Application of Human-scale Immersive VR System for Environmental Design Assessment - A Proposal for an Architectural Design Evaluation Tool

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Abstract

In order to improve the quality of everyday life in urban areas, it is important to properly design public spaces such as plazas and streets where urban residents spend many hours during commuting and their spare time. One of the hardest problems at the initial stage of environmental design is the verification and evaluation of the planning of environmental space before actual construction. The virtual reality (VR) technology could be one of the solutions for this kind of problem. Although several technologies have been introduced, such as head-mounted display (HMD) and PC-monitor-based VR (including web-3D), the lack of a sense of presence, as well as interaction methods are still unresolved issues. Therefore, we are suggesting the use of a multiprojection display system with multimodal interfaces, which is our original system for virtual experience, as a potential candidate to solve the lack of presence and interaction. In this study, several experiments related to urban environmental design evaluation have been carried out. The first was about the evaluation and verification of public space design such as those of arcades and eaves above streets between high-rise buildings. The result showed that there was an emotional release from the oppressive feeling in the streets between high-rise buildings when an appropriate arcade design was adopted compared with when no arcade was adopted. The second was about human behavior in public open spaces concerning seat preference in public squares and the distribution of the surrounding people. Furthermore, we carried out several basic psychophysical experiments on human distance perception in virtual space, which revealed the compression of distance perception in VR space. In this paper, we also introduce one of the main points of this study, which is the unique and elaborate cooperative relationship between architectural and nonarchitectural departments of our university when conducting human behavior experiments using heavily computer-oriented devices. To carry out the experiments, the multiprojector display system, D-vision, which has a 180° viewing angle, and the original navigation interface, Turn-table, were used to provide a high sense of presence and high-resolution images to the user.

Keywords: environmental design; design assessment; human scale immersive virtual reality system; interfaces

1. Introduction

Environmental design in public spaces has become an increasingly important part of urban planning because such design has a tremendous psychological and physical influence on the everyday life of urban residents. In order to design the environment and surroundings of a city as a place to relax and be comfortable in, the evaluation of environmental design is an essential process before the actual construction.

Even though the best way of evaluation is to use the real environment, it is almost impossible to use the real world itself as a comparative evaluation object because the variations of environmental design are usually fixed to those applicable in the real world at the time when the assessments are carried out. In the design verification process, it is difficult to exchange alternatives. This is one of the most difficult obstacles in the verification and evaluation process of environmental design in the real world.

One of the possible methods is to use endoscopy with small-scale models to experience the unbuilt environmental space (Ohno, 2001). Although it is a good method of representing the planning of open spaces or street design proposals, with video cameras and mock-up models providing images as if the user

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is standing inside the model world, the user is still required to wear a pair of spectacles or to watch the monitor. Also, the absence of interaction between the user and the representation is another demerit of the camera-video-based method. Furthermore, this kind of system has some difficulty in providing several variables, interactive factors, and active behaviors of the user during the evaluation process, because preparing and exchanging the parts of the small-scale models require cost and labor.

The augmented reality (AR) system, by which three-dimensional (3D) virtual objects are generated and rendered into a real environment in real time, may be another method of realizing computer graphics (CG)-generated representation of urban design (Azuma, 1997; Shen, 2001; Broll, 2004). The visual incorporation of the rich information available in the real world into the VR world is one of the merits of this kind of system. Although the user interaction in this VR space is limited because of the need to wear a pair of spectacles, AR is an effective method for providing the sense of presence. However, the limited resolution of the video image when merging it with CG-generated objects in VR is the disadvantage of this application. Also, the short focal distance of the head-mounted display from the eye causes visual fatigue in long-time tasking.

Recently, human-scale immersive virtual environments are being considered as a useful verification and evaluation tool for environmental design. The first prototype of immersive virtual environments, CAVE, a projection-based VR system developed by Illinois University in 1993, has four flat screens to provide a wide viewing angle to the user inside the system (Cruz-Neira, 1993). Compared with other VR systems such as HMD, the human-scale system has several merits such as high resolution, wide viewing angle, and active human behavior or interaction in the system, for example, self-motivated walking for navigation, which is an essential function during the assessment process of environmental design. Also, it is reported that the use of virtual environments as virtual experimental laboratories provides better approximations of the perception and interaction with spatial and architectural features of naturally occurring settings than do other types of simulation (such as drawings, scale models, and slides) and offers ample means of carefully registering and studying behavior in the desired environments (De Kort, 2003).

