INTERACTIVE LIVING SPACE FOR NEO-NOMADS:

AN ANTICIPATORY APPROACH

by

Asma Naz

APPROVED BY SUPERVISORY COMMITTEE:

____
Mihai Nadin, Chair

____
Charissa N. Terranova

____
Ryan P. McMahan

____
Frank Dufour

____
Regis Kopper

In memory of my father Ershad Uddin Ahmed

AN INTERACTIVE LIVING SPACE FOR NEO-NOMADS:

AN ANTICIPATORY APPROACH

by

ASMA NAZ, B. ARCH., M.S.

DISSERTATION

Presented to the Faculty of

The University of Texas at Dallas

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY IN

ARTS AND TECHNOLOGY

THE UNIVERSITY OF TEXAS AT DALLAS

May 2017

ACKNOWLEDGMENTS

This dissertation is the outcome of an extended process of learning, experiment and discovery to which many contributed. To all those who through the years guided and supported me I hereby express my respect and gratitude. Direct contributions by those who provided guidance during the entire process of developing and finalizing this dissertation are herewith respectfully acknowledged. Members of the Supervising Committee—Professors Frank Dufour, Regis Kopper (Duke University), Ryan McMahan, Mihai Nadin and Charissa Terranova—assisted me with knowledge from their respective fields. Insightful suggestions, hard questions and encouragement from them informed my research and are reflected in the dissertation. Specifically, Dr. Kopper and Dr. McMahan assisted in designing the Virtual Environment experiment, suggested by the Chair of the Supervising Committee, and in the processing of data. My presentation at the prestigious IEEE VR Conference (Los Angeles, March, 2017), where results were presented, confirms their vote of confidence in the quality of the hypotheses tested and in the general concept. Dr. Kopper understood the relevance of my research in the DiVE at Duke University, donating lab time, his own expertise, and providing assistance when necessary. Additional thanks to David Zielinski for his generous cooperation in DiVE training and research. The IRB Board at UTD and Duke University cooperated in a manner that made the work progress in time. The Virtual Reality experimental phase benefitted from the financial assistance of a Dissertation Research Award from The University of Texas at Dallas and by support from Duke University.

This dissertation would not have been possible without the continual support of Dr. Mihai Nadin, Chair of the committee, one of my professors within ATEC. It is through his inspiration and guidance that a raw idea, addressing a real-life problem, was initiated, formed and developed. His active involvement in the research leading to my dissertation encouraged me to seek opportunities for research and interaction with the academic community at UTD and around the world. This included participation in the international conference “Anticipation Across Disciplines” at the Hanse Wissenschaftskolleg (Germany), and the publication of my conference paper. During the peer review process of the volume (published in the highly respected Springer Cognitive Systems Monograph Series), I found many opportunities to exchange ideas with distinguished scholars. Dr. Nadin also extended support to me on a personal level, through his understanding, patience, kind words and a compassionate ear at times of critical need, especially during the extremely difficult time when my father passed away. Among his many students, I am probably one of those, among many, who will never be able to fully convey their appreciation. His mentorship and presence have made us not only better researchers, but also better persons.

In this sense, no less important is the realization that my family, especially my parents, helped me overcome many hurdles in pursuing my PhD. Through their unconditional support, they were the source of love and strength that made my work possible, and the transformation of my dreams into reality. I cherish the love, patience and help from my husband, Ahsan, throughout the years. I also thank the Fatemis for welcoming me into their family and enriching my life with their love. Thanks to Ali, Mrs. Sarah Fatemi and Mrs. Elvira Nadin for their warm welcome and generosity that have made me feel at home in a land far away from home. Finally, I thank the presence of the many friends, acquaintances and well-wishers in my life—too many to name here—who have encouraged and kept me motivated to complete my research.

March 2017

AN INTERACTIVE LIVING SPACE FOR NEO-NOMADS:

AN ANTICIPATORY APPROACH

Asma Naz, PhD
The University of Texas at Dallas, 2017

Supervising Professor: Dr. Mihai Nadin

This dissertation proposes a design concept for an interactively modifiable living space aimed to support the lifestyle of *neo-nomads*. Popularly known as Silicon Valley talent, this new breed of highly mobile, technology-dependent, creative professionals is currently facing a severe housing crisis (limited availability, often resulting in higher rent). The proposed architectural concept consists of a single, multi-functional living space. It is designed to offer an adaptive, highly optimized spatial solution that reflects and enhances the transitional, temporal, minimalist living of young mobile professionals.

The proposed design is informed by awareness of anticipatory processes. The proposed dwelling is designed to allow occupants the technical possibility to generate affective spatial qualities adapted to their needs. This is made possible through interaction with space characteristics (such as texture, color, contrast and other aesthetic parameters) in order to accommodate their current and emergent emotional, psychophysiological needs. Affective space-making is acknowledged as a primary goal of architecture. The traditional space articulation technique is introduced in the realm of interactive design with the goal of modifying sensory design elements of color,

brightness, texture and material that can be perceived by the occupant as warm, cool, exciting, calm, spacious or intimate. The proposed design was evaluated in a six-sided interactive Virtual Environment. The experimental component had the goal of providing data to support the description of an underlying aesthetic framework. The data acquired helps define a guideline for meaningful human-space interaction design.

As a testament of its time, architecture represents a way of life, symbolizing contemporary and emergent technologies, lifestyles and ideologies. The proposed design attempts to define interactive architecture that is physical, tangible and essentially spatial in nature, and which provides a platform for further research and experimentations for a humane and aesthetic living solution for the target group.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Research Overview

This dissertation integrates architectural knowledge of space design with interactive system design in the field of habitable interactive architecture. A new design concept of an interactively modifiable living space is introduced as a real-world dwelling that consists of a single living space with variable design parameters of color, brightness, texture and material used to generate affective or emotional experiences of spaces. Through human interaction with physical space, occupants generate possible sensory-perceptive, affective spaces by means of spatial articulation in real time with the goal of accommodating their evolving emotional, psychological, physiological and aesthetic requirements associated with daily activities. Here, spatial articulation—a space creation technique of traditional architecture—refers to modification of overall visual quality of space, i.e., character, feel and appearance, by manipulating the variables of visual space perception. These variables generally include but are not limited to light, material, color and texture.[1] In the input-output (action-response) mechanism of human-space interaction, living space articulates spatial quality in response to an occupant's perception or emotional responses to its affective dimensions.

In the initial user study phase of research, design parameters of color, brightness and texture are used as means of spatial articulation to examine user perception of specific affective or psychophysiological dimensions of space. These are feelings of warmth, coolness,

---

1. Steven Holl, Juhani Pallasmaa, and Alberto Pérez-Gómez, *Questions of Perception: Phenomenology of Architecture* (San Francisco, CA: William Stout, 2006).

spaciousness, intimacy, excitement and calmness. Based upon the study findings, some modifications are further made to the design scheme. Material is added as a fourth design parameter and two additional affective dimensions—muted and saturated—are included in the later design phase.

Design of proposed interactive living space explores two different aspects of creative problem-solving: a) enabling anticipatory capacity in design to generate possible spatial experiences in order to satisfy design goals of supporting emergent minimalist lifestyles; b) formulation of an aesthetic framework for the interactive system to regulate meaningful human-space interaction. The anticipatory dimension of living space is explored and examined in its capacity to generate possible affective spatial experiences to accommodate an occupant's moods, emotions, actions and functions that may occur in daily living. An anticipatory design looks at prior and possible future conditions and prepares for emergent needs by making affordances in its current condition.[2] In the proposed design, human-space interaction is driven by possibilities of psychophysiological spatial experiences that may emerge to potentially meet current and future needs and desires of occupants. Design is also investigated in order to formulate a set of aesthetic principles based upon which human-space interaction will generate meaningful spatial possibilities in response to an occupant's needs. The aesthetic principles are design guidelines formulated from correlations established between variable design parameters and occupant's perceptions of psychophysiological spaces—i.e., emotional responses to spaces. Correlations are measures of the extent to which each design parameter impacts perception. A Virtual

2. Mihai Nadin, "Anticipation and the Artificial: Aesthetics, Ethics, and Synthetic Life," *AI & Society* 25, no. 1 (April 2010): 103–118, doi:10.1007/s00146-009-0243-0

Environment is used as an evaluation tool to test proposed design concept and gather relevant data from which the aesthetic principles can be formulated. In a user study conducted in a six-sided immersive Cave Automatic Virtual Environment (CAVE)-type display, living space is simulated with adapted equivalent parameters of color, brightness and texture to test affective space creation. Both quantitative and qualitative research methodologies are applied with the aim of measuring the extent to which design parameters influenced emotional responses to perceived spaces.

The chief research question posed in this research is: Can Virtual Environment serve as a viable evaluation tool for architectural design concepts where variable design parameters can be adapted to replicate real-world affective space creation? Generated data confirmed the hypothesis posed in the user study that real-world influence of affective space creation can be successfully replicated in a simulated environment with adapted design parameters. Relevant data pertinent to design is further analyzed in order to formulate a set of aesthetic principles. Underlying aesthetics provide a framework based upon which the interactive control system meaningfully interprets an occupant's subjective sensory perception of desired psychophysiological spatial qualities and regulates the output of articulated spatial feedback that is purposeful and effective in human-space interaction.

The final outcome of the dissertation is the formulation of an aesthetic framework for the interactive system in the form of design guidelines on how to regulate the behavior of human-space interaction of the living space. This involves processing of received occupant inputs and articulation of possible affective spaces as outputs that are meaningful for occupants and can potentially support their psychophysiological needs. Databases for design parameters of color, texture and material are constructed in association with design principles for the interactive system to use. Fuzzy logic system, a soft computation method, is implemented for the interactive system in order to analyze and process qualitative, linguistic perceptual data received from occupants, and respond through modifications of color, brightness, texture and material to articulate living space as output data that is meaningful and effective. As examples, rendered images of a series of designed articulated spaces are also provided as outcomes of some possible human-space interaction scenarios.

1.2 Target Occupants

The conditions of globalization—the open market, the worldwide integration and assimilation of ideas, products and cultural views, the unprecedented changes in communication, digital and social networks, innovative computer technologies reshaping the urban infrastructure, new waves of migration and multi-national identities—have led to the rise of a new class of workers: the "neo-nomads." Similar to the historical nomads, they are characterized by mobility and adaptability.[3] The mobility of neo-nomads is not necessarily only physical or spatial displacement, but also mental and digital, referring to the displacement or detachment from one's historical or cultural roots.[4] As a cultural hybrid, the neo-nomads are a highly adaptable population that can establish a new sense of belonging in new contexts and situations, similar to traditional nomads.

---

3. Anthony D'Andrea, "Neo-Nomadism: A Theory of Post-Identitarian Mobility in the Global Age," *Mobilities* 1, no. 1 (March 2006): 95-119.

4. Yasmine Abbas, "Neo-Nomads and the Nature of the Spaces of Flows" in *UbiComp in the Urban Frontier* Conference proceedings, September 2004. Nottingham, England: UbiComp 2004: 12-13.

"Neo-nomads" is a broad concept that includes expatriates, migrants, global workers, as well as frequent travelers. Various researchers have attempted to define the modern-day nomadism. In his paper *Neo-nomadism in the Global Age*, Anthony D'Andrea discusses the "global nomad" or the "expressive expatriate." While the nomadic concepts of the refugee and the immigrant diaspora are linked to experiences of cultural uprooting, cultural confusion, as well as ethnic or national "nostalgic melancholia,"[5] the global nomads are known as a new breed that rejects a single identity tied to a fixed idea of a homeland.[6] Many of these modern-day expatriates select location-independent jobs and travel to remote locations around the world—such as technology hubs and tourist resorts—for work, cultural exploration and entertainment. Not completely detached from their own home, these constant travelers are motivated by the need for self-exploration and cultural assimilation in order to form an identity that belongs to the global.[7]

In his book *Free Agent Nation: How America's New Independent Workers Are Transforming the Way We Live*, author Daniel Pink discusses the rise of another group of mobile professionals who are freelancers. The decline in long-term job security during the past decades has led to the rapid rise of self-employed, independent contractors who work in various professions, such as advertising, information technology, animation and the movie industry. These workers own the manufacturing tools and search for contract jobs that provide the

---

5. Tim Oakes and Claudio Minca, "Tourism, Modernity, and Postmodernity," in *A Companion to Tourism*, eds. Alan. A. Lew et al., (UK: Blackwell publishing, 2004), 283.

6. Anthony D'Andrea, "Neo-Nomadism: A Theory of Post-Identitarian Mobility in the Global Age," *Mobilities* 1, no. 1 (March 2006): 95-119.

7. Ibid.

opportunity to develop skills and forge new partnerships in order to enrich their resumés.[8] Embedded computing has increased mobility and location independence for these new-generation freelance professionals. The freelancing professionals are always connected and accessible through web and social media, extending their identity beyond the physical and into the new context of the digital. The existing infrastructure of free wireless network at cafés and retail technology outlets support their nomadic lifestyle, enabling them to travel and work from any remote location.[9]

In this dissertation, the living space is designed for a specific segment of the neo-nomads. These are the new-generation information technology professionals, entrepreneurs and freelancers, also popularly known as Silicon Valley workers. This is a new breed of a highly mobile, technology-dependent, wireless population who can work and correspond remotely.[10] Portable computing devices, mobile technology, digital and "cloud" media, social networking and constant internet presence dematerialize the digital-dependent world they inhabit. Moving from café to café, these target occupants are highly adaptive to new, dynamic settings, with no fixed sense of belonging.[11] The past decades have witnessed a rapid increase in the number of these tech literate, young professionals and entrepreneurs in pursuit of remote jobs at various

8. Daniel H. Pink, *Free Agent Nation: How America's New Independent Workers Are Transforming the Way We Live* (New York: Warner Books, 2001).

9. Dan Fost, "Where Neo-Nomads' Ideas Percolate," *SFGate*, March 11, 2007, http://www.sfgate.com/news/article/where-neo-nomads-ideas-percolate-new-2610920.php.

10. Yasmine Abbas, "Neo-Nomads and the Nature of the Spaces of Flows" in *UbiComp in the Urban Frontier* Conference proceedings, September 2004. Nottingham, England: UbiComp 2004: 12-13.

11. Dan Fost, "Where Neo-Nomads' Ideas Percolate," *SFGate*, March 11, 2007, http://www.sfgate.com/news/article/where-neo-nomads-ideas-percolate-new-2610920.php.

technology hubs around the world.[12] The booming industry of internet, social media and smartphone technology of San Francisco experienced a recent influx of job growth that, in addition to space shortage and higher rent, has contributed to the severe housing crisis.[13] The phenomenon of transitional living of rapidly growing information-age professionals and the ongoing housing crises have led many researchers, architects and interior designers to seek new design vocabularies with computer-mediated spatial solutions, and affordable concepts of compact living to accommodate the transitional lifestyles of these technology-dependent, mobile professionals.[14]

The proposed concept of multi-functional single space is inspired by the current trend of efficiency or studio apartments, and "micro-apartments" available in overcrowded, high-density big cities, such as San Francisco, New York and Seattle, that are rented by the digital-age population.[15] Many of these tiny apartments consist of single, multi-functional living areas that are as small as 9.3 m^2 or 100 sq ft.[16] Such housing intends to accommodate the overlapping, shared activities of work, sleep, eating or socializing of young professionals with minimal

---

12. Anna Hart, "Living and Working in Paradise: The Rise of the Digital Nomad," *The Telegraph*, last modified May 17, 2015, http://www.telegraph.co.uk/news/features/11597145/Living-and-working-in-paradise-the-rise-of-the-digital-nomad.html.

13. Lauren Hepler, "The Shadow of Success: Inside Silicon Valley's Affordable Housing Crisis," *Silicon Valley Business Journal*, last modified January 31, 2014, http://svbj.tumblr.com/post/75132767372/the-shadow-of-success-inside-silicon-valleys.

14. Mike Weinstock, "Terrain Vague: Interactive Space and the Housescape," *Architectural Design* 75, no. 1 (2005): 46-50.

15. Neal J. Riley, "S.F. Supervisors Back Micro-Apartments," *SFGate*. last modified November 20, 2012, http://www.sfgate.com/bayarea/article/S-F-supervisors-back-micro-apartments-4055493.php.

16. "What is the Tiny House Movement?" *The Tiny Life*, accessed June 14, 2016, http://thetinylife.com/what-is-the-tiny-house-movement/.

belongings in a single multi-purpose space with compact furniture and storage.[17] In most cases, spatial transformation for these minimalist living spaces is mostly limited to furniture design. Limited space is optimized through smart design solutions of multi-purpose, compact furniture and storage design to add a feeling of spaciousness.

This dissertation proposes a design concept as an optional living solution, a real-world alternative to expensive built dwellings for this rapidly growing population. A subset of this population is selected as target occupants based upon examination of their profile. Spatial flexibility and optimization are sought through creative spatial solutions beyond conventional multi-functional furniture design aimed at complementing their minimal, transitional lifestyle, computation-based interconnectedness and constant mental shift to dynamic territories. An online survey was conducted as part of the background study for this dissertation in order to gain insight into the lifestyles of a segment of the technology-dependent, modern-day students and professionals (see Appendix: A). A total of 85 people participated in this study who are accustomed to using various mobile technologies and portable computing devices, such as smartphone, laptop, tablet and PDA for their daily personal, professional and social activities. Survey results were analyzed in order to gain an insight into their residential space usage patterns, and their preferred living environments for performing various daily activities. Although the data were not directly used for design purposes, they were helpful in gaining an understanding of space use preferences for domestic and professional activities.

---

17. Nellie Bowles, "The Real Teens of Silicon Valley: Inside the Almost-Adult Lives of the Industry's Newest Recruits," *The California Sunday Magazine*, accessed May 2015, https://stories.californiasunday.com/2015-06-07/real-teenagers-silicon-valley.

Most of the participants (38%) belonged to the 25-34 age group, while 19% of the participants were within the age group of 18-24 and 25% were between 35-44. Survey findings revealed that the majority of participants (65%) were professionals; 42% of the participants performed their job-related activities from an office or workplace away from home, while 39% of the participants worked or studied from home. Smartphones and/or portable computers were used mostly for communication (phone or text) and social media. Other important but less frequently performed activities were related to occupation (work and/or study) and recreation, as well as for socializing (chat or video apps). The primary living situation for most participants consisted of two or more rooms. The majority lived with roommates or family. Most participants used their primary living space for sleeping, eating and working. Other less frequent activities included recreational and creative pursuits—i.e., watching TV, playing games, reading, art and design. The majority of participants never entertained guests at home, did not have a second bedroom, family/living room, a separate study or office space in their primary residence. The bedroom of the primary residence of most participants was used for sleeping, studying and often for working. The following spatial environments were selected by most participants for carrying out certain daily activities:

i) For sleeping: private, calm and intimate

ii) For work or study: calm, spacious and private

iii) For recreation: exciting and spacious

iv) For contemplation, meditation, prayer or similar activities: private, calm and very intimate

1.3 Rationale

This dissertation investigates the concept of interaction in the realm of architecture that is physical, tangible and essentially spatial in nature. It excludes interactive projects and theories that have been developed in the fields of art, cybernetics, artificial intelligence, as well as conceptual theories of predictive technology and “anticipatory architecture”[18] based on Paskian systems still at a development stage, and which have not been implemented yet in the realm of architecture that is habitable. The genre of “responsive architecture,” including parametric or generative systems that are based upon biomimicry and biological systems of self-organization are also excluded from the scope of research for the same reason.

In the current practice of habitable interactive architecture, human interaction with physical space is enabled by embedded microchips and sensors. Buildings and physical spaces embody wireless interconnectedness of information technology and respond to human input and behavior.[19] Through formal and visual changes, reconfigurations and personalization, buildings respond to the occupant’s input. The last decade has witnessed a boom in the field of interactive design. A range of multi-disciplinary, collaborative projects have been developed by artists, designers and architects greatly inspired by interactive technology. Some researchers predict embedded interactive computing to redefine human relationship with built spaces in the coming

18. Michael Fox and Miles Kemp, *Interactive Architecture* (New York: Princeton Architectural Press, 2009) ebrary, 3.

19. Antonino Saggio, "Interactivity at the Centre of Avant-Garde Architectural Research." *Architectural Design* 75, no. 1 (2005): 23-29.

years, and stress the urgency of research on computing-enabled spatial adaptation for contemporary "information-able" architecture.[20]

However, a growing number of researchers and practitioners, such as Fox, Wiberg and Weinstock, criticize the current trend of buildable and habitable interactive architectural projects for their disregard and insensitivity towards the traditional role of architecture as a spatial entity having distinct spatial functions. The interactive "intelligent" or "smart" environment is criticized for its market-driven, surface-deep focus on gadget and media design.[21] The intelligent architectural systems or automation is primarily geared toward energy optimization, cost-efficiency in management, environmental sustainability, and security aspects. On the other hand, the practice of interactive digital façade is criticized for its treatment of buildings solely as objects of art, digital canvases or computer interfaces instead of interactive architecture.[22] These researchers argue that the current practice of interactive architecture is removed from traditional "architectural thinking"[23] of spatiality with its conceptual, aesthetic and functional aspects. They urge designers to explore the creative opportunity computing technology offers in order to dynamically enhance and articulate living spaces in real time. Some researchers also ask designers to investigate how it can support the highly mobile lifestyle of information-age professionals.[24]

---

20. Ibid., 25.

21. Weinstock, "Terrain Vague: Interactive Space and the Housescape."

22. Mikael Wiberg, *Interactive Textures for Architecture and Landscaping* (Hershey: IGI Global, 2011).

23. Ibid., 134-135.

24. Weinstock, "Terrain Vague: Interactive Space and the Housescape."

The urgency for thoughtful collaborations between interactive system design and architectural design of recent years has also led to workshops, such as "Human-Building Interaction," to focus on the necessity to integrate interactive design—i.e. interactive media, sensor-actuator systems, automation and interface designs, as well as the new mobile lifestyle of people resulting from ubiquitous computing—into the architectural design ideology.[25] They also stress the integration of architectural concepts and theories in the realm of interaction design, for understanding the complex human decision-making and behavior in the physical, spatial and social aspects of interactive built environments.

This dissertation is such an attempt to coordinate the complexity of human behavior and decision making, and emerging mobile lifestyle with interactive system design in the realm of spatial designs of architecture. It attempts to bridge the gap by introducing traditional architectural knowledge of space-making to coordinate with interactive computation as a creative design tool to enhance usability of living spaces. Design of interactive living space acknowledges the real-world emotional responses to space that is predominantly influenced by sensory engagement with space design parameters of light, color and texture. Affective space-making of traditional architecture supports or modifies human activities and behavior through sensory-perceptive, visually engaging spatial experiences, articulated to elicit emotional responses from the occupant. Spatial articulation is acknowledged as a fundamental architectural technique that enhances psychophysiological aspects of the human condition, further shaping

25. Hamed S. Alavi et al. "Interaction and Architecture: Deconstructing Human-Building Interaction," *Interactions* 23, no. 6 (November-December 2016): 60-62.

activity, behavior and experience.[26] Spatial articulation, within the "time-space dimension" of traditional architecture, changes spatial quality in real time to accommodate the rapidly changing daily living activities of neo-nomad professionals.

The proposed design is anticipatory in its active involvement of the occupant in affective space creation, thus enabling the occupant to personalize spatial qualities. The necessity for personalization and customization of spatial qualities through subjective perception, as well as physiological, emotional, functional, aesthetic and creative explorations, prompts generation of continuous human-space interaction in an attempt to accommodate emergent lifestyles. A set of aesthetic principles forms the framework based upon which a control system interprets the occupant's input of desired spatial qualities and regulates the output of articulated space as feedback in an effective, meaningful way. The formulation of an underlying aesthetic framework, composed of a set of design principles, will guide the interactive control system of living space in regulating the input-output mechanism of human-space interaction.

1.4 Virtual Reality as an Evaluation Tool

This dissertation defines virtual reality (VR) as a viable evaluation platform for new architectural concepts that explores psychophysiological, experiential spaces with adapted variable design parameters in simulated virtual space. Here, VR is used to quantify aesthetic parameters of architectural space-making pertinent to design by replicating the three-dimensional, multi-sensory real-world spatial experiences with use of alternative sensory-

26. Joanne Jakovich and Kirsty Beilharz, "Interaction as a Medium in Architectural Design," *Leonardo* 40, no. 4 (2007): 368-69, http://www.jstor.org/stable/20206449.

perceptive methods within the technological constraints of graphical methods. This requires understanding of how real-world sensory perceptions can be overridden, further providing the affordance for a new aesthetics that conforms to the medium, influencing its capacity and efficiency.[27] VR provides controlled conditions for conducting scientific experiments, the ability to manipulate visual attributes of simulated space, interactive components, and high-resolution graphics with a high level of perceptual realism, all of which are necessary for simulated architectural perceptual studies, and can potentially be an effective tool for conducting psychophysiological experiments. [28]

Although evaluation of architectural design is not new in the practice of VR technology, there are very few studies conducted on qualitative spatial aspects in architecture, specifically on sensory and psychological dimensions of space perception. Literature review suggests that the psychological, emotional or metaphysical dimensions of color, light, texture and materiality, essential parts of affective space creation, are yet an unexplored area in VR. Architectural design evaluation by VR has mainly been in the exploration of unbuilt or difficult-to-realize concepts in the arena of educational, recreational and communal sectors in a collaborative setting for decision-making purposes or other participatory inputs from architects, designers and clients.[29] Walk-throughs and prototyping systems are used in architectural studies in VR. Prototyping

---

27. Mihai Nadin, "Negotiating the World of Make-believe: The Aesthetic Compass." *Real-Time Imaging* 1, no. 3 (August 1995): 173-190.

28. Gerald Franz, Markus von der Heyde, and Heinrich H. Bülthoff, "Predicting Experiential Qualities of Architecture by its Spatial Properties" in *Designing Social Innovation: Planning, Building, Evaluating* (Cambridge, MA: Hogrefe, 2005), 157-166.

29. George Drettakis et al. "Design and Evaluation of a Real-World Virtual Environment for Architecture and Urban Planning," *Presence: Teleoperators and Virtual Environments* 16, no. 3 (June 2007): 318-332.

systems have user-centric designs during early development phases while walk-throughs allow users to navigate free.[30] The first head-mounted display (HMD) for immersive architectural space in VE,[31] designed by Sutherland, later developed into the first room-sized VR called CAVE,[32] with four 10-foot projection screens and interactive user interfaces. Multiple perspectives—at both ground and global (above-ground) levels—were introduced for architectural design in a prototyping system called CALVIN in CAVE.[33]

VR has been used for measuring both qualitative and quantitative factors of architectural space design. The quantitative studies pertain to size, scale, proportions and distance perceptions, while the qualitative studies include measurement of environmental, and affective or psychophysiological spatial aspects. For quantitative affective appraisals of space, some basic models were used in environmental psychology. Semantic differential scales (non-numerical scales) used pairs of oppositional adjectives as descriptors of environmental aspects of mood to measure affective aspects of space. These adjectives assigned both emotional and physical meanings to perceived architectural spatial aspects relating to size, shape, style, structural details, apertures, color, luminance, temperature, such as: pleasant and unpleasant, bright and dull, arousing and calm, narrow and spacious, dark and bright, open and enclosed, and warm and

---

30. Ibid.

31. Ivan E. Sutherland, “The Ultimate Display,” in *Proceedings of IFIP Congress* 65, no. 2 (1965): 506-508.

32. Jaeho Ryu et al. “Application of Human-scale Immersive VR System for Environmental Design Assessment - A Proposal for an Architectural Design Evaluation Tool,” *JAABE* 6, no. 1 (May 2007): 57-64.

33. Jason Leigh and Andrew E. Johnson, "CALVIN: An Immersimedia Design Environment Utilizing Heterogeneous Perspectives," in *Proceedings of the Third IEEE International Conference on Multimedia Computing and Systems*, June 1996. Hiroshima, Japan: IEEE: 20-23. doi: 10.1109/MMCS.1996.534949

cold.[34] Some VR studies drew comparisons between qualitative virtual perception to corresponding real-world perception in order to find similarities, and established quantifiable correlations, between perceived affective aspects and spatial volumes: scale, lighting, architectural details and artifacts.[35]

Attempts have been made to integrate VR in architectural design curricula in order to improve design quality of students.[36] In mid-1990s, walk-throughs were conducted in VE to find design flaws. A more sophisticated, immersive CAVE system was used in design studios by Fröst and Warren in the late 1990s that proved VR a better design tool for concept development, analysis, testing and construction of architectural designs than traditional paper and pencil design sessions.[37] In one such example, the College of Architecture and Planning (CAP) at Ball State University introduced HMD-based VR for students to study spaces with affective meanings in terms of everyday semantics, and replicate real-world functional spaces in VE.[38] Some studies also focused on emotional responses to spatial features. In another VR-based perceptual study,

---

34. Gerald Franz, "An Empirical Approach to the Experience of Architectural Space" (PhD diss., Max Planck Institute for Biological Cybernetics, Tübingen and the Bauhaus University, Weimar, 2005).

35. Daniel Henry and Tom Furness, "Spatial Perception in Virtual Environments: Evaluating an Architectural Application," in *Proceedings of IEEE Virtual Reality Annual International Symposium*, September 1993. Seattle, WA: IEEE: 33-40. doi: 10.1109/VRAIS.1993.380801

36. Mark P. Mobach. "Do Virtual Worlds Create Better Real Worlds?" *Virtual Reality* 12, no. 3 (September 2008): 163-179.

37. Peter Fröst and Peter Warren, "Virtual Reality Used in a Collaborative Architectural Design Process," in *2000 IEEE Conference on Information Visualization. An International Conference on Computer Visualization and Graphics*, July 2000. London:568-573. doi: 10.1109/IV.2000.859814.

38. Drettakis, "Design and Evaluation of a Real-World Virtual Environment."

still images of interior spaces were used to establish correlations between physical openness of a room—its size, openings—and affective spatial qualities.[39]

VR has been proven beneficial in architectural design studies for its immersive, high resolution, photorealistic interactive system. For the user study conducted in this dissertation, the mixed-reality environment of immersive CAVE-type display, with human-scale simulations, photorealistic high resolution, real-time projections on six screens, and enhanced sense of presence with 360-degree view has been considered most appropriate.

1.5 Dissertation Overview

The following three chapters (Chapter 2-4) pertain to relevant background studies. The second chapter of this dissertation (Chapter 2) addresses the notion of affective space creation in traditional architecture, and the relationship between space articulation and human emotions, mood and behavior. Here, analysis of the visual perceptual process of space is limited to examination of subjective affective dimensions of two variables of space perception—color and texture as sensory stimuli—as well as materiality. Discussion involves relevant psychophysiological significance of these design variables in the context of architecture. Architectural space-making process is explained as a meaningful construction of sensory-rich, spatial narrative intended to evoke emotional and aesthetic responses. Subjective perception and meaningful interpretation of spatial narrative is structured around emotion and imagination. Many renowned architects of the past, such as Kahn, Le Corbusier, Wright and Gropius, and

---

39. Gerald Franz, Markus von der Heyde, and Heinrich H. Bülthoff, "An Empirical Approach to the Experience of Architectural Space in Virtual Reality—Exploring Relations Between Features and Affective Appraisals of Rectangular Indoor Spaces," *Automation in Construction* 14 (2005): 165-172.

contemporary architects Zumthor, Pallasmaa and Holl have actualized these mental spaces with emotional functions to fulfill an occupant's spiritual need, through exploration of the metaphysical, psychological and metaphorical implications of light, color and material as design tools of spaces, acknowledging their impact on human emotions and behavior.

The third chapter (Chapter 3) defines the notion of flexible and adaptive space within the scope of this dissertation, and analyzes the concept of spatial adaptability in Modernist architecture. Historically, architecture has perpetually transformed and adapted itself to support changing individual, social and environmental needs, seeking rational solutions in innovative technologies. Spatial adaptability is evident in vernacular architecture, as well as in the 20th century Modernism that sought new conditions of life, and pragmatic living solutions for the working class population during the industrial era through integration of innovative technologies. Traditional Japanese and Modern architectural spaces of Loos, Mies van der Rohe, Wright and Rietveld changed in real time to adapt to everyday activities. The living spaces of the Modernism era reflected new ideas, political, socio-cultural, economic and aesthetic conditions. Flexible open plans, modularity and prefabrication indicated advances in construction techniques, giving way to rational solutions with multi-functional living spaces and furniture to address the housing crisis for low-income working class people in 1920s Modernism. Le Corbusier's minimalist, adaptable living spaces transformed with user participation. The flexible, space-saving functional space and furniture designs of Ferdinand Kramer reflected the mobility and pragmatism of the Industrial Age. In recent years, human-centered information technology has moved towards social, cultural, creative, mobile and embodied human "interactions."[40] Some researchers predict embedded computing technology to play a crucial role in our interaction with the surrounding built environment in the coming years. Architectural solutions are needed for the new living conditions of this digital-age population through exploration of technologies, and adaptable space-making methods to accommodate their transitional lifestyle.

The fourth chapter (Chapter 4) defines the notion of interaction and interactive architecture within the scope of this dissertation, including characteristics, current trends, as well as the aesthetics and materiality of human-space interaction. In this dissertation, interaction is understood as a basic input-output mechanism, similar to Malcolm McCullough's definition of a "deliberative" two-way exchange between man and machine.[41] An action must be reciprocated with a deliberate response in order to complete an interaction. In the realm of architecture, interaction occurs when a physical structure or space with embedded computing systems changes shape, appearance or environment in response to inputs (action) from human or external weather conditions.[42]

The final three chapters (Chapter 5-7) introduce and discuss proposed design. In the first chapter (Chapter 5), the concept of an interactively modifiable living space is introduced and its anticipatory dimensions of spatial possibilities are explored in the conceptual, functional, aesthetic and creative realms of design. The second chapter (Chapter 6) describes the process of data collection pertinent to formulating aesthetic principles through a user study conducted in

---

40. Malcolm McCullough, *Digital Ground*: *Architecture, Pervasive Computing, and Environmental Knowing* (Cambridge: The MIT Press, 2004).

41. Ibid., 20.

42. Fox and Kemp, *Interactive Architecture*, 12.

Virtual Environment as an evaluation tool. The user study is conducted with a total of 33 participants in the proposed living space simulated in a six-sided, immersive CAVE-like display. The study measures perceived emotional dimensions of virtual spaces in nine categories: warmth, coolness, excitement, calmness, intimacy, spaciousness and comfort, as well as spatial preferences for two activities: work and rest. Since emotional responses to space depend on context, the influence of activity on perception was also assessed by evaluating responses from two groups of users: an active group that performed a typical daily activity and an inactive (passive) group. In a quantitative study, participants rate psychophysiological spatial aspects of a set of virtual spaces. In the qualitative portion of the study, a qualitative, open-ended question is posed to participants, engaging them in a pseudo-interaction with living space in order to gain insight into their subjective emotive and aesthetic perception pertaining to the spatial modifications they desire in order to satisfy their need. Data findings confirm the hypothesis that affective space creation of the real world could be replicated in a simulated environment with adapted design parameters of color, brightness and texture. Quantitative and qualitative correlations between aesthetic parameters of light, color and texture and perception are established, and inferences are drawn to articulate a set of aesthetic principles. In the last chapter (Chapter 7), design of an interactive control system is discussed, based upon formulated design principles as a guiding framework. Databases for design parameters are constructed and a fuzzy logic system is implemented to process qualitative input and output data. Images of a set of designed interactive spaces are given as examples for some possible human-space interaction scenarios that may emerge.

This dissertation considers shortage of space as one of the primary reasons for the existing housing crisis for neo-nomads in highly populated, urban areas. A possible solution is proposed that focuses on space optimization and spatial adaptability through meaning-driven, anticipatory spatial solutions. Interactive technologies offer interior surfaces that constantly modify a single living space through articulation of color, brightness, and texture. A single space is thus transformed into multiple environments to support multiple functions. Such a space is designed to not only support a transitional lifestyle structured in time, shifting between domesticity and work, private and shared activities, but also to take part in an occupant's creative exploration in redefining his/her relationship with a dynamically evolving domestic space.

Future work involves further exploration of affective spaces, design means, as well as the affective, symbolic and temporal quality of simulated natural light as a primary design element. Construction of interactive space requires investigation into the emergent interactive technologies and innovative nanotechnology-driven smart materials for their ability and effectiveness. Further studies in interactive space design brings an opportunity to also examine the potential of VE as an aesthetic medium. Future work also includes further research on the adaptive processes of the interactive living space that has the ability to "learn."

This dissertation is an attempt to define the field of interactive architecture. It offers a humane and aesthetic approach towards sustainable, efficient living conditions. Its innovative approach thus qualifies as original.

CHAPTER 2

AFFECTIVE DIMENSIONS OF ARCHITECTURAL SPACES

2.1 Introduction

Architectural design is essentially about experiential space-making in an explicit or implicit manner. Spatial quality is perceived as a whole—i.e., its scale and proportion, openness and enclosure, relation to other spaces, and the sensory elements of light, color and texture that modulate the space. The visual space perceptual process relies on the visual properties of various architectural elements, such as color, light, material, texture, size and shape, as well as their interactions with each other.[43]

Affective architecture articulates atmospheric attributes of color, light, texture and materiality to create sensory stimulating, visually engaging spatial experiences for eliciting emotional responses. Psychological scenarios are presented to occupants through construction of spatial narratives in order to derive subjective meanings. Renowned architect Peter Zumthor argues that the primary goal of architectural space creation is not about forms, but creation of emotional experiences through multi-sensory engagements.[44]

This chapter discusses notions of meaningful emotional and aesthetic spaces. "Affect" is defined in the context of architectural space design. Various concepts, theories and practices for affective space creation in traditional architecture, as well as the models of emotions commonly used for evaluation of affective spatial dimensions, are explained. This dissertation focuses only

---

43. Francis D. K. Ching, *Architecture: Form, Space, and Order* (Hoboken: Wiley, 2007).

44. Amy Frearson, "Architecture Is Not about Form: Peter Zumthor," *dezeen*, February 6, 2013, https://www.dezeen.com/2013/02/06/peter-zumthor-at-the-royal-gold-medal-lecture-2013/

on visual sense perception. As variables of visual space perception, the psychological, physiological and aesthetic dimensions of color, texture and materiality are further analyzed in the context of architectural space articulation.

2.2 Space Design: Meaning and Aesthetics

In his article *Architecture and Meaning*, Robert G. Hershberger quotes architect Romaldo Giurgola: "It is the peculiar task of architecture to reach meaning: the human habitat is pivoted around meanings, not objects."[45] Architectural design is concerned with meaning. Space becomes meaningful in its ability to successfully communicate its intended function to the user, and moreso, in its ability to satisfactorily accommodate intended functions—physically, psychologically and functionally. Meaning is in the architectural "expression" intended by the architect, and in the "impression" received or inferred by the observer through perceivable, identifiable properties of design elements.[46] Meaning is conveyed through definitive or implied formal and sensory expressions at various emotional, physiological, symbolic or metaphorical levels; and observer selectively derives or infers meanings through observer's interpretations of these expressions. The architect carefully selects and articulates forms, shapes, or sensory elements of color, light, material and texture that have perceivable, associated relations in order to express suggested meaning. Observers identify elements that are representational of their culture, tradition and beliefs in order to derive meaning. For instance, color is perceived not only as a sensation, but also as associated relational meanings that are culture and context driven. In a

45. Robert G. Hershberger. "Architecture and Meaning," *The Journal of Aesthetic Education* 4, no. 4 (October 1970): 37.

46. Kurt Brandle, *Architecture and Meaning* (Michigan: Brandle Publishing, 2012) iPad edition, 15.

space where all unlocked gates are painted blue and all locked gates are painted yellow, the colors become particularly meaningful through their association with freedom of movement. Repetitive associations and derived mental or physical, pleasant or unpleasant experiences endow these colors with new meanings at a conceptual level for the observer beyond cultural connotations.[47]

Meaning can be objective or subjective, denotative or connotative, i.e., directly related to physical attributes and function or have emotional dimensions. A "large" space directly refers to the physical attribute, while a space perceived as "pleasant" has emotional implications. Objective meaning can be derived from the interpretation of architectural elements or forms. The shape of a door as an opening to walk through, the slope of a ramp as a surface to climb, or the wall as a barrier—these elements have objective meanings based upon perceived affordances that indicate what type of action they can afford.[48] Architecture shaped as a nest, such as the Olympic Stadium in Beijing, is iconic and connotes a shelter. In relation to form and content, symmetry and order can bring formality and focal interest to architectural spaces as well. On the other hand, subjective perception of architectural elements may extend beyond their physical limitation or immediate intended function. Emotion, culture, imagination and experience play a crucial part in the selective process of deriving meaning. A wall, a specific color or a shape of a door can be observed or contemplated as an element separate from its context and can be ascribed subjective qualities that have roots in culture, values and experience.

