164	12.9
29	174	1361	7.8
30	167	1580	9.5
Average	170.8	1601.8	9.8

Fig.4. Scanpath During 2 Minutes (Subject 1)

3.2 Setup of Time Frame for Scanpath Analysis

Six time frames (2 minutes/1 minute/30 seconds/20 seconds/10 seconds/5 seconds) were used for scan path analysis and then the scanpath characteristics were analyzed. Visual understanding was tracked for 2 minutes. First, eyes moved horizontally and then focused on some points while circulating to both sides. These movements were discontinuous. However, since a lot of scanpaths and point numbers overlap Fig.1. and there are several scanpath patterns, these cannot be utilized for feature analysis. In contrast, a subjects' sight line started from the center and moved horizontally to the left and then to the right repeatedly. During longer time frames, several scanpaths overlapped, and otherwise, there was a high probability that the scanpaths revealed a fragmentary pattern. When all the observation data were analyzed in the same way with the same time frame, as in Table 3., the scanpaths within the 5-second time frame were mostly

included in the 10-second time frame, while in the 20-second time frame, several scanning patterns were mixed with one another. Therefore, for the rest of the analyses, the 10-second time frame was used Table 4.

Table 3. Scanpath in Different Time Frames

Time	Scanpath	
2 minutes		
1 minute		
30 seconds		
20 seconds		
10 seconds		
5 seconds		

3.3 Scanpath Patterns

Scanpath is formed by connecting successive observation points where the eyes stopped to acquire information for visual understanding. It is possible to analyze the characteristics of subjects' space search by organizing these successive observations. The analysis of scanpath patterns in 10-second time frames revealed five scanning patterns: circulating, horizontal, vertical, mixed, and concentrated.

The patterns are as follows:

- ① Circulating Scanning: Sight line circulates (clockwise/counterclockwise)
- ② Horizontal Scanning: Sight line moves horizontally (including diagonally)
- ③ Vertical Scanning: Sight line moves vertically
- ④ Mixed Scanning: Patterns ①②③ are mixed

Table 4. Scanpath by 10 Seconds (No. 1 Subject)

Time	Scanpath	Time	Scanpath
1"		11"
~		~	
10"		20"
~		~	
21"		31"
~		~	
30"		40"
~		~	
41"		51"
~		~	
50"		60"
~		~	
61"		71"
~		~	
70"		80"
~		~	
81"		91"
~		~	
90"		100"
~		~	
101"		111"
~		~	
110"		120"

⑤ Concentrated Scanning: continuity on the fovea, based on observation data in an area that expanded a little beyond the parafoveal area (Table 5.)

4. Characteristics of Scanning Frequency by Time Frame

4.1 Scanning Pattern by Time Frame

The characteristics of space search were examined based on subjects' scanning patterns. Those patterns were decided based on their similarity, which is shown in Table 6.

The analysis of these scanning patterns by time frame enables analysis of the features that subjects observed in the space. During the 0–10-second time frame, a considerably high proportion of the scanning patterns were horizontal (15 subjects/62.5%), and at 30 seconds circulating scanning occurred with high frequency (10 subjects/41.7%). The other time frames (40 seconds/80 seconds/90 seconds/120 seconds) all contained a lot of mixed scanning and concentrated scanning, followed by circulating and horizontal scanning.

Table 5. Type of Scanpath Patterns

Scanning Pattern	Image	Symbol
Circulating		○
Horizontal		=
Vertical
Mixed		◆
Concentrated		▼

4.2 The Frequency of Scanning Patterns

The average scanning frequency was high for mixed scanning (34.4%) and horizontal scanning (29.5%), and was the lowest for vertical scanning (2.1%). Vertical scanning was only observed for a few subjects, whereas horizontal scanning was seen for all subjects except for Subject 25. All subjects except Subject 28 spent the most time engaged in mixed scanning. Concentrated scanning, where the eyes are concentrated on one particular point, was observed in nine subjects (37.5%) and only occurred frequently for Subject 1. The least frequent scanning pattern was vertical scanning, which was only observed in four subjects (16.7%). Thus, there is little vertical scanning during space observation.

When the scanning time for each pattern is calculated, the results show that during the 2 minutes of scanning, subjects engaged in mixed scanning for 41.3 seconds, horizontal scanning for 35.4 seconds, and circulating scanning for 28.8 seconds. The time spent focused on a particular point was 12.1 seconds, and 2.5 seconds were spent on vertical scanning, which