In this paper, we will introduce several experiments on urban environmental evaluation using human-scale immersive virtual environments, distance perception experiments concerning the differences between virtual space and real space, and the unique and elaborate cooperative process between the different departments at the Tokyo Institute of Technology (TIT) when conducting heavily computer-related technical-skill-required architectural experiments.

2. Virtual Reality in Architecture

VR technology, developed from computer graphics, has a great capability to visualize the images of nonexistent or difficult-to-realize objects in the real world. Because of this high visualization capability, the architectural discipline, among the various industrial fields, has been considered to have profited the most from VR technology. An architectural creation mostly appeals to visual expression, which is the most powerful function of VR. Consequently, VR provides a means of simulating the sense of being inside a building and provides observers with a qualitative advantage over other means of representation (Kalay, 2004).

In the early stage of VR technology, the low quality of visual representation was a critical problem that affected the sense of presence of the user in virtual space, which relies heavily on the computer graphics progress and the hardware system for creating virtual environments. The HMD was the first immersive virtual environment that was used in the industrial field (Sutherland, 1966). Even today, the HMD system still has a relatively low resolution of the display image compared with the resolution ability of the human eye and this must be improved. Furthermore, the eye fatigue problems such as headache, vertigo and nausea caused by the long task time and the short focal
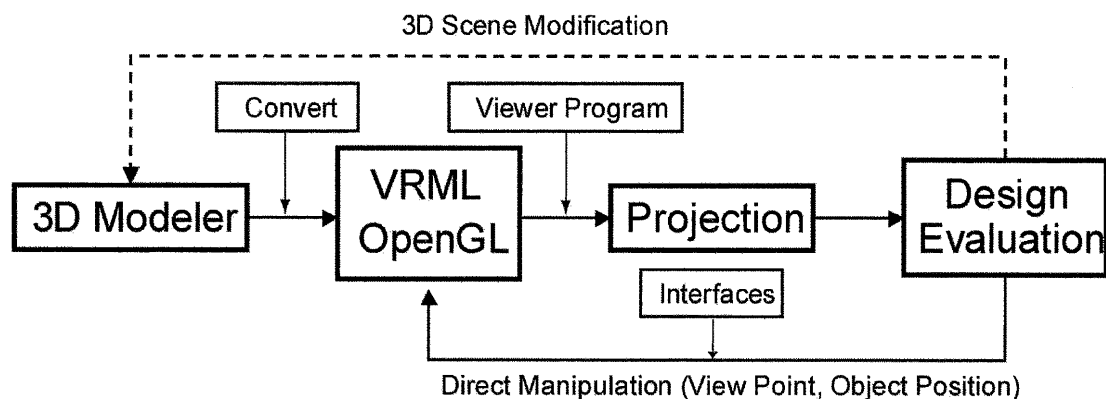

Fig.1. Workflow of Virtual Modeling Task for Design Evaluation

distance to the image displayed on the screen, remain unsolved.

The first human-scale immersive virtual environment, CAVE, has four 10-foot screens and a user interface for interaction. After the introduction of the first human-scale immersive virtual environment, several architectural applications were researched and proposed to support the architectural design process. For example, Leigh reported a study about the multiperspective collaborative design process in a networked virtual environment and CALVIN, a collaborative architectural layout with immersive navigation (Leigh, 1996). He developed the techniques required to support general collaborative work in persistent virtual environments. He also emphasized the importance of using the multiple perspectives to apply VR in the earlier, more creative, phases of the design process, rather than merely for a walkthrough of the final design. In another research, Hill proposed VADeT as a virtual architectural design tool (Hill, 1999). VADeT provides a computer-aided design capability to enhance the conventional method of sketching a design concept on paper and to simulate the thinking. He also introduced menu tools for building models in virtual environments at various scales. Even though there have been some proposals concerning creative methods of architectural design, the usability of human-scale virtual environments as an evaluation tool of environmental design has not been investigated sufficiently from the viewpoint of various aspects such as psychophysics, human factors, and non architectural cooperative work.

3. Environmental Design Evaluation Tool Using the Human Scale VR System

The human-scale immersive virtual environment is the most powerful system for evaluating environmental design, including urban planning and architectural design. One of the commercial VR products of Matsushita company, CyberDome, is used as a VR environmental project support tool for reviewing and consensus-building processes in civil engineering and urban developmental projects by construction companies, civil engineers, planners, designers, and residents (Shibano, 2003).

Fig.1. illustrates the typical workflow for realizing the visual presentation and evaluation process in the human-scale immersive VR system. The preliminary architectural design work must be converted into a 3D model that can be projected onto the screen via the computer graphic program in the VR system. The virtual reality modeling language (VRML) file format, which is common 3D model data format for VR viewer programs, can be used in our system.

