DOES COLOR HAVE WEAKER IMPACT ON HUMAN COGNITION THAN MATERIAL?

CHIU-SHUI CHAN
Iowa State University, USA

Abstract. This project intends to develop a method for using virtual reality (VR) to represent a built environment for simulating environmental influences on occupants. Objectives of the project were to explore: (1) what environmental stimuli would affect habitants' perception, and (2) what possible factors in the built environment would affect occupants' cognition. An office was selected as the subject of study. Methods were to create a number of digital models, each containing an embedded variable, and then test the impact of environmental influences on visual perception. Results obtained in this study indicate that materials have stronger impact to human perception than colors, and VR has great potential for design decision making and post-occupancy evaluation.

1. Information Impacts on Human Cognition

Based on major concepts from information-processing theory (Newell and Simon 1972) and verified by various research conducted in the field of neuroscience (Bear Connors and Paradiso 2001), the fundamental assumption of this research is that the human brain is constantly processing information (Singer 2007). It accepts information input from the environment and generates certain reactions as output. This sets up the basic premise of this research project.

A building houses human activities which could be affected by the quality of the building. An office building, for example, is a working environment that produces various sensory stimuli—light, sound, color, texture, temperature—to which occupants react on both conscious and subconscious levels. All this sensory information is intangible, but subtly influences human cognition and perception in ways that yield intellectual responses (Reed 1992). Because the mind experiences architecture through visual perception (Eberhard 2000), if good information is received and perceived, the response should be positive and productive. This study, therefore, posits that "the information generated in a space affects human

A Dong, A Vande Moere & JS Gero (eds), CAADFutures'07, 373-384.

cognitive performance and an effective workplace environment would provide positive stimuli to promote productive cognitive responses.” Under this hypothesis, understanding what the occupants’ actions and reactions are, as well as how and why they occur in a particular environment, would help designers to improve their designs (Wierenga Hase and Call 2004). This project intended to develop feasible methods to explore this idea.

2. Exploring Visual Information

Audio and visual information are the most immediately recognizable inputs in any given space. Visual information relates to images of objects perceived through forms, materials, and colors, whereas audio information consists of the sounds occurring in the environment. The appearance of objects and sounds in space are the major sources of sensory information for human cognition. This paper provides a set of experiments focusing on visual information and discusses findings in the context of an ongoing study of broader scope.

Typically, experiments for studying sensory impacts or causal effects in environments are conducted in physical buildings to observe results first-hand. However, if there are different experimental settings that must be changed sequentially for different tasks, it is too time-consuming to modify settings and too costly to run short experiments at different settings, especially if the task is complex and the settings are complicated. A virtual reality (VR) environment, however, is suitable for such circumstances. Virtual environments that can generate a high degree of presence are thought to be more effective and better suited to task performance (Slater 1994; Nunez and Blake 2001).

3. VR Representation for Visual Information

Virtual reality—a scientific, three-dimensional representation of objects displayed digitally—is an exciting new technology that offers a way to address many aspects of human behavior in a simulated environment (Thalmann and Thalmann 1994; Chan Hill and Cruz-Neira 1999; Chan Tong Dang and Qian 2003; Vince 2004). A virtual environment that allows an investigator to modify a model and immediately see the results is even better. A full-scale, immersive VR environment (e.g. three-sided or six-sided VR facility, see Figures 1 and 2) is superb, for it provides more direct information for studying impacts, as it yields a greater sense of presence (Chan and Weng 2005).

Figure 1. Three-sided VR facility.

Figure 2. Six-sided VR facility.

The concept of sense of presence relates to the sense of "being there" and the sensation of reality in the projected space. Three major conditions are used to judge the sense of presence created by a system: image quality, image size, and viewing distance (Lombard and Ditton 1997). In general, larger, higher-resolution images and close proximity between viewers and images yield a higher sense of presence, as they provide more reality, intimacy, involvement, and participation for the viewers with the environment. A full-scale immersive system thus serves the purposes even better, for it closely approximates actual size and distance with full-scale, high-resolution 3D objects generated in real time. Therefore, the immersive VR environment of three- or six-sided CAVEs may create a much more vivid sense of presence than other facilities with head-mounted or bench displays.

Following this line of thought, it is justifiable to say that experiments conducted in full-scale virtual environments are reasonable representations of the visual experiences obtained from real-world interactions. Therefore, applying VR technology as a study tool to represent a building and examine its design through perception is very appropriate (Patel Campion and Fernando 2002). Because visual perception provides us with more content and meaning than other senses, it more easily triggers the sense of presence.