---

47. Ibid.

48. James J. Gibson. *The Ecological Approach to Visual Perception* (New York: Psychology Press, 2015).

Aesthetics is the sensory assessment of the nature and quality of beauty, art, pleasure and displeasure. In architectural design study, aesthetic feelings of beauty or delight arises from the meaning that is derived from human assessment of properties of architectural elements pertaining to form, space, sensory attributes, and relationship with other architectural elements. Aesthetic feelings of pleasure, displeasure and comfort form a combined psychological and physiological sensation stemming from perceptions of architectural sensory properties. The positive or negative feelings arising from perceptions of properties—i.e., warm, cool, exciting, calm, depressing, inspiring, gloomy, soft, hard, open and enclosed—have emotional, physical, physiological and behavioral dimensions.

There are innate, objective aesthetic values in symmetry, proportion, order, harmony, balance, contrast and rhythm that are part of the architectural design process as principles. The golden ratio has been used in art, architecture and other visual media as an aesthetically pleasing proportion. Subjective aesthetic values in architecture are sensory, emotional and cognitive. The sensory elements of color, light and texture have ascribed psychological, metaphysical and metaphorical meanings from which aesthetic experiences are derived. Beauty is also a subjective assessment conditioned by cultural constraints, personal taste, education, age, as well as political or moral values. In Japanese architecture, aesthetic values are deeply ingrained in religion. Naturalism plays a significant role at the cultural core, and aesthetic experience in spatial design is sought in simplicity, movement and stillness of wind, water, trees and other natural elements. Sculptural ornamentations, formal and spatial arrangements, and articulations with color, light and materials in traditional Indian architecture have strong religious and spiritual meanings structured around ritualized lifestyles. On the contrary, in Islamic architecture, beauty is sought in both the simplicity and complexity of geometry, patterns, proportions and purity of shapes.

2.3 Affective Space-Making

In architectural space studies, the terms “emotion” and “affect” have been used synonymously.[49] Emotion is a psychological state generated by subjective interpretation of interaction with an external stimulus or situation resulting in both physiological and behavioral expression.[50] In other words, emotion is a psychological state that impacts physiology and behavior. Mood is a brief or prolonged state of mind caused by or contributing to specific emotions, and can be heavily influenced by thoughts, physiological states, physical activities, temperature and weather conditions.[51] Affect is a broader concept that encompasses moods, emotions, feelings, preferences and attitudes.[52]

Renowned architect Louis I. Kahn believed that a room’s size, surfaces, openings and lighting as a whole has an influence on its occupant’s mood and action in that space.[53] Perception of experienced spatial environment and the occupant’s emotional state or mood are

---

49. Gerald Franz, “Space, Color, and Perceived Qualities of Indoor Environments” in *Environment, Health and Sustainable Development (IAPS 19 Conference Proceedings),* 2006. Alexandria, Egypt: IAPS.

50. Don H. Hockenbury and Sandra E. Hockenbury, *Discovering Psychology* (New York: Worth Publishers, 2007).

51. Scott Brave and Clifford Nass, “Emotion in Human-Computer Interaction,” in *The Human Computer Interaction,* eds. Andrew Sears and Julie A. Jacko (Boca Raton: Taylor & Francis, 2009), 54-65.

52. Michael W. Eysenck and Mark T. Keane, *Cognitive Psychology: A Student’s Handbook* (New York: Psychology Press, 2015).

53. Peter Loewenberg, “Architectural and Emotional Space,” in *Center17: Space & Psyche,* eds. Elizabeth Danze and Stephen Sonnenberg (Canada: Center for American Architecture and Design, 2012), 16-43.

interdependent, one influencing the other. It is not only the basic sensations of sensory elements—i.e., light, color, texture, sound, smell, temperature—but also aesthetic preferences, cultural associations, memories, experiences, and previous or prevailing emotional states that influence subjective emotional responses to perceived spatial quality. Affective space-making in architecture has psychological, physiological and aesthetic dimensions with the capacity to alter emotions, mood, attitudes, behavior and impact physiological responses. Spatial functions are supported by creation of various material and metaphysical experiences intended to evoke feelings, such as warm, cool, soft, dark, bright, spacious, intimate, open, enclosed, narrow, exciting, calm, pleasant, beautiful, unpleasant, inspiring, informal, formal, relaxing, depressing, natural and artificial.

Space creation, reorganization and articulation techniques of traditional architecture extend beyond the physical boundaries of space. In the *Poetics of Space*, Bachelard explains the perceptual process of space as a subjective reconstruction of memory and imagination.[54] The spatial, architectural imageries and sensations associated with one's memories of past lived spaces are intertwined with symbolic meanings, dreams and subjective interpretations that evoke a variety of emotions in us human beings. The openness, enclosure, warmth, lightness, and darkness of past domestic habitats are imbued with emotions and feelings of safety, solitude, intimacy, creativity and/or danger.[55]

Architects create affective spaces through construction of spatial narratives at conceptual, creative, aesthetic, and psychological realms structured around subjective human perception,

---

54. Gaston Bachelard, *The Poetics of Space* (Boston: Beacon Press, 1994).

55. Ibid., 9.

imagination and emotion. Symbolism in architecture, combined with sensory-rich elements, stimulates the senses and evokes meanings. Cultural, metaphysical and temporal meanings of natural light, material, color and texture to provide imaginative dimensions to the perceived space.[56] Aesthetics of space relies on the emotions that emerge from subjective meanings, essences and sensuousness of color, light and material as sensory elements.[57] Some spaces have aesthetic dimensions that carry higher levels of consciousness. Figure 2.1 shows two such examples.

(a) Ronchamp Chapel[58] (b) Exeter Library[59]

Figure 2.1. Examples of Affective Space-making

56. Juhani Pallasmaa, "Hapticity and Time: Notes on Fragile Architecture," *Archit. Rev*. 207, no. 1239 (2000): 78–84.

57. Peter Zumthor, *Thinking Architecture* (Basel: Birkhäuser, 2010).

58. Source: http://www.france2.fr/emissions/le-monument-prefere-des-francais/monuments-2015/la-chapelle-notre-dame-du-haut-de-ronchamp-region

59. Source: http://raquelportillo.pbworks.com/w/page/38143218/Louis_20Kahn_2C_20Exeter_20Library

In Le Corbusier's chapel of Notre Dame du Haut in Ronchamp (Figure 2.1-a), the carefully constructed light wells generate a deliberate play of natural light through colorful stained-glass windows on coarse concrete surfaces intended to arouse feelings of awe, silence and serenity. The illuminated large central space of Kahn's Exeter Library is a play of direct "white" light and indirect "blue" light symbolizing knowledge and learning,[60] and designed for no other programmatic function but to provide inspiration and excitement (see Figure 2.1-b).

2.4 Concepts and Theories for Spatial Narratives

Analysis of affective dimensions of architectural elements in creation of spatial narratives has necessitated many researchers to delve into the realm of evolutionary psychology. The psychological model of Maslow's *hierarchy of need* in the context of architectural space design suggests that the primary goal of domestic space is to fulfill the basic psychological and physiological needs essential to survival. Pleasure is gained from architectural spaces engendered by safety and comfort as an innate survival instinct of the prehistoric hunter-gatherer human.[61] Pleasure is a positive psychological, physiological and cognitive response that also indicates aesthetic preferences in spaces.

In architectural design, several theories are practiced that can be directly linked to basic human need for comfort and pleasure. The theories of *prospect and refuge*, *mystery*, *risk and reward* are applied by architects in their spatial narrative. The *prospect and refuge* theory, proposed by Jay Appleton (1975) in his book *Experience of Landscape* suggested that prehistoric

60. Shannon Mattern, "Geometries of Reading, Light of Learning: Louis I. Kahn's Library at Phillip Exeter," *Nexus Network Journal* 12, no. 3 (September 2010): 389-420. doi: 10.1007/s00004-010-0042-4.

61. Grant Hildebrand, *Origins of Architectural Pleasure* (Berkeley: University of California Press, 1999).

man desired certain degrees of protection, as well as freedom from his domestic space as a necessity for survival.[62] This means taking refuge in a shelter, as well as having an unobstructed access to the vast savannah that held prospects for hunting and exploration for food.

The occupant's preference of the degree of openness or enclosure, spaciousness or intimacy, brightness or darkness in a domestic space, reflects subjective perception of containment and freedom that is satisfied through manipulation of size, proportion, openings and other sensory qualities of architectural space. Spaces with lowered ceilings, warm and softer lights or visually heavy structure and materials—such as a fireplace in a living room—may reflect a shelter-like containment protected from weather. Open, unobstructed views, waterbodies, visually light-weight structures, bright lights and smooth, bright materials may create feelings of openness and spaciousness. Transitional spaces, such as corridors, balconies and terraces also contribute to the narrative of *prospect and refuge*.

Several other architectural theories are linked to evolutionary psychology associated with spatial exploration stemming from the need for challenges and adventures of the prehistoric human to remain alert and active as part of survival. Psychophysiological and cognitive pleasure is derived from these architectural experiences related to theories of *mystery, risk, reward, thrill* or *peril*, as well as *familiarity* and *predictability*. These theories revolve around anticipations of aesthetic experiences of heightened pleasure—i.e., pleasant, positive experiences of reaching a satisfactory goal of a psychologically or physiologically pleasant environment, a surprising

---

62. Jay Appleton, *The Experience of Landscape* (London: Wiley, 1975).

discovery that stimulates the senses, or an initial negative expectation turning into a positive experience.[63]

In space design, a clear distinction is made between fear and pleasure in the exploration of the unknown by maintaining a level of awareness and clarity in design pertaining to perceived threat or control. Architects practice various formal and sensory spatial articulations in order to heighten the level of curiosity and encourage exploration: e.g., use of directional elements of wall curvatures, creation of visual focal points with light or color, lighting effects from dark to light, a sudden change in texture or material, partially obscured views, creation of sensory stimulating tactile or aural environments that invite engagement.

Complexity and order is a space design theory that translates the beauty found in the sensory-rich, complex and fractal geometries of nature into architectural design. Order brings symmetry, clarity, coherence and spatial hierarchy to geometrical compositions. In space design, psychological, cognitive and aesthetic pleasure are derived from the complexity of textural details and contours of building surfaces, exposed structure and materials, and movement of light and shadow patterns that create stimulating, visually enhanced environments.

Figure 2.2 shows examples of spaces designed by architect Tadao Ando that explore natural light and shadow, texture and materiality to create various aspects of *prospect-refuge* and *mystery*. In the residential design of the *Koshino House*, feelings of enclosure or spaciousness, warmth and comfort are enhanced by inviting natural light to come in through various strategically located narrow apertures in a cave-like concrete residence (see Figure 2.2-a).

63. Sander Van de Cruys and Johan Wagemans, "Gestalts as Predictions – Some Reflections and an Application to Art." *Gestalt Theory* 33, no. 3/4 (2011): 325-344.

Church on the Water is a small, secluded chapel that is hidden from public view by a surrounding wall on three sides. Visitors step down a narrow stairway into the prayer hall that opens to the view of a vast, undisturbed natural landscape, enhancing feelings of safety and security and a heightened level of aesthetic experience (see Figure 2.2-b).

(a) Koshino House, Japan[64] (b) Church on the Water, Japan[65]

Figure 2.2. Space designs of architect Tadao Ando

2.5 Evaluating Affective Dimensions of Architectural Space

Many experimental and observational studies have been conducted by researchers to establish correlations between various architectural design elements and affective dimensions of experienced space. As affective responses are highly subjective and may be triggered by stimulus beyond tested parameters, empirically-backed standardized rules or theoretical frameworks are difficult to establish, despite the great number of comprehensive literature available on this

64. Source: http://www.archdaily.com/161522/ad-classics-koshino-house-tadao-ando.

65. Source: http://www.pritzkerprize.com/1995/works.

subject.[66] It is more difficult to find affirmations concerning impacts of interactions of design elements on emotions. However, some generalized objective guidelines could still be inferred or hypothesized based on certain patterns or trends observed in these studies.

To understand affective dimensions related to architectural spaces, researchers have used several models of emotions to create correlations between emotional dimensions and architectural spatial aspects, in order to measure psychological (personal preferences, taste, attitudes) and physiological responses to stimuli, as well as aesthetic dimensions.

A model of emotions developed by professor of Industrial Design Peiter Desmet has been applied in evaluation of both architectural spatial quality and product design containing three variables: appraisal, concerns and stimulus (see Figure 2.3-a).[67] The model considers perceived architectural space as a stimulus. *Appraisal* is the evaluation or assessment of architectural spatial experience that elicits emotion. *Concerns* indicate the user's expectations, desires or past experiences that need to be satisfied. The combination of these three variables indicate the type of emotional response the architectural space will evoke, such as happiness, boredom, surprise, pleasure or excitement. Positive or negative emotional response depends on whether the experience has been deemed favorable or unfavorable to human concerns.

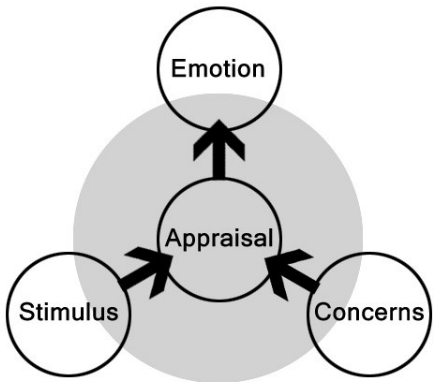
Other models of emotions used in architectural studies have been borrowed from environmental psychology, i.e., a study of human behavior pertaining to environmental quality. An emotional state model for affect pertaining to physical and sensory properties of architecture has been commonly used in many empirical studies for quantitative affective assessments of

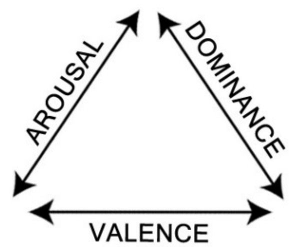
---

66. Franz, "Space, Color, and Perceived Qualities of Indoor Environments."

67. Simon Droog and Paul de Vries, "Emotion in Architecture: The Experience of the User," *issuu.com*, October 24, 2009, https://issuu.com/pauldevries/docs/20090202_emotioninarchitecture_big

architectural spaces. The model developed by Mehrabian and Russell is the Pleasure-Arousal-Dominance (PAD) emotional state model representing three primary measures: pleasure (valence), arousal and dominance (see Figure 2.3-b),[68] commonly used in various scientific and observational studies. Linguistic scaling techniques (semantic differential scales) are generally used for affective appraisals, using variables with pairs of oppositional adjectives as descriptors of environmental aspects of mood.





(a) Peiter Desmet's Model of Emotions [69] (b) Pleasure-Arousal-Dominance (PAD)

Figure 2.3. Models of Emotions

In the context of architectural space studies**,** valence is positive or negative emotion related to aesthetics—i.e., pleasure or beauty. Arousal is related to excitement and interest, and dominance is related to seriousness and formality. The architectural principles of order, balance,

---

68. Robert. G. Hershberger and Robert. C. Cass, "Predicting User Responses to Buildings," in *Environmental Aesthetics: Theory, Research, and Applications*, ed. Jack L. Nasar (Cambridge: Cambridge University Press, 1988), 195–211.

69. Droog and de Vries, "Emotion in Architecture," 12. Figure is adapted from source.

variety (diversity) in design have aesthetic dimensions associated with valence, whereas both complexity and variety have associations with arousal.[70]

Several studies on affective appraisals of architectural elements have pointed out a direct or indirect relationship between pleasure (valence) and physical comfort related to body movement and posture, light (brightness), temperature, moisture, sound, tactile sensation of rough or smooth surfaces, as well as the aesthetic aspect of textural patterns.[71] While proportion of space has a significant relation to valence, the feeling of spaciousness has been related to valence and dominance.

2.6 Affective Dimensions of Color

Color is an emotional, physical and physiological stimulant. Artists, architects, interior designers, scientists, physicians and psychologists have worked with the science of color—i.e., its impact on the human physiology, psyche and behavior, its natural and cultural associations, and various interactions among colors. Perception of color is contextual. The causes behind emotional and physiological responses to a color are manifold and complex, yet interrelated. Perception of red, as a symbol of romance, passion, power, criticism, anger, warning or violence may stem from its natural or biological associations with health, blood, stamina, vigor, heat or flame.[72] Similarly, blue as the color of the sky may soothe and calm. On the other hand, the idea of "feeling blue" as an expression of sadness may have biological roots with emotional and

70. Franz, "Space, Color, and Perceived Qualities of Indoor Environments."

71. Franz, *An Empirical Approach to the Experience of Architectural Space*.

72. Adam Alter, *Drunk Tank Pink* (New York: The Penguin Press, 2012).

cultural associations. Cultural connotations of a color can have strong impact on human attitude and behavior. Experiments have demonstrated that student engagement in class could be improved by avoiding the use of red in grading papers, and male aggression in jail cells could be reduced by painting interior walls pink, a color that is culturally recognized as feminine.[73]

2.6.1. Color Attributes

To discuss various findings of scientific and observational studies, as well as the application and perception of color in architectural space design, it is important to provide a brief overview of the color attributes that are manipulated to various extents in order to articulate types, intensities and brightness levels of spatial color. As illustrated in Figure 2.4, a traditional, three-dimensional Munsell color system[74] is used to understand and explain the three main attributes of color, as follows:

Hue: Hue is an attribute of color. It indicates the name (or type) of a color independent of its saturation, intensity, lightness or darkness levels, such as red, blue, orange or green. In the traditional, three-dimensional color space Munsell color system, warm and cool hues are arranged along horizontal bands according to color temperature. The hue spectrum is a continuous, smoothly changing gradient of primary and secondary hues, and their various combinations organized in their natural order. The spectrum consists of five primary hues: red, yellow, green, blue and purple, and five secondary hues: Yellow-Red (YR), Green-Yellow (GY), Blue-Green (BG), Purple-Blue (PB), and Red-Purple (RP). The rest of the hues are combinations

73. Ibid.

74. "How Color Notations Work," *Munsell Color*. Accessed January 30, 2016. http://munsell.com/about-munsell-color/how-color-notation-works/

of primary and secondary hues. For scientific use of color, the Munsell hue circle is divided into 100 hues.

Value: The color attribute of value is the lightness or darkness of color that represents its perceived brightness. Value is the amount of white (tint) or black (shade) in a color. Color with low value is perceived darker, and color with a high value is perceived comparatively lighter. The value spectrum of a color indicates the range of values for each hue. It extends vertically from lightest (absolute white) to darkest (absolute black), or darkest to lightest of any given hue in the three-dimensional color space. For any hue located on its vertical value spectrum, the hues below it are its shades (darker) and the hues above are its tints (lighter).

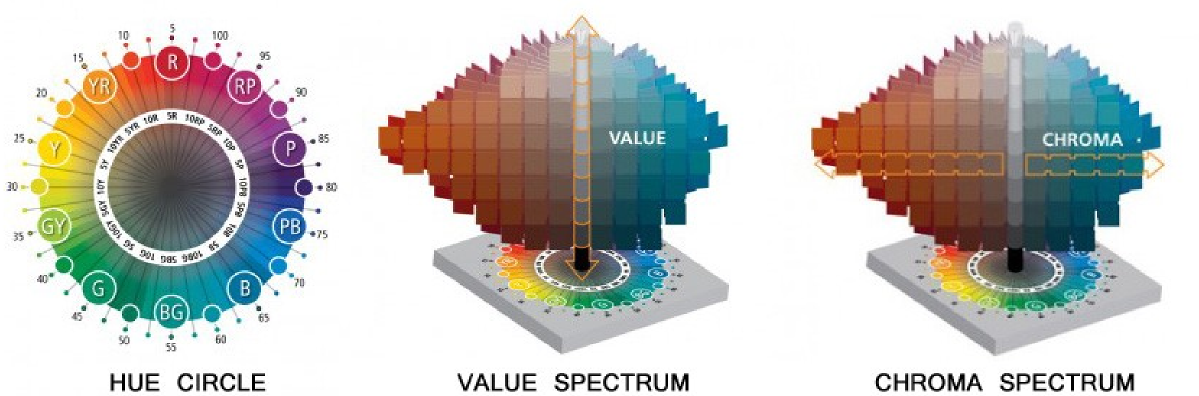


Figure 2.4. The Munsell Color System[75]

Chroma: Chroma is an attribute of color that indicates its strength, intensity or level of saturation. Although the terms "saturation" and "chroma" are used synonymously, they are not interchangeable.[76] High saturation indicates high chroma for a color, with less gray, and are

75. Source: http://munsell.com/about-munsell-color/how-color-notation-works/

76. George A. Agoston, *Color Theory and Its Application in Art and Design* (New York: Springer-Verlag, 1986).

perceived as strong or vivid. Colors with more gray have low *chroma*, low saturation level, and can be perceived as muted, soft, weak or dull. The *chroma scale* is the range of chromas for each hue. Colors closer to the center of the three-dimensional color space have low chroma, whereas colors further away from the center have less grey, more saturation, and higher chroma. In the highly asymmetrical, spherical color solid of Munsell color space, the highest chromas and their corresponding value levels vary from color to color. The “strong” colors, such as red, blue and purple have more chroma steps and reach highest intensity and saturation at 50% gray on the value scale. The “weak” colors, such as green and yellow, have fewer chroma steps and reach full saturation and intensity at 70-80% gray on the value scale.

2.6.2. Scientific and Observational Studies

Warm and *cool* are sensorial emotions related to color. Warm colors are at the red end of the color spectrum, consisting of red, orange, yellow and their combinations. Cool colors are at the opposite end of the spectrum, consisting of blue, green, purple and their combinations. Warm colors feel arousing or exciting, while cool colors feel calming.[77] In his paper *Space, Color, and Perceived Qualities of Indoor Environments,* Gerald Franz summarizes findings of various scientific and observational experiments pertaining to emotional responses to color.[78] These studies acknowledged certain affirmations regarding affective aspects of color related to arousal and dominance, which are applicable in architectural space design. According to these findings, hue (warm and cool) and chroma (saturated and muted) are associated with arousal, whereas

---

77. Maud Hårleman, “Daylight Influence on Colour Design: Empirical Study on Perceived Colour and Colour Experience Indoors” (PhD diss., Royal Institute of Technology, Sweden, 2007).

78. Franz. “Space, Color, and Perceived Qualities of Indoor Environments.”

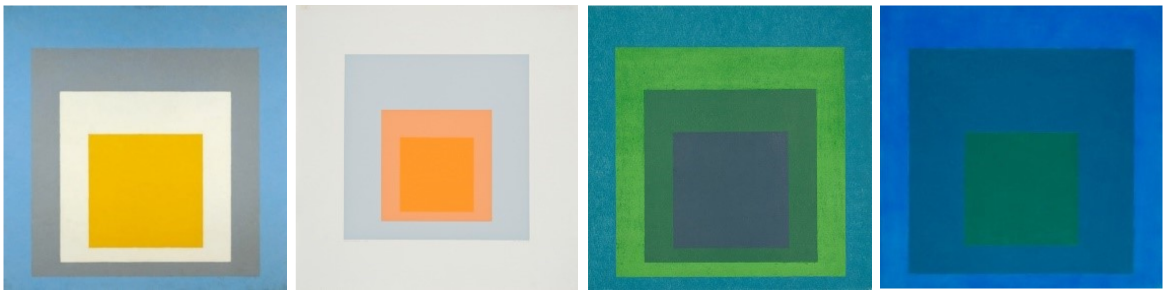
value (lightness and darkness) is associated with dominance. Color is found to have an impact on perception of spaciousness of a space, as well as on distance perception. Franz's studies further observe that light, cool and desaturated colors increase perceived spaciousness, whereas dark, warm and saturated colors decrease perceived spaciousness. Warm colors are known as "advancing colors" that appear to be closer, and cool colors are known as "receding colors" that appear to be farther away.[79]

Josef Albers, a Bauhaus artist and educator, explored the science of color, its perception and various interactions between colors, and introduced several color concepts, such as simultaneous contrast, additive and subtractive attributes of color, and optical illusions. In his book *Interaction of Color* (1963), Albers stated that "In visual perception a color is almost never seen as it really is—as it physically is."[80] Color is always perceived in relation to other colors. In his series *Homage to the Square*, an examination of interaction between groups of selected gradations and arrays of colors, he developed series of square studies exploring hues, as well as color values, to give three-dimensional depth to two-dimensional surfaces. Each scheme of the series generally consisted of three to four flat colored shapes (squares) nested one inside another in a symmetrical composition, but shifting towards the bottom edge asymmetrically on the vertical axis. Some schemes appear to have three-dimensional depth, while other schemes appear to have various levels of visual illusion. Different colors appear to move towards the foreground or background, increase or decrease in size, or draw near or move further away based upon their warmer and cooler hues, lightness or saturation levels (see Figure 2.5-a). The same color with

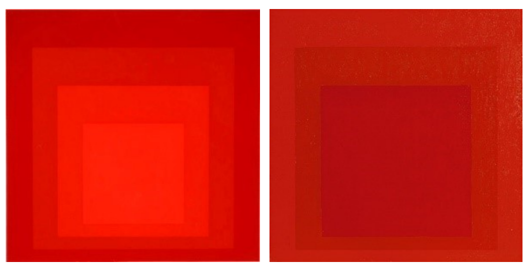
79. Reynold J. Bailey, Cindy M. Grimm, and Chris Davoli, "The Real Effect of Warm-Cool Colors." Technology Report WUCSE-2006-17 (2006), http://openscholarship.wustl.edu/cse_research/166

80. Josef Albers, *Interaction of Color* (New Haven, Conn.: Yale University, 2006), 1.

gradations in value may create an illusion of three-dimensional depth (see Figure 2.5-b). Additionally, in some cases schemes containing arrays of colors with varying hue or value, an optical illusion called halation (glow) occurs at the edge of two inner squares of adjacent colors.



(a) Arrangement of different hues and/or values can create an illusion of spatial depth



(b) Same hue with varying values can create an illusion of spatial depth and halation

Figure 2.5. Study of spatial depth in Josef Albers: *Homage to the Square* series [81]

Figure 2.6 illustrates "atmospheric perspective," a popularly used technique that is used by artists to create spatial depth with color on flat two-dimensional surfaces. It is a painting by Fauvist artist André Derain that utilizes the visual phenomenon of advance-and-recede effects of warm and cool colors to create depth. Figure 2.7 illustrates spatial depth created by gradations in

81. Source: Ibid.

value of the same color, objects appearing to fade away as they move towards the background into the distance. Overlapping of objects enhances sense of depth.

Figure 2.6. Atmospheric Perspective: The Pool of London: Artist André Derain (1906)[82]

Figure 2.7. Spatial depth created by gradations in color value[83]

82. Source: http://www.artyfactory.com/art_appreciation/art_movements/fauvism.htm.

83. Source: silvercreekart.weebly.com.

2.7 Color Concepts in Architectural Space Design

Artists, painters and architects from early Modernism, De Stijl, and the Bauhaus movements explored perception of the chromatic phenomena, their complex relations with geometric shapes and forms, and psychological effect related to spatial use of color. Development of color theories for architectural space design initiated in the early 1920s. Architects Le Corbusier and Ozenfant employed "constructive" colors in architectural spaces, assigning specific functions to colors. During post-war Modernism, use of colors became experiential and subjective in spatial design.

Architect Bruno Taut, the pioneer of polychrome architecture in Modernism, used colors symbolically to typify certain housing complexes in order to elevate the social status of working class members. Bright, contrasting, complementary colors, together with strategically placed pure and bright colors in the sunlight, signified color as a symbol of life, enhancing feelings of happiness and self-esteem (see Figure 2.8).[84]

Figure 2.8. Color concept for housing: Bruno Taut[85]

---

84. Barbara Klinkhammer, "The Spatial Use of Color in Early Modernism," in *Legacy + Aspirations: Considering the Future of Architectural Education: Proceedings of 87th ACSA Annual Meeting*, eds. Geraldine Forbes and Marvin Malecha (Washington D.C.: ACSA, 1999), 222-225.

85. Source: http://blogdephaco.blogspot.com/2014/05/bruno-taut-le-moderniste-rebelle.html.

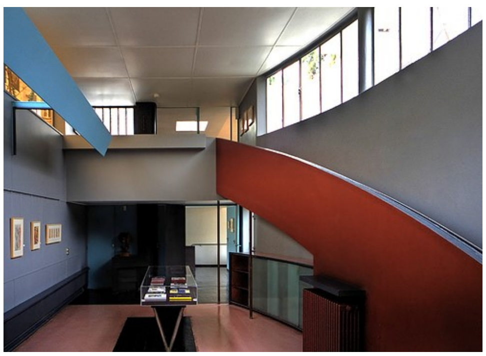
Le Corbusier's concept of architectural polychromy explored how forms defined color, as well as the various physiological and psychological effects of stimulating colors in creating and articulating spaces. Varying color values were also used to give three-dimensional effects to flat surfaces, enhancing sense of depth. In his text, *Polichromie Architecturale*, Le Corbusier introduced color concepts, including the Salubra wallpaper collections,[86] and established certain relationships between architectural elements and ranges of lightness of color. However, not all relationships were properly explained. He employed three major color sets in order to enhance perception of spatial proportions, stabilize and "solidify" volumes, and "camouflage" architectural elements, providing spatial unity and balance, as well as giving rise to various psychological scenarios (see Figure 2.9-a).

The *grande gamma* of "constructive" colors with natural pigments, such as brown, red-ochre, yellow, sienna, white, black, ultra-marine and their specific derivatives, were perceived as more "human" and used in constructing spatial volumes, in order to enhance perceived formal and spatial proportions. Employing the advance-and-recede visual phenomenon of volumetric colors,[87] Le Corbusier placed light and bright colors, such as yellow or white, strategically under daylight to enhance warmth and light, while the darker, earthy colors were used in the background to create spatial depth and provide stability to volume. The "dynamic" colors of lemon-yellow, oranges, vermilions, light cobalt blue and other "animated" colors were employed to enhance a feeling of movement. "Transitional" synthetic colors of specific greens were

86. Jan de Heer. *The Architectonic Colour: Polychromy in the Purist Architecture of Le Corbusier* (Rotterdam: 010 Publishers, 2009). Le Corbusier designed two series of wallpapers for Salubra, a Swiss wallpaper manufacturer. His color sets represented his choice of color schemes assigned for various types of spaces or wall surfaces.

87. de Heer. *The Architectonic Colour*.

believed to have no impact on depth perception and were used only for tinting surfaces. Ozenfant suggested similar color theories to solidify and strengthen architectural forms with pure and neutral colors.[88] Le Corbusier also conceived spaces with planar surfaces with contrasting surfaces—setting pure and vibrant colors against exposed "real" materials to examine their interactions and elicit emotional responses (see Figure 2.9-b). However, his later works reflected use of bright spectral colors, without strict association to any form, evoking strong physiological sensations, as can be seen in the chapel at Ronchamp (Figure 2.1).



(a) Villa la Roche (1923-25)[89]

(b) High Court, Chandigarh (1956)[90]

Figure 2.9. Le Corbusier's Color Concepts

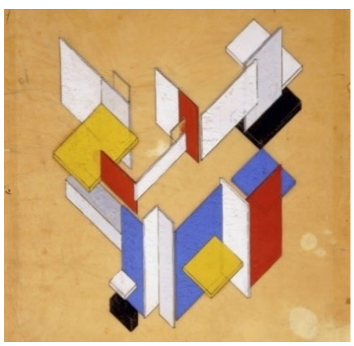
In the architectural space design of *de Stijl* (1917), colors did not have a constructive or functional purpose. With floating painted surfaces, forms and colors were rather in a sculptural composition, creating spatial tension. Architectural spatiality was examined by artists and architects with highly reductive orthogonal lines and a color palette of primary hues (red, blue

88. Carolyn Kane, "Broken Colour in a Modern World: Chromatic Failures in Purist Art and Architecture," *Journal of the International Colour Association* 14 (2015): 1-13.

89. Source: http://www.ecomanta.com/2011/01/le-corbusiers-villa-la-roche.html.

90. Source: http://www.sightunseen.com/2015/11/robert-storey-set-designer-for-kenzo-nike-and-more/.

and yellow) and neutrals (black, white and gray). The composition of primary colored elements and their juxtaposed chromatic sensations aimed to evoke emotional responses. Aesthetic and metaphysical beauty and order were sought in the energy, movement and contrast evoked by weightless or "floating" vibrant, contrasting colors in perfect harmony with opposing geometric surfaces, forms and their proportions. Figure 2.10-a shows Theo van Doesberg's color concept: *The Construction of Space and Time*. Painter, sculptor and architect Van Doesberg, inspired by artist Wassily Kandinsky, designed architectural spaces as tilted geometric compositions with vibrant colors, creating spatial tension between form and color in a unified, sculptural composition to open up constructional, "closed" architectural volumes.[91]



(a) Theo van Doesberg [92]

(b) Rietveld's Schröder House [93]

Figure 2.10. *de Stijl* Color Concepts

The Schröder House, designed by Gerrit Rietveld, is known as a perfect manifesto of the *de stijl* style with its colored planes and lines, integrating structural elements and furniture into

91. Klinkhammer, "The Spatial Use of Color in Early Modernism."

92. Source: https://www.artsy.net/artwork/theo-van-doesburg-the-construction-of-space-time-iii

93. Source: http://www.archdaily.com/99698/ad-classics-rietveld-schroder-house-gerrit-rietveld.

the harmonious, unified spatial composition (see Figure 2.10-b). Among Bauhaus architects, Alfred Arndt was the first to apply polychromy in constructive spatial design in Auerbach Haus in Jena (1924) and used color to delineate and articulate geometric spatial proportions.[94]

Although there is no homogenous approach pertaining to color-space programmatic relations that are practiced by contemporary architects and designers in spatial design, the psychological, physiological and phenomenological aspects of color are examined and explored by many. Figure 2.11 shows two such examples.

(a) Architect Luis Barragan[95]

(b) Architect Steven Holl[96]

Figure 2.11. Contemporary Color Concepts

Renowned Mexican artist and architect Luis Barragan, who referred to his house as a refuge, “an emotional piece of architecture, not a cold piece of convenience,”[97] used a wide

94. Ibid.

95. Source: https://creativethresholds.com/2014/11/27/postcolonial-thoughts-barragans-spiritual-transcendence-through-color/

96. Source: http://www.stevenholl.com/projects/

97. Della Hansmann, “Pioneering Modernist: Luis Barragan,” *moss*, March 8, 2016. http://moss-design.com/barragan/

range of strong, high contrast chromatic sensations to create strong emotional impact and enhance spirit (see Figure 2.11-a). Similar to Le Corbusier's Ronchamp, architect Steven Holl's spatial designs explore color as sensations of light and utilize colored surfaces of varying shapes to filter or reflect natural light that changes over time (see Figure 2.11-b).

2.8 Texture and Materiality

Texture is the feel, appearance, consistency of a surface.[98] Texture refers to the surface property of materials that construct perceived space. Roughness and smoothness of texture are characteristics of texture graininess, varying in density, size, orientation and depth of grain. Texture is sensory-perceptive.

For a space constructed with several materials, the perceived spatial quality inherits its own spatial texture with distinct character or sensuousness and which is a combination of the perceived texture of each material that constructs that space, as well as the overall texture of each surface constructed by several materials. It is the composition of complementary materials and texture of a room that constructs a visually pleasing spatial quality and ultimately influences the user's psychological or physiological feeling of comfort/discomfort, invitation/rejection.

Visual perception of texture involves the memory of tactility. "Vision reveals what the touch already knows."[99] Visual perception of spatial texture is informed by past tactile experience of material weight, shape, resistance, warmth, coolness, pleasure or displeasure. Without touch, or the memory of a material's tactile quality, it is not possible to receive

98. Wiberg, *Interactive Textures for Architecture and Landscaping*.

99. Juhani Pallasmaa, *The Eyes of the Skin: Architecture and the Senses* (West Sussex: John Wiley & Sons, 2012), 42.

information about its density, hollowness or thickness. Our tactile experiences may inform our perception of a material as hostile or inviting. Despite its limitations, vision alone reveals certain qualities of a material through light reflection, refraction, absorption and depth of texture—a perception that is enhanced by motion. Movement is a vital part of perception,[100] as it changes the way we observe light reflection, and refraction on material surface, providing information about depth of graininess, and softness or hardness of texture.

2.8.1 Affective Dimensions of Texture

Texture is an attribute or characteristic of material. Perception of texture is essentially related to perception of the material in represents. Affective qualities of perceived texture are inherited from material quality—the visual, tactile, psychological, physiological or other phenomenological aspects, such as the temporality of age, origin, weathering, inherent permanence or impermanence, origin and construction process. Our engagement with materials is physical, sensory, emotional and cognitive; and perception of materials and surfaces establishes a relation with its cultural and temporal meanings. For instance, stone represents age, strength and durability, and wood represents construction process, age and origin.[101] Through imagination one can empathize with a time, place and event related to the materiality of an object, as certain features of past lives come into one's understanding. [102]

100. James J. Gibson, "What Gives Rise to the Perception of Motion?" *Psychological Review* 75, no. 4 (1968): 335-346.

101. Pallasmaa, "Hapticity and Time: Notes on Fragile Architecture."

102. Sandra Dudley, "Materiality Matters: Experiencing the Displayed Object." *University of Michigan Working Papers in Museum Studies* 8 (2012): 1-9.

In his book *Experiencing Architecture*, Steen Eiler Rasmussen explains the affective dimensions of material expressed through texture as warm, cool, hard, soft, rich, dull, honest, alive, with or without spirit. A rough texture of brick or stone that displays its inner structure may appear richer in character, exciting and "honest" in its origin, while smooth texture, such as plaster, may appear comparatively dull or boring.[103] Depending on material quality and darker or lighter color tone, the perceived character of texture may be hard or soft, heavy or light, warm or cool. Depending on visual weight and tactility of material and its texture, a space may feel spacious or intimate, warm or cool.

2.8.2. Texture and Materiality in Architectural Space Design

In this book *Thinking Architecture*, Peter Zumthor speaks of the essence of each material as having culturally conveyed meaning, the meaningful use of material bestowing a poetic quality to space. Aesthetic experience is gained from the subjective meanings and essences of material and texture. Zumthor describes the perceptual process of texture and materiality, comparing it to music. Details of surface materials express the "separation, tension or lightness, friction, solidity, fragility" of the entire space, just as the perception of the overall composition of texture and materials of space gives sense to the details of construction.[104]

Architecture deals with the use and notion of materials in buildings. Materiality gives life and character to architectural spaces. Sensitive and effective, contrasting yet complementary

---

103. Steen Eiler Rasmussen, *Experiencing Architecture* (Cambridge: MIT Press, 2000).

104. Zumthor, *Thinking Architecture*, 15.

materials enhance the textural character and tactile qualities of materials, stimulates the senses and create sensory-rich, visually pleasing environment (see Figure 2.12).

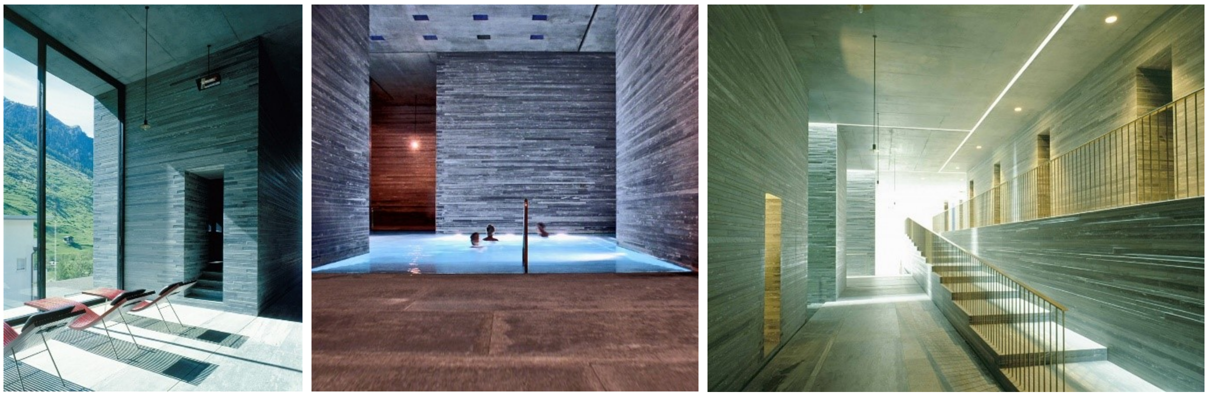


Figure 2.12. Texture and materiality explored in Peter Zumthor's Therme Vals (1996)[105]

Combinations of contrasting materials—such as, rough concrete with smooth steel columns, rough brick with smooth mortar, heaviness and solidity of stone with lightness and transparency of glass—enhance surface properties of materials. Using light and shadow, architects further enhance their textural character to arouse the senses.

A building surface or façade built with several different materials is perceived as a whole, acquiring a unique texture and materiality of its own. Architects design façades with patterns of linear or fractal geometry with complexity and order, exploring the solid and void, light and shadow, to create a unique, aesthetically pleasing visual tactility. Figure 2.13 shows some such examples.