In more detail, the designer can create an architectural and landscape model using the common 3D-modeler and convert it into the VRML file format.

The OpenGL code is also usable to express the object at this stage. The viewer program can import the VRML data file with texture images as the 3D object and the mapping image to represent the virtual space. The modification of the VRML file format will return to the 3D modeler stage.

3.1 D-vision

We have used our original display system, "D-vision", which is a multiprojection system, to create the virtual space for the subject. D-vision has a 6 meter (width) x 4 meter (height) x 1.5 meter (depth) screen and 24 projectors to realize stereoscopic image display. The central flat part of the screen is for rear projection using eight projectors that display images with SXGA, 1280 x 1024 pixel resolution. The remaining part of the screen is for front projection using sixteen projectors with XGA, 1024 x 768 pixel resolution. The projectors were set up at the positions indicated in Fig.2. The projectors for front projection are mounted on posts. Eight pairs of projectors are used to project stereoscopic images, the left-eye image and the right-eye image, onto the rear projection screen and the upper and lower cylindrical parts of the front projection screen. We used orthogonal linear polarized light to project each image for the left and the right eye.

In D-vision, the user can walk freely in the virtual world using Turn-table as the locomotion interface. There are four pressure sensors below Turn-table that send the stepping pressure data to the computer. By checking the value of each sensor, the computer calculates the direction of the user and rotates Turn-table to make the user face the front screen. The user always faces the screen directly through the control of the rotation of Turn-table. For this reason, the viewer can walk to any direction infinitely while facing the front screen. The actual walking action causes the viewer to feel a high sense of immersion in D-vision.

3.2 Environmental Design Evaluation Experiments

Experiments concerning environmental design have been conducted for several years through the
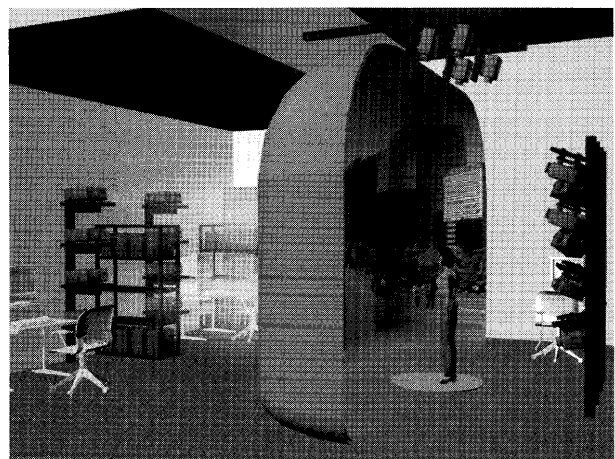

Fig.2. The Composition of D-vision

cooperation of two laboratories in the departments of built environment and computer science at TIT. The survey scope of experiments is wide: from human behavior research to the psychophysical effects of environmental design. In this paper, we will introduce some of them to explain the usefulness of adopting the human-scale immersive environments for the assessment of environmental design evaluation.

3.2.1 Evaluation of Architectural Treatments to Reduce Oppressive Feelings in Streets

We have conducted an experiment to examine the effectiveness of architectural treatments in reducing oppressive feelings caused by high-rise buildings along city streets (Soeda, 2003). The oppressive feelings caused by these high-rise buildings are becoming a serious problem in urban areas because there is a greater frequency of walking among such high-rise buildings. We set up architectural treatments, such as arcades and eaves, as experimental constraints for the awareness of the vertical direction, and window display and transparent glass for the awareness of horizontal direction. The 5-meter wide streets and 35-meter and 7-meter high buildings along the streets are adopted as the experimental variation. Through the use of Turn-table, the user can navigate freely, such as walk, turn, and stop, in the virtual city street, just as in real space, as shown in Fig.4.