4. Cognitive Processes in Human Perception

Perception occurs after the information presented in the environment has been attended and received. The perceived information is encoded in the visual register (visual buffer) in its original form. At this time, the mind performs pattern recognition and searches for stored knowledge associated with the pattern, to help decide appropriate actions to be taken (Anderson 1980). If the new input does not match any stored patterns—if the coding is different—then learning occurs. Consequently, decisions could be affected, actions could be changed, and results could be either strengthened or weakened. Therefore, the information provided by the living or working environment may exert a great deal of influence on cognitive processes which affects occupants' level of comfort in the environment. The possible information (environmental stimuli) includes materials and colors of artifacts in the space, which leads to the following hypotheses.

5. Theoretical Hypotheses

In building design, certain materials are used for certain components to meet certain structural requirements. Thus, the attributes and properties of materials should match with the typology of the building. If material use does not match building typology, then the perceived image is likely to elicit a certain cognitive response.

On the other hand, color is considered one of the most useful and powerful design tools to affect human emotions and perceptions. People respond to different colors in different ways, and these responses take place on a subconscious and emotional level. Birren (1978) defined two systems of color: warm and cool. Warm colors are those between red and yellow on the spectrum, whereas cool ones are between green and violet. Warm colors tend to stimulate the human organism. When human beings perceive warm colors, blood pressure, pulse rate, respiration, and perspiration accelerate and brain waves increase; feelings of restlessness and excitation may follow. There also is a noticeable muscular reaction (tension) and greater frequency of eye blinks. Conversely, cool colors are relaxing and retard bodily processes. Blood pressure and pulse rate are lower, skin response (perspiration) is less, and brain waves tend to decline.

Goldstein (1939) similarly found that red incites activity and is favorable for emotionally-determined actions; green induces a meditative mental state and creates an environment favorable to meticulousness. Red may be suited to produce the emotional state out of which ideas and action will emerge. Environmental colors have also been documented as affecting learning ability. A three-year experiment conducted on rooms painted light blue, yellow, yellow-green, and orange found that a variance of up to 12 points could be measured on standardized intelligence tests. Certain colors, including white, black, and brown, caused a drop in measured IQ. Researchers found that popular colors also stimulated alertness and creativity; white, black and brown playrooms made children less active. In advertising, this knowledge suggests that color evokes feelings or memories that encourage viewers to keep the goods on display. In hospitals, a green color scheme has been used to create a relaxing environment to help ease stress for patients.

Symbolically, each color has certain positive and negative meanings (Nolan 2002; see Table 1). But colors are subtle with great variations, and it is difficult to make clear-cut or absolute statements on their meanings. It is the same in perceiving materials. However, if there is a tool that could be used to systematically represent materials and scientifically control the variation of colors, then results of perception could be recorded for justifying the embedded value in color and material. Applying virtual reality as a study tool to understand how color and material affect human perception and reaction would serve the purposes and further demonstrate the application value of virtual reality.

TABLE 1. Positive and negative meanings of color.

Color item	Positive meaning	Negative meaning
White	Clean, innocent, pure	Cold, empty, sterile
Red	Strong, brave, passionate	Dangerous, aggressive, domineering
Green	Natural, tranquil, relaxing	Cold, depressing, gloomy
Blue	Strong, trustworthy, authoritative	Jealous, inexperienced, greedy

Based on the biological findings of Birren and Goldstein, it is assumed that red (warm) colors in a space will stimulate and excite occupants, and blue (cold) color will have a calming effect on occupants. Thus, the second hypothesis assumed that cool (blue) color would generate more comfortable feelings in a stressful office environment than warm (red) color did. However, emotion might also have connections with previous experience stored in memory. Thus, from a cognitive psychology point of view, occupants' remembered experience and personal preference on colors might add an extra dimension to their reaction to environmental input. As such, emotion and personal experience would be different from person to person due to the individual differences. But, this second hypothesis applies primarily to studying the level of comfort elicited by color, and it is necessary to find a common denominator across individuals.

6. Methodology

The Adaptable Workspace Laboratory (AWL), an office environment located on the seventh floor of the US General Services Administration (GSA) headquarters in Washington, DC, was selected as the study subject for this project. The AWL encompasses 11,000 square feet and houses about four-dozen federal agency employees. This lab was designed and installed in 1999 by the General Services Administration, Carnegie Mellon University, and Oudens + Knoop Architects to turn the 85-year-old historic space into a modern office facility. Subsequently, the American Institute of Architects (AIA) has partnered with GSA to include neurological/cognitive research on how occupants react to their physical surroundings. This project is a part of those efforts.