105. Source: http://ideasgn.com/architecture/therme-vals-switzerland-peter-zumthor/.

(a) Designs by Architect Kengo Kuma; [106] (b) Federation Square, Melbourne[107]

Figure 2.13. Examples of unique texture and materiality for façades

106. Source: http://www.archdaily.com/199442/gc-prostho-museum-research-center-kengo-kuma-associates.

107. Source: http://www.yoshis-travels.com/travelogues/australia.html.

CHAPTER 3

ADAPTIVE SPACES OF MODERN ARCHITECTURE

3.1 Introduction

Architectural design vocabularies and trends have changed over time to accommodate new needs and new lifestyles pertaining to changing personal, demographic, environmental, socio-cultural, aesthetic, technological, economic and political conditions. Architects and designers practice ways to incorporate new ideas and beliefs, meet changing socio-economic and cultural demands, and integrate available, innovative technologies in their architectural design vocabulary.

Researchers and practitioners have offered various terms and concepts for architecture that adapts to change, such as “flexible” and “adaptive” architecture. This dissertation uses “flexible architecture” as a broad term for all types of architecture that adapts to change. This encompasses concepts of adaptive, transformable, re-configurable and interactive architecture.

In this chapter, “flexible architecture” is defined, and the concepts of flexible living spaces are discussed together with a historical look at the adaptation processes of architecture during the Modernist era. The underlying ideas, principles and mechanisms of Modernism related to “flexible” architecture are discussed to clarify the context and manners in which architectural design has sought spatial and structural solutions to meet demands of a changing society. The evolution of flexibility and adaptability of living spaces is explored only in the realm of habitable, residential architecture. To elaborate, some case studies of Modernism and contemporary flexible architecture are presented as examples as well.

3.2 Architectural Need for Adaptability

The primary function of architecture is to provide shelter against adverse environmental factors. It is a shelter that modulates external climate to create a physically comfortable indoor environment. Human lifestyle is continuously changing in the face of technological advancement that facilitates new types of communication, transportation, energy use methods (e.g., artificial light, heating and cooling). Human activities are shaped not only by needs, but also by beliefs rooted in culture, subjective knowledge, experience and religion. An occupant's socio-spatial hierarchy in living spaces changes in terms of privacy, comfort, aesthetics, values and belief systems. Additionally, a multitude of demographical needs impacts living conditions as it becomes necessary to reconfigure living spaces. As a family grows or shrinks, needs change from an individual to a couple, from a nuclear family to an extended family, and includes occupants of different age ranges. With change of economic conditions pertaining to affordability, ownership or tenancy, living scenarios change as well. For instance, a residence may require eventual include of or conversion to an office over time.

Flexible architecture perpetually transforms, adapts, adjusts and refines itself to accommodate the changing lifestyle and activities of the inhabitants, based on their individual, socio-economic and environmental needs.[108] It does so through spatial reconfiguration, reorganization and articulation for both physiological and psychological—i.e., emotive and aesthetic—aspects, further shaping human activity, behavior and experience. Architectural flexibility can occur at various scales, ranging from assembling or reassembling of building parts

108. Fox and Kemp, *Interactive Architecture*.

(or modules) that require a longer period of time, to adjustments of partition walls, furniture, heating or cooling systems that can be performed instantaneously.

3.3 Defining Flexible and Adaptive Spaces

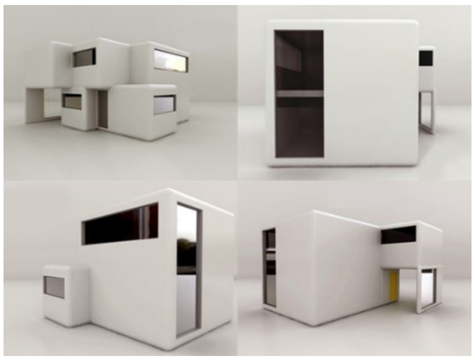
This section discusses the various definitions, notions and characteristics of flexibility in architectural design proposed by contemporary architects and researchers. The notion of "flexible" and "adaptive" spaces are also redefined within the context of this dissertation.

In his book *Flexible: Architecture that Responds to Change*, Kronenburg describes the adaptive capacity of buildings to the changing needs of human and environment as an economically and ecologically viable adjustment or response reflected in the building's use or location. He typifies flexibility of living spaces according to the extent physical changes can be made in order to accommodate needs. These changes can happen in four ways and are not mutually exclusive: transformation, adaptation, mobility and interaction.[109]

Figure 3.1 illustrates Kronenburg's classifications of flexibility in architecture, described as follows: A living space can "transform" and reconfigure through physical or formal changes. It can "adapt" to new functions without any physical changes made to the form or fabric. Living space may have the capacity to be "mobile" and relocate to a new location to accommodate needs. Spatial reconfiguration and articulation can be achieved through "interaction" between user and architectural elements which may not necessarily involve automated systems. Figure 3.1-a shows the OFT Transformable House, designed by Sand & Birch, in which modular pieces can be assembled or shifted to create various spatial configurations. Figure 3.1-b shows Shigeru

109. Robert Kronenburg, *Flexible: Architecture that Responds to Change* (London: Laurence King, 2007).

Ban’s Naked House, a single “adaptive” space that uses movable furniture and partitions. Figure 3.1-c is a movable caravan used as both a house and a vehicle. Figure 3.1-d is the traditional Japanese house in which the user “interacts” with architectural space through movable *shojis*.



(a) OFT Transformable House (2008)[110]

(b) Naked House (2000)[111]

(c) Movable House[112]

(d) Typical Japanese house[113]

Figure 3.1. Flexible living spaces

---

110. Source: http://www.architecturelist.com/2008/03/03/oft-transformable-house-by-sand-birch/

111. Source: http://www.shigerubanarchitects.com/

112. Source: http://inhabitat.com/japanese-pals-recycle-old-truck-into-transforming-two-story-mobile-home/

113. Source: http://cbei.tk/ancient-japanese-homes/

Tomasz Jaskiewicz characterizes flexible architecture as adaptive only when the adaptation process is frequent and limited to spatial changes that are small in scale, such as movable, sliding or foldable doors, partition walls, furniture, roof and deck.[114] Tatjana Schneider and Jeremy Till define flexibility as a characteristic of architecture that allows formal or technological changes to be made to the building, both temporary—i.e., with sliding or folding of walls and furniture—and permanent, such as addition of rooms.[115] They have a similar definition for "adaptable" space as Kronenburg, describing these spaces as "polyvalent"[116] that do not require any physical changes or spatial reconfigurations to accommodate new needs.

In this dissertation, the terms "flexible" and "adaptive" have specific definitions. "Flexible" architecture broadly indicates all buildings or living spaces that have the capacity to adapt to emerging needs of occupants. The adaptation process of flexible spaces can be long-term or short-term, regardless of its frequency, and the type of interior or exterior physical changes this requires. Flexibility acknowledges "change" as a design criterion. The degree of uncertainty in design pertains to demographics—i.e., family size, type, and age range—as well as social, cultural, economic, technological and environmental factors which can be subjected to unpredictable changes in the future. Flexible architecture makes design allowances for the various types and extents of changes that may occur in the future, making it inherently

114. Tomasz Jaskiewicz, "Towards a Methodology for Complex Adaptive Interactive Architecture." (PhD diss., Delft University of Technology, 2013).

115. Tatjana Schneider and Jeremy Till, *Flexible housing* (Oxford, UK: Architectural Press, 2007).

116. Bernard Leupen, "Polyvalence, A Concept for the Sustainable Dwelling," *Nordic Journal of Architectural Research* 19, no. 3 (2006): 23-31.

sustainable. Occupants can participate in the design process either during the planning stage to customize, or during the post-occupancy stage to make spatial adjustments.

"Adaptive" is a type of flexible architecture in which the adaptation process is instantaneous or occurs within a short amount of time. In an adaptive space, space is articulated or reconfigured with the use of various sensory or kinetic design elements: changeable surface color or opacity, movable screens or walls, or configurable openings. All "adaptive" spaces are flexible, but all "flexible" spaces are not adaptive. These two terms are similar in many ways, but not interchangeable.

Architecture that is "anticipatory" is flexible. In anticipatory architecture, the changes that might happen in the future are anticipated as possibilities, and spatial, structural or technological provisions are made to the current state of design to accommodate possible future changes. "Interactive architecture" is "adaptive," characterized by the direct user and space "interaction" that is immediate—with or without the mediation of automated sensor-actuator systems.

3.4 Adaptive Spaces: Characteristics and Principles

In the long history of flexible architecture, various adaptive capabilities have been endowed in buildings as formal, spatial or structural characteristics, enabling them to accommodate new occupant requirements that change over time. An adaptive architectural space has two essential characteristics: provision of uncertainty in design, and active user involvement.

In adaptive living space design, the architect chooses to give up a certain level of control over design and grants the user the ability to have some input throughout the decision-making processes regarding ideas of living and behavior patterns. User participation is key, and users do not need assistance of any specialized workforce to make formal or spatial changes.

The underlying parameter for formulation of design principles in adaptive living spaces relies on how it prepares to accommodate predictable and anticipated changes. Design approaches for adaptive spaces are reductive. The inflexible architectural elements—such as structure, core or building envelope—are simplified by reduction in number for a successful design. There are some generic principles for spatial or structural flexibility that have been used during the Modernist era and were later transferred into the contemporary scene of adaptive architecture.

3.4.1 Spatial Adaptability

Provision of specific types of living spaces allow for successful adaptation to future functional requirements. These spaces are open plans, incomplete spaces and "slack" spaces with undefined functions. Many adaptive architectures have polyvalent or multi-purpose spaces, i.e., a use-neutral, open plan having no specificity of functions. Such uninterrupted open spaces can accommodate various types of functions without any formal changes. For instance, many schools have multi-purpose halls that can be used for various functions (see Figure 3.2-a). Open plans allow buildings to change over time to house different functions. Such concepts can also be seen in the "speculative office block" principle of Modernism in which office buildings could be converted into art galleries or other similar spaces.[117]

---

117. Jeremy Till and Tatjana Schneider, "Flexible Housing: The Means to the End." *Architectural Research Quarterly* 9. No. 3/4 (2005): 288.

Architects construct "incomplete" spaces with designated or specified functions to allow future occupants to customize them to suit their own needs. These adaptable spaces are deliberately left unfinished, to extend horizontally or vertically. Specific design suggestions are provided to motivate users to adapt in a specific manner. The Central Beheer Insurance Company Headquarters in the Netherlands (1967-72) demonstrates incomplete, polyvalent spaces, where the working "islands" of the office are left unfinished for the staff to customize according to their own needs, within specific boundaries set by design (see Figure 3.2-b).

(a) Apollo Montessori School, Amsterdam (1980-83)[118]

(b) Central Beheer Headquarters[119]

Figure 3.2. Examples of Open Plan and Incomplete Spaces

118. Source: http://pc.blogspot.com/2007/04/apollo-montessori-school-amsterdam.html

119. Source: http://www.e-architect.co.uk/architects/herman-hertzberger

Architects may also provide functionally indeterminable “slack spaces” for potential future expansion in the form of terraces, balconies, courtyards or storage space.[120] Visual cues, such as beams, columns or projecting corbels, assist in transforming these spaces to accommodate various functions within a short period of time.

Spatial adaptability can be accomplished in two ways: reconfiguration and articulation. Spatial reconfiguration is formal change of space related to size and shape. Spatial articulation is the change in sensory experience of a space pertaining to its feel and appearance. Adaptive spaces generally use kinetic elements or transformable objects—e.g., partitions, doors, furniture—to change size, shape or appearance. In the early nomadic lifestyle, kinetics was applied primarily for pragmatic reasons: safety, transportation, space optimization and cost efficiency. Dynamic forms, shapes and functions evolved that can adapt to technological innovations. With the invention of microchips and mobile technology, the traditional kinetic aesthetics are explored with technological innovations in contemporary adaptive spaces.[121]

Spatial Articulation: With adjustment of sensory design elements, such as color, light, texture and material properties of surfaces, an open plan can be altered in spatial quality and accommodate multiple functions without any physical changes or spatial reconfigurations. For instance, interior light or color can be altered; louvers or opacity of materials can be changed in order to create aesthetically pleasing sensory experiences and physically comfortable spaces, or to enable privacy for performing specific functions. Figures 3.3-a gives an example of spatial

120. Schneider and Till, *Flexible Housing*, 137.

121. Fox and Kemp. *Interactive Architecture*.

articulation in an office space through use of opacity changing “smart” glass. Figure 3.3-b is the interior of the Croatian Pavilion, World Expo 2008 in Spain that uses sensor-driven light and color for spatial articulation that responds to movement in order to create an underwater environment.

(a) Changing opacity of “Smart Glass International[122] (b) The Croatian Pavilion[123]

Figure 3.3. Spatial Articulation with Sensory Elements

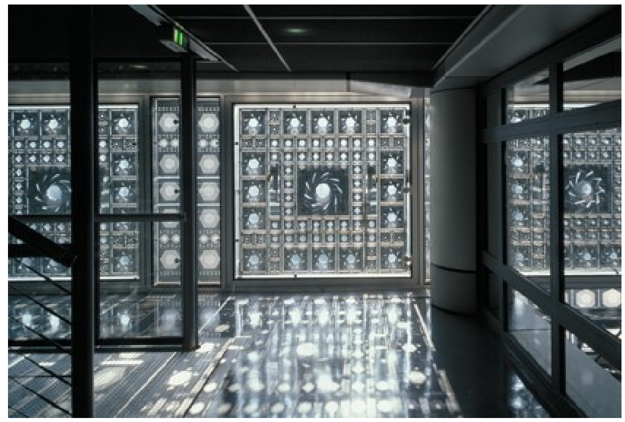
Building skin can be altered to adapt to external environment or modulate internal environment, e.g., heat, light or air movement. In tropical countries, vernacular residences are designed with strategically placed louvers to control air flow and create physically comfortable spaces during summer. With sensor-driven interactive technology, “dynamic” building façades interact with external environment in real time to control access of natural light, heat and thermal gain and to modify internal spatial quality with aesthetically pleasing patterns of light and shadow. Figure 3.4-a is a conceptual render of the Louvre museum in Abu Dhabi (under construction) in which expanding and shrinking kinetic roof elements are used for controlled

122. Source: Kronenberg, *Flexible Architecture*.

123. Source: http://www.architravel.com/architravel/papernews/croatian-pavilion-expo-2008/

access of sunlight into the interior. Figure 3.4-b shows the Arab World Institute in Paris, France (1987) interior that uses motorized apertures on the façade to control the amount of natural light entering the interior space by reacting in a manner similar to a camera shutter.

(a) Louvre Abu Dhabi Museum



(b) The Arab World Institute

Figure 3.4. Spatial Articulation: Controlling External Environment[124]

Spatial Reconfiguration: Residential open plans can be subdivided by means of kinetic elements—sliding, folding or movable screens, doors and furniture—to change spatial configurations. With user participation, alteration of size and shape of spaces are constant and immediate. The Schröder House (1924) is an example of a reconfigurable open plan residence (see section 3.7.1). Kinetic elements are also used for space optimization to accommodate various activities and varying numbers of people in a single space, such as convention halls. These elements support different functions in the same space by enabling privacy, level changes or adjustable fenestrations.

124. Source: http://www.archdaily.com/510226/light-matters-mashrabiyas-translating-tradition-into-dynamic-facades

3.4.2 Structural Flexibility

The focus of structural design flexibility is to reduce the number of loadbearing walls or columns, and have clearly identifiable and separable structural layers. Open plan designs commonly use supporting structures—loadbearing columns and beams, also known as f*rame construction*—to create a large span of uninterrupted space, with a core that contains access and services. Non-loadbearing partitions or surfaces can be removed, shifted or erected to subdivide new spaces. The *shell-core structure* is also used to create adaptive spaces, consisting of a central core with staircase, entrance and services grouped together. The building skin surrounds a free open space for flexible use.

3.5 Flexibility in Modern Architecture: A Historical Overview

Modernism in flexible architecture began with the aim of liberating users from the controls of architects and planners. Modernism (1851-1945) stood for change and dynamism. Architecturally it was manifested in the reconciliation of technological advancement with architectural design principles, through the process of urbanization and industrialization. Modernism brought new ideas, art movements and new ways of living that influenced the West. Flexibility is an attribute of progress in Modernism. Various socio-political and art movements resulted in numerous design schools with conflicting or converging architectural styles. Some of these styles, such as the Bauhaus and *de Stijl*, were adopted by influential artists, architects and educators. Some of these styles still continue to be pursued in present-day architecture.

In Modernism, traditional architecture paradigms were reinvented and explored in search of variable and flexible plan forms in response to an acute housing crisis and industrialization.

True to Modernist philosophy, the search for new conditions of living was explored through integration of new technologies and pragmatic solutions. The individual became an important aspect of design, and the aesthetic characteristics of Modernism were made visible through "Form follows Function," such as unornamented, simple forms with horizontal and vertical lines and integration of innovative technology and natural materials. Reinforced concrete and steel frame structures were predominant and had a significant impact on the extent of flexibility in space designs.

The Industrial Revolution and technological advances influenced artists and architects, giving rise to *machine aesthetic* of product design that was manifested in automobiles, ships and aircraft. Le Corbusier, fascinated by the "engineering exactitude,"[125] visualized the house as a "machine" to live in that should respond to need and provide solutions to present-day problems.[126] Le Corbusier conceived the Maison Dom-Ino in 1914, a structural prototype of a low-cost and mass-producible housing frame. In 1925, he published the *Five Points towards a New Architecture* that promoted the notion of free plan. In his book *Modern Architecture: A Critical Theory*, Frampton states that the Dom-Ino was not only a device for mass production, but also represented the standardization of a housing unit that could be combined and assimilated the way dominos are stacked and formed in a game.[127]

The acute housing shortage of the 1920s post-World War I era, especially the lack of provision for minimal housing of the low-income working class, triggered the development of

---

125. Kenneth Frampton, *Modern Architecture: A Critical Theory* (London: Thames and Hudson, 1992), 152.

126. Krista Sykes, ed. *The Architecture Reader: Essential Writings from Vitruvius to the Present* (New York: George Braziller Publishers, 2007).

127. Frampton, *Modern Architecture: A Critical Theory*.

flexible architecture. The typical bourgeois apartments or the English terraced housings were not fit to meet their needs in terms of economics, scale and density. The notion of flexibility was thus introduced, initially to find a pragmatic solution to this problem. As space was limited, the goal was to design for the most efficient and flexible space usage possible.

Modern flexible architecture initiated and promoted modularity and prefabricated technologies as essential elements of design. Western Modernist architects had gained inspiration from the iconic simplicity and modular flexibility of the traditional Japanese house (see Figure 3.1-d). As Bauhaus architect Walter Gropius states:

> Our modern architectural requirements of simplicity, of outdoor-indoor relation, of flexibility, of modular co-ordination and pre-fabrication, and most importantly, of variety of expression, have found such fascinating answers in the classic domestic architecture of Japan that no architect should neglect its stimulating study. [128]

The traditional Japanese house is also reflected in Frank Lloyd Wright's timber frame construction and indoor-outdoor connectivity. The transfer of traditional vernacular modularity into the industrialized system was a focus of Modernism.

Processes of urbanization, industrialization and prefabrication gave rise to new concepts of flexible housing during the 1930s to 1940s. Many residential designs were envisioned as components or units to be shifted, moved or stacked on top of one another for expansion purposes (see Figure 3.5). Motivated by post-World War II technological advances, better quality, low-cost construction enabled more variety in flexible arrangements of prefabricated units. Beside standardization of size, division and furniture, the focus was also on the usage

128. Schneider and Till, *Flexible Housing*, 174.

patterns of spaces. Dutch architects performed studies and temporal analyses on various family sizes and their diurnal present and future cycles of domestic activities.

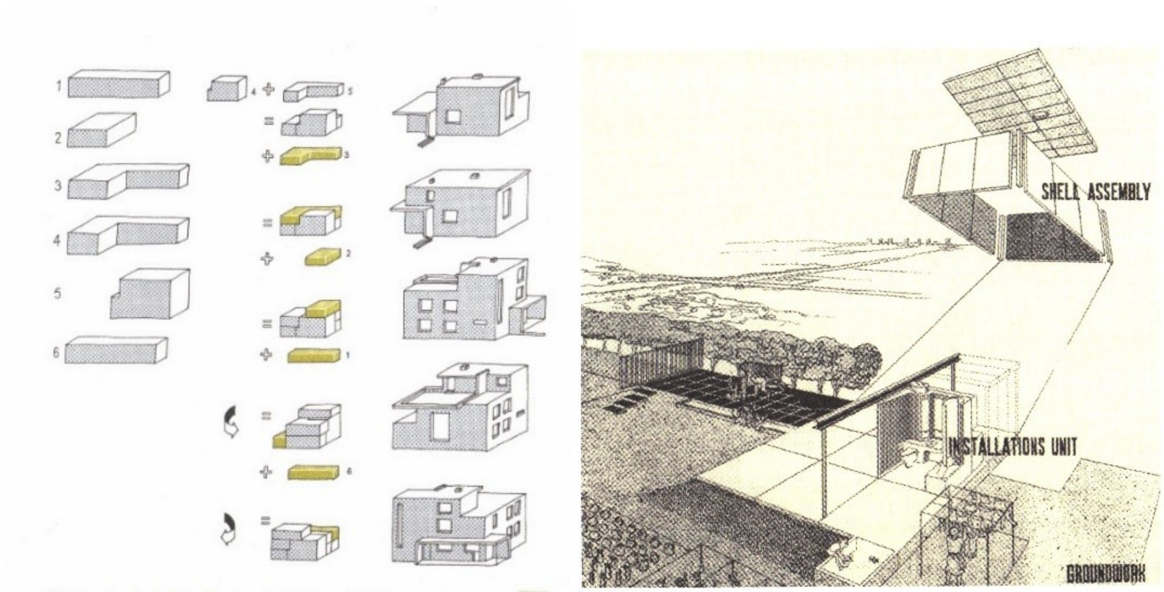


Figure 3.5. Residential Components and Prefabrication [129]

Established minimal space standards were promoted and practiced by many architects in order to optimize space usage. Le Corbusier's residential projects, such as the Weiβenhofsiedlung (1927) in Stuttgart and Maisons Loucheur (1928) in France, represented the idea of the railway sleeping car designed with day-night scenarios in which flexibility of a multi-functional space was facilitated through the use of sliding partitions and foldable, transformable furniture.[130] This concept of reconfigurable open space was also studied in architect Carl Fieger's Kleinwohnung (1931) in Germany (see Section 3.6.2). User participation in the planning and

129. Source: Ibid., 22-23.

130. Ibid.

design stage of architecture inspired the "Open Building" movement of support-infill system. Occupants installed customized prefabricated infills of partitions, finishes, partitions, mechanical equipment and furniture without affecting the structure.

The industrial designs of Ferdinand Kramer, an architect and designer briefly associated with the Bauhaus, were a direct response to the acute housing shortage, unemployment and inflation of post-World War I. His designs focused on affordability, mass production and optimization of space. Kramer worked both in Europe and America (1938-1951). His designs included standardized architectural elements and everyday objects, such as doors and windows, door handles, light fixtures and electric appliances, as well as various types of ready-to-assemble furniture (see Figure 3.6).

Figure 3.6. Furniture Designs of Ferdinand Kramer[131]

The functionalist, transportable furniture designs reflected his vision of modernity and of new ways of living inspired by the practicality and flexibility of mobile lifestyles of people—a vision that continues to be pertinent even in the present day.[132] His architectural style also

131. Source: Ibid.

132. Katharina Horstmann, *Ferdinand Kramer: Original Designs According to Functional Principles*, trans. Jonathan Uhlaner (Goethe-Institut e. V., October 2014), https://www.goethe.de/en/kul/des/20436267.html

focused on rationality and affordability. The multi-functional "cubical" design of the Geothe University Library in Frankfurt, Germany, reflected his idea of creating inspiring environments that would motivate people to sleep, work and read in a single space.[133]

3.6 Case Studies

In this section, some case studies of adaptive architecture from early Modernism to the contemporary era were discussed. The conceptual, formal and aesthetic analysis of these designs pertain to the various socio-economic, artistic and political movements of their respective eras, as well as available technological innovations and advances.

3.6.1 The Schröder Huis, the Netherlands, 1924. Architect: Gerrit Rietveld

Modernism witnessed one of the major art movements, *de Stijl*, that originated in the Netherlands. While the movement focused on artistic expression, the Schröder House was one of the very few architectural designs that came out of it. The house was an attempt of architect Gerrit Reitveld to apply the spatial concepts of *de Stijl* through the simple elements of the emerging art form, representing universality of essential forms and color. It embodied Theo van Doesburg's 1924 manifesto on architecture with its economic, anti-decorative functional design.[134]

---

133. Adeline Seidel, "A Systematic Approach to Living and Loving," *StylePark*. November 24, 2015, https://www.stylepark.com/en/news/a-systematic-approach-to-living-and-loving

134. Jeanne Willette, "De Stijl Architecture." *Arthistoryunstuffed.com*. April 29, 2011, http://www.arthistoryunstuffed.com/de-stijl-architecture/

The flexible open plan adhered to the manifesto through its connection between interior and exterior, the space flow further emphasized by the moving non-loadbearing partitions. The flexibility executed Modernist thoughts of clarity and purity. The core, containing the staircase, is placed in the center of the plan. The single first floor open space could be subdivided into three rooms—two bedrooms and one living-cum-dining space—by means of hinged sliding or foldable screens. The house switches between openness and enclosure through active user participation. The user pushes movable, foldable or sliding walls and foldable furniture in order to create one continuous space during the day. At night, the screens are closed, and each room can be accessed separately from the hall that forms in the center (see Figure 3.7). The two-storey house was designed for a mother with three children, intended primarily to suit the client's specified needs through a very particular set of requirements. The architect played with the social and spatial hierarchy in response to the client's desires.

The building aesthetically advocated the artistic philosophy with strong asymmetry, geometry of straight lines, colored square and rectangle elements, the use of primary colors along with black and white, and simplified visual compositions that extended in both vertical and horizontal directions. Artist Piet Mondrian's cubist paintings of linear composition, combined with painter and architect Theo van Doesburg's plates, were the inspiration for the anti-gravitational, floating effect of de Stijl architecture.[135] However, the architectural style has been criticized by some researchers for ignoring the "form follows function" rule of architecture as the

135. Alfred H. Barr, Jr., "De Stijl." *The Bulletin of the Museum of Modern Art* 20, no. 2 (2012): 6-13.

design focus of abstract, geometric system with flat, primary colors are utilized without having any impact on functionality of spaces.[136]

Figure 3.7. The Schröder Huis[137]

3.6.2 Kleinwohnung, Germany, 1931, Architect: Carl Fieger

This project, designed by Bauhaus architect Carl Fieger, is an example of adaptable housing that utilizes the minimal space standard and optimization of space usage through user participation. Inspired by the idea of a railway sleeping car designed with day-night scenarios, the single use-neutral, multi-functional living space transforms into a living, dining and study area during day, and two separate bedrooms by night (see Figure 3.8).[138] The project shared a similar concept with Le Corbusier's series of minimal apartments, such as Maisons Loucheur of France that were designed based on day-night scenarios in 1928.

136. Ibid.

137. Source: http://www.archdaily.com/99698/ad-classics-rietveld-schroder-house-gerrit-rietveld

138. Source: http://www.archdaily.com/99698/ad-classics-rietveld-schroder-house-gerrit-rietveld

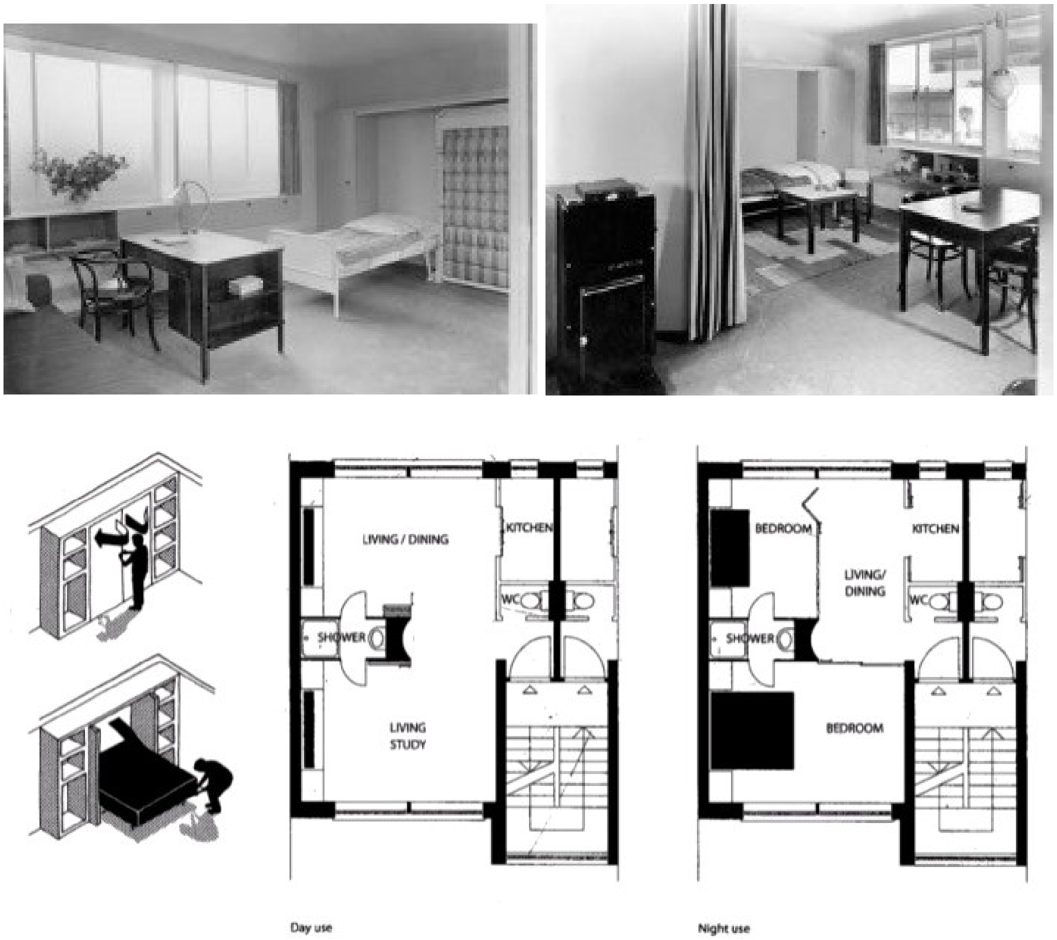


Figure 3.8. The Kleinwohnung Apartment[139]

This study project, a prototype of the apartment built for the Berlin Building Exhibition in 1931, is a small-scale apartment ($40m^2$) designed for more than one occupant. The large uninterrupted space is a living cum study during the day and two bedrooms at night by means of foldable partitions and furniture. The space is partially divided into two parts with a shower room in the middle. The service area, consisting of a kitchenette and WC, are grouped together and located against the stairway to be accessed from the foyer-like hallway at night. Circulation

139. Source: Till and Schneider, *Flexible Housing*, 63

limited to a minimum ensures minimum interruption and maximum privacy. During day, the foldable furniture, including two beds, are kept in wall recesses, almost disappearing from sight during daytime. At night, beds are folded down and foldable partition doors further convert the spaces into distinct rooms, providing additional privacy.

3.6.3 Wohnzeile, Weiβenhofsiedlung, Stuttgart, Germany, 1927. Architect: Mies van der Rohe

Bauhaus architect Mies van der Rohe regarded flexibility as one of the most important concepts of architecture and emphasized the efficiency of frame construction to provide flexibility and meet the changing needs of the occupants in order to extend the lifespan of buildings longer than their initial intended function. [140]

The apartment block at Weiβenhofsiedlung in Stuttgart had frame construction with a predominantly open plan with few internal column structures. Mies van der Rohe commissioned twenty-nine architects to design the interior for the apartment block for various family sizes and living patterns (see Figure 3.9). The infill, or the non-loadbearing walls, and services were separated from the supporting structure. The apartment block was a row of four modular units with large spans, placed side by side: Haus 1, Haus 2, Haus 3 and Haus 4. Typical of flexible architecture, each core, consisting of stairway, kitchen and bathrooms, was located away from the larger uninterrupted living spaces and shared by two adjacent modular units. Apartments ranged from 45m^2 to 72 m^2.

140. Ibid.

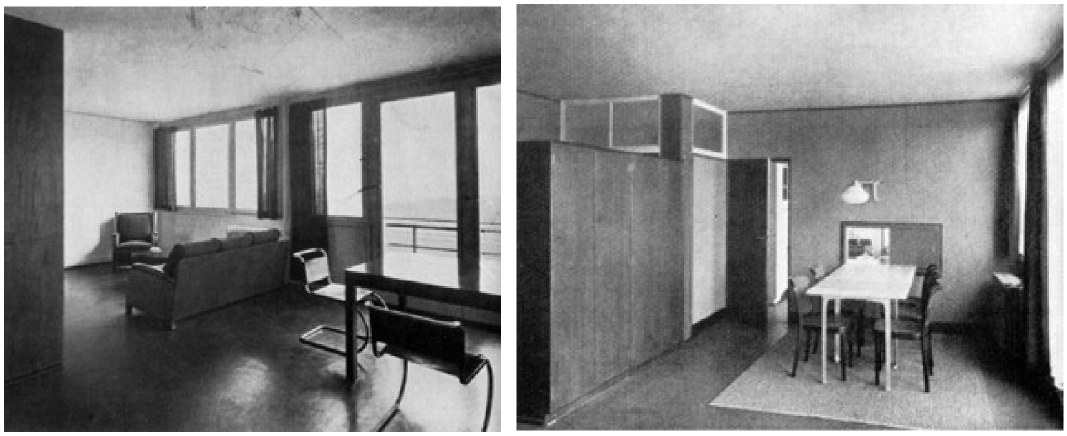


Figure 3.9: Apartment block at Weiβenhofsiedlung[141]

Flexibility was achieved through the indeterminate open plan and central service core concept. Non-loadbearing, ply panel partitions and sliding doors were used to rearrange, divide or connect variety of internal spaces. Foldable and movable furniture was also used to divide the spatial functions into day and night use. The building served its purpose of accommodating different family sizes and different living scenarios. The units were designed to suit the individual needs of the tenants, varying in size and spatial arrangements based on family size. (The apartment block temporarily served as a children's hospital soon after World War II.)

3.6.4 Garden Hut, Catalonia, Spain, 2004. Architect: Eightyseven Architects

This award-winning project is an example of an adaptive, transformable architecture that responds directly to seasonal changes. It is a garden hut situated in the owner's garden, adjacent to his house (see Figure 3.10). The built form is sculptural and made of Brazilian hardwood,

141. Source: https://thecharnelhouse.org/2015/03/14/stuttgart-weisenhof-1927-modern-architecture-comes-into-its-own/.

glass and rusted steel. The prefabricated steel wall, also known as "weathering steel," changes into bright orange or a reddish color when exposed to air through application of an oxide coating. This material can create a variety of colors and changes with environmental conditions and exposure. In summer, the garden hut can be opened up to become a gazebo and blend with the surrounding color. The walls slide open and fold back as the interior space flows freely into the garden. During winter, the hut converts into a closed, small hardwood storage unit. With segmented roof, the sculptural hut opens and closes similarly to foldable furniture.[142]

Figure 3.10. The Green Hut[143]

3.6.5 Cellophane House, MOMA, New York, 2008. Architect: Kieran Timberlake Associates

This interactive project is a temporary house installed on site for the exhibition on "Home Delivery" commissioned by MOMA (The Museum of Modern Art, New York). It is an 1800 square-foot, five-story residence with two bedrooms, two bathrooms, a living cum dining space, a roof terrace, and a carport (see Figure 3.11). Each building segment was constructed off site.

142. Ibid.

143. Source: Kronenburg, *Flexible: Architecture that Responds to Change*, 151.

The prefabricated building is flexible and interactive. Any part of the building—walls, skin, bathroom—can be altered, replaced or upgraded at any point. The programmable building façade not only interacts with the environment for heat, ventilation and temperature control, it also interacts with the user to a certain extent.

The building utilizes "NextGen SmartWrap" as the exterior skin, a 0.04 inch thick polyester film substrate, composite material that protects the façade against the weather. The material is programmable by the user, and responds by changing transparency, lighting up the panels or display images. The skin is also mass-customizable, and can be programmed by the user through a computer. It combines organic printed photovoltaics and light-emitting diodes. The user can customize the transparency, patterns, color and images to be displayed. The façade regulates the interior environment and controls temperature. The photovoltaic panels on the roof collect passive solar energy, and the photovoltaic membrane of the skin generates electricity. Depending on the external weather, the building monitors air temperature through insulation and air flow control through its double-layered skin, providing cool air during summer and heat during winter. The building is primarily naturally ventilated.[144] The building skin changes transparency and can become partially visible (translucent) through user control.

The materials adapt in response to the climate and changing weather conditions. The skin—possessing climate control, lighting, power generation and information display capabilities—comes "alive" against the static frame of the building. The aesthetics derives from the adaptability of the materials to changing conditions and occupant desires.

---

144. "Jason Timberlake by Deven Golden," *BOMB*, May 2008, http://bombsite.com/issues/104/articles/3145.

Figure 3.11. The Cellophane House[145]

3.7 Conclusion

Architecture is a symbol of its time. It is a product of technology and lifestyle that reflect changing social-economic and cultural conditions and user needs. The characteristic of architecture is to gravitate towards the concurrent technological impulses, its various typologies reflecting new aesthetics supported by the prevailing technology.

In our time, ubiquitous computing and mobile technology have given rise to a new group of users: young mobile professionals with a new culture of mobile, transitional lifestyle. The acute housing crisis, especially for transient tech industry professionals, gave rise to micro, tiny houses and shared apartment living in high density cities (see Section 1.2). The socio-economic scenario and severe housing problems demand a new architectural vocabulary that will address the culture of techno-centric mobile professionals. Solutions should be sought in the integration of available innovative technologies in a mediated, adaptable architectural design that is specifically suited to their transitional lifestyle.

---

145. Source: http://inhabitat.com/kieran-timberlake-cellophane-house/.

CHAPTER 4

INTERACTION IN ARCHITECTURE

4.1 Introduction

In this chapter, the abstract idea of "interaction" between human and built environment is defined and its meaning, characteristics and technologies are explored through its role in the adaptation process of habitable architecture. Architecture's primary function is considered as providing a shelter, capable of shaping human activities, experience and behavior by means of spatial organizations, transformations and articulations. Interaction in architecture is understood as a simple input-output mechanism in which an input of a stimulus generates an immediate output or response. Interactive architecture is adaptive. Here, human actions act as stimuli to fulfill a need, and the responses are ways in which architecture is designed to adapt to the need. Interactive architecture is anticipatory in that it makes allowance for addressing otherwise not apparent needs and preferences (space of possibilities). The chapter discusses interactive architecture in which interaction is based upon automated or sensor-driven systems. The concept of interactive architecture is re-evaluated through discussion of its current trends and criticisms. Innovative interactive technologies and materials are discussed and analyzed in order to elicit an understanding of their potential affective and aesthetic roles in architectural space making, taking mainly visual sense perception into account.

4.2 Defining Interaction in Architecture

In simple technical terms, interaction consists of an input and an output. It is the intermediary condition or the transitory state through which an action (input) generates a reaction (output). The word "interaction" also suggests an exchange of information between two or more parties. There must be deliberation over this exchange,[146] which means an action should be reciprocated with a response in order to complete an interaction. Joanne Jakovich and Kirsty Beilharz define interaction as a "combined reciprocal action" for exchanging information between two or more related natural or artificial agents in a system, where the agent can be human, computer or building.[147] For example, in a simple form of human-computer interaction, a single click on the mouse (input) changes the display on the computer screen (output).

In the context of architecture, interaction can be defined in similar terms. Interaction is an automatic or intuitive reciprocation of buildings to the action of the user.[148] In architecture, the artificial agent is the building or built environment, including any machine or computation technology that is integrated with architecture. Natural agents are inhabitants and environmental factors: sun direction, natural light, temperature, humidity, wind direction and speed, and weather conditions related to seasonal changes, etc. In a typical interactive architecture, interaction may occur when one agent (human or environment) performs an action or input and the opponent agent (building) generates a reaction, response or output.[149] It is important for each participating agent to necessarily have the ability to act or respond, or both, based on the context and specificity of the information gathered from opponent agent. The nature and characteristics of interaction is restricted to or limited by the affordances of the technology that enables it.