Fewer subjects noticed the change in the atmosphere caused by the height of buildings when transparent glass and arcades were provided along the street, as shown in the graph in Fig.3. The results showed
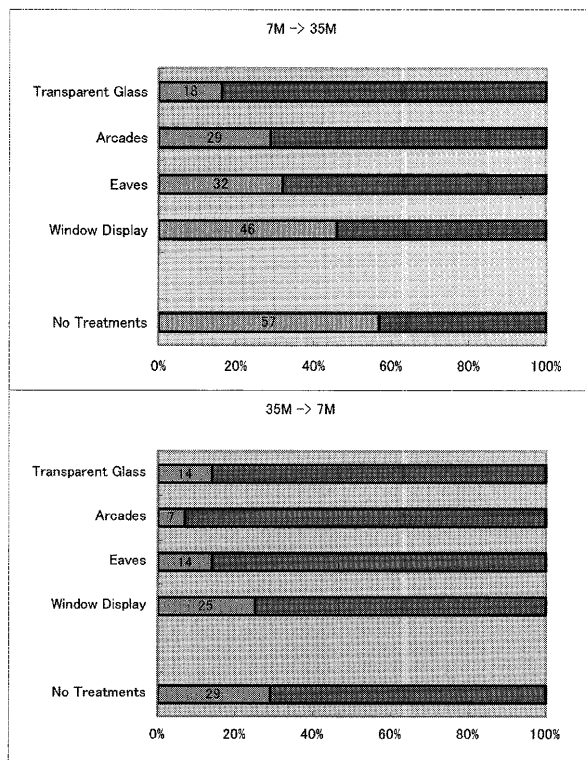

Fig.4. Evaluation of Architectural Treatment in Street

that covering the overhead space with arcades and providing a horizontal spatial expansion by installing transparent glass at the ground floors of buildings can control people's awareness of vertical direction and significantly reduce feelings of oppression.

The fact that the immersive human-scale virtual environment can provide an image with a 180° viewing angle is one of the factors that enable the setting up of various building conditions and architectural treatments in experiments. In particular, the semispherical screen provides an effective upper field of view for subjects inside the system, as shown in Fig.4. This human-scale VR system has the merits of providing not only various conditions but also a high sense of presence.

3.2.2 Preference of Place to Stay in Public Space

A human behavior experiment was conducted to survey people's seat preferences in a public plaza and the influence from the distribution of the surrounding people using D-vision with the Quake- III game engine that enables high-quality scene rendering with little effort (Ryu, 2006). In this study a series of experiments in both real and virtual settings has been conducted in order to extract quantitative relationships between subjects' seat preferences and the presence of nearby

7M -> 35M

Transparent Glass	18
Arcades	29
Eaves	32
Window Display	46
No Treatments	57

0%   20%   40%   60%   80%   100%

35M -> 7M

Transparent Glass	14
Arcades	7
Eaves	14
Window Display	25
No Treatments	29

0%   20%   40%   60%   80%   100%

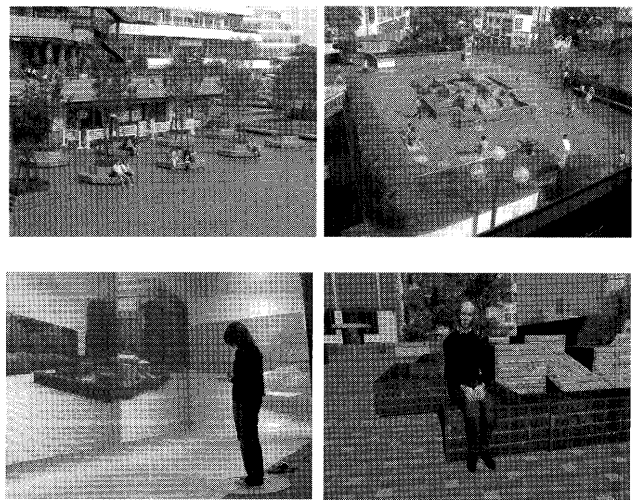Fig.3. The Ratio of the Subjects Who Felt the Difference of Atmosphere Caused by the Change of Building

Fig.5. Preference of Place to Stay Experiment in Real & VR

strangers and to clarify what factors influence seat choices, as shown in Fig.5. For the characteristics of the experiment methods, a situation such as a person sitting on a public bench is a difficult task requiring many actors and much effort. To survey the quantitative effects of other people sitting on near benches, the systematic variations of sitting people are necessary, which is difficult to accomplish.

Two sets of experiments were conducted. In the first experiment, two existing public squares were used (see Fig.5.). At each site, 19 subjects (8 male and 11 female university students) were asked to walk about and to evaluate each of several predesignated positions, supposing they wished to sit there to 1) have a brief rest, 2) read a book, and 3) eat food. In this process, subjects were also asked to rate the seats assuming there are no other people at the site. The subjects rated the preference for a site on a scale of 0 to 20 for resting, reading, and eating. The second experiment was conducted in a virtual reality simulation laboratory at the Tokyo Institute of Technology. Subjects were asked to conduct the same tasks as described above, this time employing virtual reality simulations of the two squares used in the first experiment. The validity of using visual simulation was evaluated by comparing the ratings made by each subject in the real versus virtual square.