Based on drawings provided by GSA and AIA (see Figure 3) and an on-site survey to determine accurate dimensions of each component, a digital master model of the AWL was developed (see Figure 4). In addition to applying similar methods to those used in reconstructing historical heritage and archaeology (Gaitatzes Christopoulos Roussou 2001; Zach Klaus Bauer Karner and Grabner 2001, Chan Dang Tong 2005), this high-resolution, realistic computer model inserted certain levels of detail, personal touches, and office supplies in the cubical to suggest the existence of occupants (see Figure 5).

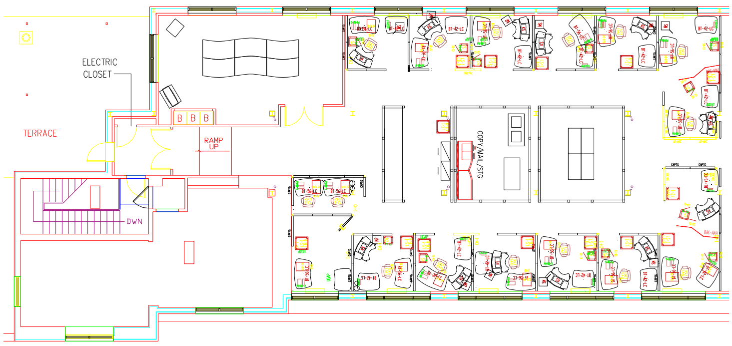

Figure 3. Floor plan of the AWL.

Figure 4. Master model of the AWL.

Figure 5. Image of a cubical.

Figure 6. Blue color on wall.

Figure 7. Red color on the wall.

After the master model was finished, four models, with identical geometry, were generated with changes in wall color. For instance, the wall color in Figure 6 is blue and red in Figure 7. The model in Figure 8 has blue painted from floor to ceiling and red is used similarly in Figure 9. The purpose is to study how colors actually impacted human perception.

Figure 8. Blue color on wall + ceiling.

Figure 9. Red color on wall + ceiling.

Figure 10. Three different materials used on all structural components.

Figure 11. Three different materials for the partition walls only.

Figures 10 and 11 show the changes in materials, including brown oak wood, dark cherry wood, and light marble. Traditional partition walls in an office environment were plastic with gray fabric. If material changes are made in a conventional space, occupants might not be able to accept the changes psychologically. If the changes are unconventional and dramatic, then the psychological reaction may be even stronger. Figure 10 shows the changes in materials on the partition walls plus structural frameworks to oak, cherry, and marble. Models in Figure 11 have only the partition walls changed to oak, cherry, and marble. These models were converted to VR model format and displayed virtually afterward.

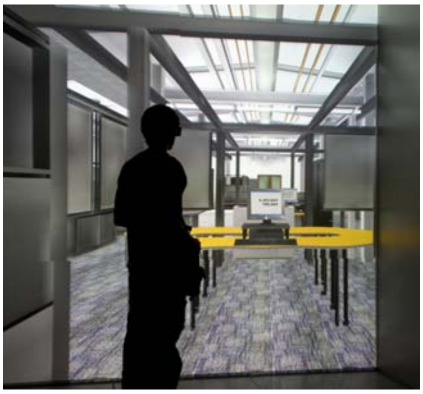

Figure 12. AWL model seen in the immersive VR environment.

Thirty-one subjects participated in the experiment, which was held in the three-sided immersive VR facilities at Iowa State University (see Figure 12). Among them, eleven were architecture majors and twenty were non-architecture majors. Subjects were required to first view the master model, navigate through the entire space and memorize the scene. Afterward, they would view the remaining ten different models representing the changes in color and material, and rank their satisfaction at the end of each model. Scores range from zero to nine, with zero meaning the subject found the change very unsatisfactory and nine meaning it was very satisfactory. The experiment time was about one hour.

7. Experiment Results

In this experiment, subjects were divided into two groups—architecture majors and non-architecture majors. The experiments had ten treatments, categorizable into two major treatment groups of color and materials. The first four columns in Table 2 represent the color group, in which the names with "–all" represent the color painted on walls and ceilings. The last six columns describe the material group. The material names ending with "p" represent that these materials are used only on partition walls, while others are used on walls plus structural frames.

The average mean scores of each treatment are given in Table 2. Row one and two of the table are the average mean score of each treatment by subject group. Row three is the overall mean for each group. Row four is the "estimated" value of least squares means through the procedure for mixed (proc mixed) model method.