Table 6. Scanning Pattern by Subject

No	0~10"	~20"	~30"	~40"	~50"	~60"	~70"	~80"	~90"	~100"	~110"	~120"	○	=	Total 	◆	▼
1	=	◆	▼	=	○	▼	▼	▼	▼	◆	◆	=	1	3	0	3	5
3	=	=	=	◆	=	◆	◆	◆	◆	▼	▼	=	0	5	0	5	2
4	▼	=	◆	◆	○	○		▼		=	=	○	3	3	2	2	2
5	○	◆	◆	◆	=	○	○	○	◆	=	○	▼	5	2	0	4	1
6	=	◆	◆	=	◆	=	=		◆	◆	=	=	0	6	1	5	0
7	◆	○	○	○	○	○	◆	○	=	○	○	◆	8	1	0	3	0
8	=	◆	○	○	○	○	◆	◆	○	=	=	◆	5	3	0	4	0
10	◆	=	▼	▼	◆	◆	○	=	○	▼	○	◆	3	2	0	4	3
11	=	◆	○	◆	◆	=	○	○	◆		◆	◆	3	2	1	6	0
13	◆	○	○			=	=	◆	○	=	○	▼	4	3	2	2	1
14	◆	○	○	○	=	◆	○	○	○	◆	▼	▼	6	1	0	3	2
16	◆	○	○	○	○	○	◆	○	○	○	=	=	8	2	0	2	0
17	=	=	=	=	○	◆	=	=	◆	=	=	=	1	9	0	2	0
19	=	=	=	◆	◆	○	○	◆	◆	◆	◆	◆	2	3	0	7	0
20	▼	○	○	◆	○	=	◆	◆	◆	○	◆	=	4	2	0	5	1
21	=	◆	○	=	◆	=	○	○	◆	○	=	◆	4	4	0	4	0
23	=	=	=	◆	=	○	○	=	▼	▼	=	=	2	7	0	1	2
24	=	=	▼	◆	=	◆	=	◆	◆	◆	○	=	1	5	0	5	1
25	▼	▼	◆	◆	○	◆	○	◆	◆	◆	◆	◆	2	0	0	8	2
26	=	○	=	○	○	○	◆	◆	◆	◆	▼	◆	4	2	0	5	1
27	=	○	○	◆	◆	◆	=	=	=	◆	◆	◆	2	4	0	6	0
28	=	=	=	=	=	=	=	▼	=	=	=	=	0	11	0	0	1
29	=	◆	=	◆	◆	◆	▼	◆	▼	◆	◆	▼	0	2	0	7	3
30	=	◆	○	▼	◆	=	=	◆	◆	▼	◆	◆	1	3	0	6	2

○: Circulating, = : Horizontal, || : Vertical, ◆ : Mixed, ▼ : Concentrated

was rare. These findings reveal the characteristics of space search by time.

4.3 Characteristics of Concentration Frequency by Scanning Pattern

A review of the scanning patterns with high frequency during space observation reveals the characteristics of concentration frequency by scanning pattern. In order to find out what scanning pattern the subjects used the most, frequency patterns for each subject (Table 7.) were classified as "High" (over 30%) or "Very High" (over 50%). Out of the 120 patterns, 10.8% (13 patterns) were classified as "Very High" and 16.7% (20 patterns) were classified as "High."

The concentration frequency of each scanning pattern enables us to determine what scanning styles subjects used in the space. Of the patterns classified as "High," circulating scanning was used 10% more than horizontal scanning, and mixed scanning was used 15% more than circulating scanning. In contrast, for patterns classified as "Very High," horizontal and circulating scanning were similar to each other, but the frequency of mixed scanning was twice as high as circulating scanning. Out of all scanning patterns classified as "High" or "Very High," mixed scanning was used the most often (45% and 46.2%, respectively) during the 10-second time frame.

4.4 Characteristics of Scanning Pattern Change by Time Frame

To examine the overall scanning tendency, the frequency of scanning patterns by time frame was examined for patterns with "High" (30%) and "Very

Table 7. Frequency of Scanning Patterns for Each Subject

Subject	○	=		◆	▼
1	8.3%	25.0%	0%	25.0%	41.7%
3	0.0%	41.7%	0%	41.7%	16.7%
4	25.0%	25.0%	16.7%	16.7%	16.7%
5	41.7%	16.7%	0%	33.3%	8.3%
6	0.0%	50.0%	8.3%	41.7%	0%
7	66.7%	8.3%	0%	25.0%	0%
8	41.7%	25.0%	0%	33.3%	0%
10	25.0%	16.7%	0%	33.3%	25.0%
11	25.0%	16.7%	8.3%	50.0%	0%
13	33.3%	25.0%	16.7%	16.7%	8.3%
14	50.0%	8.3%	0%	25.0%	16.7%
16	66.7%	16.7%	0%	16.7%	0%
17	8.3%	75.0%	0%	16.7%	0%
19	16.7%	25.0%	0%	58.3%	0%
20	33.3%	16.7%	0%	41.7%	8.3%
21	33.3%	33.3%	0%	33.3%	0%
23	16.7%	58.3%	0%	8.3%	16.7%
24	8.3%	41.7%	0%	41.7%	8.3%
25	16.7%	0.0%	0%	66.7%	16.7%
26	33.3%	16.7%	0%	41.7%	8.3%
27	16.7%	33.3%	0%	50.0%	0%
28	0.0%	91.7%	0%	0%	8.3%
29	0.0%	16.7%	0%	58.3%	25.0%
30	8.3%	25.0%	0%	50.0%	16.7%
Average	24.0%	29.5%	2.1%	34.4%	10.1%
Time	28.8sec	35.4sec	2.5sec	41.3sec	12.1sec