Through comparison of the spatial preferences between real and virtual space, the validity of using visual simulation for the psychophysics experiment is proved by the similar results obtained for several subjects. Table 1. shows the correlation coefficients between the real and virtual space data obtained from each subject. The results showed that there is a high correlation between the experiments in real and VR spaces, the average value of which is over 7.0 points for 19 subjects. Even though subjects E, G, P, and S showed low correlation coefficients and large variance in a certain situation, most of the other subjects responded similarly in both spaces.

In this experiment, we also used virtual characters as people nearby who influence whether the subject decides to sit down, as shown in Fig.5. Even though the actual sitting behaviors could not be represented in this experiment, the human-scale display and the walking interface are proved to be useful for this kind of environmental behavior experiment.

4. Discussions Concerning Using the VR System for Environmental Design

There is one doubt as to whether the user feels and navigates similarly in the virtual environments as in the real world. There is constant interest in to what extent people behave in virtual space as they do in reality. It is usually said that users in the VR world feel differently from in the real world. There are several studies on investigating how humans recognize space in VR systems. The fundamental experiment is a comparison

Table 1. Correlation Coefficients and Average Variance between Real and Virtual Space Data

Subject	Resting		Reading		Eating	
	CC	(AV)	CC	(AV)	CC	(AV)
A	0.82	(4.46)	0.86	(3.85)	0.89	(4.19)
B	0.73	(2.04)	0.84	(1.89)	0.86	(1.15)
C	0.81	(2.21)	0.77	(2.50)	0.73	(2.31)
D	0.87	(2.46)	0.75	(0.33)	0.79	(2.27)
E	0.37	(5.43)	0.36	(4.20)	0.62	(3.73)
F	0.77	(2.56)	0.79	(1.96)	0.48	(1.85)
G	0.72	(3.31)	0.55	(4.67)	0.56	(3.75)
H	0.68	(4.33)	0.72	(3.67)	0.80	(2.92)
I	0.86	(2.35)	0.79	(2.65)	0.55	(3.42)
J	0.76	(2.44)	0.78	(2.46)	0.76	(2.44)
K	0.52	(2.38)	0.82	(1.88)	0.94	(1.21)
L	0.82	(3.33)	0.82	(2.80)	0.81	(2.88)
M	0.68	(2.75)	0.79	(2.06)	0.72	(1.60)
N	0.50	(4.09)	0.81	(2.89)	0.77	(2.76)
O	0.90	(2.17)	0.80	(2.48)	0.76	(2.76)
P	0.38	(3.47)	0.28	(3.52)	0.70	(2.74)
Q	0.89	(1.86)	0.85	(1.84)	0.86	(2.16)
R	0.82	(2.49)	0.71	(2.96)	0.34	(4.92)
S	0.57	(4.35)	0.87	(2.50)	0.48	(4.62)
Average	0.71	(3.08)	0.74	(2.85)	0.71	(2.82)

CC: Correlation coefficient   AV: Average variance

of the real and virtual environments by measuring the perception of distance, because distance estimation is the most basic knowledge necessary for a human to behave in a space.

Also, how to merge the perception of multimodal sensors, including visual, audio, and force-feedback sensors, is another problem when we use the VR system as the experimental space. Because the virtual world is perceived through the information provided in the system, it is important to understand these kinds of interface with multimodal sensors.

4.1 Distance Perception

We investigated the reasons behind the difference in perception between real and virtual space. We carried out experiments on distance estimation, which is important when VR systems are applied as a presentational tool for evaluating environmental design or planning in architecture or building simulation. In this kind of application, the short distance is more important than the long one because the scope of human behavior is relatively small in reality.