According to repeated measure ANOVA statistical analysis, the residuals are distributed normally, and there is no evidence of interaction between the treatments across the subject groups (P=0.8560). Thus, it is justifiable to compare the mean scores across treatments between the two subject groups. In comparing the differences between the two subject groups, the p-value for the architecture subjects' main effect is 0.9965. As such, it is indicated statistically that there are no differences between the average scores of the two subject groups in responding to the treatments.

In studying the significance of mean score of each treatment, the p-values for treatments are <0.0001 (standard deviation = 0.3221), which indicates that there are significant differences between at least two treatments. The score given in the last row of Table 2 shows the differences.

TABLE 2. Means of subject groups and grand means.

	blue	red	blue-all	red-all	oak	cherry	marble	oak-p	cherry-p	marble-p
Arch	**5.27**	**5.82**	**5.27**	**5.27**	**5.05**	**3.91**	**3.55**	**6.45**	**4.73**	**4.23**
Non-arch	**6.15**	**5.80**	**5.00**	**4.85**	**5.10**	**4.15**	**3.55**	**5.80**	**4.80**	**4.33**
Grand-mean	**5.84**	**5.81**	**5.10**	**5.00**	**5.08**	**4.07**	**3.55**	**6.03**	**4.77**	**4.29**
Estimate	**5.71**	**5.81**	**5.13**	**5.06**	**5.07**	**4.03**	**3.54**	**6.12**	**4.76**	**4.27**

TABLE 3. T-value and p-value in comparing color pairs.

10 models	**Treatment**	**Treatment**	**T-value**	**P-value**
Treatments	blue	red	-0.25	1.0000
Treatments	blue	blue-all	1.46	0.9169
Treatments	blue	red-all	1.64	0.8393
Treatments	red	blue-all	1.7	0.8098
Treatments	red	red-all	1.89	0.6965
Treatments	blue-all	red-all	0.19	1.0000

In order to test the effects within and between the color and material groups, pair wise comparisons were used for all treatments. In comparing the group differences among color and material groups, a contrast statement is used in SAS to test whether the average mean scores of treatments in color group is different from the average scores of treatments from material group. Results show the difference is significant ($p < 0.0001$, standard deviation = 0.1840). This indicates that some variables (treatments) in the material group are more significant than others (see Tables 3 and 4).

Regarding differences within color groups, the adjusted p-value using the Tudey-Kramer method is shown in Table 3. The p-values among the pairs of blue wall, red wall, blue wall-and-ceiling, red wall-and-ceiling were not significant (P values are greater than 0.05; standard deviation = 0.4022). This means that the color used in this experiment makes no significant differences to the subjects.

TABLE 4. T-value and p-value in comparing material pairs.

10 models	Treatment	Treatment	T-value	P-value
Treatments	oak	cherry	2.61	0.2391
Treatments	oak	marble	3.82	0.0079
Treatments	oak	oak-p	-2.68	0.2198
Treatments	oak	cherry-p	0.76	0.9990
Treatments	oak	marble-p	1.97	0.6190
Treatments	cherry	marble	1.21	0.9729
Treatments	cherry	oak-p	-5.30	<0.0001
Treatments	cherry	cherry-p	-1.87	0.7279
Treatments	cherry	marble-p	-0.65	0.9998
Treatments	marble	oak-p	-6.52	<0.0001
Treatments	marble	cherry-p	-3.09	0.0834
Treatments	marble	marble-p	-1.87	0.7327
Treatments	oak-p	cherry-p	3.45	0.0273
Treatments	oak-p	marble-p	4.68	0.0003
Treatments	cherry-p	marble-p	1.23	0.9699

However, in comparing the mean score of materials, there are significant differences within the group. Especially, the oak wood used for the cubical partition walls (represented by oak-p) has the highest score received among the entire treatments. In other words, whenever the oak material used for partition walls (oak-p) is drawn from the data for comparison, their p-value is always significant except in comparing with the oak for partition-wall-and-frames (see Table 4). In this study, marble used on partition wall and frame received the lowest score of 3.54 ($p<.0001$, standard deviation = 0.3247), which is significant in this treatment.