■ : Over 50% ■ : Over 30%

Table 8. Concentration Frequency by Scanning Pattern

Frequency	○	=		◆	▼	Total
High (over 30%)	6 (30%)	4 (20%)	0 (0%)	9 (45%)	1 (5%)	20 (100%)
Very High (over 50%)	3 (23.1%)	4 (30.8%)	0 (0%)	6 (46.2%)	0 (0%)	13 (100%)

Fig. 5. Concentration Frequency by Scanning Pattern

High" (40%) frequencies. Since the scanning features for each time frame for the 24 subjects have been found, the occupation frequency of 30% is more than 7 and that of 40% more than 9.

As seen in Table 9., it is very noteworthy that 15 participants (62.5%) engaged in horizontal scanning during the initial time (0–10 seconds). This high frequency is not found during any other time frames, suggesting a strong tendency for subjects to move their eyes horizontally during initial space search. Furthermore, when all the scanning features by time frame were reviewed based on the frequency of "Very High" scanpaths, the "Horizontal → Circulating → Mixed → Mixed → Mixed → Mixed" order was dominant. Analysis of scanning features based on only these findings reveals that space search was horizontal earlier in space observation, and then circulating, followed by repeated mixed scanning in 20–30-second intervals.

Fig. 6. shows that subjects engaged in horizontal scanning during initial space search, followed by circulating and mixed scanning, and, lastly, alternating circulating and mixed scanning until one minute before the end of the scanning time. During the latter half of the scanning time, they mostly engaged in mixed scanning, and around 2 minutes before the end of the experiment horizontal scanning occurred.

Table 9. Distribution of Scanning Pattern by Time Frame

Type	0 ~10	~20	~30	~40	~50	~60	~70	~80	~90	~100	~110	~120
○	1	7	10	5	9	8	8	6	5	4	5	1
=	15	8	7	5	6	7	7	4	3	6	8	9
	0	0	0	1	1	0	1	1	1	1	0	0
◆	5	8	4	11	8	8	6	10	12	9	8	10
▼	3	1	3	2	0	1	2	3	3	4	3	4

: High (over 30%)
 : Very High (over 40%)

Fig. 6. Characteristics of Scanning Pattern Change by Time Frame

5. Conclusion

In this study, we analyzed the process of space search and what visual activities subjects engage in when looking at the lobby of a public space by tracking their scanpaths. When scanning time was short, there was a considerable amount of horizontal scanning, and when scanning time was long, mixed scanning was dominant. Consequently, the duration of the scanning time frame may play a critical role in scanpath patterns.

First, when the scanpath features were analyzed with six time frames, several scanpaths overlapped at longer time frames, and fragmentary patterns were observed at shorter time frames. Accordingly, the time frame of 10 seconds was found to be the most appropriate for analyzing scanning features by time frame.

Second, during two minutes of scanning, subjects engaged in mixed scanning (41.3 seconds), horizontal scanning (35.4 seconds), and circulating scanning (28.8 seconds). Scanning focused on a particular point only occurred for 12.1 seconds, suggesting that the majority of observation time was used for space search.

Third, when the scanning time was 10 seconds, mixed scanning made up 45%–50% of the scanning patterns, indicating that most of the space search was accomplished through mixed scanning.

Fourth, horizontal scanning was seen at earlier observation times and was not seen during other time frames. This indicates a strong tendency for subjects to initially search a space by moving their eyes horizontally.

Fifth, the examination of scanning features by time frame revealed that subjects scanned horizontally at earlier time points and then repeated circulating and mixed scanning in 20–30-second intervals.

Considering these above conclusions, while subjects had different scanpaths, it was possible to analyze the characteristics of space search based on scanpaths. The characteristics of a scanpath can be analyzed through scanpath tracing. These can be utilized as background information when adopting evacuation plans that reflect the unique characteristics of the user of the space, useful signs for both space exploration and finding one's way, as well as visual activities and the type of spatial structure that facilitate the discovery of unique features within the space.

Notes

- ¹ ViewPoint Eye Tracker PC-60 Scene Camera: Arrington Research.
- ² While experimenting with early devices in Russia, Yarbus (1967) performed the experiment of eyeball tracking for 3 minutes, and Kim and Choi (2009) experimented the observation for 3 minutes in a living room space, but recently Choi (2011) is suggesting 2 minutes as the optimal time after experimenting the propriety of observation time in an indoor space.

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