Not only in architectural applications but also in many fields of industry, accurate and proper distance representation is one of the most required functions when the user walks around the virtual space during the evaluation process. Defining and clarifying the factors related to spatial cognition will help the constructor of VR systems to compensate for the difference between the real and the virtual world in order to represent the environment on screen with similar characteristics as those of real space. Also, the investigation of the human recognition of distance is a fundamental research area in the realization of accurate VR systems for architectural or urban design evaluation.
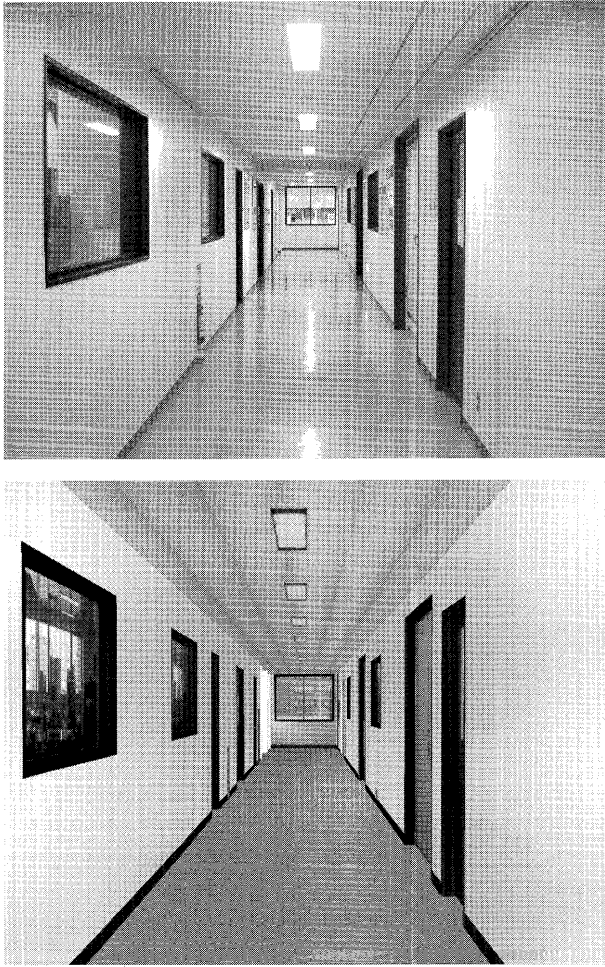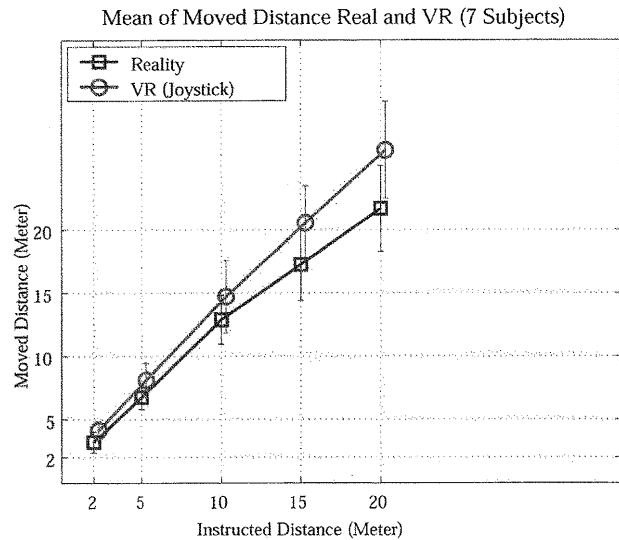
Fig.6. Real & Virtual Hallway

Mean of Moved Distance Real and VR (7 Subjects)

$F = 17.304 > 4.\ 001\ P = 0.0001 < 0.01$

Fig.7. Graph of Perception of Distance in Real & VR

Table 2. Comparison of Estimation by Physical Distance in Real & VR Space

		2M	5M	10M	15M	20M
VR	Estimation	4.1	8.1	14.7	20.5	26.3
	Estimation /Physical	205%	161%	147%	136%	131%
Real World	Estimation	3.2	6.7	12.8	17.2	21.6
	Estimation /Physical	160%	134%	128%	114%	108%

Before performing the experiment, we proposed the hypothesis that the insufficiency of information provided to the user in VR causes a distance estimation difference from that in the real world, because we noticed that users are usually comfortable with moving fast over long distance in VR environments, unlike in real space, as shown in Fig.6. We inferred that the different behavior resulted from the shortage of information from sensors in many aspects.

Comparing the distance estimations in real and virtual space is not very easy because making an experimental environment in the real world has limitations, such as those of space, time, and cost. Therefore, many researchers have used the existing real space for comparison with the virtual space. To make an experiment possible in real space, we chose the hallway near the D-vision system room as the experimental environment, as shown in Fig.6. The hallway is about 30 meters long, which is sufficient for estimation distances of 2, 5, 10, 15 and 20 meters. The proximity to the system room of immersive virtual environments is another reason why we chose this hallway, because the subject can move to the virtual space quickly.

First, we verified the distance estimation by the walked-distance judgment in the real and virtual hallways. We recorded the walked distance of subjects instructed to walk to 2, 5, 10, 15, and 20 meters without counting time or steps in both real and virtual hallways while looking straight ahead. The results showed that the distance in virtual space was underestimated by about 20% - 40% compared with the distance estimation in real space, as shown in Fig.7. These results support the experimental hypothesis that an insufficiency of information to the user in VR causes a different distance sensation from that in the real world. Also, the gap between the distance estimation and the physical distance was large for short distances between real and virtual space, as shown in Table 2. The much greater gap at the initial stage of walking behavior is probably caused by the much smaller amount of information including that from the proprioception organs.