---

146. McCullough, *Digital Ground*.

147. Jakovich and Beilharz, "Interaction as a Medium in Architectural Design," 369.

148. Kronenburg, *Flexible: Architecture that Responds to Change*.

149. Ibid.

A fundamental model of interaction is introduced by Don Norman in his book, *Design of Everyday Things*. The model describes the process of interaction that is initiated by setting a prior goal or desire by the user. Execution and evaluation are two essential actions that constitute the interaction process. The user's initial specified action is executed in order to achieve the desired goal. Once the action (input) is executed, the user perceives and interprets the response (output) and evaluates it by comparing it to the desired goal set initially. In human-machine interaction, *feedforward* is known as the information—cognitive, sensory or physical—the user has prior to choosing what type of action to take. *Feedback* is the immediate result of user's action communicated by the system through sensory perceptive means—e.g., visual, aural and tactile.[150] As a direct or indirect result of interaction, feedback can potentially drive further interaction. The user may choose to execute another action within the limitations and allowance of the system until the desired goal is met or a new goal is set.[151]

Figure 4.1 shows adaptation of Don Norman's model of Interaction and its application to demonstrate the process of interaction in a conceptual architectural space. In the feedforward phase of human-space interaction, the user makes an input in order to achieve a desired goal from a living space. The goal may be a specific quality of space that the user desires to satisfy a specific mood or emotion. The input is generally in the form of modification of architectural elements: manual push or pull of elements, press a switch or trigger a sensor. As a response to the input, physical space modifies and transforms in appearance, form, feel or function. The modified spatial quality (output) is the feedback that is perceived, interpreted and evaluated by

---

150. Dan Norman, *Design of Everyday Things* (Basic Books: New York, 2013).

151. Ibid.

the user when comparing it to the initially set goal. Spatial feedback either satisfies the user's needs, influencing and motivating the user to alter mood, behavior and activity pattern or it gives rise to new sets of goals to achieve from the living space.

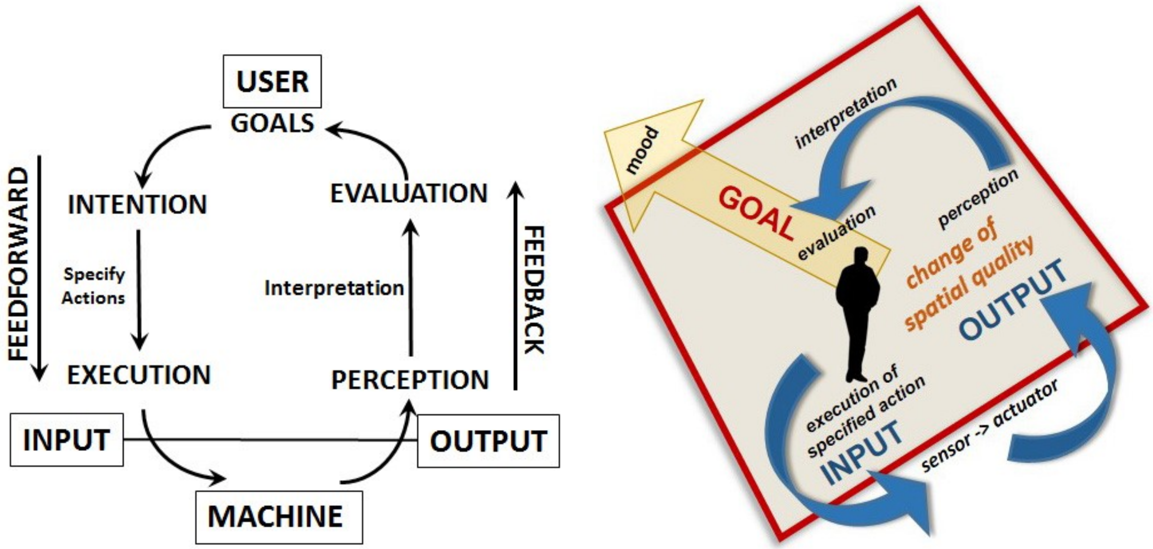


Figure 4.1. Don Norman's Interaction Model in an architectural space

4.2.1 Other Definitions

The concept of *interaction* in architecture has its roots in the theories of Gordon Pask, a cybernetician of the 1960s who collaborated with architects and advanced his "Conversation Theory."[152] The theory proposed that human-machine interaction should take the form of a real conversation, where both user(s) and machine (architecture) provide feedback to each other. In a two-way interaction between user and machine, machines have no set pre-determined actions, but through human feedback form their own conclusions, goals and outputs. Architect Cedric Price was the first to adopt this cybernetic concept in Fun Palace. The Paskian concept of

152. Fox and Kemp, *Interactive Architecture*, 14.

interaction has been considered ideal by many researchers in the context of design of interactive environments.[153] Over the years, leading practitioners in the field of architecture and cybernetics, such as, Haque, Oosterhuis and Kronenburg have attempted to expand on Paskian theory of *anticipatory* systems and redefine interaction.

The simple action-response definition of interaction is being discarded by some in favor of a more complex open-ended interaction where both parties are active participants. Based upon the Paskian concept of two-way conversation, some practitioners have introduced the concepts of *predictive technology* and *anticipatory architecture*[154] in the field of interactive architecture. Michael Fox and Miles Kemp suggests that interaction should be essentially a "two-way street" where both parties are active participants.[155] Architect and educator Oosterhuis defines interaction similarly and proposes the development of proactive and anticipatory buildings where buildings act, respond and change configurations in an unpredicted manner in real time.[156] Similarly, architect Usman Haque also re-defines interaction as a multi-loop conversation where architecture responds to the action of human or environment in a "linear-causal" manner within a pre-programmed structure.[157] The concept of Paskian anticipatory systems have been applied in

---

153. Lucy Bullivant, "Alice in Technoland." *Architectural Design* 77, no. 4 (2007): 6-13.

154. Fox and Kemp. *Interactive Architecture*.

155. Ibid., 13.

156. Mark Garcia, "Otherwise Engaged: New Projects in Interactive Design." *Architectural Design* 77, no. 4 (2007): 44-53.

157. Usman Haque, "Distinguishing Concepts: Lexicons of Interactive Art and Architecture." *Architectural Design* 77, no. 4 (2007): 26.

his various interactive projects, such as *Moody Mushroom Floor* and *Open Burble*.[158] The automation technology of contemporary interactive architecture is being developed to implement *predictive technology* for energy efficiency.

This dissertation excludes these concepts of two-way interaction that are yet to be explored in the realm of habitable architectural projects. The notions of interaction based upon the conversation theory are still at a developmental stage and have been examined mostly in interactive art installations and digital media.

Responsive architecture is another genre of architecture that is also not considered within the research scope of this dissertation. Similar to living organisms, responsive architecture "senses" and transforms to adapt to changing circumstances.[159] This genre is based upon the idea of self-organization as a natural system, and is integrates various concepts of biomimicry, autopoiesis, morphology, and hybridized environments among other disciplines. Focusing mostly on material science and data-driven structural engineering, this genre includes parametric systems, generative designs, and concepts of "living" architecture. Responsive structures or systems generate new computation-based forms or shapes that are non-predetermined in order to withstand physical forces or weather conditions. Responsive materials, like living organisms, respond to sensations, light, or chemical actions through self-repair, self-generation or change its characteristics. These concepts, at the initial stages of research and development, are yet to be successfully adopted in the domain of habitable architecture.

---

158. Usman Haque, "The Architectural Relevance of Gordon Pask." *Architectural Design* 77, no. 4 (2007): 54-61.

159. Philip Beesley, Sachiko Hirosue, and Jim Ruxton, "Toward Responsive Architectures," in *Responsive Architectures: Subtle Technologies*, eds. Philip Beesley et al., (Toronto: Riverside Architectural Press, 2006), 3-11.

4.2.2 Interaction as an Adaptive Architectural Process

The concept of action-response mechanisms between human and architecture (i.e., spaces or elements) existed in architectural history long before the invention of automated systems. One such example can be seen in the traditional Japanese architecture. Here, in simple human-architecture interaction, the human input of pushing or pulling the sliding partition (*shoji*) with muscle force results in the architectural output of the expansion or reduction of living space as a response. The indigenous builder in the village also reconfigures and reshapes his hut to adapt to indoor and outdoor activities, constantly modifying living spaces with diurnal and seasonal changes.[160]

Jaskiewicz describes architecture as both a product and a process, a combination of constant adaptation to natural environment and evolving human needs and activities.[161] Human activities and needs define architectural space. Space is adapted to both external natural environment and artificially created indoor environment. To protect from external environment, indoor environment is modulated not only through design of architectural elements, but also through artificial environment of light, temperature control, etc. Environmental conditions (i.e., thermal, visual, acoustic) are adapted to human activities through spatial modification and articulation. In a feedback loop, spatial conditions influence human behavior, activities and experience. Architectural affordances and indoor environment, through sensory stimuli, influence and alter human activity patterns.

---

160. Fox and Kemp, *Interactive Architecture*.

161. Tomasz Jaskiewicz, "Towards a Methodology for Complex Adaptive Interactive Architecture."

In the adaptive process of architectural design, interaction thus occurs in two levels. One: the user interacts with architecture to meet desired goals related to needs and activities driven by prevailing mood, emotions, experience, personal taste, lifestyle, knowledge, culture and religion. The personalization and customization of architectural space is a process in which the user formulates of physical, emotional, aesthetic and social meanings with lived space.[162] In traditional flexible architecture, the user interacts with space through sliding, folding or altering the size, shape, texture or transparency of architectural components (e.g., partition wall, curtain, louver or blinds) to generate a variety of spatial configurations and qualities. Two: architecture is in continuous interaction with environment, controlling and modulating external environment and monitoring interior environment. In contemporary architecture, pre-programmed sensor-actuator functions enable buildings to respond to environmental factors through mechanical systems, energy controls and kinetic elements, such as vents, blinds and other shading devices.

4.2.3 Characteristics of Interactive Architecture

As previously discussed, interaction in architecture is not dependent on a specific technology, as the concept of human-space interaction has existed throughout the history of architecture. The traditional *shoji* screens of Japanese architecture are kinetic elements that not only reconfigure space, but also allows daylight modulation and connection to exterior to articulate space. However, with the advent of *ubiquitous computing*, many contemporary

162. Lucy Bullivant, "Alice in Technoland."

architects consider the presence of automatic systems with sensors and actuators for both kinetic and intelligent materials as a requirement for classifying an architecture as interactive.[163]

The primary function of interaction in architecture is the reconfiguration, modification, articulation and/or enhancement of space in response to the user's wishes. The spatial output of human-space interaction is sensory perceptive. It is discernible in size, shape, feel or appearance. Modifications made to building skin or envelope have spatial impact both indoors and outdoors.

The user is necessarily an active participant in interactive architecture, constantly "engaged: asked, enticed, manipulated, directed, or coerced" [164] in a dynamic human-space interaction. This particular participatory role of the user distinguishes interactive architecture from other forms of flexible architecture.

In interaction, there is real-time immediacy in the architectural response. Contrary to reconfigurable architecture, where building parts or modules require a specialized workforce in order to be assembled or dismantled,[165] interactive architecture requires no specialized assistance for the user to alter and articulate spaces. The user's action creates instantaneous alteration or articulation to space.

4.3 Interactive Architecture: Current Trends

According to Fox and Kemp, the idea of interaction was translated into the domain of architecture in the 1970s for the purpose of environmental control and management. Notions of

---

163. Kronenburg, *Flexible: Architecture that Responds to Change*

164. Fox and Kemp. *Interactive Architecture*, 138.

165. See Section 3.3.

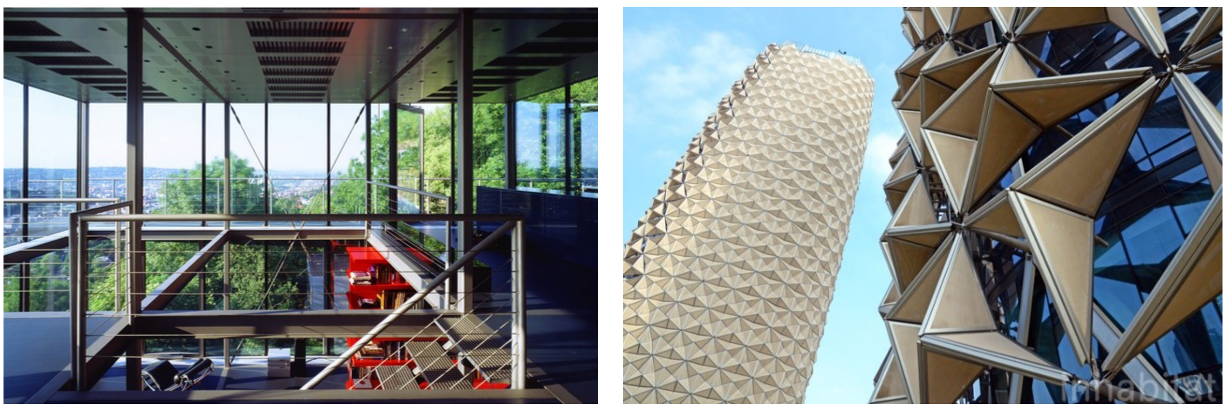
Intelligent or *smart* environments and *ubiquitous computing* simultaneously evolved during the 1980s when embedded digital technologies and communication devices were integrated with architectural design spaces to aid and enhance the user's daily activities. The invention and rapid development of computers in the 1980s followed by cultural and commercial interest and economic feasibility in the early 1990s brought two important trends in interactive architecture.

One trend is the data-driven *smart* or *intelligent* environment where various seamlessly integrated computation devices coordinate in space and energy optimization. These devices include wireless networks, mobile technology, GPS, sensor-driven security systems, and lighting, temperature and ventilation controls. Architects search for ways to integrate technological innovations to improve building performance in respect to environmental management, efficiency, energy conservation and economic feasibility. The *smart* homes and offices utilize the idea of seamless integration of internet, wireless networks, mobile technology and embedded computation in living spaces. In intelligent automation, there are two main components: a sensor that identifies the need, and an actuator that responds by carrying out an action. Current research and development in this area is focused on integration of monitoring systems that, with various wearable technologies, can orient and inform occupants and personalize exhibits in functional spaces based upon occupant's daily lifestyle, health, personal preferences and behavior pattern. For instance, in a *smart* kitchen, digital interfaces inform use of appliances; sensor-driven flooring monitors the user's movement to assist in safety; kitchen appliances communicate with the user to facilitate productivity.[166] Figure 4.2-a is an interior of a

---

166. Chia-Hsun Lee, Leonardo Bonanni, and Ted Selker, "The Kitchen as a Graphical User Interface," *Digital Creativity* 16, no. 2 (August 2004): 110-114, doi: 10.1145/1185884.1185989.

"smart" house—The R128 House in Stuttgart, Germany—a self-sufficient, solar powered home with security, heating, and lighting controlled by computer automation and voice recognition devices. Figure 4.2-b shows the computer-driven, automated, parametric façade of Al-Bahar towers in Abu Dhabi, which uses real-time analysis to follow sun movement in order to regulate heat and radiation gain.



(a) The R128 House in Stuttgart, Germany[167] (b) Al-Bahar towers in Abu Dhabi[168]

Figure 4.2. Smart technology for security, energy and environmental control

The other trend is characterized by interactive technologies that explore real-time kinetic aesthetics of sensor-operated doors, walls, roof and furniture in order to dynamically modify space in its form, feel and appearance. This includes the "culture of the changing façade"[169] that explores communication possibilities of building façades. Digitally programmable digital

167. Source: Kronenburg, *Flexible: Architecture that Responds to Change*

168. Source: http://inhabitat.com/exclusive-photos-worlds-largest-computerized-facade-cools-aedas-al-bahr-towers/.

169. Lucy Bullivant, "BIX Matrix Realities: United Kunsthaus Graz Austria," *Architectural Design* 75, no. 1 (January-February 2005): 84.

building surfaces are dynamically modified through image projections, video, color or lighting patterns in response to human movement in space, mobile text messages, sound installations and meteorological changes. Figures 4.3 presents some of these examples, explained as follows:

(a) Wonderwall in Tokyo, Japan (2000)[170]

(b) Kunsthaus Graz, Austria (2003)[171]

(c) Enteractive, Los Angeles, USA (2006) [172]

(d) Tower of Winds, Japan (1986)[173]

Figure 4.3. Performative and Communicative Programmable Surfaces

---

170. Source: http://www.klein-dytham.com/i-fly-virgin-wonderwall/.

171. Source: http://www.crab-studio.com/kunsthaus.html.

172. Source: https://www.electroland.net/#/enteractive/.

173. Source: http://www.bta.it/txt/a0/02/bta00289.html.

The interactive *iFly Virgin Wonderwall* in Tokyo, Japan (see Figure 4.3-a) uses mobile phone technology to quiz and receive answers from passers-by. The programmable interactive façade of *Kunsthaus Graz* in Austria (see Figure 4.3-b) acts as a social, communicative media platform that displays requests from artists and performers through text, narration, images or video content in real time. The sensor-driven LED tiles light up on the building façade and interior surfaces of *Enteractive*, an interactive building in Los Angeles, California, through "sensing" people's movements. This encourages more user participation, creating an entertaining, playful, videogame-like atmosphere (see Figure 4.3-b). The programmable building surface of the *Tower of Winds* in Japan interacts with surrounding noise levels from the city, and wind speed and direction in order to produce aesthetically pleasing neon rings in various patterns and colors (see Figure 4.3-c).

4.4 A New Materiality

Advances in nanotechnology have opened up new possibilities for interactive architecture. There are interactive materials that respond to touch and interact through light, sound or color transformations. Nanotechnology and microprocessor-controlled embedded sensors concern experiments in material characteristics. Some high-tech materials can continuously reconfigure themselves, while deceptive extreme performance materials, such as *aerographite*, a nanoparticle-based material, appears light-weight, but are extremely strong and versatile. Another high-strength, light material, called *microlattice*, with a thickness of 100 nanometers, can be potentially used on the interior surfaces of airplanes for reducing weight.[174] Electronically activated variable transmission materials (see Figure 4.4) can be programmed to control view and privacy and natural light modulation in the interiors of homes and offices.[175]

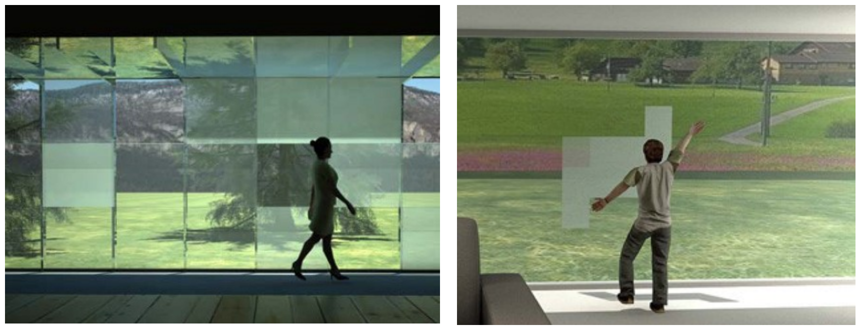


Figure 4.4. Opacity-changing Glass[176]

The last decade has witnessed an upsurge of innovation in *smart* materials, especially textiles, with microprocessor-controlled embedded sensors that change in color and luminance, move, "breath," shrink or expand in response to human touch and sound. Smart Textiles have aesthetic and emotive qualities that open up and close in response to light, change appearance in different temperatures, or become more colorful over time. Figure 4.5-a shows *Digital Dawn,* a biomimetic "smart" fabric stores energy and changes luminosity in response to varying brightness levels of the immediate environment.[177] Fabric with shape-memory alloys

174. Bob Yirka, "Boeing Demonstrates Lightest Metal Ever," *Phys.org*., October 15, 2015, https://phys.org/news/2015-10-boeing-lightest-metal.html

175. Orkan Telhan et al., "Interaction Design with Building Facades." in *TEI 2010,* January 25-27, 2010. Cambridge, Massachusetts:ACM: 291-294

176. Source: Ibid.

177. Mathias Gmachl and Rachel Wingfield, "Auspicious Tangents," in *Responsive Textile Environment*, eds. Sarah Bonnemaison, and Christine Macy (Halifax: Tuns Press, 2007), 26-35.

"remembers" previous deformations and changes shape with temperature fluctuations (see Figure 4.5-b).

(a) Digital Dawn[178]

(b) Shape Memory Alloy Textile[179]

Figure 4.5. Smart fabrics

In *Breathing Room*, a spatial installation, an interactive textile can simulate the manner of breathing in response to a viewer's motion and touch (see Figure 4.6-a).[180] *Whiskers,* of Interactive Façade in Cambridge, MA, is a kinetic interactive façade (see Figure 4.6-b) with sensor-driven whiskers that move in response to a viewer's motion.[181] However, human sensory engagements with the aesthetic and emotive qualities of these *smart* materials and textiles are being explored primarily in the realm of spatial art installations, and have yet to be explored in habitable architecture. While some of these materials have the tactility and materiality of

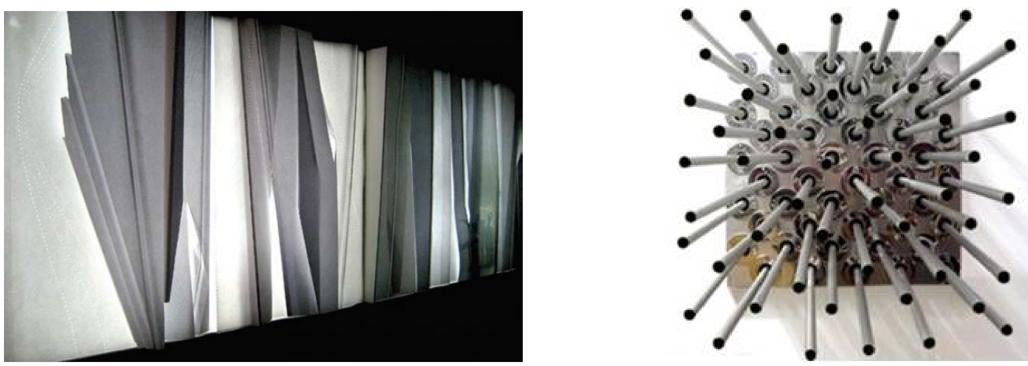
178. Source: http://loop.ph/portfolio/digital-dawn/.

179. Carole Collet, "The Next Textile Revolution," in *Responsive Textile Environment*, eds. Sarah Bonnemaison, and Christine Macy (Halifax: Tuns Press, 2007),14-25.

180. Mette Ramsgard Thomsen, "Metabolistic Architectures," in *Responsive Textile Environment*, ed. Sarah Bonnemaison, and Christine Macy (Halifax: Tuns Press, 2007), 36-45.

181. "Interactive Façade," *foxlin.com*, January 7, 2015, http://foxlin.com/interactive-facade/.

traditional materials, others display new types of materiality. As the touchscreen computer has given birth to a new haptic sensation, evolving artificial and synthetic interactive materials offer a new sensation as well.



(a) Breathing Room[182] (b) Whiskers of Interactive Façade [183]

Figure 4.6. Smart materials in art installations

4.4.1 Aesthetics of Interaction

The aesthetics of space refers to the way in which one interacts with it, as well as the manner in which the space is explored. The real-time input-response drives the aesthetic experience. Joanne Jakovich and Dagmar Reinhardt quote Krueger on "response as a new art medium based on real-time interaction between men and machines."[184] In human-space interaction, interactivity itself is a design tool. On one hand, the architect designs the behavior and motion of people based on meaning that derives from the sensor-based material structure. On

182. Source: Mette Ramsgard Thomsen, "Metabolistic Architectures."

183. Source: http://foxlin.com/interactive-facade/.

184. Joanne Jakovich and Dagmar Reinhardt, "Trivet Fields: The Materiality of Interaction in Architectural Space." *Leonardo* 42, no. 3 (2009): 217, http://www.jstor.org/stable/20532649.

the other hand, the user gives life and meaning to a space by engaging with it, transforming it. Architecture is a platform that establishes the relationship between user, physical structure and interactive technology. In interactive architecture, the aesthetic experience is in the real-time interaction driven by meaningful affective engagements evoking emotional responses from the user. Fox and Kemp cite Hoberman, stating that the connection to transformation is felt physiologically as "a physical sensation, and a mental and perceptual sensation."[185] Kinesis establishes emotional connection between life and transformation.

4.5 Conclusion

As mentioned previously,[186] the contemporary trends of interactive architecture have been criticized by many researchers for the preference of digital displays over aesthetic and functional aspects of spatiality, physicality and materiality of buildings. In her book *Adaptive Sensory Environments: An Introduction*, Maria Lorena Lehman stresses the "human" element in interactive building design for the future—i.e., the human perceptual process, the emotional, psychophysiological, aesthetic and spiritual aspects—and suggested an interdisciplinary approach that integrates knowledge from various fields (such as neuroscience, nanotechnology and biophilia) with *smart* technology in order to explore how buildings can learn and adapt to an occupant's needs.[187] Embedded computing in everyday things are gradually changing the conventional notions and use of architectural elements (enclosures, walls and furniture). In his

---

185. Fox and Kemp. *Interactive Architecture*, 31.

186. See Section 1.3

187. Maria Lorena Lehman, *Adaptive Sensory Environments: An Introduction*. (London: Routledge, 2016).

article *Changing the Rules: Architecture and the New Millennium*, Kirsh quotes William Mitchell stating, "works of architecture function as both shelter and symbol, and the introduction of digital technology opens up new ways to perform the symbolizing role." [188]

In a workshop "Human-Building Interaction," held at *Biennale Architettura 2014*, contemporary architects discussed rethinking architectural ideologies in order to incorporate interactive technologies, as well as address the new spatial needs of occupants whose lifestyles have changed due to mobile technology.[189] They also stressed on the importance of a symbiotic relationship between interaction design and architecture, suggesting knowledge of architectural theories in interaction design.

For successful integration of interactive technology, architectural theories need to be redefined to incorporate interaction design concepts, such as ubiquitous computing, embodied interactions and media spaces.[190] On the other hand, interaction design should include traditional design concepts: form-function relationship, formal and sensory elements in space definition, space design theories, and the various organizing or ordering principles of space. Similar to traditional architecture, interactive elements should necessarily serve a spatial function and contribute to the definition, articulation, organization and enhancement of architectural spaces.

---

188. David Kirsh, "Changing the Rules: Architecture in the New Millennium." *Convergence: The Journal of Research into New Media Technologies* 7, no. 2 (2001): 113-125.

189. Alavi et al., "Interaction and Architecture: Deconstructing Human-Building Interaction."

190. Ibid.

CHAPTER 5

AN INTERACTIVE LIVING SPACE

5.1 Overview

This dissertation proposes design possibilities of an adaptive, interactively modifiable living space intended to support the minimalist, evolving lifestyles of *neo-nomads*. The living space is envisioned as a real-world, habitable dwelling that consists of a single, multi-functional living space, sufficiently large to support daily activities, such as sleeping, eating, studying and working, as well as to contain storage for minimal living needs (see Figure 5.1). The space is enclosed by six surrounding programmable, surfaces: four walls, a ceiling and a floor.

The design goal of the living space is to accommodate lifestyles of young, mobile professionals through the creation of possible sensory-perceptive spatial experiences with affective dimensions that can potentially support their emotional, physiological, psychological and aesthetic needs and desires required for daily living. These affective spatial dimensions are: warm, cool, spacious, intimate, exciting, calm, muted and saturated.

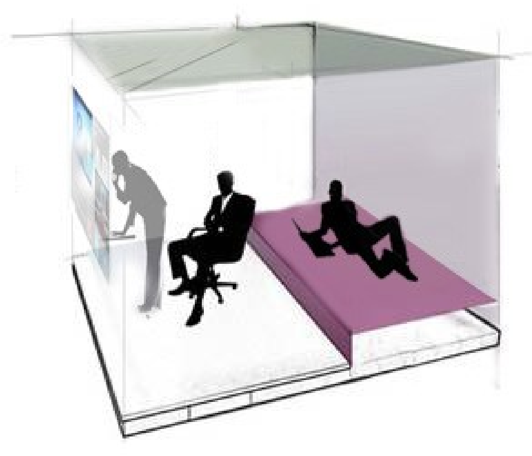


Figure 5.1. Conceptual Living Space

The interactive living space has real-time spatial articulation capabilities driven by human-space interaction. The space articulation technique is borrowed from affective space-making methods of traditional architecture applied in interactive space design in order to create sensory-perceptive spaces. The design parameters used for space articulation are color, brightness, texture and material. Here, sensory perception is limited to the visual domain.

The visually perceived sensorial spaces intend to stimulate the senses and trigger emotional responses to space. In the human-space interaction of design, the occupant's input is his/her emotional response to perceived affective qualities of space provided via an analog interface. In response to user input, the interior surfaces—walls, floor, and ceiling—modify design parameters of surface color, brightness, texture and material in order to create sensory-perceptive spatial qualities aiming to satisfy the user's daily needs. The occupant thus has the capability to modify and customize spatial qualities in an attempt to suit his/her psychophysiological and aesthetic needs.

This chapter investigates the adaptive process of the proposed design concept, i.e., how it anticipates in order to achieve its design goals. Design provides anticipatory affordances in its current state by taking into account the prior and possible future actions of occupants. The living space adapts to emergent user needs by enabling the occupant the ability to search for possible spatial solutions in order to meet his/her current and future needs, desires and actions that have not yet been realized. In this chapter, the adaptive process of living space is discussed through exploration of its anticipatory dimensions from multiple perspectives: i) inception of design idea established on known and predicted needs and requirements of target occupants; ii) the formulation of the design criteria and provision of anticipatory design affordances to meet design goals; and iii) an occupant's aesthetic and creative exploration of an impermanent, dynamically evolving domestic space of undetermined function.

5.2 Design of an Adaptive, Minimalist *Action-Space*

At the core of any architectural design is a "concept" or an "idea" of the function and activity patterns the space intends to shelter, from which the forms and structure of the space generate.[191] Architecture is anticipatory in its initial stages of concepts, schematic drawings and model scenarios that are produced as abstract representations of possible actions and interactions that may occur in future.[192] These future states of possibilities are derived from establishing known and perceived needs, desires and expectations that impact the current state.[193] According to Lehman, "occupant narrative" drives the explicit and implicit program (function) designed for an architectural space.[194] This narrative is formulated from an occupant's needs, expectations and desires for his/her living space that the space must provide for. Understanding an occupant's narrative is essential to designing the spatial narrative or *action-space* that supports current actions and possible future actions**.** *Action-space* is defined by the everyday actions and activity patterns predicted or expected to take place, as well as the interactions, not only between people, but also between complex human behavior and available technology, that are redefining

---

191. Timothy K. Casey, "Architecture," in *Handbook of Phenomenological Aesthetics*, eds. Hans Rainer Sepp and Lester Embree (Dordrecht: Springer, 2010): 25–28.

192. Theodore Zamenopoulos and Katerina Alexiou, "Towards an Anticipatory View of Design," *Design Studies* 28, no. 4 (July 2007): 411–436.

193. Mihai Nadin, "Anticipation: A Spooky Computation," *International Journal of Computing Anticipatory Systems, Proceedings of CASYS* 9, no. 6 (CHAOS: Liege, Belgium, 1999), 3-47.

194. Lehman, *Adaptive Sensory Environments: An Introduction*.

conventional use of domestic space.[195] This complex interaction with technology satisfies the need to accommodate multiple, overlapping activities in a single space, such as reading, working, web browsing, watching TV, listening to music, socializing, dining and resting. Technological advances promote minimalism in lifestyles, allowing the domestic and the professional to overlap.

Design criteria are formed based upon the study of *action-space* for target occupants. To derive the configuration of *action-space* for neo-nomads—size, shape, usage patterns, environmental and spatial flexibility of space—their demographic data and lifestyles are examined in order to anticipate potential use of technology, as well as future possible actions and interactions that may take place in their living environment. The neo-nomadic lifestyle has been studied through observation, literature, and subjective personal experiences pertaining to individual, socio-cultural, economic and technological aspects.

Study reveals that neo-nomads "live light" in terms of personal belongings and spatial requirements. Their minimalist living is characterized by multi-functionality and optimization of space. The boundaries of *action-spaces* for their daily living activities are blurred. The proposed neo-nomadic living space must embody space optimization and spatial flexibility in the form of a use-neutral living space that adapts to the constant transitional and temporal shifting from living to working, personal to social, and physical to digital (see Figure 5.2). Spatial solutions must extend beyond the conventional multi-purpose furniture design of compact living into the architectural realm of space-making.

---

195. Kirsh, "Changing the Rules."

One criterion is to design an adaptable living space that can change in spatial quality, i.e., feel and appearance, according to the user's needs. Spatial solution is sought in the creative realm of affective, experiential space design that transcends the strict physical boundaries of size and shape. Affective space creation of traditional architecture with variables of space perception—color, texture and materiality—is introduced as a means of spatial transformation in which visually perceivable sensorial spaces intend to accommodate an occupant's multiplicity of possible functions at conceptual, psychological, physiological, creative and aesthetic levels. As activity depends on context—prevailing mood, emotions, spatial setting or atmosphere—the intention of performing an activity and efficiency of performance rely on physiological and emotional comfort triggered by perceived psychophysiological and aesthetic spatial qualities.

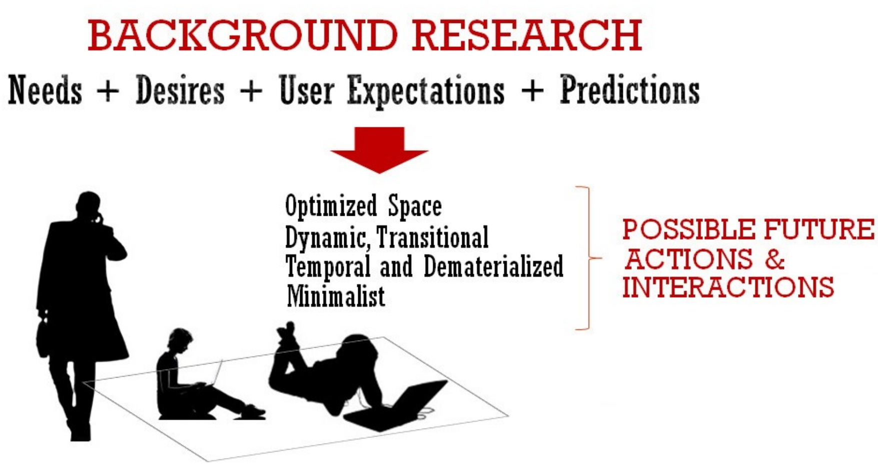


Figure 5.2. Background research to formulate design criteria

Another design criterion is to grant the occupant the ability to customize and personalize space according to his/her desire through modification of affective spatial qualities in order to carry out desired functions. The ability to personalize space is key for occupants residing in a dematerialized context. Abbas explains the manner in which mobile professionals search for an identity in order to inhabit a place of transit, such as, a hotel room, through the creation of personal associations to objects, ambience or artifacts that make them feel "at home."[196] This "at home" feeling pertains primarily to feelings of comfort, security or having the ability to personalize and customize in search of an association. To inhabit a space, one seeks a connection to memories of events, environments or objects in order to establish a notion of propriety or a personal territory that is beyond the physical.[197] As Bachelard states in *The Poetics of Space*, home is found in the openness, enclosure, warmth, lightness or darkness of "fragments of spaces" that conjure memories of past domestic habitats filled with emotions and feelings of security, safety, intimacy or solitude.[198] Personalization through light or color to create the appropriate mood or ambience may be sufficient for grounding one in a physical environment as a place to inhabit.

5.3 Enabling Anticipatory Capacity

Based on design criteria, certain features have been integrated in design to ascribe to it the anticipatory capacity to achieve its goals. The first design feature is the integration of interactive technology. The interactive surfaces of the living space have the ability to change appearance by means of modification of the design parameters of color, brightness, texture and

---

196. Yasmine Abbas, "Neo-nomads: Designing Environments for Living in the Age of Mental, Physical and Digital Mobilities" (PhD diss., Harvard University, Cambridge, MA, 2006), 92.

197. Ibid.

198. Bachelard, *The Poetics of Space*, 9.

material in response to occupant input. A second design feature is the application of space articulation techniques intended to transform spatial quality in a visually expressive, sensory-perceptive way through modification of the design parameters. Design acknowledges the strong impact of color, texture and materiality as space-making elements on human moods and emotions. The space articulation technique is integrated in the interactive medium in which modification of design parameters can potentially create various spatial qualities that are meaningful to the occupants. The process of meaningful space creation with the application of space articulation techniques is based on the formulation of design guidelines (further explored in Chapter 6).

Interactive technology and space articulation technique are the two components of design establish the backdrop for an adaptive, spatio-temporal living space based on human activity, mood and emotion. They set a stage in which the occupant expects possible psychological scenarios to emerge through active sensory engagement and interaction with space. Design assumes interactive technology to trigger human-space interaction in order to articulate space in real time and produce a set of spatial possibilities for achieving the design goal of accommodating the lifestyle of young professionals.

The human-space interaction in this design is between human and machine, between occupant and the living space. Each deliberate action or input of an occupant is reciprocated with a response or output from the living space controlled by the embedded interactive system. The occupant's input pertains to his/her desirable affective qualities of space to satisfy needs. It is the emotional response to perceived affective qualities of living space, such as degree of warmth or coolness, spaciousness or intimacy. The output of living space is in the form of modified or articulated sensorial spatial quality as spatial feedback through manipulation of surface attributes of color, brightness, texture and material (see Figure 5.3).

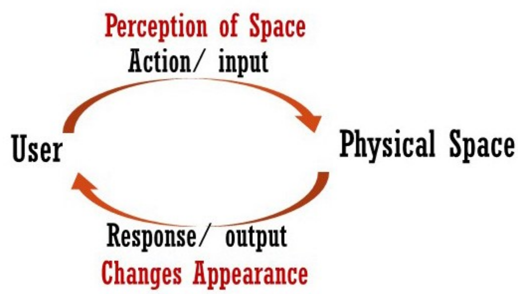


Figure 5.3. Human-Space Interaction of Living Space

Interaction is driven by the user's expected satisfaction of spatial goals.[199] Spatial goal is an occupant's desire or need from the living space regarding events and functions to be carried out, and which includes associated emotional, physiological, aesthetic or spiritual fulfillment. The occupant's attempts to fulfill existing or new spatial goals is a process of constant personalization and customization of affective spatial qualities. Human-space interaction is also meaning-driven. Spatial goals are realized through satisfactory subjective perception, interpretation and formulation of physical, psychological, emotional, behavioral, aesthetic and socio-cultural meanings of sensory-perceptive spatial quality as system feedback.

5.4 Creative and Aesthetic Goals

Anticipation of possibilities in spatial feedback is essential for continual interaction with space. Perception and interpretation of each spatial feedback is informed by prior spatial

199. Fox and Kemp, *Interactive Architecture*.

experience that can inspire new sets of anticipation as well as formulation of new spatial goals never conceived before by the occupant. The subjective perception and interpretation of space relies on context: memory, imagination, thoughts, culture, as well as prevailing mood and emotional states. As mood influences how space is experienced and interpreted, the experienced space also has an impact on prevailing mood and emotions. The anticipatory element of interaction is thus contextual and non-predetermined at feed-forward. Through formulation of new spatial goals, the occupant's exploration of experiential space-making may extend into creative realms beyond satisfaction of basic psychophysiological needs.

In anticipatory design, imagined ends drive creative and aesthetic processes with underlying anticipations of possible outcomes.[200] An occupant's creative exploration of space-making imagines goals of possible psychological scenarios. Similar to the theatrical *mise-en-scène*, living space transforms into scene renditions, setting the stage for specific actions to take place, with sensory design elements for visual storytelling. In this process, generated spatial experiences can have infinite variations in which each sensation is unique and personal.

The occupant's action and behavior are influenced not only by spatial context, but also by the abilities to interact and modify spatial experiences in real time. Monika Fleischmann and Wolfgang Strauss discussed the phenomenon of "active participant" in which the observer's role reverses as he/she actively engages with the "identity giving machines" of interactive media art and design.[201] Interaction converts ideas into immediate actions, forging unique relationships

---

200. Mihai Nadin, "Anticipation and the Artificial: Aesthetics, Ethics, and Synthetic Life."

201. Monika Fleischmann and Wolfgang Strauss, "Interactivity as Media Reflection between Art and Science," in *The Art and Science of Interface and Interaction Design*, eds. Christa Sommerer et al., (Verlag Berlin Heidelberg: Springer, 2008): 78.

with machines and objects and endowing new meanings.[202] As an active participant, the occupant is engaged in a continuous dialogue with the living space, facilitated by experiential space-making and its influence on the perceptual process of space. This interaction adds a unique dimension to the role of architectural space influencing human behavior.

The awareness of decision-making capabilities of occupants in human-space interaction redefines the occupant's conventional relation to domestic space. In architectural design, each element carries possibilities of functions and spaces that can be constructed around it. An interior wall has well-defined functions and conventionally assigned roles in relation to its surrounding space. It can be a partition that divides a larger space, a setting or backdrop for specific functions, a display or canvas for artifacts, or an element designed to direct movements and circulation of inhabitants (see Figure 5.4). For a space that is transient and constantly evolving, the anticipation in the architectural element is challenged. The dynamically changing interior surfaces shift to the foreground as active participants, as well as engage in the real-time space-making process with the occupant. These architectural elements no longer have rigid, assigned roles in the occupant's perceptual process of the domestic environment.

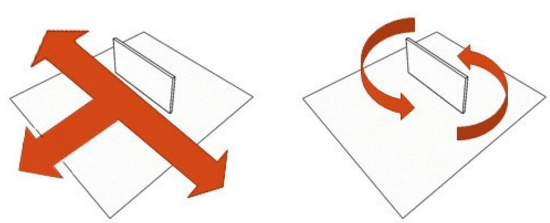


Figure 5.4. Possible circulation and space usage around a wall

202. Ibid.

The physicality of an interior wall, its materiality and material effects influence the human's relationship with the space that surrounds it. Materials such as stone and brick, suggestive of inherent stability and permanence, are popularly used in a den or for a fireplace, often arousing a feeling of enclosure of a shelter. Whereas wood and glass are relatively light-weight and tend to evoke a sense of lightness or openness of space. However, in an interactive space, the perception and sensation toward architectural elements constructed with impermanent and dynamically changing material are uncertain. In such cases, relationship with materiality will change the way space is used.