8. Discussion

In this study, the purposes were to test and explore the environmental stimuli that would affect visual perception and to explore the factors that impact human cognition. The methods included: (1) developing a VR model representing a built environment, (2) sequentially changing the model to simulate various changes of the environment, (3) recording the reaction from viewers to verify the impacts, and (4) analyzing the data from comparing each variables to justify the significance of each impact. Through the analysis, it is very interesting to find out from data that material plays an important role in the visual perception of the environment. Oak wood (oak-p) is the popular element (mean score of 6.1273, standard deviation = 0.3221) that is welcomed by viewers followed by cherry (cherry-p, 4.7636, standard deviation = 0.3221) and marble (marble-p, 4.2761, standard deviation = 0.3221) regardless if viewers have trained design knowledge background to make judgment or not. In office design typology, the modern standardized material used for cubical partition is fabric. Marble is mostly used in grand scale of buildings or public buildings, which is also not a convention used in semi-private working spaces. Therefore, spaces having marble shown in partition walls and structure framework (represented as marble) are unusual, which is the reason why it is treated as uncomfortable environment with mean score of 3.6472 (standard deviation = 0.3247). Maybe there are other emotional factors attached to it, but, hypothesis one that "if the use of material does not match the building typology, then the perceived image would have some cognitive reactions" is confirmed in this round of study.

Regarding color factors, blue had the highest mean score (6.15, $p<0.0001$, standard deviation = 0.3838) among the four color treatments in the non-architecture group; but second highest in the architecture group. It also found that the models with blue ceilings (blue-all) had scores equal to or greater than red in the two subject groups (see Table 2). The higher scores on blue-all than on red-all group slightly proved the hypothesis two, even though the statistical analysis doesn't show significant p-value in comparing this pairs.

Another reason for the slight difference between the two colors could be explained as that color effects are always temporary (Birren 1978). Exposure to color does not cause reactions of any substantial duration. The reaction to color is similar to the reaction to alcohol, tobacco, coffee – up to a short period and then down. In fact, if red is stimulating after a length of time bodily responses may fall below normal. But, this hypothesis addresses mainly, again, on studying the level of comfort agitate by colors. On the other hand, the applied statistical analysis treated subjects as random sample, which means that the subject pool participated in this study have no influence to larger sample pool. Thus, if the population size of subjects increases, the result might have changed accordingly.

It is not surprising that the differences among architectural group and non-architecture group were not statistically significant. This is due to the facts that: (1) the architecture pool is a small pool of eleven, and (2) five out of eleven in the architecture group were freshmen, who do not have enough training in architectural design at the time of participating the experiments for this to be a factor in their responses. It is assumed that trained designers would definitely have good design knowledge on color and better understanding on the use of material to fit special functional requirements in design.

Based on the data analyses on the series of VR experiments, two hypotheses were tested and slightly proved to some degree, which yielded two findings. The first one relates to the discovery of factors in the built environment. The factors affecting viewers' perception are materials and colors shown in artifacts in space. Material factors are statistically stronger than color in the effectiveness on visual perception. Viewers could perceive the existence of these environmental stimuli through the texture and color of materials on surfaces. Based on their previously stored visual memory, viewers would react to the perceived image and express their satisfactory level immediately. For instance, one subject in the architecture group who commented on color immediately noted that "the red color shown on ceiling is a strange look and presumably is not acceptable in a federal office building," which leads to the second study.

The second study relates to the factors in a built environment that would affect human cognition. These factors could be the design representation used by designers and the design knowledge owned by viewers. The design representation includes the common design convention applied in the profession and possibly the design knowledge that viewers have learnt previously. For instance, if there are unconventional design shown in the built environment, viewers would perceive the representation, do pattern recognition, search for design related knowledge in memory and respond the matching results back afterwards. If the perceived image does not match with the information stored in knowledge repertoire, then new information would fit into existing one (assimilation), or alter the existing one in order to accommodate new information (accommodation), or a new knowledge representation is created. That is why the design representation affects learning through perception; which changes the knowledge structure affecting human cognition.

9. Conclusions

This study is a long term study pursuing a larger scope on human cognition in space. The intentions on setting up the experiments were to be testing whether people with prior training in architecture respond differently to changes in materials and colors than people without such background. In order to collect more data for verifying this hypothesis, an advanced method of protocol analysis should be applied. In fact, protocol analysis had been applied to a couple of subjects, but, will be a part of future studies.

After all, the most amazing result in this study shows the value of applying virtual reality to simulate a physical environment. This study demonstrated that VR is a very good tool for building performance evaluation. If this study could get more subjects involved to increase the subject population size, it would improve the statistical significance to validate (confirm or refute) the concept and theory further, which will be the goal for future studies.

Acknowledgements

This project was funded by the General Services Administration and the American Institute of Architects from 2002 to 2005. Thanks go to YuNgok Lo and Qian Chen for digital modeling and Kerstin Hovland for development of algorithms. Eight figures shown in this paper were created by Qian Chen. Special thanks also go to Kevin Kampschroer, John Eberhard, John McRae, and Edward Jackson for their encouragement and support; and to the Virtual Reality Applications Center at Iowa State University for the use of the immersive three-sided virtual reality facilities.

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