Up to now, we have verified the difference distance in estimation between real and virtual space. Therefore, what are the factors behind this different perception of distance in virtual space? There may be two factors that are believed to affect the underestimation of distance in virtual space. Regarding the image, the resolution, brightness and stereoscopy are included in this category. Regarding the system, the field of view (FOV) and other sensory interfaces such as force feedback are included in this category. These will be future research topics.

4.2 Multimodal Sensing of Information

There are other issues in architectural design using the VR applications. For example, the multimodal interface will provide not only visual information but also force feedback information to the user. The architectural application, MovingDesk (Ryu, 2004), is a support system for designing the interior of a living room using the force feedback interface, SPIDAR (Ishii, 1994). When we use such kinds of interface that enable us to manipulate objects directly, we should consider the effects of adopting them in virtual environments. Furthermore, the effects of multimodal interfaces on the degree of presence or distance perception are complicated and remain unclear. Also, the conventional and the new methods of virtual environments for the design process must be reconsidered and investigated to provide a firm foundation and direction for these kinds of research.

5. Proposition for Collaborative Research

The environmental design evaluation experiment is an interdisciplinary issue because both psychophysical theory and technical knowledge are required to carry out the experiments. Usually, the main pursuits of the academic fields of concern in this paper are quite different, that is, one is to realize better human environmental design and the other is to achieve technical advance. Therefore, some special considerations are necessary in such a collaboration of two major fields to complete this kind of research.

Fig.8. shows the conceptual workflow of the collaboration between two departments. The diagram shows a circular workflow, initiated from the request of the architectural department, which can improve both the system and the experiment. The merit of this kind of collaboration is that we can utilize the characteristics of each field to achieve the synergy effect. The architectural department is responsible for the 3D modeling task and setting up the scenarios of experiments.

The computer department is responsible for the calibration and preparation of experimental devices and the experimental computer programming. Occasionally, a director in the overlapping area is required as an experienced manager who has knowledge of both fields. For example, the modeling tasks must be performed by the architectural department that is planning the experiments on the evaluation of architectural treatments considering the sensitive limitation and the parameters of the system requirement. After the completion of modeling, the system management group constructs the virtual world using the modeling data. Sometimes, there are subtle requests concerning experimental variations such as walking speed, sensing of the head direction, and special events to help smooth the experimental process. Cooperating with the computer departments to cope with these kinds of requirement relieves the load of the
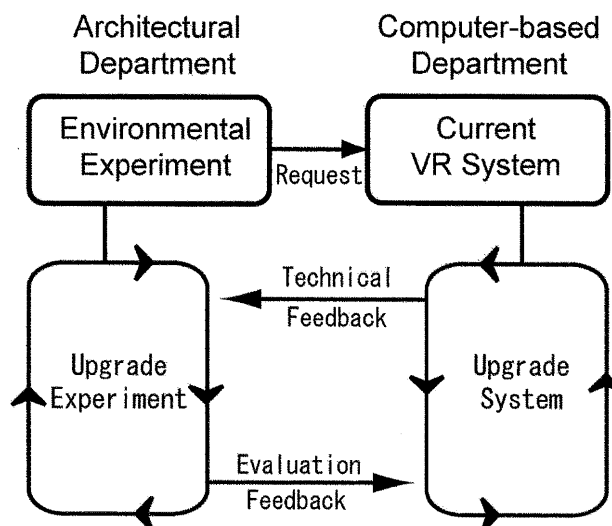

Fig.8. Diagram of Collaborative Research

architectural department, enabling it to concentrate on the theory or the contents of the experiments.

One of the secondary advantages is that the computer department can understand the actual requirements concerning the VR system from the perspective of a non-developer. The nontechnical researchers' criticisms are often sharp because they compare the VR representation with the real environment without considering the technical limitations. In general, the requirements for the experiments are quite high in order to satisfy the expectations of the user. Without this type of collaboration, the developers of VR systems must decide the direction of progress by themselves. Sometimes the direction of development does not match the real requirements. By using the VR system in real applications and collaborating with actual users, the developer can obtain the proper evaluation feedback from the system. Consequently, it is an excellent opportunity to improve their VR system.

6. Conclusion

In this paper, we have proposed the application of an original human-scale immersive virtual system, that is, a multiprojector with the multimodal interface system D-vision, to assess urban environmental design and to perform experiments on human behavior. We also examined several problems in using the VR system as the experimental space, such as the validity of using the VR system instead of a real space, the distorted distance perception, and the effects of multisensory interfaces. Also, the unique collaborative experiments of architectural and computer-based disciplines, the workflow diagram, and its advantages are explained, giving several examples.