Aesthetic experience derives from the unpredictability of reaching an imagined spatial goal and in the anticipatory exploration of a satisfactory, pleasant, positive spatial experience. Aesthetic experience may also emerge from exploration of relationship with materiality. Materiality of a space exists at an unstructured, transitory state that not only is multi-sensory—i.e., a unified perception through all senses—but also emerges from individual properties of surface color, texture and lighting conditions. According to Jakovich and Reinhardt,[203] interaction with architectural space generates a unique "materiality of interaction" that emanates from material structures via programmable devices. Architecture provides a platform that organizes the relationships between the occupant, the physical structure and the interactive technology through action and response.

Here, interaction itself is a design tool for space-making. For an occupant interacting with the living space, the aesthetic experience can transcend the visual beauty of space, extending into the temporality of materials, real-time interaction with architectural spatiality and the

203. Joanne Jakovich and Dagmar Reinhardt, "Trivet Fields," 217.

relationship of action and response.[204] This materiality of interaction is instantaneous, temporal, evolving and personal. Beauty and heightened pleasure also derive from in the real-time spatial transformation as a physiological and perceptual sensation.[205]

---

204. Ibid.

205. See Section 4.3.

CHAPTER 6

AN AESTHETIC FRAMEWORK

6.1 Rationale

Design of the proposed interactive living space investigates an essential question: How is space articulated to trigger specific emotions? In other words, to what extent is each sensory design element—i.e., color, brightness, texture or material—manipulated in order to create the intended affective dimension of space that is meaningful to the observer?

As previously discussed,[206] architectural space designs have intended meanings, and the process of spatial articulation is based upon careful modifications of sensory design elements to convey specific meanings. In the visual perceptual process, users selectively perceive identifiable attributes of design elements, interpret and evaluate their characteristics, as well as their affective impact, in order to infer meanings. Aesthetic experiences pertaining to psychological and physiological feelings of pleasure, displeasure, beauty, delight, or comfort emerge from positive meanings inferred from spatial experience. Hence, a meaningful space not only is successful in communicating its intended function to the user, but also accommodates given functions through satisfaction of relevant emotional and aesthetic needs.

In this dissertation, subjective aesthetic values are explored in regard to sensory design elements of color, texture and materiality that, when manipulated, can potentially evoke specific psychophysiological pleasure and comfort, such as a feeling of warmth, coolness, spaciousness, intimacy, excitement or calmness. Here, the user's inferred meaning is subjective, contextual and

206. See Section 2.2.

based upon various factors, including personal taste, experience, culture, beliefs and values. For spatial articulation, it is crucial for the designer to understand prevailing cultural contexts and values and how design attributes may affect the feelings and behavior of target users.

An aesthetic framework or set of principles is needed as a fundamental design guide based upon which attributes of sensory design elements can be selected and articulated to convey suggested meanings with the proper understanding of how their contextual, affective, explicit or implicit sensory expressions can be perceived and inferred by the user. Moreover, the principles should also be integrated into the context of an interactive medium. Underlying aesthetics give meaning to interpretation that conforms with the context of the medium and increases the medium's efficiency and capacity.[207] For an interactive medium, the underlying aesthetics allow creation of compelling environments that trigger emotional responses and potential activeness through perception of sensorial spatial elements.

In this chapter, meaningful space creation through space articulation technique is investigated in order to formulate an underlying aesthetic framework for an interactive space. Formulation of aesthetic principles requires the understanding of the extent to which design parameters individually and collectively influence subjective emotional responses to affective spatial dimensions studied in this research. The principles are based upon correlations that need to be established between design parameters and perception of affective spaces. To collect relevant data on subjective emotional responses to space for a specific segment of the target population, a user study was conducted in a Virtual Environment. The perceptual study gathered subjective data through both the quantitative method of semantic rating scales and qualitative

---

207. Mihai Nadin, "Negotiating the World of Make-believe: The Aesthetic Compass."

inferences drawn from open-ended questions in order to establish necessary correlations. The chapter discusses the user study procedure, participant selection process, research methodologies and data analysis used to gather relevant data in order to formulate the aesthetic principles for an interactive space.

As previously mentioned,[208] the user study articulates space with three design parameters—color, brightness and texture—in order to examine perception of specific affective dimensions of space. Based on user study findings, some modifications were made to the design scheme discussed in Section 6.10.

6.2 Research Question

For the purposes of this dissertation, a Virtual Environment (VE) way used as an evaluation tool to find correlations between design parameters and perception. It evaluates the capacity of proposed design concepts to articulate spaces for creating affective spatial qualities. A six-sided immersive Cave Automatic Virtual Environment (CAVE)-type display was chosen to conduct a user study in the proposed living space simulated with adapted equivalent parameters of color, brightness and texture. As VR substitutes real-world sensory methods with equivalent two-dimensional graphical methods, it is important to find out if within its technological constraints VE can replicate the real-world affective space creation that are essentially multi-sensory and three-dimensional. In other words, the user study aims to find out if adapted design parameters have an impact on emotional responses, and to what extent they are comparable to real-world perceptions.

---

208. See Section 1.1.

The main research question asked in this study is: Can Virtual Environment act as a viable evaluation tool for architectural design concepts where variable design parameters can be adapted to create experiential spaces with affective dimensions? If study findings confirm that perceivable emotional aspects of real-world spaces could be successfully generated through simulation of adapted design attributes in the virtual space, relevant data can be gathered for quantifying aesthetic parameters in order to formulate design principles for the real-world interactive living space.

6.3 User Study: Objectives and Hypothesis

In the user study, perceptions of affective spatial aspects are examined with three adapted real-world equivalent design parameters of color, brightness and texture to create a set of variable virtual spaces with affective dimensions. Emotional responses to virtual spaces are examined in three main categories, each represented by a pair of oppositional adjectives: temperature (warm and cool), size (spacious and intimate), and level of arousal (exciting and calm). Space perception is also assessed in terms of comfort, overall satisfaction and spatial preferences for two activities: work and rest. Since emotional responses to space depend on context, the influence of activity on perception is also assessed.

The study is based upon a hypothesis that affective space-making of traditional, real-world architecture can be successfully replicated in a simulated VE through modification of design parameters of color, brightness and texture. In other words, it is hypothesized that perceivable emotion-affecting spaces in the VE can be created through modification of *simulated* color, brightness and texture. Based on this hypothesis, subjective user responses are analyzed to examine the extent to which design parameters influenced emotional responses to virtual spaces. The user study aims to accomplish the following research objectives in order to confirm the hypothesis, quantify the aesthetic parameters and establish virtual environment as a viable evaluation tool for the proposed design concept:

a) Establish quantifiable correlations between design parameters and affective space perception in VE
b) Compare affective space perceptions represented by oppositional adjectives to verify if they evoke contrasting emotions
c) Draw parallels between subjective responses in VE and corresponding real-world standard (normative) perceptions, in terms of color, brightness and texture.

6.4 Participants

A total of thirty-three (33) participants was recruited for the user study. Subjects included undergraduate, graduate, doctoral and post-doctoral students, as well as faculty and staff members of Duke University. Recruitment was done on the university campus through non-probability sampling. Available students and young professionals at the campus were considered representative of the target population, as familiarity with mobile technology, portable computing, digital and social media is characteristic of such a sample, considered as a common neo-nomadic trait. There was no restriction on gender, race, ethnicity, educational background and profession.

Participation was voluntary. Recruitment for the study was conducted via campus email announcements, posters and flyers. A few participants were also recruited through positive word-of-mouth publicity from respondents who had already completed the study. A major criterion was to ensure a large number of students and young professionals among the respondents. Recommended age for recruitment was initially set at 18–45. However, participants older than 45 years were also accepted. Participants were required to have correct or corrected-to-normal vision, with no family history of photosensitive epileptic seizure. Refreshments were offered to subjects to encourage participation.

A total of twenty-nine participants (88%) belonged to the 18–40 age range (Mean =27, SD=4.8). Only four participants (12%) belonged to the 41–76 age range. Eighteen participants (55%) were male. Twenty-seven (82%) participants were students and six (18%) were professionals. Among the student participants, there were five (19%) undergraduate students, nine (33%) master's students and thirteen (48%) doctoral or postdoctoral students. Among professionals, four (67%) participants had graduate degrees and two (33%) participants had doctoral degrees.

Other participant demographic data revealed that there were nineteen (58%) Caucasians, five (15%) South Asians, four (12%) Hispanics of any race, three (9%) East Asians, one (3%) African-American, and one participant (3%) of two or more races. Twelve (36%) participants did not wear any glasses or contact lenses during the test. Eighteen participants (55%) never had any prior experience with immersive VE, whereas ten participants (30%) had experienced it once or twice. Only five participants (15%) had experienced Immersive Virtual Environment quite a few times.

The data of participant demographic are provided in a tabular form in Appendix: B.

6.5 Overview of Research Methods

The user study used employed quantitative and qualitative research methods, designed to be conducted one after the other in the same user study test session with no interval or recess in between. In the first phase of the experiment, a quantitative research method was conducted in which quantifiable correlations were sought between design parameters and user perceptions of affective dimensions of virtual spaces. Respondents were asked to rate perceived affective qualities of each virtual space on a continuous rating scale of 1 to 10. Here, 1 represented the lowest, most negative rating and 10 represented the highest, most positive rating. The affective dimensions of perceived virtual spaces were assessed in seven categories—warm, cool, exciting, calm, intimate, spacious and comfort—as well as spatial preferences for two activities—work and rest. The influence of activity on space perception was examined by evaluating responses from two groups of users: active (performing a typical daily activity) and inactive (passive).

The experiment used a mixed design factorial ANOVA with three *within-subject* factors and one *between-subjects* factor. A *within-subject* design was conducted to establish quantitative correlations between the design parameters—color, brightness and texture—and participant's perception. The design parameters were the *within-subject* factors or independent variables, each with two levels: color (orange and blue), brightness (dark and light) and texture gradient (rough and smooth). The quantitative ratings of participants were the dependent variables. A *between-subjects* design was conducted to measure the impact of activity on participant's perception. The *between-subjects* factors are: inactivity (passive) and activity (performing a daily activity).

Thirty-two participants were randomly distributed over two experimental conditions, as shown in Table 6.1. In the *active* condition, sixteen participants were required to perform a minimal-effort daily activity. They were asked to fold real clothes from a laundry basket and pile them up on a real table. In the *inactive* condition, the remaining sixteen participants did not perform any activity and remained still.

Table 6.1. *Between-subjects* design of the user study

Experimental Condition	Activity	Participants	Male/Female Ratio
Active	Yes	16	9/7
Inactive	No	16	8/8

Data analysis searched for statistically significant data to establish the correlations. The validity of results was evaluated by drawing comparisons between perceptions represented by pairs of oppositional adjectives. Results were also compared to corresponding standard real-world perceptions.

The second phase of the experiment utilized a qualitative methodology. Each participant was shown the virtual space he/she is least satisfied with—i.e., the space that received his/her lowest rating in overall satisfaction—and asked an open-ended question concerning that space. Participants were asked to elaborate on what sort of modifications they desired to their respective virtual space in order to satisfy psychophysiological needs. The modifications pertained to their subjective spatial preferences for a daily living environment. The open-ended question intended to gain insight into the types of affective space—emotional and aesthetic—users would desire and the modifications they would need to obtain them.

The quantitative study findings were used as a basis for analysis of qualitative study findings. The outcome of the user study—quantitative and qualitative combined—was data relevant for development of an aesthetic framework for the proposed interactive space.

6.6 The Virtual Environment

In this experiment, the virtually simulated living space was conceived as a single, square-shaped room. It was envisioned as a single, multi-functional living space that reflects a minimalist lifestyle, sufficiently large enough to contain a minimum of multipurpose furniture—e.g., a futon sofa or a small bed, a study table and chair, and space for minimal storage. The living space was enclosed by four walls, including one accent wall, provided to add variety in material and texture, and to create a focal point of interest in an otherwise ordinary, bland space.

6.6.1 Space Layout

A six-sided CAVE-type display was used to simulate a single living space with the dimensions 3.35m x 3.35m x 3.35m. It was enclosed by four walls, a ceiling and a floor. The space was extended beyond the actual display size of 2.9m x 2.9m x 2.9m in order to stimulate depth perception that occurs due to binocular disparity. Screen resolution was 1920x1920. To provide a sense of scale and enhance presence, both real and virtual furniture were used. In a mixed reality (MR) setup, the furniture consisted of a virtual study table, a small virtual bed, a real chair, and a real round table, as shown in Figure 6.1. The study table and the bed abutted opposing walls (Figure 6.1-a). The chair was placed in the middle of the room with its back towards the door to the CAVE-type display. It faced the accent wall and was placed approximately 210cm away from it. The round table was an activity prop placed next to the chair. A real laundry basket full of unfolded clothes was placed on the ground in front of the chair as another activity prop (Figure 6.1-b).

(a) Simulated furniture in VE

(b) Real furniture and props in VE

Figure 6.1. Mixed reality setup of real and virtual furniture

An Intersense IS-900 ultrasonic tracker (head) was used to measure location and orientation of participants for proper computer simulation. The space configuration, furniture layout and the activity props remained unchanged across two experimental conditions. The calibrating gridlines of the display floor were used as reference to ensure that the real furniture and activity props were placed in the same location for every test session. The test did not involve any navigation, travel or interaction techniques with objects or surfaces. The user wore active stereo shutter glasses and was allowed natural head movement. The user eye sight was approximately 1.25m above the floor from a seating position. Participants remained seated in the chair throughout the entire test session.

6.6.2 Texture Mapping

Image-based texture maps were used in the virtual space for materials—stone, drywall and carpet (fabric). The texture maps were applied on enclosing virtual surfaces and simulated furniture. Texture maps represented the actual scale of the real materials. The accent wall was mapped with a stone texture. The other surrounding walls and the ceiling had drywall texture mapping. The floor was mapped with a carpet texture. The virtual bed and virtual table had texture mapping of fabric and wood respectively in a predominantly neutral color in order to avoid any interaction or conflict with surface colors (see Figure 6.2).

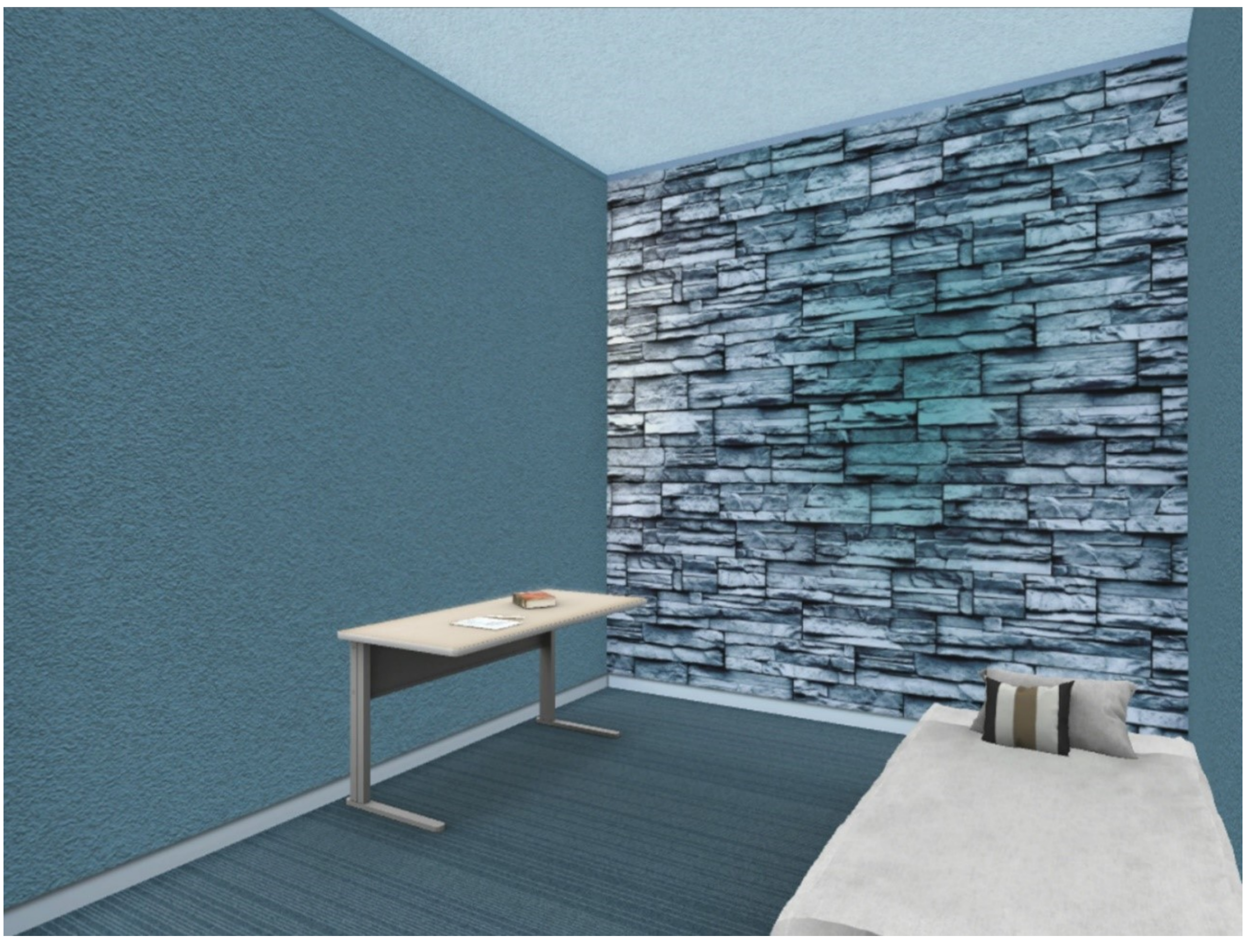


Figure 6.2. Texture mapping of simulated space

6.6.3 Simulation of Design Parameters

The three design parameters of the living space are color, brightness and texture of the simulated surfaces. These represent color, illumination and texture (surface property of materials) of real-world architectural space. Each of these parameters have two levels or attributes:

1. *Color*: Two surface colors (hues) were chosen for all virtual surfaces of the living space. Two complementary hues—orange (HSB 18,58,84) and blue (HSB 200, 48, 55)—were selected from the opposite spectrum of the traditional color wheel (see Figure 6.3).
2. *Brightness*: Two brightness levels were selected for the virtual space: bright and dark. The color tones of virtual surfaces were manipulated to create two brightness levels for the space. For both orange and blue color, the *brightness* level was decreased and *saturation* level was increased from their HSB (Hue, Saturation, Brightness) values to create darker color tones. The hues were kept intact (see Figure 6.3).
3. *Texture*: High resolution, photorealistic, image-based texture maps were used for each material. There were two types of texture gradients—rough and smooth—that were created to closely represent rough and smooth surface attributes of each material. Texture graininess was increased in contrast, depth and sharpness to appear more rough. Random tiling, and added shadow and highlight created a more natural and realistic look for the materials (see Figure 6.4).

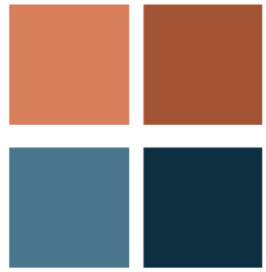


Figure 6.3. Color tones of orange and blue: bright (left) and dark (right)

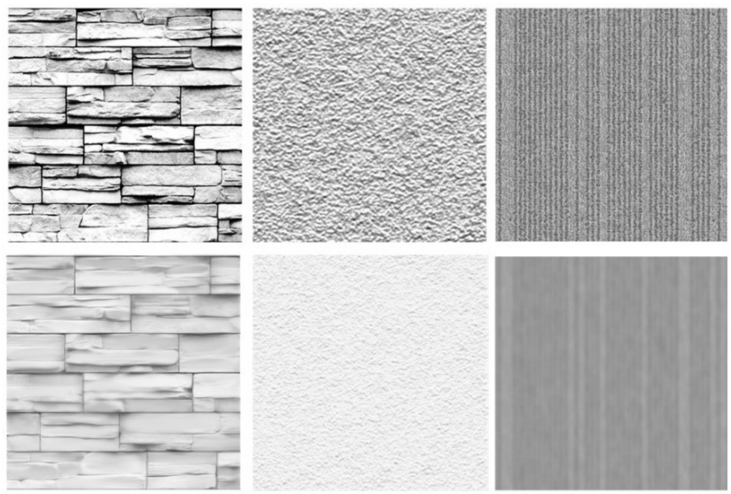


Figure 6.4. Stone, Drywall and Carpet texture: rough (top) and smooth (bottom)

6.6.4 Virtual Test Spaces

Eight unique living space configurations were created with two levels of three design parameters, as shown in Table 6.2. Each of these virtual test spaces consisted of a unique combination of attributes of each design parameter. These spaces were displayed to the users in a randomized order for assessment of perception. Randomization was performed in order to minimize participant biases that could arise from boredom or familiarity. In each experimental group (active or passive), each of the sixteen participants was allocated a unique randomized sequence. The randomization sequences were paired between groups.

Table 6.2. Each virtual test space consists of one attribute of each design parameter

Design Parameters			**Virtual Test Spaces**
Color (Type)	**Brightness (Levels)**	**Texture (Gradients)**	
Orange	Dark	Rough	Orange – Dark – Rough
		Smooth	Orange – Dark – Smooth
	Light	Rough	Orange – Light – Rough
		Smooth	Orange – Light – Smooth
Blue	Dark	Rough	Blue – Dark – Rough
		Smooth	Blue – Dark – Smooth
	Light	Rough	Blue – Light – Rough
		Smooth	Blue – Light – Smooth

6.6.5 Data Collection Methods

The question-answer session for both quantitative and qualitative methods in the user study was verbal. Data collection involved audio recording by a voice recorder and transcription of interviews. Field notes were also taken during open-ended question-answer sessions.

6.7 User Study Procedure

Two pilot studies were conducted prior to the actual test session to evaluate the time, methods and feasibility of the user study. Participants were recruited once user study methods were finalized. Participants were required to sign an informed consent form and fill out a demographic questionnaire before the test session began. Brief instructions were then given to them regarding the testing procedure. Instructions were read from a script carefully prepared to avoid any unintentional or accidental priming of the participants. Users were then taken inside the VE containing of both real and virtual furniture, as well as the activity props. Participants of the *active* group were instructed how to carry out the activity with use of the activity props.

Participants were asked to sit on the chair and wear the active stereo shutter goggles in order to view the mixed reality setup. At this stage, the virtual surfaces did not have any texture maps but an overall neutral gray color. A voice recorder was kept inside the virtual environment to record user responses. For each participant, it took approximately half an hour for the whole experiment to complete. The door to the CAVE-like display remained closed throughout the test session to allow users privacy and comfort.

Each user was presented with a set of eight virtual spaces in a pre-defined random order. Every time a new space was displayed, the active participants were instructed to perform the task of folding clothes and pile them up on the table. Each space was displayed for 20 seconds followed by a set of questions regarding that space. Active participants were asked to stop their activity once the questionnaire session started. However, the inactive participants were allowed to stare at the virtual space during those 20 seconds.

6.7.1 Quantitative Study Phase

Participants were asked a set of questions for each virtual test space displayed (see Appendix: C). They were expected to evaluate and rate the affective aspects of each space: warm, cool, spacious, intimate, exciting, calm and comfort. They were also asked to rate each space for two activities—rest and work—as well as overall satisfaction. In a non-comparative, continuous rating scale used, participants were asked to rate each affective aspect on a scale of 1 to 10, where 1 indicated the lowest negative ranking, with the qualitative description “not at all,” and 10 indicated the highest positive ranking, with the qualitative description “very much.”

Prior to the test session, the semantics or contextual meaning of each psychophysiological terms used in the questionnaire were explained to the respondents to ensure that these terms were properly understood without priming. The spatial terms were explained in terms of pairs of oppositional or bipolar adjectives: warm and cool, spacious and intimate, and exciting and calm. Participants were asked to understand *intimate* spaces as the opposite of *spacious* spaces, and *exciting* spaces as the opposite of spaces that are *calming.* The term *cool* was described as the opposite of *warm,* to be understood in the context of eliciting a feeling of a warm or a cool temperature in the spaces.

6.7.2 Qualitative Study Phase

Once quantitative ratings were completed for all eight virtual spaces, the living space was reverted to its neutral gray color. With a pause of 20 seconds, one last virtual test space was displayed to the seated participant. For each participant, the displayed virtual space was his/her lowest rated virtual space in terms of overall satisfaction.

A qualitative, open-ended question was posed to the user regarding the virtual space displayed (see Appendix: D). Each user was asked about the type of modifications he/she desires to make to the displayed space in order to obtain a spatial quality ideal to live in. To encourage them to engage in a pseudo-interaction with the living space, participants were further asked to give commands to the space concerning the type of changes they desired: color, size, material, texture or any other visual features. The question was unstructured and did not suggest any predetermined answer.

To gain insight and assist users in full expression of opinion, they were asked to elaborate on their responses when it appeared that there was more to be answered. For example, to encourage more detailed answers from respondents, additional questions were asked that started with “What do you mean when you say…?” or “Can you elaborate what you mean by…?”

6.8 Quantitative Study: Data Analysis and Findings

Data analysis was conducted with IBM SPSS 24, a statistical analysis software. A mixed-design factorial ANOVA was performed with three repeated-measures factors and one between-subjects factor. Data is reported as statistically significant at $p<.050$. Data was visually inspected and verified as approaching normality. In figures 6.5–6.10, statistically significant differences are denoted by an asterisk (*) and error bars represent standard errors.

6.8.1 Main Effects

Statistically significant main effects of color were found on perceptions of *warmth, coolness, excitement, calmness, intimacy, comfort,* and environments for *working* and *resting*. Orange was found significantly more *warm* ($F(1,30)=153.162$), *exciting* ($F(1,30)=22.087$) and *comfortable* ($F(1,30)=31.772$) than blue at $p<.001$ for all measures. Orange was also found significantly more *intimate* than blue ($F(1,30)=4.960$, $p<0.05$), and significantly preferable for *resting* ($F(1,30)=10.732$) and *working* ($F(1,30)=10.247$) than blue both at $p<.005$. Blue was found to be significantly more *cool* ($F(1,30)= 97.117$, $p<0.001$), and *calm* ($F(1,30)=4.918$, $p<0.05$) than orange. Figure 6.5 shows a summary of the main effects of color.

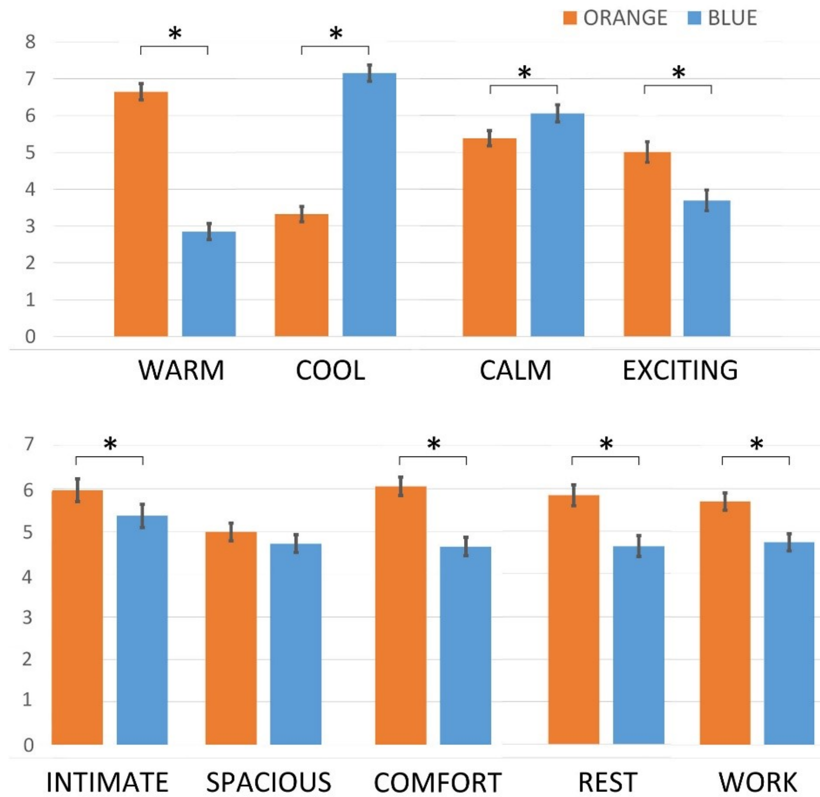


Figure 6.5. Main effects of color

A significant main effect of brightness was observed only on perception of *spaciousness*. As shown in Figure 6.6, bright space was found more *spacious* than dark space ($F(1,30)=5.615$, $p<0.05$). Also, a near-significant trend points in the direction that dark spaces were preferred over bright spaces for *resting* ($F(1,30)=4.169$, $p=0.05$).

No significant main effects of texture and activity were found on users' perceptions of emotional spaces. Although a strong trend towards significance ($p=0.061$) was found, which suggested that active participants perceived spaces more *intimate* than inactive participants.

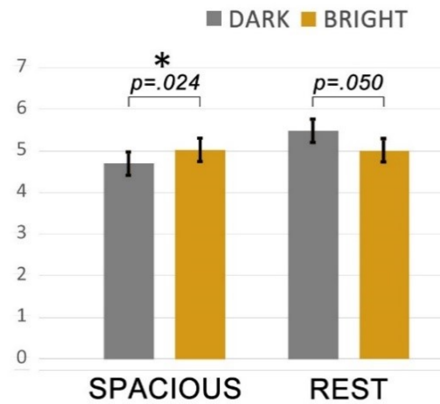


Figure 6.6. Brightness effects

6.8.2 Interaction Effects

Significant interaction effects were found between color and brightness on perceptions of *warmth* ($F(1,30)=11.262$, $p<0.005$); *coolness* ($F(1,30)=9.060$, $p<.05$); *excitement* ($F(1,30)=7.922$, $p<.05$), and *intimacy* ($F(1,30)=6.753$, $p<.05$).

Pairwise comparisons show that for orange spaces, changing brightness made a significant difference to perception in specific situations. Orange felt significantly *warmer* and more *intimate* in dark environments, whereas orange felt significantly *cooler* in a bright environment (see Figure 6.7). To the contrary, blue felt significantly more *exciting* in bright environments, but significantly *calmer* in dark spaces. Orange felt significantly more *intimate* than blue only in dark spaces.

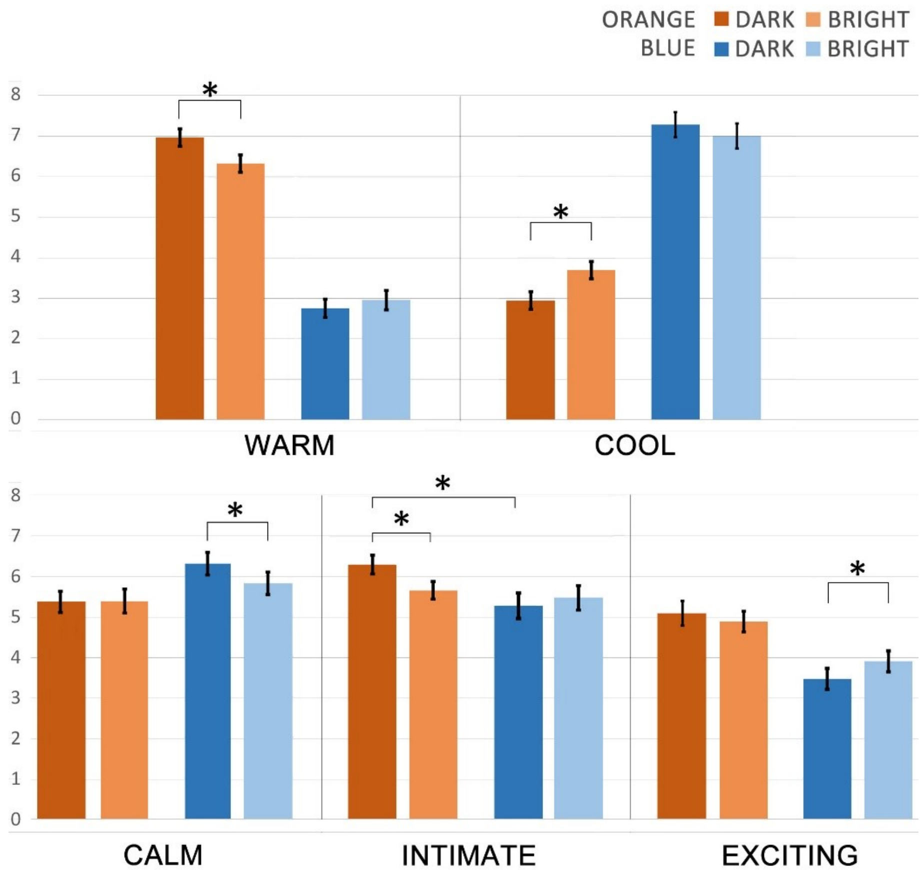


Figure 6.7. Interactions: Color and Brightness

There was a significant interaction effect between brightness and texture on participant's perception of environment preferable for *working* (F(1,30)=4.815, p<0.05). Pairwise comparisons show that in dark environments, smooth texture was found more preferable for *working* than rough texture, whereas no significant differences were found in light spaces (see Figure 6.8).

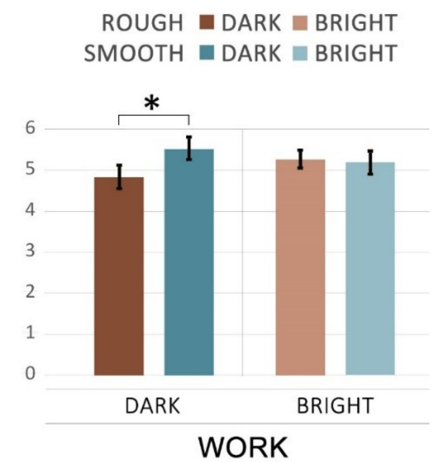


Figure 6.8. Interactions: Brightness and Texture on Environment for *Working*

A significant interaction effect between color and activity was also found on the perception of *intimate* spaces ($F(1,30)=5.221$, $p<0.05$). For inactive participants, changes in color made a significant difference in perception of *intimacy,* while no differences were observed in active participants. Inactive participants found orange significantly more *intimate* than blue, whereas no such significant difference was observed for active participants. Active participants found blue significantly more *intimate* than inactive participants, while the same effect was not observed with orange spaces (see Figure 6.9).

Significant interaction effect of brightness and activity was found only on the perception of *warmth* ($F(1,30)=4.395$, $p<0.05$). For active participants, changes in level of brightness made a significant difference in the perception of *warmth*. Active participants rated dark spaces more *warm* than bright spaces. No such significant difference was observed for inactive participants (see Figure 6.10). Finally we found a significant four-way interaction effect among color, texture, brightness and activity on perception of *intimacy* of space ($F(1,30)= 4.651$, $p<.05$).

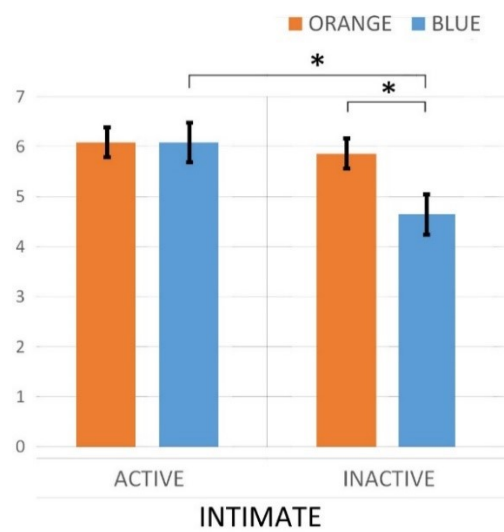


Figure 6.9. Interactions: Color and Activity on *Intimacy* of Space

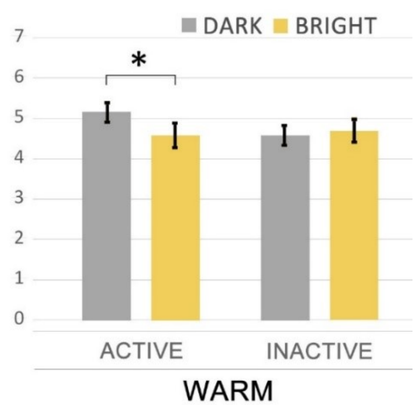


Figure 6.10. Interactions: Brightness and Activity on *Warmth* of Space

6.8.3 Discussion

Comparisons were drawn between pairs of oppositional adjectives—warm and cool, exciting and calm, spacious and intimate—to find out if perceptions of spatial aspects represented by oppositional adjectives elicit contrasting emotional responses. Data revealed that orange was found significantly more *warm* and *exciting* than blue, whereas blue was found significantly more *cool* and *calming* than orange, regardless of level of brightness. It can be deduced from this data that spatial qualities represented by oppositional adjectives evoked contrasting emotional responses. These data provide evidence that the VE can generate spatial aspects of *warmth, coolness,* and *excitement* and *calmness* that were perceivable to participants. Thus, the hypothesis posed at the beginning of this paper as a basis for this study can be confirmed.[209]

However, comparisons of data between oppositional adjectives *spacious* and *intimate* reveal a different result. While color had a significant impact on the perception of *intimate* spaces, it did not have any significant impact on perception of *spaciousness*. In fact, brightness was found to have a significant effect on perceived spaciousness of *space*. From these data, it can be concluded that the participants chose to consider a different or broader semantic meaning for the word *intimate* in their understanding of space. It is possible that they did not perceive the word *intimate* as a directly oppositional adjective to the word *spaciousness* of spatial experience.

The study was able to replicate certain real-world perceptions related to color and brightness in the virtual study. In real-world color perception, warm colors are generally found more exciting than cool colors, whereas cool colors are found more calming than warm colors. Also, in real-world perception of space, warm colors appear to be closer in distance than cool colors. The data gathered in this virtual test revealed that orange was perceived *warmer,* more *exciting* and *intimate* than blue. On the other hand, blue was perceived more *calm* and *cool* than orange. This correlated with real-world color experience. Additionally, the user study could also

209. See Section 6.3.

replicate the real-world experience of brightness having a significant impact on perception of *spaciousness* of a space.

6.9 Qualitative Study: Data Analysis and Findings

A *representational approach* was taken for analysis of responses to open-ended questions.[210] The affective dimensions of space examined in the quantitative study were assigned as themes or categories for qualitative data analysis. User responses were carefully searched for words and phrases that referred directly to these common categories or their sub-categories. Responses were also searched for words or phrases that were either synonymous or represented unique affective spatial dimensions.

Data analysis revealed new words introduced by a number of participants as descriptors of their desired spatial environment. These words did not associate with the affective spatial dimensions examined in the user study. Participants used words, such as *soft*, *sober* or *natural*, indicating a spatial quality that evokes a feeling of softness—a quality that has both visual and tactile aspects. Moreover, the participants associated these words with colors or materials that have muted, soft or "natural" tones. To represent the feelings associated with these words, two unique oppositional affective dimensions are introduced: "muted" and "saturated." These oppositional adjectives are commonly related to perceptions of color. These adjectives are categorized under "softness." Table 6.3 shows categories and sub-categories of affective spatial dimensions pertinent in participant's emotional responses to space.

---

210. Roel Popping, "Analyzing Open-Ended Questions by Means of Text Analysis Procedures," in *Bulletin de Méthodologie Sociologique* 128 (October 2015): 23-39, doi: 10.1177/0759106315597389.

Table 6.3. Categories of Affective Spatial Dimensions

Themes or Categories	Sub-Categories	List of words found in user responses, synonymous or directly referring to themes
Temperature	Warm	Warm
	Cool	Cold
Size	Spacious	Big, wide, airy, open
	Intimate	Small, narrow, cosy, confined, prison-like
Level of Arousal	Exciting	Colorful, interesting, lively, upbeat, noisy
	Calm	Peaceful, sober, quiet, private, soothing, boring, dull, flat, dismal, bland, sparse
Softness	Muted	Soft, sober, natural
	Saturated	Harsh, strong, loud, hard, vibrant

Quantitative study findings were used as a basis for correlations established between user's perception of spatial qualities and corresponding suggested design modifications. Additionally, qualitative study findings were analyzed to establish further correlations, explicit or implicit, based on inferences drawn from user responses. The following summarizes the design modifications suggested by participants to obtain desirable affective qualities of spaces.

6.9.1. Temperature

Color was found as the primary design parameter most users chose to manipulate perceived temperature of a space. Data analysis revealed that a total of twenty-one (21) respondents desired warmer spaces. Among those respondents, fourteen users (67%) asked for warmer colors that were variations of red, orange, yellow or brown. Two users (9%) asked for colors that were neither too warm nor too cold. In a blue-colored space, one user (5%) asked for purple and green as warmer shades of blue. The remaining four users (19%) did not make any suggestions that could be directly or indirectly related to warmth or coolness of space (see Figure 6.11).