This research is still on going to realize more complete VR applications for the planning and evaluation processes of environmental or architectural design. To satisfy the requirements of actual users, human factor issues, such as sensory perception

and psychological cognition, must be researched in greater detail. In a future work, we are planning to use this system in the conceptual design process with a hand-manipulated force feedback interface. Another application of interest is as an educational system for disaster preparedness training.

References

1) Azuma, R.T. (1997). "A survey of augmented reality." Presence: Teleoperators and Virtual Environments. Vol. 6, Issue 4, August 1997, pp.355-385.
2) Cruz-Neira, L., Sandin, D. and DeFanti, T. (1993) "Surround-Screen Projection-Based Virtual Reality: The Design and Implementation of the CAVE." Proceedings of ACM SIGGRAPH'93, pp.135-142.
3) De Kort, Y., Ijsselsteijn, W., Kooijman, J. and Schuurmans, Y. (2003) "Virtual Laboratories: Comparability of Real and Virtual Environmental for Environmental Psychology", Presence: Teleoperators and Virtual Environments, Vol. 12 Issue 4, Aug 2003, pp.360-373.
4) Han, S. (2006) "A Study on the Distributed Collaborative Architectural Design System", Journal of Asian Architectural and Building Engineering. 5(1), pp.67-74.
5) Hill II, L.C., Chan, C-S. and Cruz-Neira, C. (1999) "Virtual Architectural Design Tool (VADeT)." Third International Immersive Projection Technology Workshop (IPT 1999), pp.1-11.
6) Ishii, M. and Sato, M. (1994) "A 3D Spatial Interface Device Using Tensed Strings." Presence: Teleoperators and Virtual Environments, Vol. 3, Issue 1, pp.81-86.
7) Leigh, J., Johnson, A., Vasilakis, C. and DeFanti, T. (1996) "Multi-perspective collaborative design in persistent network virtual environment." Proceedings of IEEE Virtual Reality Annual International Symposium'96, pp.253-260.
8) Ohno, R., Aoki, H., Soeda, M. (2001) "A Visual Simulation by Realtime CG Overlaid on the Video Image of a Scale Model." AIJ J. Technol. Des. No. 12, pp.135-138.
9) Ryu, J., Hasegawa, S., Hashimoto, N. and Sato M., (2004) "Multi-Projection Display System for Architectural Design Evaluation." The 9th Conference on Computer-Aided Architectural Design Research in Asia (CAADIRA) 2004, Paper Number 81, pp.901-910.
10) Ryu, J., Hashimoto, N., Sato, M., Soeda, M. and Ohno, R. (2006) "A Game Engine Based Architectural Simulator on Multi-Projector Displays." Computer Aided Architectural Design Research in Asia (CAADRIA) 2006, pp.613-616.
11) Soeda, M., Ryuzo, O., Ryu, J. (2003) "The Effect of Architectural Treatments in Reducing Oppressed Feelings Caused by High-rise Buildings." Proceedings 6th EAEA Conference, Bratislava, pp.28-35.
12) Shen, J., Wu, Y. and Liu, H. (2001) "Urban Planning Using Augmented Reality." Journal of Urban Planning and Development, pp.118-125.
13) Shibano, N., Hareesh, P.V., Hoshino, H., Kawamura, R., Yamamoto, A., Kashiwagi, M. and Sawada, K. (2003) "CyberDome: PC Clustered Hemi Spherical Immersive Projection Display." 13th International Conference on Artificial Reality and Telexistence
14) Broll W., Lindt I., Ohlenburg J., Wittk amper M., Yuan C., Novotny T., Schiecky A.F., Mottramy C. and Strothmannz A. (2004) "ARTHUR: A Collaborative Augmented Environment for Architectural Design and Urban Planning." Journal of Virtual Reality and Broadcasting, Volume 1, No. 1, pp.1-10
15) Kalay. Y. E. (2004) "Architecture's New Media"
16) 1966, Sutherland creates first computer-based head-mounted display: Sutherland created a tethered head-mounted display (HMD) using two CRTs mounted beside each of the wearer's ears, with half-silvered mirrors reflecting the images to the user's eyes. Another system determined where the user was looking and projected a monoscopic wireframe image such that it appeared as if a cube was floating in mid-air. The bulk of the system was attached to the ceiling above the wearer's head. http://www.media.mit.edu/wearables/lizzy/timeline.html