From both statistical data and qualitative analyses, it can be concluded that color can be modified to create perceived feelings of *warmth* or *coolness*. A warmer shade of color can increase *warmth,* whereas a cooler shade can increase *coolness*.

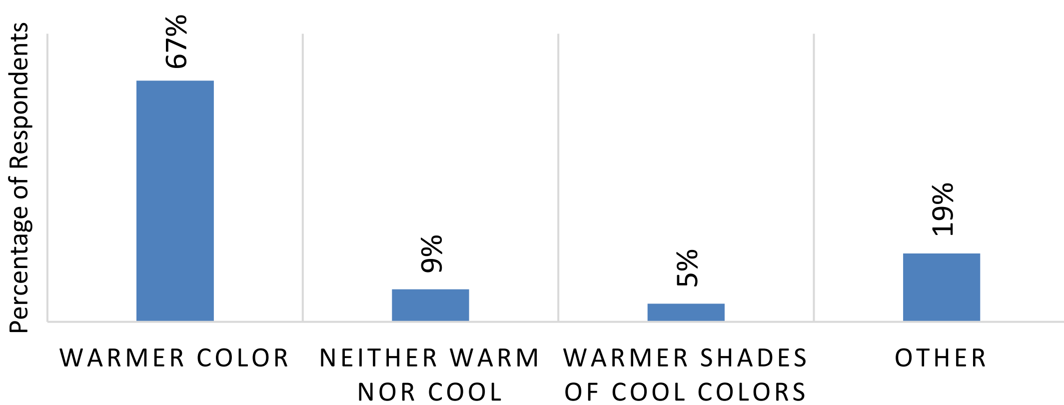


Figure 6.11. User recommendations for increased *warmth*

6.9.2. Size

Brightness was found as the primary design parameter most users chose to manipulate the perceived size or spaciousness of a space. Moreover, a number of participants perceived stone on the accent wall making the space feel too "confining." Data analysis revealed that a total of 24 respondents desired a more spacious space. Eleven users (46%) asked to increase the level of brightness. Ten users (42%) asked for brighter spaces through various combinations of design elements. They desired additions of windows, exterior views and natural light. Three users (12%) users did not make any specific suggestions that could be directly related to spaciousness. On the other hand, a total of three respondents asked for a more intimate space, out of which two respondents (67%) recommended a darker space (see Figure 6.12). Data analysis also reveals that a total of eight (8) participants perceived stone as too confining, making the space feel like a prison.

It can be concluded that brightness levels can be used as a primary design parameter to increase or decrease the feeling of *spaciousness*. Materials that are light-weight and perceived as less confining than stone, such as wood or fabric, can be introduced as well.

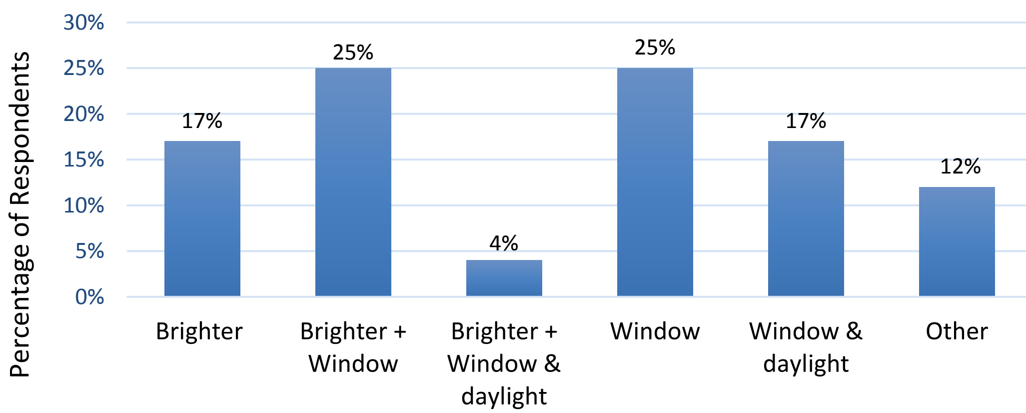


Figure 6.12. User recommendations for increased *spaciousness*

6.9.3. Level of Arousal

Surface texture was found as the primary design parameter that most users chose to modify in order to increase level of excitement. However, some participants asked to brighten surface color in order to increase level of excitement. A total of nine respondents asked for a more exciting space. Most of these users asked for visually interesting elements to adorn the enclosing surfaces of the space. Six users (67%) wanted interesting texture, visuals, painting, surface details or decorations. Three users (33%) asked for brighter or more colorful surfaces. A total of four users asked for calmer spaces. Texture and color were selected to increase level of calmness. Two of these users requested natural materials and brownish hues, one user asked for refined texture, and another user asked for brighter color.

6.9.4. Softness

A number of respondents desired muted or "soft" spaces. Various suggestions were made by different participants to soften specific spatial qualities which they found too loud or harsh. These suggestions referred mostly to color and material. Out of a total of seven users, five users asked for wood, sandstone, brick or fabric with "softer" or muted colors. A number of participants asked for wood with "natural" colors. Two participants asked for fabric curtains or rugs of various pastel colors to soften perceived quality of space. From data analysis, it can be inferred that color was considered a primary design parameter by most participants to create muted or soft environment.

6.10 Design Modifications and Aesthetic Principles

Findings from both quantitative and qualitative studies have been combined to draw a set of correlations between design parameters and perception of affective spatial qualities. Moreover, inferences are drawn by comparing each pair of oppositional affective dimensions in order to establish design suggestions for each affective spatial aspect. For example, data for *cool* and *calm* spaces are inferred from data found for *warm* and *exciting* spaces respectively. Relevant data for *intimate* spaces are also inferred from data found on *spaciousness*. Here, the term *intimate* is considered as an exact opposite adjective of the term *spaciousness*.

Based upon qualitative study findings, some modifications are made to the initial design scheme of proposed interactive space:

i) Material has been added as a fourth design parameter for spatial articulation.

ii) Two new affective dimensions—muted and saturated—have been added to the design scheme as they were found pertinent to user's perception of preferable domestic environment. These dimensions can be categorized under *softness* as a spatial quality, indicative of affective dimensions of color.

The aesthetic principles are presented in the form of a correlation chart, shown in Table-6.4. These principles are suggested guidelines for space articulation in order to create intended affective dimensions. The principles include study findings relevant for active occupants.

Color is the primary design parameter that can be modified to create feelings of *warmth, coolness, excitement* and *calmness*. To increase perceived *warmth* of a space, a warm color or its warmer shades can be used. For any given color, its warmer shades are its adjacent colors that are located closer to red in the color wheel. On the other hand, to increase perceived *coolness* of a space, a cool color or its cooler shades can be used. For any given color, its cooler shades are its adjacent colors that are located closer to blue in the color wheel. For instance, yellowish-orange is considered a warmer color than yellow, and greenish-blue is considered cooler than green.

As a primary design parameter, brightness levels can be modified to increase or decrease the feeling of *spaciousness* and, by inference, the feeling of *intimacy*. The study revealed that materials with more visual weight, such as stone, can make space feel less spacious and confining. This suggests that materials with lighter visual weight, such as wood or fabric, can be used to increase the feeling of *spaciousness*. On the contrary, visually heavy materials, such as stone or brick, can be used to increase the feeling of *intimacy*.

For increased visual *softness* of spatial quality, muted or less saturated colors can be used. While muted colors with less saturation can be perceived as *calm*, soft or even dull, as a spatial aspect, colors with increased saturation can be perceived as strong, vibrant, exciting, loud or harsh. To increase level of *excitement*, a rougher texture and stronger (saturated) colors can be used. For *calmer* spaces, smoother texture and muted colors can be used.

Table 6.4. Correlation Chart as Aesthetic Guidelines

Desired Affective Spatial Aspects		**Primary Design Parameters to modify**	**Aesthetic Principles**
Temperature	Warm	Color	Use warmer colors – variations of red, orange or yellow Use warm shades of cool colors Use of colors that are moderately warm For active occupants, decrease brightness
	Cool	Color	Use cooler colors – variations of blue, green or purple Use cool shades of warm colors Use of colors that are moderately cool For active occupants, increase brightness
Size	Spacious	Brightness Level Material	Increase brightness Use materials that have less visual weight
	Intimate	Brightness Level Material	Decrease Brightness Use materials that have more visual weight
Level of Arousal	Exciting	Texture Color	Roughen texture Use stronger or more saturated colors
	Calm	Texture Color	Smoothen texture Use muted colors
Softness	Muted	Color	Use muted colors
	Saturated	Color	Use stronger or more saturated colors

CHAPTER 7

DESIGN OF AN INTERACTIVE SYSTEM

7.1 Introduction

Design of the interactive living space involves design of a control system that regulates behavior of the living space. The system controls how living space interacts with the occupant—i.e., receiving inputs, and generating corresponding spatial outputs through adjustments of appropriate design parameters structured around a set of aesthetic principles formulated to give interaction a meaningful intent. Design of the control system involves decision making pertaining to input and output variable specifications, types and ranges of design parameter attributes to be controlled, determining satisfactory goals for the system, and proper application of the aesthetic principles to maintain outcome at desired levels throughout the interaction process.

In the first part of the design, the user input and spatial output variables are defined and input-output correlations are established based upon set design principles. Databases are specified for design parameters as systematic collection and organization of color, texture and material attributes for the control system to access and modify. In the second part of the design, a mathematical model is applied to design the system. For human-space interaction that is based upon qualitative user input and interpretation of linguistic terms pertaining to perceptions and opinions of spatial qualities, fuzzy logic system—a soft computation method—is deemed appropriate to compute, interpret and process input and output data. Data processing is conducted through making inferences instead of representing classical data in the form of absolute true or false. In the input-output mechanism of the interactive system, the specified input and output variables are regulated by fuzzy control rules that are founded upon the aesthetic principles.

Finally, *design scales* are applied to map numerical output data derived from the mathematical model calculations to corresponding color and material to modify appropriate surface attributes as final output. *Design scales* limit and regulate access to color, texture and material databases in a systematic manner, specifying the extent to which design parameter attributes can be modified by the control system to generate intended spatial qualities. Some design conditions are also formulated for constraints and uncertainties in the interactive system.

7.2 Overview of Surface Modification

The square-shaped, single living space contains an accent wall. Any modification made to one or more of the three design parameters—color, brightness and texture—apply to all six enclosing surfaces simultaneously. The accent wall has variable surface materials that can be modified per user input. As a focal point of interest, the appearance of the accent wall is designed to have an impact on perceived affective spatial quality. Three types of materials have been designated for the accent wall: stone, wood and fabric (as curtain). Materials of remaining five enclosing surfaces remain unmodifiable. These surfaces are clad with materials commonly found in residences. A drywall material is applied to the ceiling and three surrounding wall surfaces. Fabric (carpet) is applied to the floor. The living space is envisioned as a single colored space. A lighter tone of the same color is used for the ceiling and edge trims, as commonly seen in most residences.

7.3 Defining Input and Output Variables

The user inputs for the interactive system are occupant's emotional responses to perceived spatial qualities of living space. The psychophysiological dimensions of spaces that the occupant responds to can be categorized into four groups: temperature, size, level of arousal and softness. Occupants rate the perceived affective dimensions of spaces in each category represented by a pair of input variables that are oppositional adjectives (see Table 7.1). These eight input variables are: warm, cool, spacious, intimate, exciting, calm, muted and saturated.

Table 7.1. User input categories and variables

Categories	**Input variables**
1. Temperature	Warm, cool
2. Size	Spacious, intimate
3. Level of Arousal	Exciting, calm
4. Softness	Muted, Saturated

The occupant's inputs are received via a user interface in the form of numerical ratings. The interface consists of four continuous rating scales with sliders that are formed with pairs of extreme or opposite variables for each category of affective spatial dimensions, as shown in Figure 7.1. Each category is rated quantitatively on a scale of 0 to 10, where 0 and 10 indicate two opposite (contrasting) variables. The midpoint (5) indicates a neutral position. For instance, the rating scale for *temperature* is represented by 0 as "very cold," 10 as "very warm" and 5 as "neither warm nor cold." If the living space feels too cold, occupant moves the slider to mark 0 or any other appropriate point closer to 0, indicating the number that represents their subjective perception of degree of how cold the space is. Similarly, if the space feels too warm, occupant will move the slider to 10 or a point closer to 10. The numerical range of the scale has an increment of 0.25. The scale allows input values with decimal points.

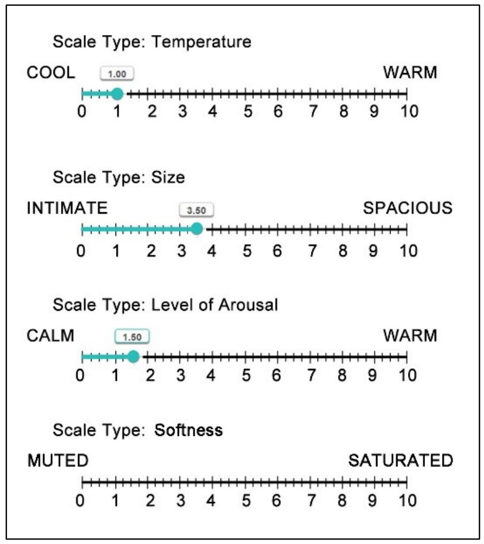


Figure 7.1. User interface with rating scales for user input

There are five output variables: hue, chroma, value, graininess and material type. These are specific surface attributes pertaining to the design parameters. *Hue, chroma* and *value* are attributes of color.[211] *Hue* is an attribute of color that indicates the level of warmth or coolness of color. *Chroma* is an attribute of color that indicates how intense, strong or saturated a color is. *Value* is an attribute of color that indicates how light (bright) or dark a color is. *Graininess* is an attribute of surface texture of any material. It indicates level of roughness or smoothness of texture. It is the visual perception of how rough or smooth surface texture may appear to vision or touch. *Material type* indicates the generic name of a material, such as wood or stone. For the

211. See Section 2.5.1.

living space, the types of material are selected based upon their perceived visual weight of heavy or light materials. The variable *material type* is changed only for the accent wall.

An interactive control system manipulates these variables to change the appearance of the enclosing surfaces of the living space in order to articulate space. Surface color can be modified in both *hue* and *chroma* components. Perceived surface brightness, dependent upon the lightness or darkness of color, can be modified by changing the *value* component of surface color. Table 7.2 shows the five output variables with their corresponding design parameters and the enclosing surfaces they modify.

Table 7.2. Modifiable surface attributes (output variables)

Design parameters	**Output Variables**		**Surface modified**
Color	Hue	*Name of color*	all
	Chroma	*Intensity of color*	all
Brightness	Value	*Lightness of color*	all
Texture	Graininess	*Rough or smoothness of texture*	all
Material	Material Type	*Name of material*	Accent wall

7.4 Databases

Databases outline the types and ranges of color, brightness, texture and material that are designated for the control system to access in a systematic manner and modify surfaces.

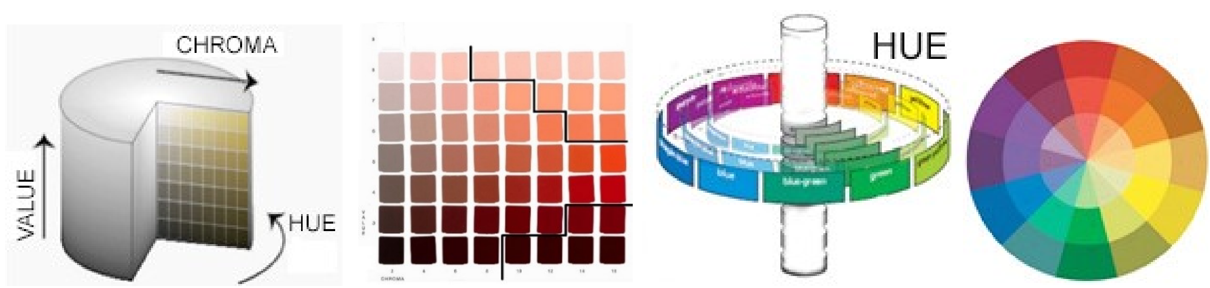
7.4.1 Color Database

The control system uses a three-dimensional color space for modifications of color and brightness levels of surfaces. It is based upon the traditional Munsell color system[212] in which

212. See Section 2.5.1.

hue spectrums are arranged along horizontal circular bands, the *value spectrum* for each *hue* is arranged along a vertical axis and the ranges of *chromas* of the *chroma spectrum* radially extend from the central vertical axis of the color space. There are no restrictions on the types and ranges of color and brightness levels that can be used for the living space. Figure 7.2 illustrates the color space for the interactive system.

The color space is envisioned as cylindrical in shape, as shown in Figure 7.2-a, for convenient measurements. This means, graphically, all colors have the same number of chroma steps. The highest chroma of "weaker" colors have been repeated along their respective chroma axes to form the cylinder, as shown in Figure 7.2-b (value-chroma chart). Hue spectrums are continuous bands along the vertical axis (see Figure 7.2-c). All colors can be displayed as part of a hue-chroma chart (see Figure 7.2-d), as well as part of a value-chroma chart for easy calculations.



(a) (b) (c) (d)

Figure 7.2. The cylindrical three-dimensional color space

7.4.2 Texture and Material Database

A texture database consists of ranges of texture *graininess* for a total of five materials used in the living space, as shown in Table 7.3. The texture *graininess* for each material ranges from very smooth to very rough. Rough texture visually represents more depth, contrast and sharpness than smoother texture grains. Figure 7.3 gives an example of rough and smooth texture graininess for each material.

Table 7.3. Materials assigned to enclosing surfaces

Materials	**Surfaces**
Stone	Accent wall
Wood	Accent wall
Fabric (curtain)	Accent wall
Drywall	Three walls and ceiling
Fabric (Carpet)	Floor

Figure 7.3. Texture: Rough (top) and smooth (bottom)

The material database consists of three materials designated for the accent wall. These are: stone, wood and fabric (curtain). These three materials differ in their perceived visual weight. Stone is perceived as more heavy and dense than wood, and wood appears more heavy and dense than fabric.

7.5 Establishing Input-Output Correlations

The aesthetic principles have been founded on correlations between the affective aspects of space and design parameters of color, brightness, texture and material. These correlations can be further expanded to include the output variables (attributes of the design parameters): *hue, chroma, value, graininess* and *material type*. Table 7.4 displays the input-output correlations for the control system.

Table 7.4. Correlations between input and output variables

INPUT: Perception of Affective Spatial Aspects		**OUTPUT: Modification of Design Parameter Attributes**	
Rating Categories	**Input Variables**	**Design parameters**	**Output variables**
1. Temperature	Warm or Cool	Color	Hue
2. Size	Spacious or Intimate	Brightness	Value
		Material	Type
3. Level of Arousal	Calm or Exciting	Texture	Graininess
		Color	Chroma
4. Softness	Muted and Saturated	Color	Chroma

Each input variable (user perception of affective spatial aspect) can be linked to one or more output variables that the system modifies. These input-output correlations are further explained as follows:

7.5.1 Warm and Cool Spaces

The *hue* component of color is modified to increase or decrease the perceived temperature—warmth or coolness—of living space. The wide range of warm and cool *hues* in a *hue spectrum* are organized according to their color temperature. Perceived temperature of a color is dependent upon its adjacent color, as well as its relative distance from the warmest or the coolest color in the spectrum. The three-dimensional color space of the control system considers pure blue (RGB #0000ff) as the coolest color, and pure red (RGB #ff0000) as the warmest color. Colors located closer to pure red are perceived as warmer than colors located closer to blue. In other words, each *hue* is perceived warmer than its adjacent *hues* located closer to pure blue, and each *hue* is perceived cooler than its adjacent *hues* located closer to pure red along the horizontal axis of *hue spectrum* (see Figure 7.4).

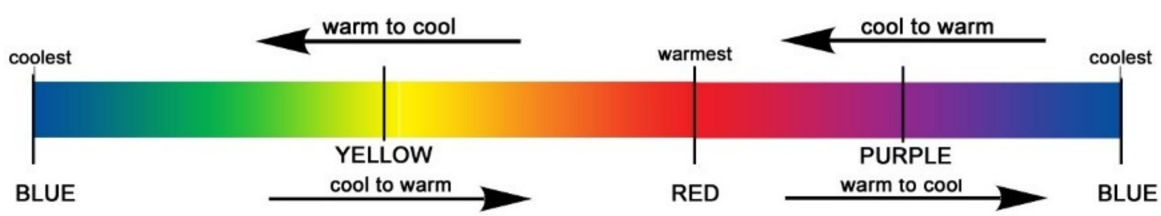


Figure 7.4. Warm and cool hues in a spectrum

To increase perceived warmth of living space, the control system selects a *hue* that is warmer than the existing surface *hue*. Similarly, to increase perceived coolness of living space, it selects a cooler *hue*. Based upon user input of desired degree of warmth or coolness, the control system shifts left to right, or right to left, along the horizontal band of *hue spectrum* to select an appropriate *hue* warmer or cooler than existing surface *hue* of living space (see Figure 7.5).

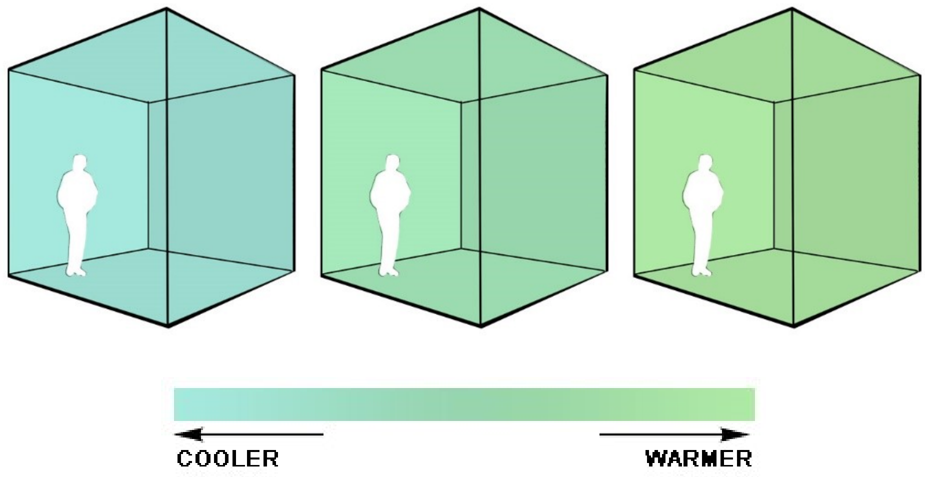


Figure 7.5. Selecting a warmer or cooler *hue* from *hue spectrum*

7.5.2 Spacious and Intimate Spaces

Two design parameters—brightness and material—are modified to increase or decrease the perceived degree of spaciousness or intimacy. Perception of surface brightness is dependent upon the level of lightness or darkness of surface color (*value*).

The control system uses the three-dimensional color space to find the *value spectrum* of existing surface *hue* (see Figure 7.6). To select appropriate level of lightness or darkness for surface color, the control system shifts from top to bottom, or bottom to top along the vertical axis of given *hue* to select a tint or a shade. Based upon user input, an appropriate tint (higher *value*) of existing surface color is selected to increase perceived spaciousness, and an appropriate shade (lower *value*) is selected to increase intimacy of living space.

Additionally, the material used for the accent wall can be changed by modifying *material type* to further enhance the feeling of spaciousness or intimacy. Perceived visual weight of a material can impact how rigid, confined, light, flexible or spacious a space feels. Among the three materials available for the accent wall, stone, as the heaviest material, imparts an enhanced feeling of confinement or rigidity, thus increasing the feeling of intimacy more than wood or fabric. On the other hand, fabric curtains, as the lightest material among the three, may enhance the feeling of spaciousness more than wood or stone. Based upon user input, control system replaces existing material for the accent wall with a heavier or lighter material.

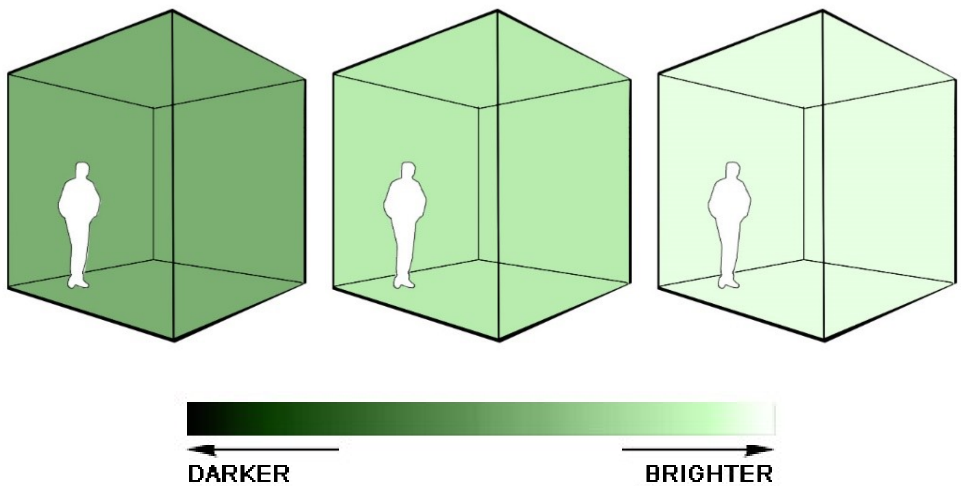


Figure 7.6. Selecting a darker or brighter *value* from *value spectrum*

7.5.3 Exciting and Calm Spaces

To manipulate the perceived level of excitement or calmness of living space, two design parameters—texture and color—are modified. Rougher texture increases perceived level of excitement and smoother texture increases perceived level of calmness of living space. Based on user input, the control system identifies surface materials and selects the appropriate level of texture *graininess* (roughness or smoothness) for those materials from the texture database.

Furthermore, modification of the color attribute of *chroma* also influences perceived level of arousal of living space. Surfaces with muted or less saturated color (low *chroma*) are perceived as calmer, whereas strong, highly saturated, or high intensity color (high *chroma*) is perceived as more exciting. Based on user input, the control system identifies the surface *hue* and moves along its *chroma spectrum* in the three-dimensional color space to select a higher *chroma* to increase excitement or a lower *chroma* to increase calmness of perceived space (see Figure 7.7).

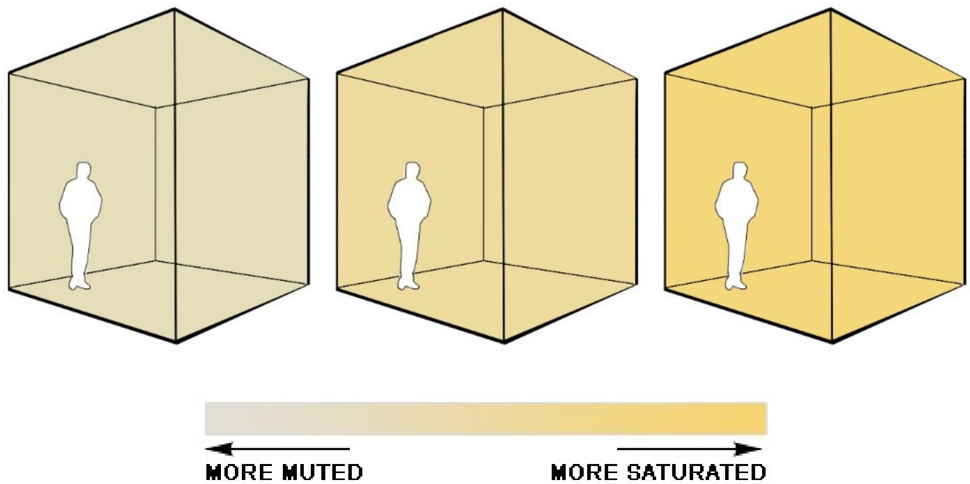


Figure 7.7. Selecting a muted or saturated color from *chroma spectrum*

7.5.4 Muted and Saturated Spaces

Muted and *saturated* are affective dimensions related to color. The color attribute of *chroma* can be modified to increase or decrease the intensity and saturation of existing surface *hue*. Muted colors with low *chroma* are perceived to increase visual softness to living space, whereas high *chroma* colors increase contrast and saturation and have the opposite spatial effect. Based upon user input, the control system shifts along the radially extended *chroma spectrum* of given surface *hue* in the three-dimensional color space to select appropriate level of *chroma* (see Figure 7.7).

7.6 Design of Interactive Control System with Fuzzy Logic

This section explains the implementation technique of fuzzy logic system, a computation methodology, in the design of the interactive control system. It includes analysis and processing of quantitative user inputs pertaining to perception of affective spatial aspects, application of aesthetic principles through fuzzy control rules to regulate the input-output mechanism, and generation of quantitative outputs. These outputs are later mapped to corresponding attributes of color, brightness, texture and material through use of *design scales*.[213]

7.6.1 The Fuzzy Logic System

Fuzzy logic system is a formal soft computational method that successfully integrates the abstract elements of human experience and behavior in sophisticated control system design knowledge. Fuzzy Logic analyzes and interprets statistical uncertainties that may emerge from complex, vague, contradictory, indefinite, ambiguous or random scenarios.[214] In fuzzy logic system, analysis of soft, linguistic data is accomplished through interpretations or suggestions and involves pattern recognition, intuitive decision making and search for implicit meanings. When processing data, fuzzy logic makes inferences through degrees of association or membership, rather than representing data as absolute true (1) or false (0) in terms of its membership to a set. The soft computing technique of Fuzzy Modeling is appropriate for

---

213. See Section 7.7.

214. Pedro Ponce-Cruz and Fernando D. Ramirez-Figueroa. *Intelligent Control Systems with LabVIEW™* (Verlag London: Springer, 2010), doi: 10.1007/978-1-84882-684-7.

processing abstract, non-numerical design data characteristic of architectural design.[215] Architecture design deals not only with quantitative (crisp) data, but also with qualitative (fuzzy), linguistic design data of opinions, behavior, experience, scenarios and metaphors. Although application of fuzzy logic is not a routine practice in architecture, it has been deemed suitable for architectural design problems that deal with qualitative, non-analytical, non-quantifiable information to help in design decision making. [216]

Fuzzy logic system is implemented to design the control system of the interactive living space in which interaction is based upon interpretation of linguistic terms pertaining to perceptions of affective spatial qualities. For instance, user perception of how warm or cold the living space is, is relative and subjective, and responses cannot be numerically defined or classified as absolute true or absolute false to determine the degree of warmth or coolness objectively. In classifying a specific temperature as warm or cold, fuzzy logic system uses the concept of "partial truth" to accurately measure the transition between warm and cold. Through formulation of *membership functions*, fuzzy logic defines or classifies a specific temperature by assigning it a degree of relevance to a specific category. Here, a specific temperature may be both warm and cold to some partial extent. A temperature quantified as "warm" can also be considered as "slightly cold" to some degree.

215. Özer Ciftcioglu, "Design Enhancement by Fuzzy Logic in Architecture," in proceedings of *the 12th IEEE International Conference on Fuzzy Systems (Vol. II),* 25-28 May, 2003, St. Louis, Missouri: FUZZ-IEEE 2003: 79-84, doi: 10.1109/FUZZ.2003.1209341.

216. Özer Ciftcioglu and Sanja Durmisevic, "Fuzzy Logic in Architectural Design," in proceedings of *EUSFLAT 2001: the International Conference in Fuzzy Logic and Technology*, 5-7 September, 2001, De Monfort University, Leicester, UK: 265-268.

Fuzzy logic system provides a method for the control system to process input data it receives from the user and to respond with output data meaningful for the user through adjustments of *membership functions* and application of *fuzzy control rules*. *Membership functions* are graphical curves with numerical ranges mapped with corresponding linguistic variables constructed to assign degrees of membership to each user input. In similar manner, *membership functions* also convert linguistic output variables into quantitative crisp output data.

7.6.2 Application of Fuzzy Modeling in Design

Implementation of fuzzy logic system involves necessary design decisions taken in several steps. In the first step, appropriate *membership functions* are defined for both input and output variables depending on desirable outcome of input-output mechanism. In the second step, the aesthetic principles are transformed into *fuzzy control rules* in the form of IF-THEN conditional linguistic statements to regulate how the system responds to each user input with corresponding output. These rules give structure and meaning to relations between input and output variables.

Figure 7.8 shows a diagram of the interactive control system constructed with the three-part process of fuzzy modeling. In the *fuzzification* process, the control system receives crisp input data (quantitative ratings) from user and, with the help of *membership function* computations, converts crisp data to linguistic data with fuzzy components to varying degrees. In the fuzzy inference process, relevant *fuzzy control rules* are applied that, combined with input data, derive control outputs. In the *defuzzification* process, the linguistic control outputs are converted back to crisp outputs.

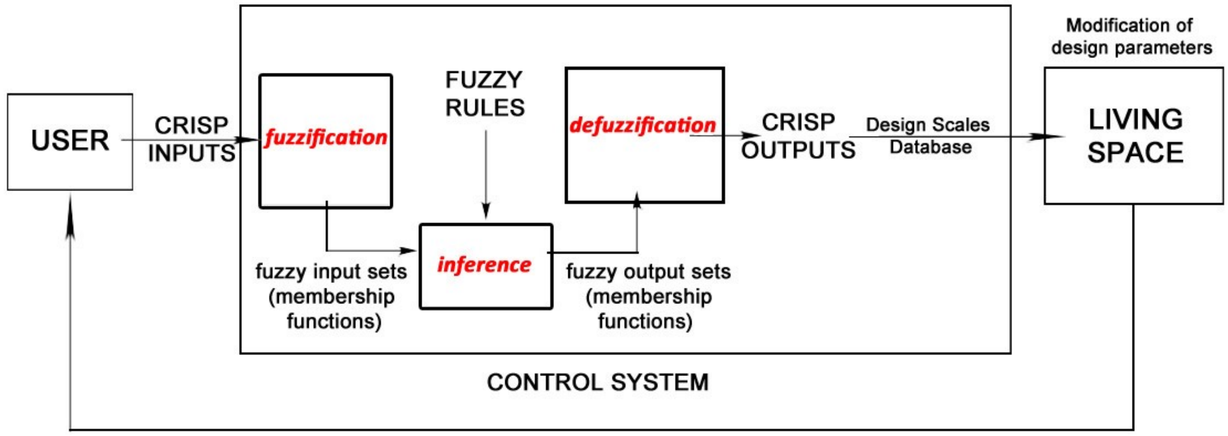


Figure 7.8. Diagram of Interactive Control System with Fuzzy Logic

7.6.3 Membership Functions

In the fuzzification process, all input and output variables are represented by linguistic variables in the form of graphical representations of *membership functions*. There are four input categories of *temperature, size, level of arousal* and *softness* represented by trapezoid *membership functions* ranging from 0 to 10 that correspond to the quantitative range of the user rating scale. Each crisp user rating is calculated and mapped to a *degree of membership* (DOM) or equivalent membership value between 0 and 1 on the vertical axis. There are five output variables—*hue, chroma, value, graininess* and *material type*—also visually represented by either triangular or trapezoid membership functions on a range of 0 to 10 with a set of linguistic variables. The output linguistic variables refer to the extent of modifications for surface attributes. Table 7.5 and Table 7.6 list the linguistic variables of each input and output variable, respectively.

Table 7.5. Input Linguistic Variables

Input Categories	**Input variables**	**Input Linguistic variables (Fuzzy Input Data sets)**
Temperature	Warm or Cool	Very Cold, Slightly Cold, Neutral, Slightly Warm, Very Warm
Size	Spacious or Intimate	Very Small, Slightly Small, Neutral, Slightly Big, Very Big
Level of Arousal	Calm or Exciting	Very Calm, Slightly Calm, Neutral, Slightly Exciting, Very Exciting
Softness	Muted or Saturated	Too Muted, Slightly Muted, Neutral, Slightly Saturated, Too Saturated

Table 7.6. Output Linguistic Variables

Output variables	**Output Linguistic variables (Fuzzy Output Data sets)**
Hue	Coolest, Cooler, Existing, Warmer, Warmest
Value	Decreased, Slightly Decreased, Existing, Slightly Increased, Increased
Chroma	Decreased, Slightly Decreased, Existing, Slightly Increased, Increased
Graininess	Very Smooth, Slightly Smooth, Existing, Slightly Rough, Very Rough
Material Type	Lightest, Lighter, Existing, Heavier, Heaviest

Membership Functions for Temperature: The input membership function for *temperature* is associated with the trapezoid output membership function for *hue*. Figure 7.9 illustrates both the user rating scale for *temperature* and its corresponding input trapezoid membership function. The membership function has five defined fuzzy input data sets or linguistic variables—very cold, slightly cold, neutral, slightly warm, and very warm—drawn on a range of 0 to 10. Here, "neutral" indicates a temperature that is neither warm nor cold. The linguistic variables graphically represent varying degrees of perceived warmth and coolness of spatial quality of living space. The ranges correspond to the user rating scale of *temperature*.

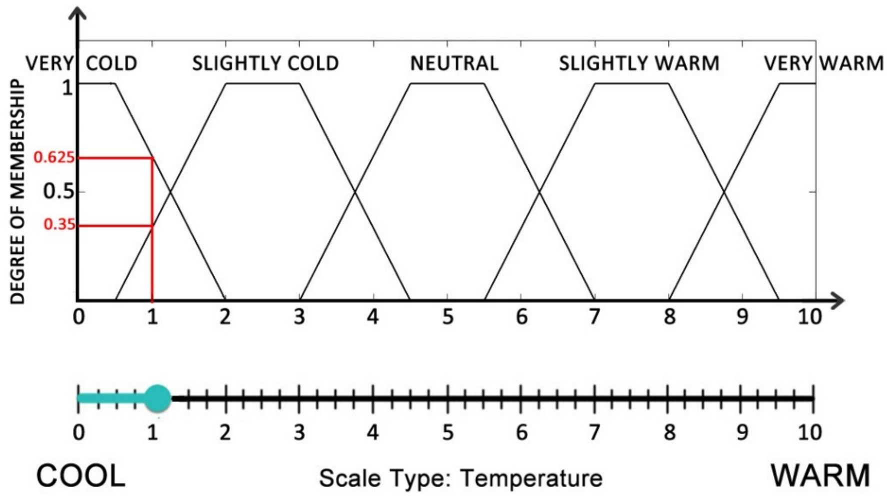


Figure 7.9. Input membership function and user rating scale for *temperature*

Figure 7.9 also illustrates the process of calculation of degree of membership in each fuzzy input set through linear interpolation. User ratings (crisp input) of *temperature* are mapped on the graphical representation to compute their corresponding membership values (μ) for each fuzzy set. For a crisp input of 1, corresponding membership values (μ) for each fuzzy set in the Membership Function *Temperature* are calculated as follows:

$\mu_{\text{temperature = very cold}}(1) = 0.65$

$\mu_{\text{temperature = slightly cold}}(1) = 0.35$

$\mu_{\text{temperature = neutral}}(1) = 0$

$\mu_{\text{temperature = slightly warm}}(1) = 0$

$\mu_{\text{temperature = very warm}}(1) = 0$

When crisp input for *Temperature* is 1, the input has a membership value of 0.65 in the fuzzy set (linguistic variable) of "very cold," a value of 0.35 in fuzzy set of "slightly cold," and a value of 0 in the fuzzy sets of "neutral," "slightly warm," and "very warm." This means, the input *temperature* belongs to “very cold” to 0.65 degree, but also belongs to “slightly cold” to 0.35 degree, and to “neutral,” “slightly warm,” and “very warm” to 0 degree.

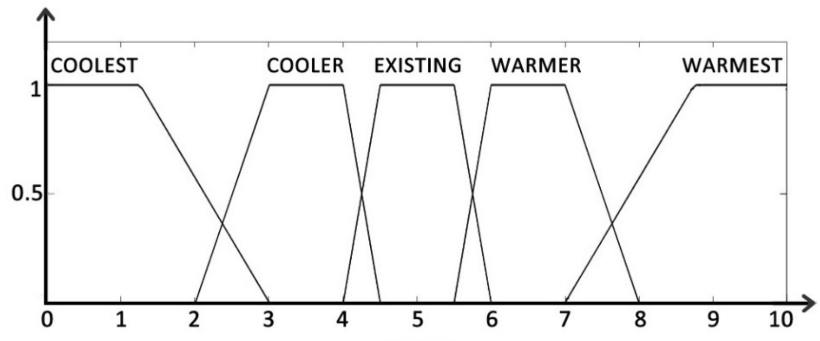


Figure 7.10. Output membership function for *hue*

Figure 7.10 is an illustration of the trapezoid output membership function for *hue*. It consists of five defined sets or linguistic variables: coolest, cooler, existing, warmer, warmest. Here, “existing” refers to retaining the existing surface *hue* as it is, with no modifications. The 0 to 10 range represents a subset of the *hue spectrum* of existing surface *hue*. The membership function indicates how much the control system shifts towards left or right along the horizontal axis of the *hue spectrum* to find an output *hue* of appropriate warmth or coolness as a response to user input for *temperature*. Table 7.7 and Table 7.8 list the linguistic variables of membership functions *temperature* and *hue*, respectively.

Table 7.7. *Temperature*: Ranges of input linguistic variables

No.	**Input Linguistic variables**	**Range of Crisp User Input**
1	Very cold	Less than 0 to +2, with 0 as the center
2	Slightly cold	+0.5 to +4.5, with 1 as the center
3	Neutral	+4.5 to +5.5, with 5 as the center
4	Slightly warm	+5.5 to +9.5, with 7.5 as the center
5	Very warm	+8 to more than +10, with 10 as the center

Table 7.8. *Hue*: Ranges of input linguistic variables

No.	Output Linguistic variables	Range of Crisp Output
1	Coolest	Less than 0 to +3, with 0 as the center
2	Cooler	+2 to +4.25, with 3.5 as the center
3	Existing	+4 to +6, with 5 as the center
4	Warmer	+5.5 to +8, with 6.5 as the center
5	Warmest	+7 to more than +10, with 10 as the center

Membership Functions for Size: Figure 7.11–7.13 illustrate the input membership function for *size* and its associated two output membership functions for *value* and *material type*. The trapezoid membership function for *size* represents varying degrees of perceived *spaciousness* or *intimacy* of spatial quality of living space with five defined fuzzy input sets: very small, slightly small, neutral, slightly big, and very big. Here, "neutral" indicates a size that is neither intimate nor spacious. The 0 to 10 range corresponds to the user rating scale of *size*.

The trapezoid membership function for *value* represents five defined linguistic sets: decreased, slightly decreased, existing, slightly increased and increased. Here, "existing" refers to keeping the existing surface color *value* as it is, with no modifications. The 0 to 10 range represents a subset of the *value spectrum* for the existing surface color *value*. The output membership function indicates how much the control system shifts towards left or right along the horizontal axis of the *value spectrum* to find appropriate *value* output in response to user input.

The triangular membership function for *material type* represents five defined sets: lightest, lighter, existing, heavier, and heaviest. Here, "existing" refers to no modifications to the type of material. The membership function calculates which material the control system selects as an output in response to user input. Tables 7.9–7.11 show the input and output linguistic variables and ranges for Membership Functions *size, value* and *material type*.

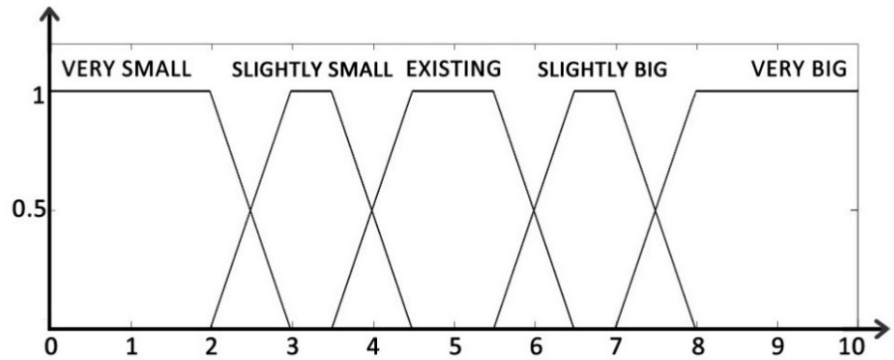


Figure 7.11. Input membership function for *size*

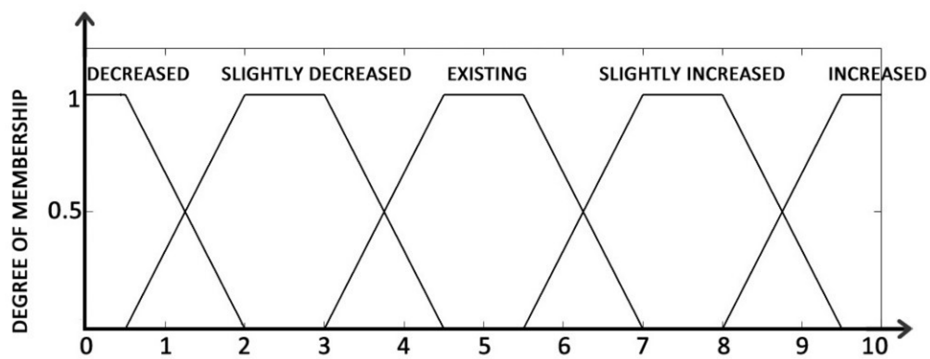


Figure 7.12. Output membership function for *value*

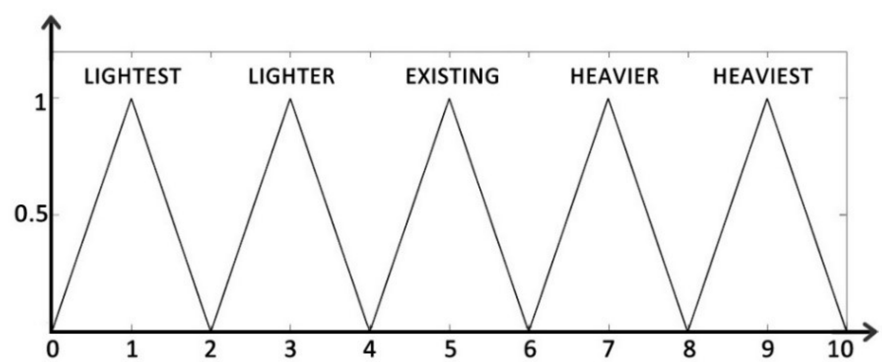


Figure 7.13. Output membership function for *material type*

Table 7.9. *Size*: Ranges of input linguistic variables

No.	Input Linguistic variables	Range of Crisp User Input
1	Very small	Less than 0 to +3, with 0 as the center
2	Slightly small	+2 to +4.5, with 3.25 as the center
3	Neutral	+3.5 to +6.5, with 5 as the center
4	Slightly big	+5.5 to +8, with 6.75 as the center
5	Very big	+7 to more than +10, with 10 as the center

Table 7.10. *Value*: Ranges of input linguistic variables

No.	Output Linguistic variables	Range of Crisp User Input
1	Decreased	Less than 0 to +2, with 0 as the center
2	Slightly decreased	+0.5 to +4.5, with 1 as the center
3	Existing	+4.5 to +5.5, with 5 as the center
4	Slightly Increased	+5.5 to +9.5, with 7.5 as the center
5	Increased	+8 to more than +10, with 10 as the center

Table 7.11. *Material Type*: Ranges of input linguistic variables

No.	Output Linguistic variables	Range of Crisp Output
1	Lightest	0 to +2, with 1 as the center
2	Lighter	more than +2 to +4, with 3 as the center
3	Existing	more than +4 to +6, with 5 as the center
4	Heavier	more than +6 to +8, with 7 as the center
5	Heaviest	more than +8 to +10, with 9 as the center

Membership Functions for Level of Arousal: Figure 7.14–7.16 illustrate the input membership function for *level of arousal* and its associated two output membership functions for *graininess* and *chroma*. The degrees of perceived excitement and calmness of spatial quality of living space are represented in membership function for *level of arousal* by five defined fuzzy input sets: very calm, slightly calm, neutral, slightly exciting, and very exciting. Here, “neutral” indicates neither calm nor exciting. The 0 to 10 range corresponds to the user rating scale of *level of arousal*.

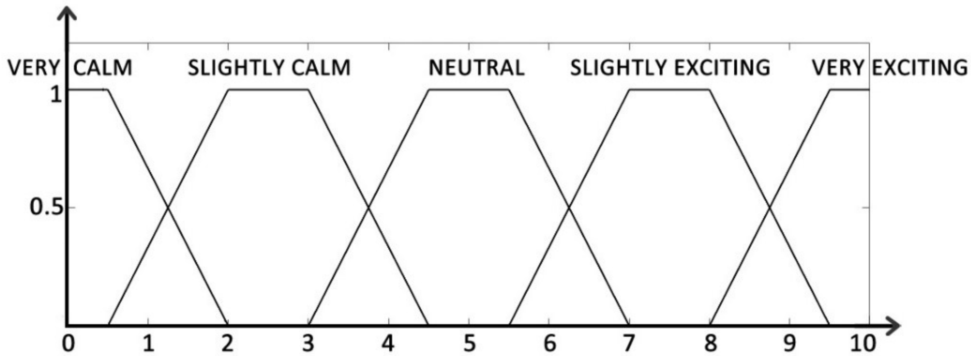


Figure 7.14. Input membership function for *Level of Arousal*

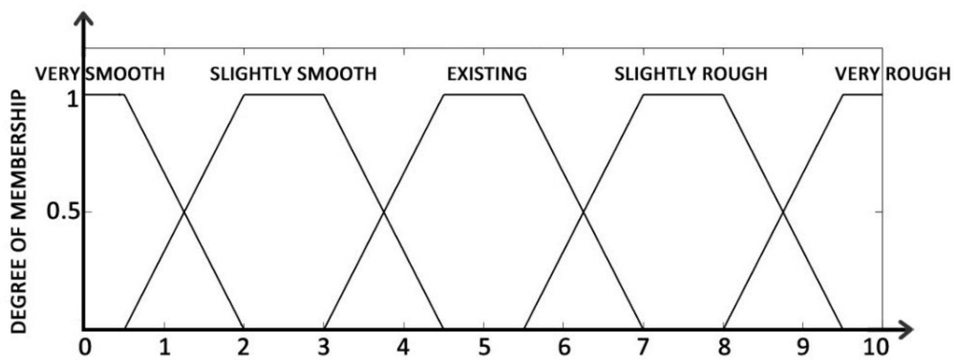


Figure 7.15. Output membership function for *Graininess*

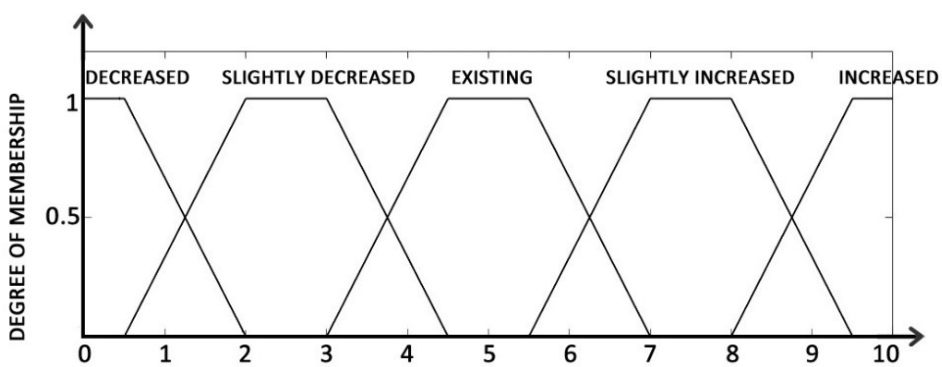


Figure 7.16. Output membership function for *Chroma*

The trapezoid membership function for *graininess* represents a range of texture graininess with varying degrees of smoothness and roughness. It represents five defined linguistic sets: very smooth, slightly smooth, existing, slightly rough, and very rough. "Existing" refers to keeping existing surface texture as it is. The 0 to 10 range represents a subset of the full range of texture *graininess* for the existing surface materials. The output membership function indicates how much the control system shifts towards left or right along the horizontal axis to find an appropriate level of graininess output as a response to user input.

The trapezoid membership function for *chroma* represents five defined linguistic sets: decreased, slightly decreased, existing, slightly increased and increased. "Existing" refers to keeping existing surface *chroma* as it is. The 0 to 10 range represents a subset of the *chroma spectrum* of existing surface *chroma*. The membership function indicates how much the control system shifts towards left or right along the horizontal axis of the *chroma spectrum* to find an appropriate output *chroma* in response to the user input.

Tables 7.12–7.14 show the linguistic variables and ranges for *membership functions* for *level of arousal, graininess* and *chroma*.

Table 7.12. *Level of Arousal*: Ranges of input linguistic variables

No.	**Input Linguistic variables**	**Range of Crisp User Input**
1	Very calm	Less than 0 to +2, with 0 as the center
2	Slightly calm	+0.5 to +4.5, with 1 as the center
3	Neutral	+4.5 to +5.5, with 5 as the center
4	Slightly exciting	+5.5 to +9.5, with 7.5 as the center
5	Very exciting	+8 to more than +10, with 10 as the center

Table 7.13. *Graininess*: Ranges of output linguistic variables

No.	Output Linguistic variables	Range of Crisp Output
1	Very smooth	Less than 0 to +2, with 0 as the center
2	Slightly smooth	+0.5 to +4.5, with 1 as the center
3	Existing	+4.5 to +5.5, with 5 as the center
4	Slightly rough	+5.5 to +9.5, with 7.5 as the center
5	Very rough	+8 to more than +10, with 10 as the center

Table 7.14. *Chroma*: Ranges of output linguistic variables

No.	Output Linguistic variables	Range of Crisp User Input
1	Decreased	Less than 0 to +2, with 0 as the center
2	Slightly decreased	+0.5 to +4.5, with 1 as the center
3	Existing	+4.5 to +5.5, with 5 as the center
4	Slightly Increased	+5.5 to +9.5, with 7.5 as the center
5	Increased	+8 to more than +10, with 10 as the center

Membership function for Softness: Figure 7.17 illustrates the input membership function for *softness.* It has an associated trapezoid output membership function for *chroma* (see Figure 7.16 and Table 7.14).

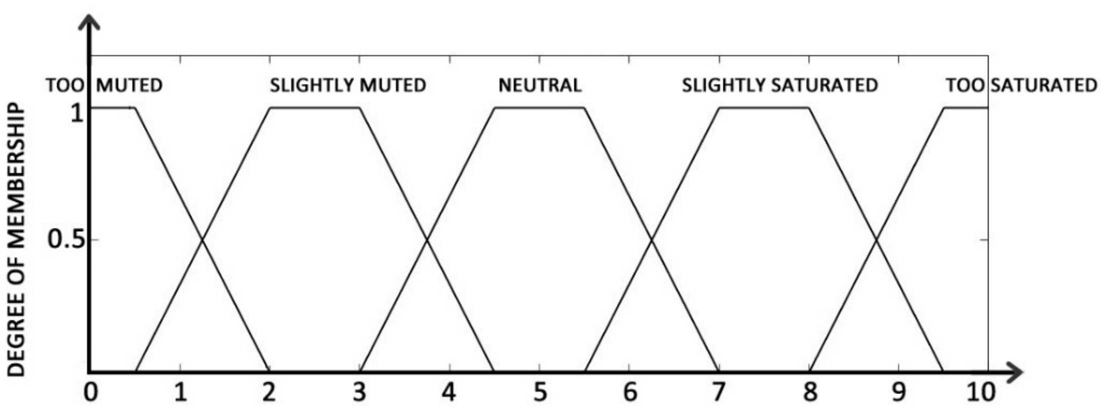


Figure 7.17. Input membership functions for *softness*

The degrees of saturation or softness of color of living space are represented in membership function for *softness* by five defined sets: too muted, slightly muted, neutral, slightly saturated, and too saturated. Here, "neutral" indicates neither muted nor saturated. The range corresponds to the user rating scale of *softness*. Table 7.15 shows the input linguistic variables and ranges for *membership function* for *softness*.

Table 7.15. *Softness*: Ranges of input linguistic variables

No.	Input Linguistic variables	Range of Crisp User Input
1	Too muted	Less than 0 to +2, with 0 as the center
2	Slightly muted	+0.5 to +4.5, with 1 as the center
3	Neutral	+4.5 to +5.5, with 5 as the center
4	Slightly saturated	+5.5 to +9.5, with 7.5 as the center
5	Too saturated	+8 to more than +10, with 10 as the center

7.6.4 Aesthetic Correlations as Fuzzy Control Rules

The aesthetic correlations established between input and output variables (Table 8) are applied in the mathematical model through construction of linguistic or *fuzzy control rules* with IF-THEN conditions that combine the user input and spatial output membership functions in order to obtain desirable outputs. These *fuzzy rules* control values of output variables by directing the control system regarding which action to take when certain conditions are met. Each *fuzzy rule* has an IF-condition and a THEN-command constructed for each input variable and their possible combinations. Once a user input is received and *fuzzified*, and one or more IF-conditions are met, the control system carries out the THEN-command. Below are a list rules constructed for fuzzy inference processes combining four input categories (Temperature, size, level of arousal, and softness) and five output variables (*hue*, *value*, *chroma*, *graininess*, and *material type*):

Rules for Membership Function for *Temperature*:

1. IF (*Temperature* is very cold) THEN (*Hue* is Warmest)
2. IF (*Temperature* is slightly cold) THEN (*Hue* is Warmer)
3. IF (*Temperature* is neutral) THEN (*Hue* is Existing)
4. IF (*Temperature* is slightly warm) THEN (*Hue* is Cooler)
5. IF (*Temperature* is very warm) THEN (*Hue* is Coolest)

Rules for Membership Function for *Size*:

1. IF (*Size* is very small) THEN (*Value* is Increased) AND (*Material Type* is Lightest)
2. IF (*Size* is slightly small) THEN (*Value* is Slightly Increased) AND (*Material Type* is Lighter)
3. IF (*Size* is neutral) THEN (*Value* is Existing) AND (*Material Type* is Existing)
4. IF (*Size* is slightly big) THEN (*Value* is Slightly Decreased) AND (*Material Type* is Heavier)
5. IF (*Size* is very big) THEN (*Value* is Decreased) AND (*Material Type* is Heaviest)

Rules for Membership Function for *Level of Arousal*:

1. IF (*Level of Arousal* is very calm) THEN (*Graininess* is Very Rough) AND (*Chroma* is Increased)
2. IF (*Level of Arousal* is slightly calm) THEN (*Graininess* is Slightly Rough) AND (*Chroma* is Slightly Increased)

3. IF (*Level of Arousal* is neutral) THEN (*Graininess* is Existing) AND (*Chroma* is Existing)
4. IF (*Level of Arousal* is slightly exciting) THEN (*Graininess* is Slightly Smooth) AND (*Chroma* is Slightly Decreased)
5. IF (*Level of Arousal* is very exciting) THEN (*Graininess* is Very Smooth) AND (*Chroma* is Decreased)

Rules for Membership Function for *Tactile Quality*:

1. IF (*Softness* is too muted) THEN (*Chroma* is Increased)
2. IF (*Softness* is slightly muted) THEN (*Chroma* is Slightly Increased)
3. IF (*Softness* is neutral) THEN (*Chroma* is Existing)
4. IF (*Softness* is slightly saturated) THEN (*Chroma* is Slightly Decreased)
5. IF (*Softness* is too saturated) THEN (*Chroma* is Decreased)

7.6.5 Defuzzification

In the defuzzification process, the control rules are combined with linguistic data of input and output membership functions to form final crisp outputs. Calculation applies the calculation method of *centroid*, commonly used for defuzzification, to measure the center of gravity of summed area under the curve as an aggregate of one or more linguistic outputs. Figure 7.18 illustrates five possible scenarios of fuzzy output calculations for five different user ratings. The scenarios are further explained as follows:

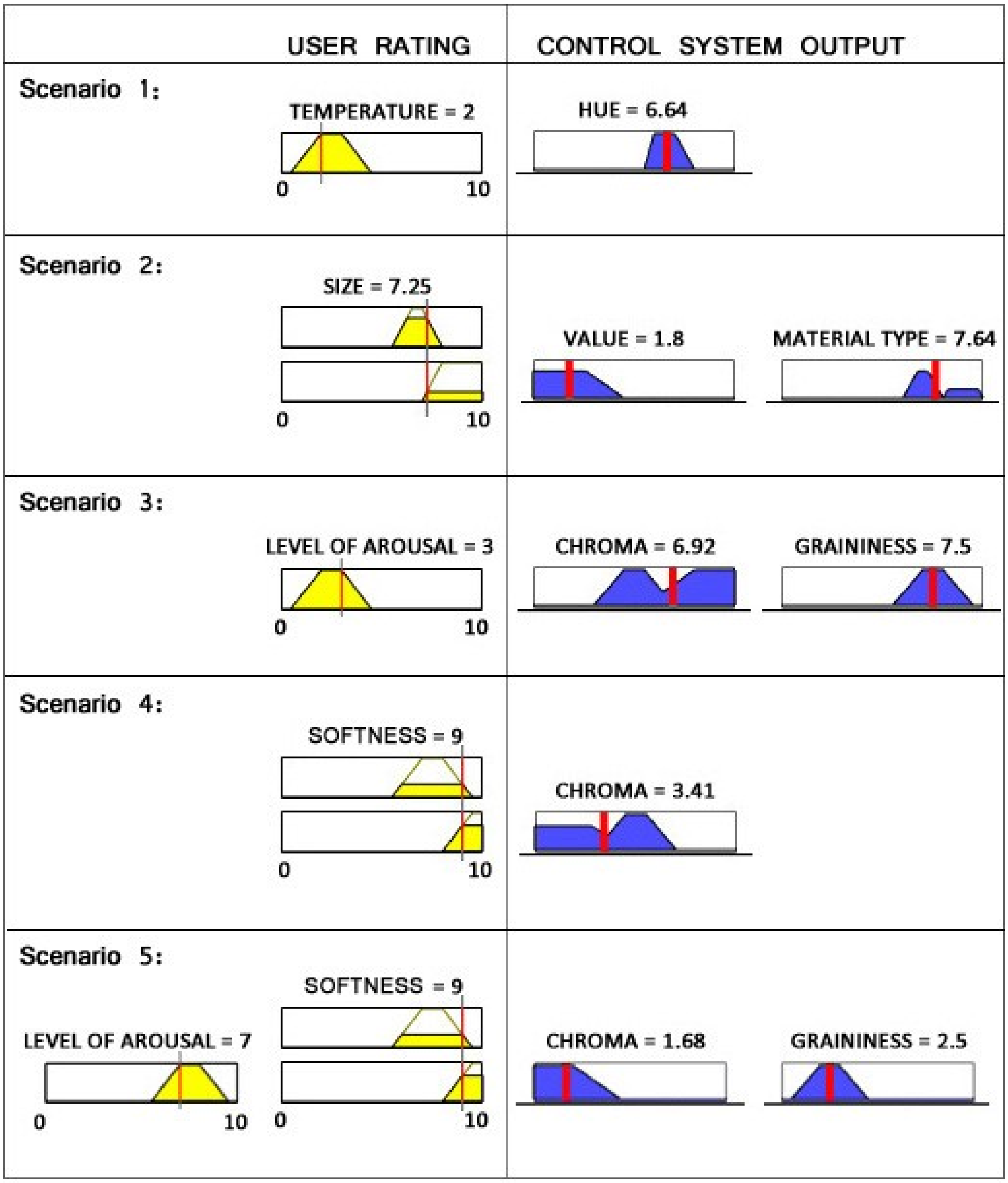


Figure 7.18. Possible scenarios of user ratings and outputs

1. Scenario 1: If the user rating for *temperature* = 2, it indicates that occupant perceives the living space as very cold. To increase warmth, the control system selects a warmer *hue* as output. The change in hue is 6.64.

2. Scenario 2: If the user rating for *size* = 7.25, it indicates that occupant perceives the living space as slightly bigger (spacious). To decrease spaciousness, the control system output darkens surface color (change in *value*=1.8) and selects a material for the accent wall that is visually heavier than the existing material (change in *material type* = 7.64).
3. Scenario 3: If the user rating for *level of arousal* = 3, it indicates that the living space is perceived as too calm. To increase level of excitement, control system output increases intensity (saturation) of surface color and roughness of surface texture. The change in *chroma* is 6.92 and the change in *graininess* is 7.5.
4. Scenario 4: If the user rating for *softness* = 9, it indicates that the living space is perceived as too saturated. To increase softness of space, output decreases surface *chroma*. The change in output *chroma* is 3.41.
5. Scenario 5: If the user rating for *level of arousal* =7, and *softness*= 9, it indicates that the living space is perceived as too exciting and saturated. To increase calmness and softness of space, output decreases surface *chroma* (1.68) and smoothens surface texture *graininess* (2.5).

7.7 Application of Design Scales

In the final stage of output data processing, *design scales* are applied to the *defuzzified* crisp output. These scales are used to map the final crisp outputs to their corresponding new color or material component for the surfaces of the living space. The application process of each design scale is described as follows.

7.7.1. Hue Scale

A *hue scale* is used to find the new surface *hue* that corresponds to the *defuzzified* final crisp output of *Hue*. The *hue spectrum* of the control system is a continuous, smoothly changing gradient converted from the forty color swatches of the Munsell Color System, as shown in Figure 7.19. To map crisp output data, the *hue scale* selects a subset or segment of *hues* from the *hue spectrum* with the existing surface *hue* at the center of the segment. The length of this segment is that of thirteen consecutive *hues* (see Figure 7.19).

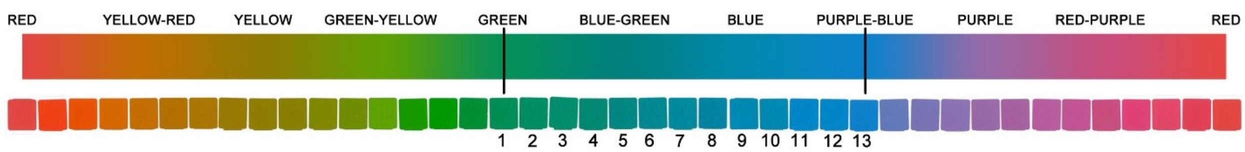


Figure 7.19. Example of a segmentation by the *hue scale*

Once the fuzzy output variable *hue* is defuzzified into a crisp output, the control system conducts the following operations, as illustrated by Figure 7.20:

1. The control system identifies the existing surface *hue* of the living space in the three-dimensional color space.
2. A subset or segment of *hues* is selected from its corresponding *hue spectrum* positioning the existing *hue* in the center.
3. The selected subset is assigned a range of 0 to 10 to align with the range of aggregated output membership function for *hue*. The crisp output data is then mapped on the *hue* subset to find out a new hue as the final output. The RGB value of *hue* is measured.

4. Control system modifies surface color with the new *hue* to increase or decrease perceived color temperature of living space.

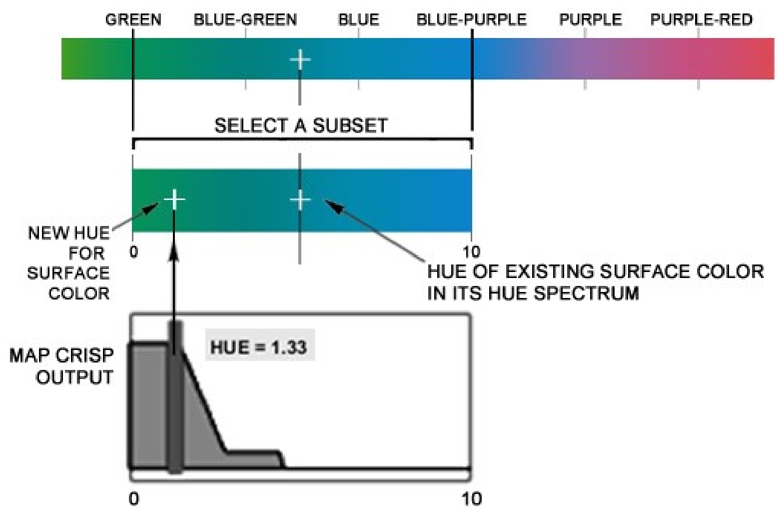


Figure 7.20. Mapping of crisp output on selected segment to find new *hue*

7.7.2. Value Scale

A *value scale* is used to find the new surface color *value* (shade or tint) that corresponds to the *defuzzified* final crisp output of *Value*. The *value spectrum* is a continuous brightness ramp or brightness gradient from pure black to pure white, as shown in Figure 7.21. The markings on the *Value Scale* indicates 10% increments in lightness of a color from pure black at the bottom of the color space to pure white at the top.

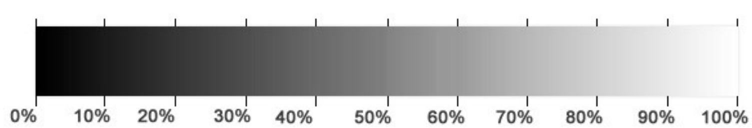


Figure 7.21. 10% increments in lightness of a value spectrum

Once the fuzzy output variable *Value* is defuzzified into a crisp output, the control system conducts the following operations, as illustrated in Figure 7.22:

1. The control system identifies the existing surface color *hue* and *value* in three-dimensional color space.
2. A subset of *values* is selected from the entire vertical *value spectrum* of the given *hue*, positioning existing *value* at the center.
3. The selected subset is assigned a range of 0 to 10 and consists of five tonal variations in 10% increments. This means, the subset has the existing *value* at the center, with a shade 20% darker on one end, and a tint 20% lighter on the other.
4. The crisp output data of *value* is mapped on the subset to find out its corresponding tint or shade as the final output.
5. Control system modifies surface color with the new *value* output to increase or decrease brightness level of living space.

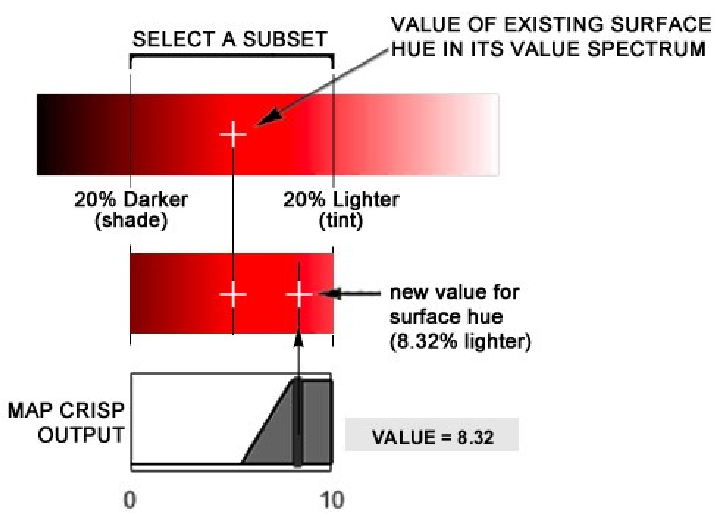


Figure 7.22. Mapping of crisp output on selected segment to find new *value*

7.7.3. Chroma Scale

A *chroma scale* is used to find the new surface color *chroma* that corresponds to the *defuzzified* final crisp output of *Chroma*. The *chroma spectrum* developed for the control system is a continuous ramp or gradient from grey to full chroma for any given hue. The incremental steps to reach full *chroma* varies from color to color. Figure 7.23 shows the Munsell *chroma* steps for *Hue* 7.5R from grey to full chroma ranging from 0 to 16. It is converted into a gradient ramp for the control system, ranging from 0 to 8. The markings on the *chroma spectrum* indicate 1 unit increments in *chroma*.

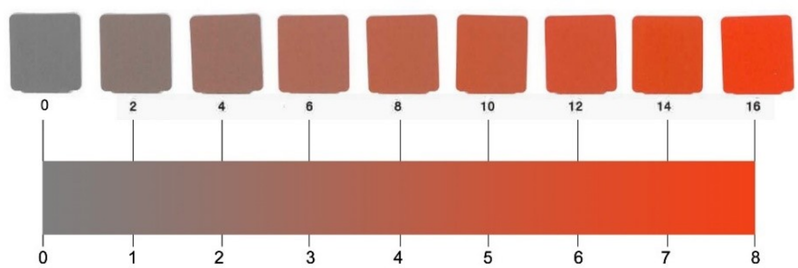


Figure 7.23. *Chroma spectrum* with 1 unit segments of *chroma* variations

Once the fuzzy output variable of *chroma* is defuzzified into a crisp output, the control system conducts the following steps, as illustrated in Figure 7.24:

1. The control system identifies both the existing surface *hue* and its *chroma* in the three-dimensional color space.
2. A subset of *chromas* from the entire horizontal *chroma spectrum* of the existing *hue* is selected positioning the existing chroma at the center. The length of subset is 4 units.

3. The subset is assigned a range of 0 to 10. The crisp output data is mapped on the *chroma* subset to find out corresponding new *chroma* as the final output. The RGB value of new color is measured.
4. Control system modifies surface color with the new *chroma* to increase or decrease color intensity of living space.

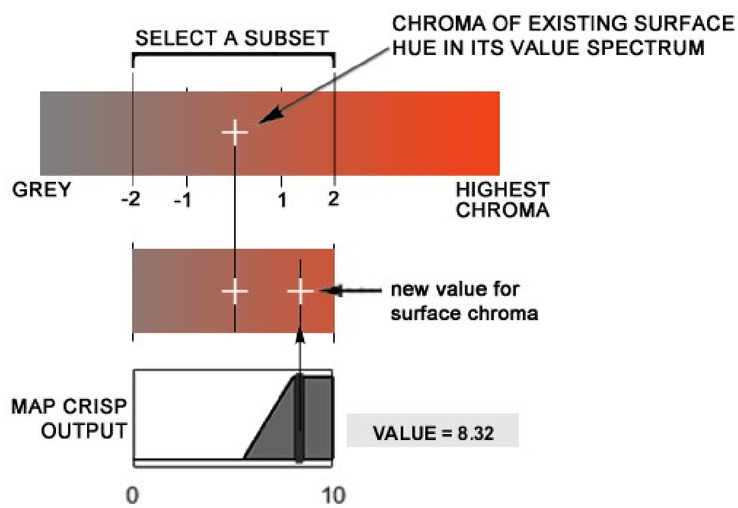


Figure 7.24. Mapping of crisp output on selected 4-unit segment to find new *chroma*

7.7.4. Texture Graininess

A *texture scale* is constructed for each of five materials: drywall, fabric (carpet), wood, stone and fabric(curtain), The *scale* consists of a range of texture graininess from 0 to 10, where 0 indicates for very smooth and 10 indicates for very rough. The scale shifts from left to right, or right to left along its horizontal axis to select a new surface texture graininess that is indicated by the value of defuzzified crisp output for *Graininess*. Once the fuzzy output variable *graininess* is defuzzified into a crisp output, the control system conducts the following operations, as illustrated in Figure 7.25:

1. Control system identifies all existing surface materials in order to use respective *texture scales*.
2. For each material, the range of *texture scale* (0 to 10) corresponds to the range of output membership function for *graininess*. The crisp output data is mapped on all *texture scales* to find new value of texture *graininess* for each material as the final output.
3. Control system thus modifies surface texture *graininess* for all surfaces in order to increase or decrease perceived level of excitement or calmness of living space.

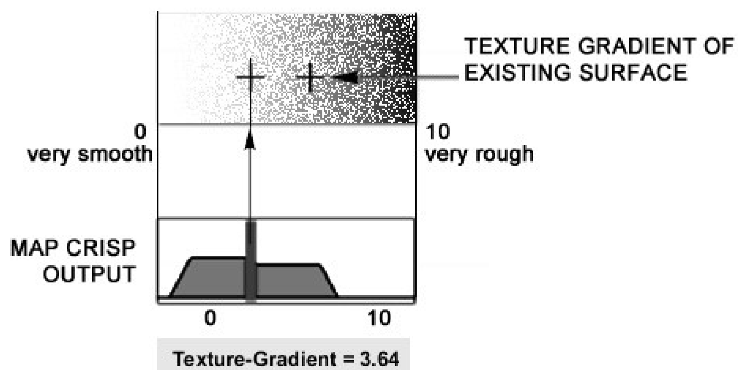


Figure 7.25. Mapping of crisp output on *texture scale* to find new *graininess*

7.7.5. Material Scale

A *material scale* is developed for the control system to select types of material for the accent wall. Selection is based upon calculated mapping of crisp output data of *material type* on the scale. There are three materials for the accent wall that can be ranked according to perceived visual weight. Fabric is lighter than wood, and wood is lighter than stone. In other words, stone is heaviest and fabric is the lightest material.

Once the fuzzy output variable *material type* is defuzzified into a crisp output, the control system conducts the following operations, as illustrated in Figure 7.26:

1. Control system identifies existing surface material of the accent wall.
2. The 0 to 10 range of *material scale* corresponds to the range of output membership function for *material type*. The crisp output data is mapped to find a new material as the final output.
3. Based upon mapped output value, control system selects a material that is lighter or heavier than existing surface material. The conditions for material selection depend upon existing surface material, as shown in Table 7.16.

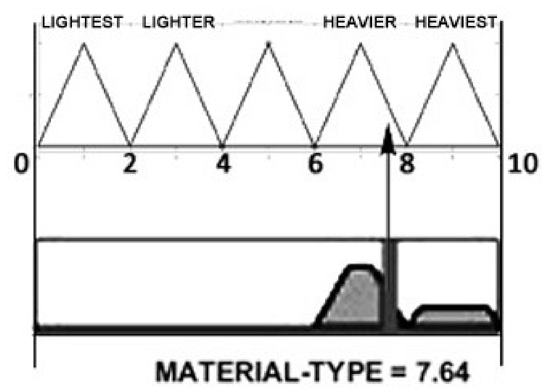


Figure 7.26. The *material scale*

Table 7.16. Perceived Visual Weight of Materials

If existing surface material is:	**Lighter**	**Lightest**	**Heavier**	**Heaviest**
Fabric	—	—	Wood	Stone
Wood	Fabric	Fabric	Stone	Stone
Stone	Wood	Fabric	—	—

7.8 Design Conditions and Constraints

Some design conditions are formulated for special conditions, constraints and uncertainties that may arise during human-space interaction. These are as follows:

1. *Color Modes:* The *hue scale* has two modes. Each mode has pure blue (RGB #0000FF) on one end and pure red (RGB #ff0000) on the other, as shown in Figure 7.27.
    a) Mode-1: It is the relatively longer segment of the *hue* spectrum of the color wheel. A third primary *hue* yellow is positioned at its center.
    b) Mode-2: It is the relatively shorter segment of the *hue* spectrum of the color wheel. Combinations of blue and red create a primary *hue* violet positioned at its center.

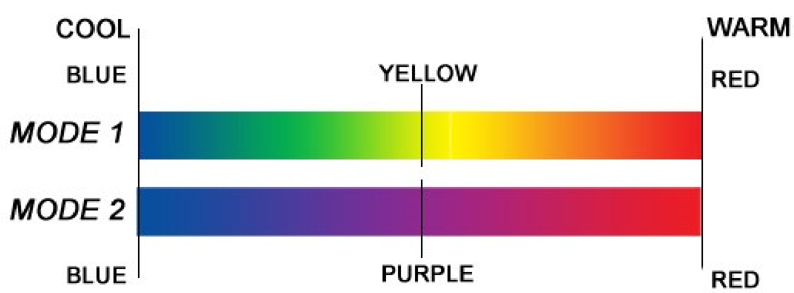


Figure 7.27. Two modes of *hue scale*

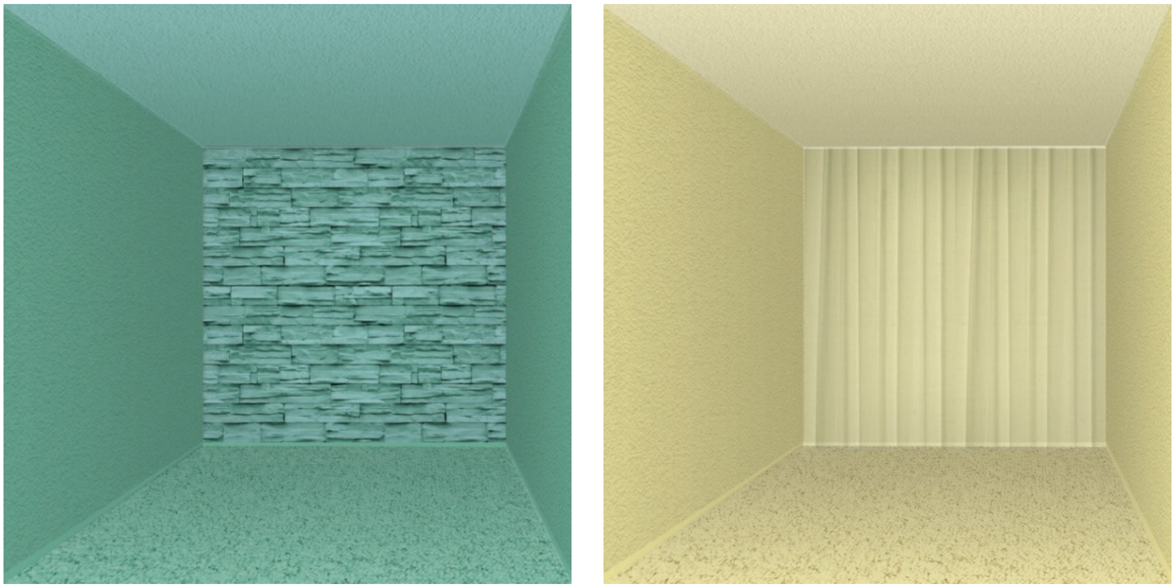
To select and modify any given *hue*, the control system utilizes only one mode at a time. The color modes switch under specific circumstances. During user-space interaction, it is possible that the surface color of living space reaches a monochromatic color: absolute black, white or gray. Under these circumstances, any further interaction with user will switch the color modes as well. If switched to Mode-1, the new surface color for the living space will be pure yellow (5Y) at its highest level of *chroma* and 50% color *value*. Similarly, if it is switched to

Mode-2, the new surface color for the living space will be pure Violet (5P) at its highest level of *chroma* and 50% color value. Material and texture will remain unchanged.

2. *Constraints with Warm or Cool Colors:* If user wants a cooler space when surface *hue* has already reached pure blue, or any of its tints or shades, the *hue* will remain unchanged, but the color value will decrease. This means, the surface color will become darker. Similarly, if user desires a warmer space when the surface *hue* is already pure red, or any of its tints or shades, the *hue* will remain unchanged and the color value will increase. This means that the surface color will become brighter.
3. *Material Constraints:* The existing surface material remains unchanged if output data for *material type* suggests a material lighter than fabric, or a material heavier than stone.

7.9 Examples of Possible Scenarios

In this section, some rendered examples have been provided for the living space demonstrating various spatial qualities that may emerge from possible scenarios of human-space interaction. Figure 7.28 displays two existing spatial scenarios: one with a cool color (green) and the other with a warm color (yellow). The living space with a green *hue* has an accent wall of stone (see Figure 7.28-a). The living space with yellow surfaces has a curtain on the accent wall (see Figure 7.28-b). The following sub-sections provide examples of how various user inputs will generate calculated outputs by the control system, modifying the color, brightness, texture and material for each scenario.



(a) cool color with a stone accent wall (b) warm color with curtain

Figure 7.28. Two existing spatial scenarios

7.9.1 Increase Warmth

A low numerical input of *Temperature* indicates that user is feeling cold. Lower input generates an output *hue* that is warmer than the existing *hue* (see Figures 7.29 and 7.30).

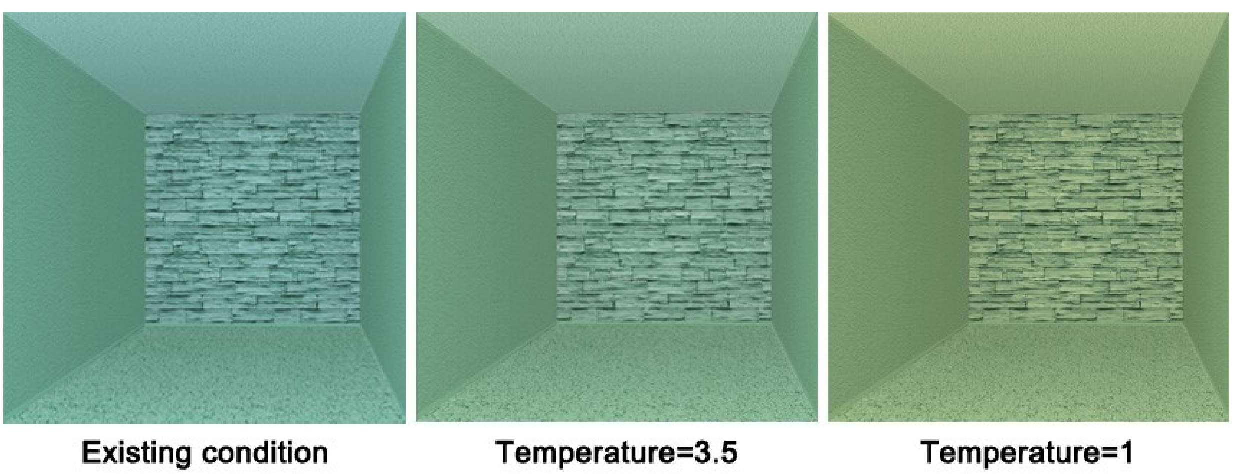


Figure 7.29. Increasing warmth: Green space

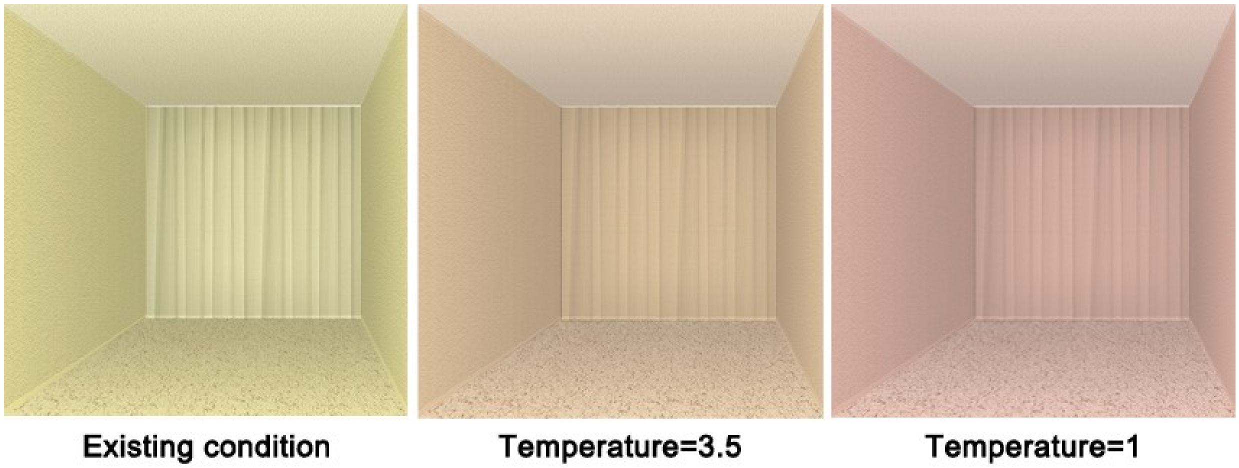


Figure 7.30. Increasing warmth: Yellow space

7.9.2 Increase Coolness

A high rating of *Temperature* indicates user is feeling warm. When rating is high, output selects a *hue* that is cooler than existing *hue* (see Figures 7.31 and 7.32).

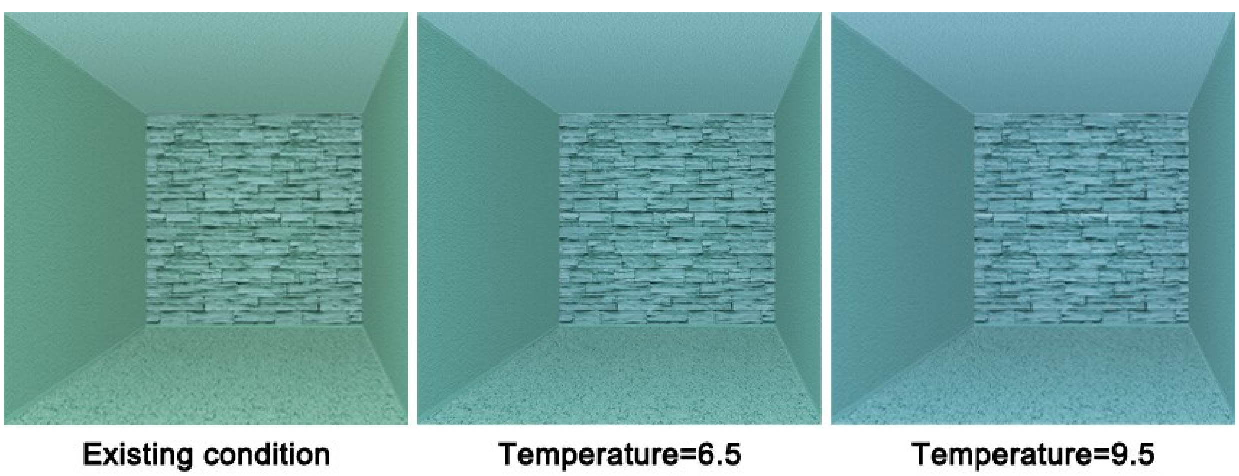


Figure 7.31. Increasing coolness: Green space

Figure 7.32. Increasing coolness: Yellow space

7.9.3 Increase Spaciousness or Intimacy

A lower numerical input for *Size* indicates that user feels the space is too small (intimate), and a higher input indicates the space is too spacious. Low input increases spaciousness (see Figures 7.33) and a high input will produce a more intimate space (see Figures 7.34 and 7.35).

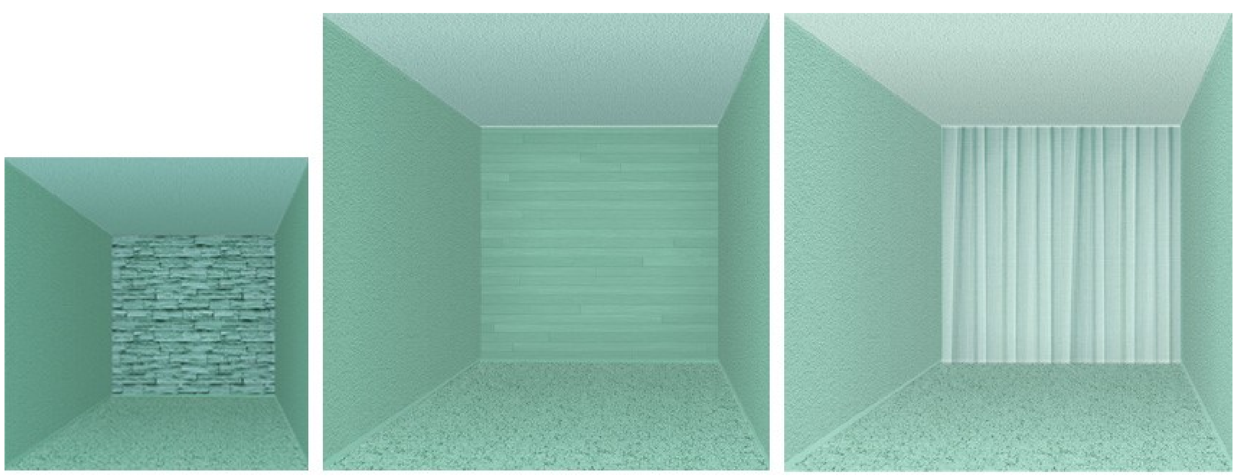


Figure 7.33. Increasing spaciousness: Green space

For increased spaciousness, space is made brighter, and a visually lighter material is selected for the accent wall (see Figures 7.34). For a more intimate space, if accent wall is already assigned the visually heaviest material (stone), it remains unchanged (see Figure 7.35).

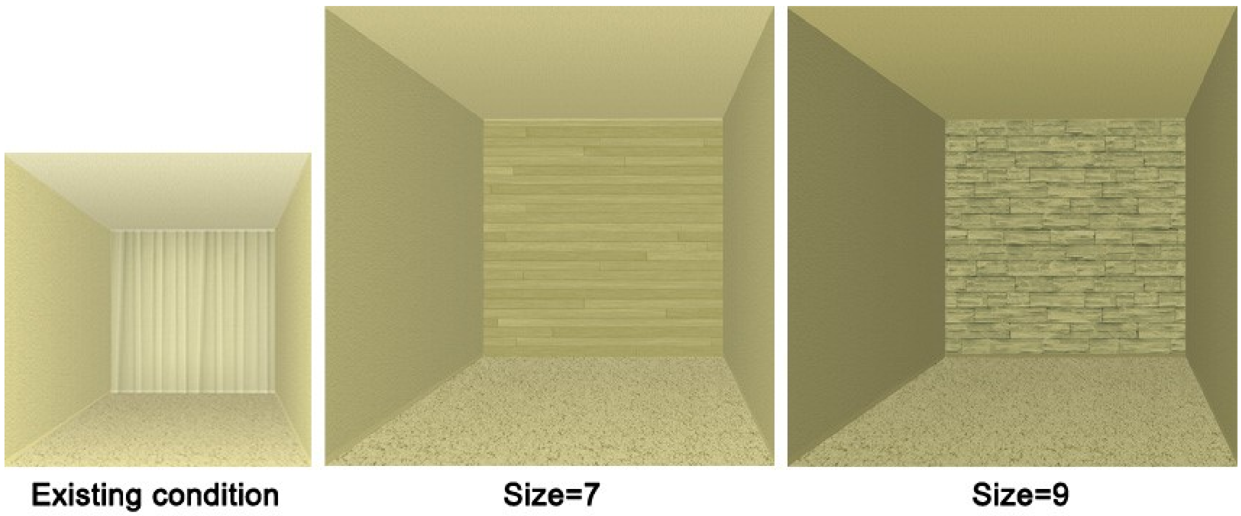


Figure 7.34. Increasing intimacy: Yellow space

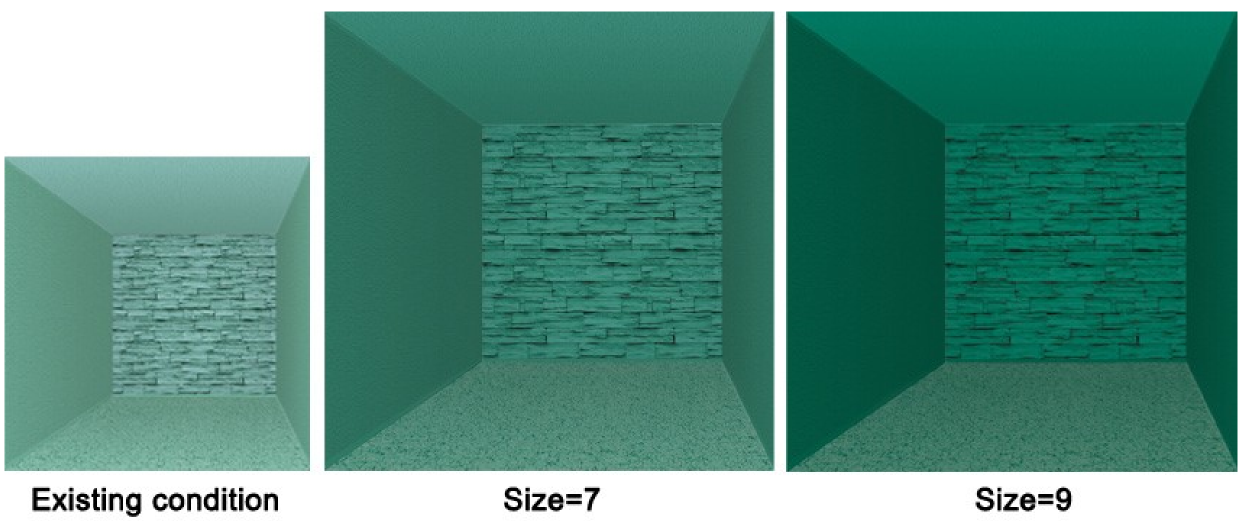


Figure 7.35. Increasing intimacy: Green space

7.9.4 Increase Excitement or Calmness

When rating *Level of Arousal*, a higher numerical input indicates that user feels the space is too exciting. Figures 7.36 and 7.37 demonstrate that a high input (*Level of Arousal*=8.5) generates a calmer space and a low input (*Level of Arousal*=3) produces a more exciting space.

Figure 7.36. Excitement or Calmness: Yellow space

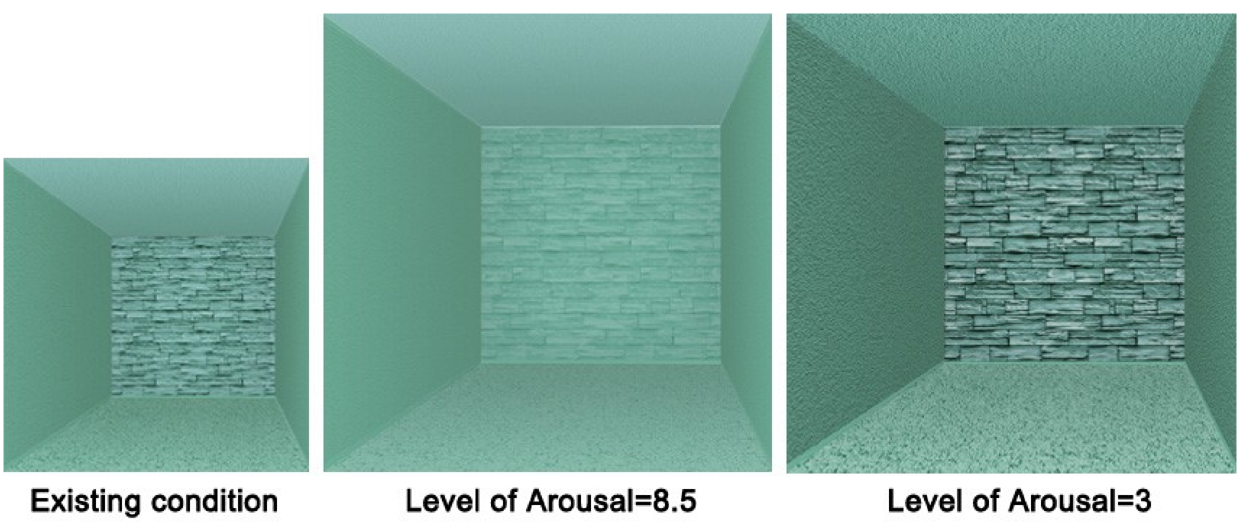


Figure 7.37. Excitement or Calmness: Green space

7.9.5 Increase or Decrease Softness

In rating *Softness*, a lower numerical input indicates that user feels the color is too saturated or intense. Figures 7.38 and 7.39 demonstrate that a lower input (*Softness*=2.5) generates a more muted color and a higher input (*Softness*=9) produces a more saturated color.

Figure 7.38. Increase or decrease softness: Yellow space

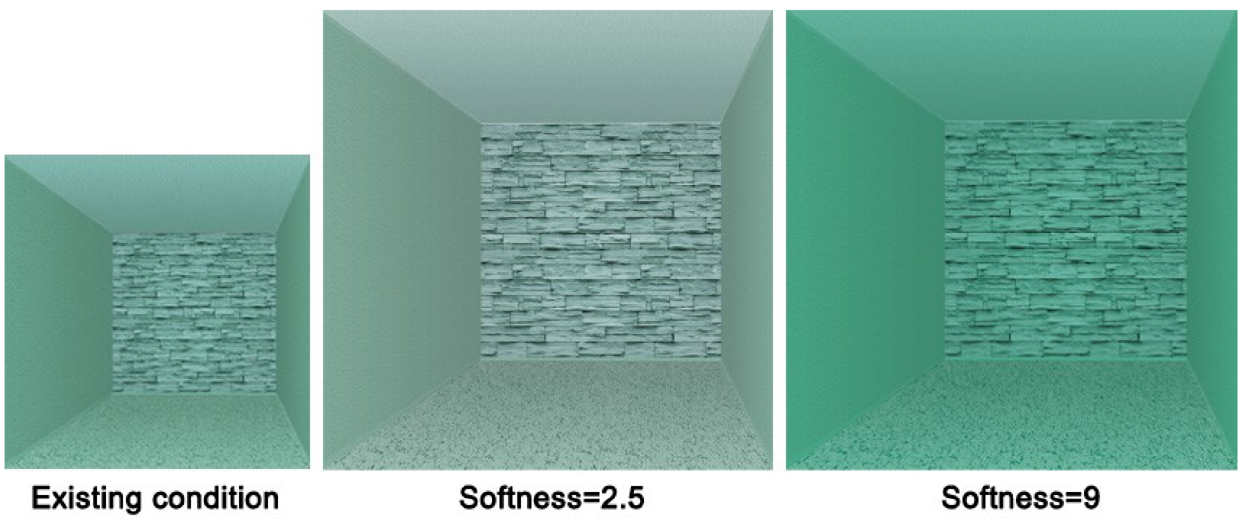


Figure 7.39. Increase or decrease softness: Green space

7.9.3 Sequential Transformations of Space

Figure 7.40 illustrates sequential articulations of space based upon user's numerical input of *temperature*, *size*, *level of arousal* and/or *softness*.

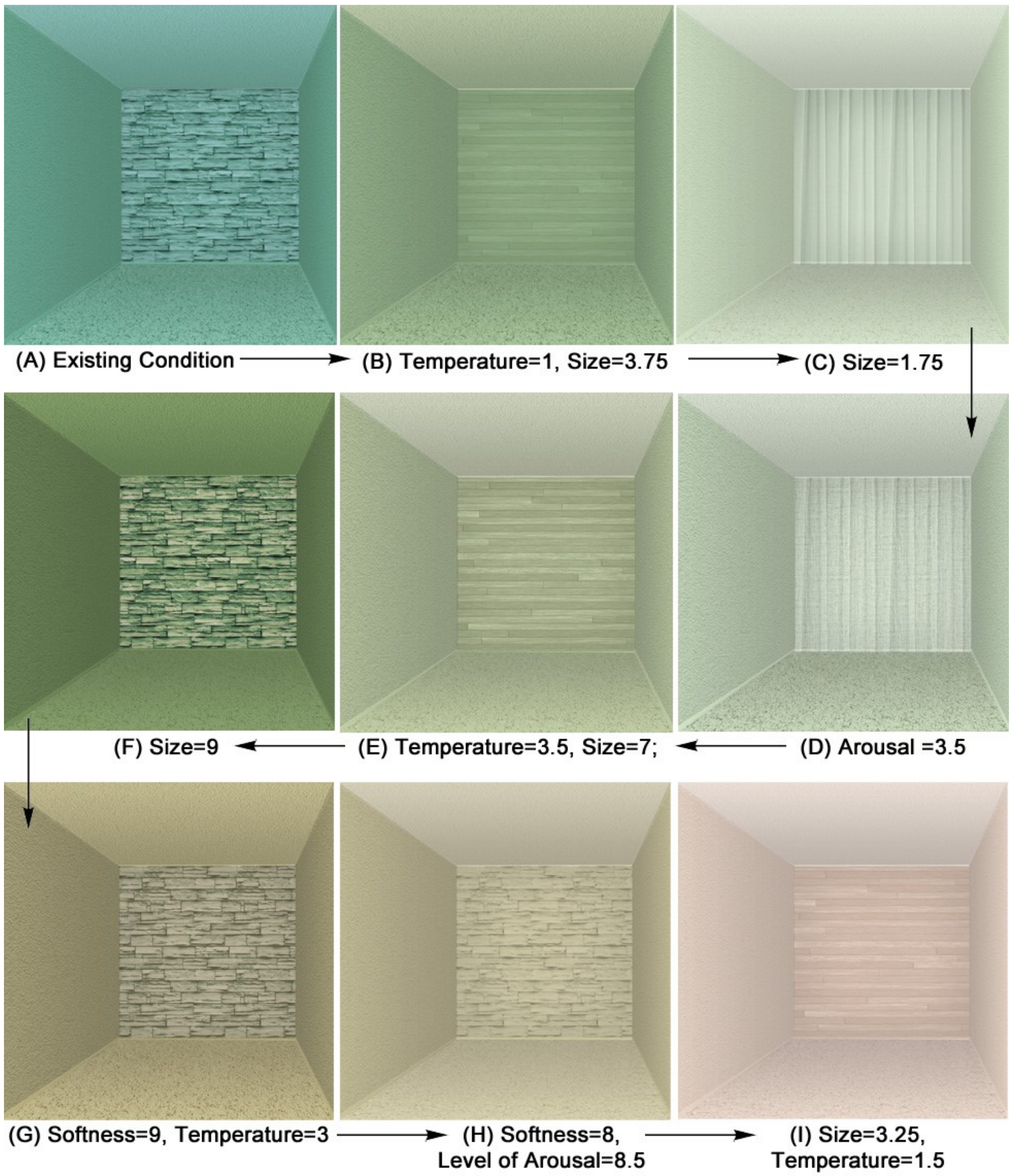


Figure 7.40. Sequential spatial articulations

CHAPTER 8

CONCLUSION

8.1 Summary

The proposed design concept of the living space is an attempt to redefine interactive architecture that integrates interaction design knowledge with traditional architectural design knowledge of affective space-making. The concept addresses the issues of space optimization and flexibility in a single living space that is anticipatory and adaptive. It is a response to the severe housing crisis that the *neo-nomads* are currently facing.

The proposed design had two major goals. One design goal was to create an exploration space for anticipation expression in which the human-space interaction is driven by possibilities of affective spatial experiences that may emerge to meet current and future needs. It is also driven by creative and aesthetic goals with underlying anticipations of imagined outcomes. Interactive technology and real-time spatial articulation technique were introduced to facilitate the anticipatory capacity of the space. The other design goal was to provide an aesthetic basis—i.e., a set of design principles—based on which meaningful human-space interaction can occur. In order to formulate the aesthetic principles, it was necessary to establish correlations between the design parameters and the affective spatial aspects examined. VR was used as a platform to conduct a perceptual study in order to evaluate the living space and gather relevant data.

The dissertation also demonstrated how the numerical user input data were to be interpreted and processed by the interactive system—through the application of the soft computation method of fuzzy logic—in order to generate spatial output based upon the formulated aesthetic framework.

8.1.1. The User Study

It was imperative to find out whether VR could successfully generate perceivable affective spaces with adapted design parameters of color, brightness and texture. The study findings were also compared to certain real-world perceptions, and new correlations were sought that could be pertinent to design. A hypothesis was formed for the user study: perceivable emotional aspects of real-world spaces could be successfully generated through simulation of adapted design parameters in the virtual space. The users were asked to quantify each affective spatial aspect—warm, cool, exciting, calm, spacious, intimate, comfortable—as well as preferable environments for working and resting. Influence of activity on perception was also measured. The qualitative study conducted a pseudo-interaction between the user and the simulated living space. It asked an open-ended question to gain insight into the type of affective spaces each user desired and the visual features or design parameters they preferred in order to modify and to achieve those spatial qualities.

8.1.2. Main Findings of the User Study

The following study findings confirmed the hypothesis posed in the user study and set a basis for gathering data for actual design:

1. Perceivable *warm*, *cool*, *exciting* and *calm* spaces could be successfully generated in the virtual environment. These spatial qualities, represented by oppositional adjectives, could generate contrasting emotions. The hypothesis was confirmed. However, an exception was found that showed that perceptions of *spacious* and *intimate* spaces did not generate contrasting emotions. It was concluded that the users probably did not consider the term

intimate as directly opposed to the term *spacious* during the test session, although they were explicitly asked to do so.

2. Certain real-world color and brightness perceptions could be successfully generated in the virtual environment. Similar to real-world perceptions, the warm color (orange) felt more *intimate* (closer) and *exciting* than the cool color (blue). On the other hand, the cool color felt more *calming* than the warm color. Brighter spaces felt more *spacious* than dark spaces.

Both direct or inferred correlations were established between the design parameters and the perceived affective spatial dimensions. Data analysis revealed main effects of color and brightness, as well as various interaction effects between color, brightness, texture and activity on perception (see Sections 6.8 and 6.9). Specific study findings were used as a basis for formulating the set of design principles, as given below:

1. Color had a significant impact on perceptions of all examined affective qualities (*warm, cool, exciting, calm, intimate, comfortable, rest and work*) except *spaciousness*.
2. Brightness had a significant impact on perception of *spaciousness*.
3. A new correlation could be inferred between texture and the perceived level of arousal (*exciting* or *calm*) of living space.
4. *Softness* was included as a significant affective spatial dimension associated with color and material tactility. This spatial dimension was represented by two oppositional adjectives: *muted* and *saturated*.

5. Material was included as an additional design parameter and was found to have an impact on perception of *spaciousness*. Visually heavily materials, such as stone, was found to be perceived as more confining than visually light materials, such as wood and fabric.

The formulated design principles are shown in Table 6.4 in Section 6.10.

In the latter part of research, the soft computation method of fuzzy logic was applied to design an interactive control system in order to regulate the behavior of the living space—i.e., how the user inputs were received, interpreted and processed, and the corresponding spatial outputs were generated. Databases and design scales were further developed for each design parameter (see Chapters 5 and 7.7). The input and output variables were defined, and the aesthetic correlations were further expanded to include attributes of color, texture and material as output variables. These were: *hue, chroma, value,* texture *graininess* and *material type.* These correlations are shown in Table 7.4. Based on fuzzy logic, the control system processed the numerical user inputs pertaining to perceived affective spatial qualities by converting them to corresponding linguistic input and output variables, and finally generating numerical outputs. These outputs were then mapped to corresponding color, texture, brightness and material from their respective databases. The fuzzy logic computation procedure is described in Chapter 7 with examples.

8.2 Future Work

Explorations of affective dimensions of space can further include a variety of affective dimensions that are desired in a real-world domestic habitat. These include, but are not limited to: feelings of security, contemplation, spirituality and creativity. Construction of these mood-related ambiences are intended for accommodation of specific functions. To realize such spaces, spatial imageries with symbolic meanings and cultural and temporal meanings of color, light and material should be explored in addition to occupant's subjective preferences in order to provide such imaginative dimensions to perceived space.

Future research also includes introduction of simulated natural light as a key sensory design element, and its various psychophysiological, metaphysical and symbolic dimensions need to be explored. Natural light has significant impact on feelings of spaciousness—a spatial aspect that needs further exploration for tiny, shared living spaces for young professionals. Design with natural light also relates to temporality. Abstract representations of modulated light and shadow, material and color on interior surfaces can reflect external weather conditions, and real-time diurnal and seasonal changes to perceptually situate occupant within the external world (see Figure 7.37).

The proposed design is conceived as a real-world habitable space that transforms without physical or virtual shifting of wall surfaces. The surfaces change only in appearance. However, the materials for constructing such space do not exist yet. As previously discussed in Section 4.3, the future of nanotechnology-driven smart materials offers new possibilities for interactive architecture. Properties of smart materials change under the influence of force, magnetic or electric fields, chemical reactions, light, temperature or humidity. Some materials interact with external stimuli and change in color, pattern or behavior. Thermo-responsive and shape-memory alloys that respond to light or touch have been popularly explored in "responsive" art installations.[217] Extreme performance "smart" materials, although deceptively thin and light-weight, are able to carry heavy load.[218]

Figure 8.1. Abstract representations of weather, diurnal and seasonal changes

Research and development of nanotechnology-driven smart materials may bring new possibilities in the development of interactive spaces. These materials may have unique characteristics with the capacity to modify color, texture, reflection or transparency in response to human interaction.

Future work may involve research on the "adaptive" process of interactive space integrated with "learning." The idea of integration of data and learning has been explored in various visual fields of graphics gaming and clothing design.[219] In this process, architectural space "learns" to solve real-world, complex problems related to decision-making that involves

---

217. Beesley et al., "Toward Responsive Architectures."

218. Yirka, "Boeing Demonstrates Lightest Metal Ever."

219. Mihai Nadin and Pino Trogu, "Arki - Inventing the Future." *YouTube* video, 3:13, 1991. https://www.youtube.com/watch?v=v6PIPdh7Wlk.

mimicking human thinking. Architectural space can "learn" and gather data over time, and through trial and error improve its capacity to make suitable spatial decisions or possibilities for its occupants. For an interactive space that is meaning-driven, learning involves various disciplines related to architectural design methods, sensory perceptual process and cognitive thinking that impact and condition emotion and behavior, and occupant's subjective personal taste, preferences, daily routine, lifestyle and habits. Knowledge from other disciplines, e.g., psychology, neuroscience and nanotechnology, can be integrated as part of the learning process. Over time, interactive space will train itself to articulate spaces tailored to user goals and needs representing occupant's reality—i.e., identity, beliefs, culture, traditions and values.

In recent years, VR's potential in the creative realm has become a subject of attention, bringing forth discussions regarding its capacity as an aesthetic medium in the creative fields of art, storytelling, documentary and other creative visual media. In a conference at the MIT Open Documentary Lab in May 2016, researchers, academicians, technologists and artists discussed the challenges VR faces in finding aesthetic and creative content.[220] While VR can serve as an architectural evaluation tool to test, replicate and evaluate real-world spatial situations, future studies on interactive space can further utilize the real-time space-making capacity of VR as a highly effective aesthetic tool, best suited for interactive perceptual studies.

In this dissertation, space perception was limited to the visual field. Future work may extend into the multisensory dimension of space perception, especially into the auditory domain. Manipulation of sound as an essential part of human ability for perceiving surrounding spatial

220. "Virtually There: Documentary Meets Virtual Reality," a conference presented by MIT Open Documentary Lab, Cambridge, MA, May 6-7, 2016. http://opendoclab.mit.edu/virtuallythere/.

volumes and its impact on psychophysiological, aesthetic and metaphysical spatial dimensions can also be further explored as a design concept for neo-nomadic living spaces.

APPENDIX A

AN ONLINE SURVEY

An online survey was conducted using the UTDallas qualtrics method. A public survey link was posted and distributed through social media (Facebook and LinkedIn) to distribute among friends, colleagues and acquaintances in the United States. Survey remained active for approximately 4 months. Total recorded respondents: 85.

The criteria for selection of target participants were listed on the introductory page of the survey, as shown in Figure A-1.

Thank you for taking the time to participate in this questionnaire!

This online survey is for:

- **Students, Professionals, Researchers and/or Entrepreneurs**
- **18 years or over**
- **People who own (or are accustomed to using) one or more of the various mobile technologies and portable computing devices - such as, Smartphone, Laptop, Notebook, Tablet, iPad, eBook, PDA, Blackberry etc.**

This questionnaire is part of a PhD dissertation research on Interactive Architecture to gain insight into the influence of mobile technology on daily domestic living situations of modern day students and professionals. The study will assist researcher's decision making in the architectural design process. The questionnaire collects information on demography, participant's technology dependence, residential and domestic space usage, as well as living space preferences.

This survey is completely anonymous.

All data obtained from participants will be kept confidential and will be reported only in an aggregate (collective) format in researcher's final dissertation. The data collected will be stored in Qualtrics-secure database until it has been deleted by researcher.

This survey should take no more than 20 minutes to complete.

Please feel free to invite your colleagues to participate!

Figure A-1. Survey Introduction

The following figures illustrate participant responses to all survey questions in graphical form:

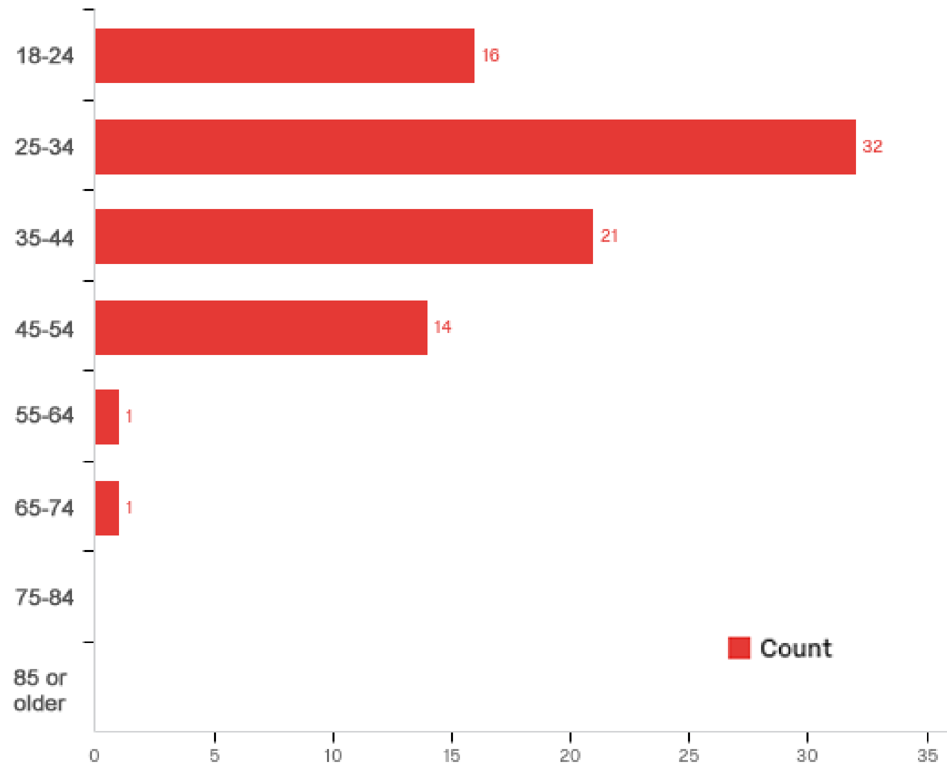


Figure A-2. Age of respondents

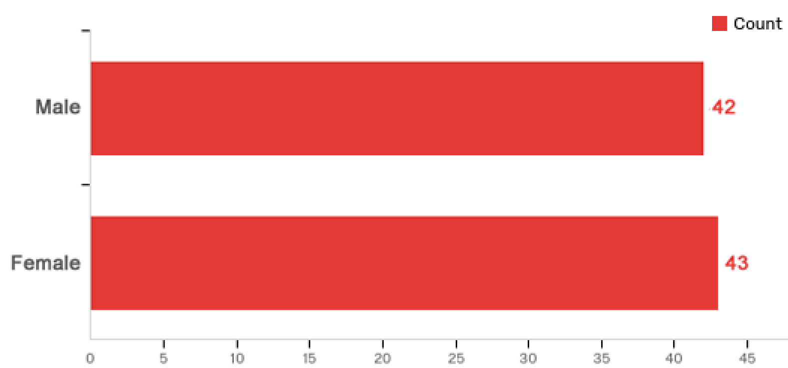


Figure A-3. Gender of respondents

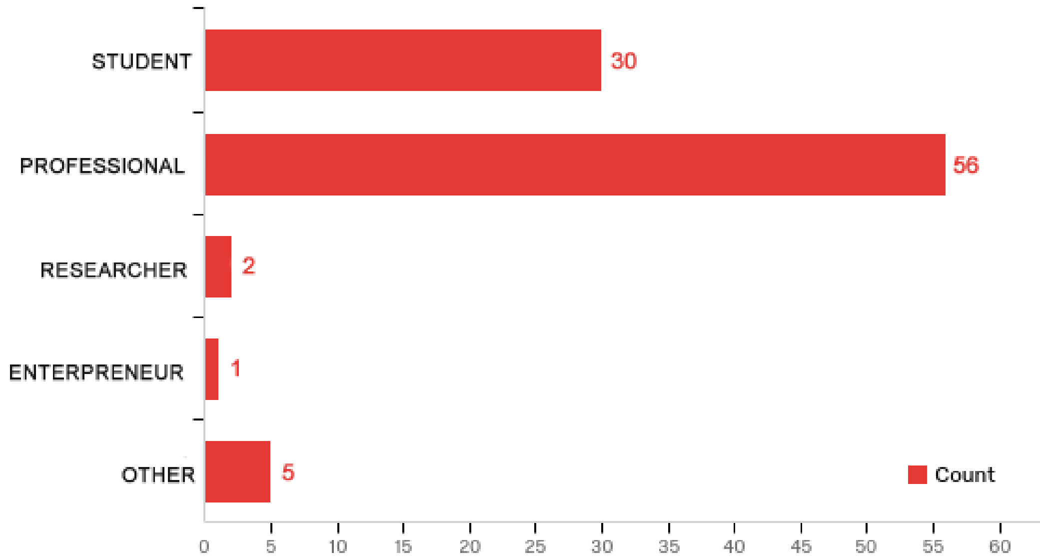


Figure A-4. Occupation of respondents

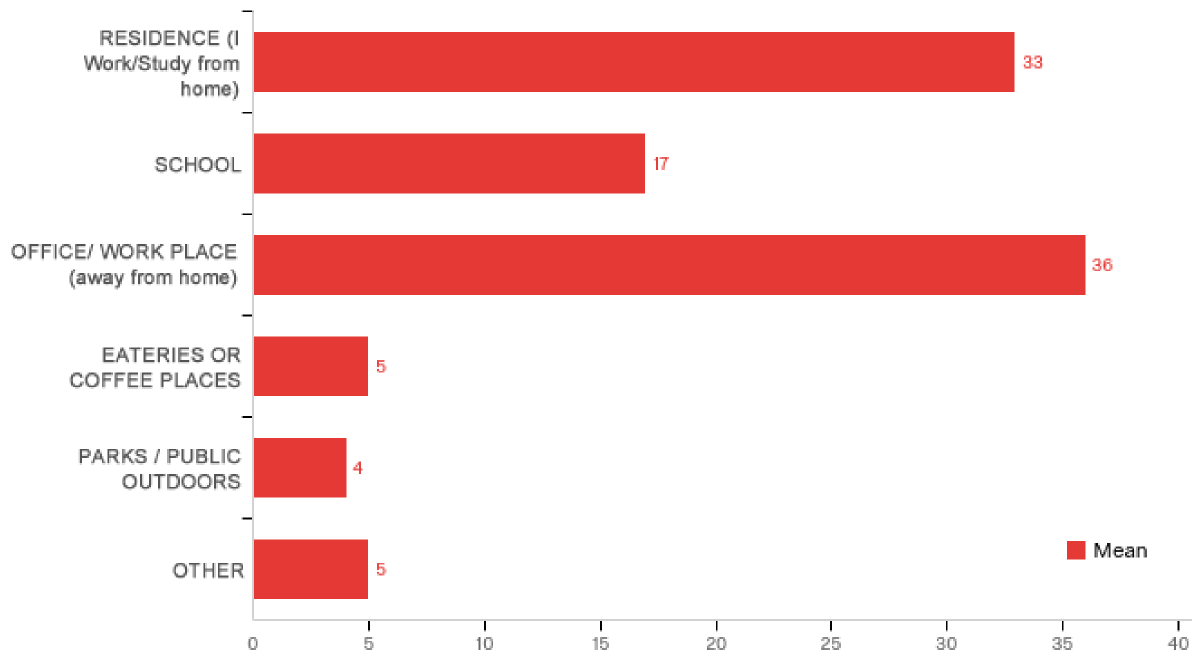


Figure A-5. For job-related activities, average time spent at locations every month (%)

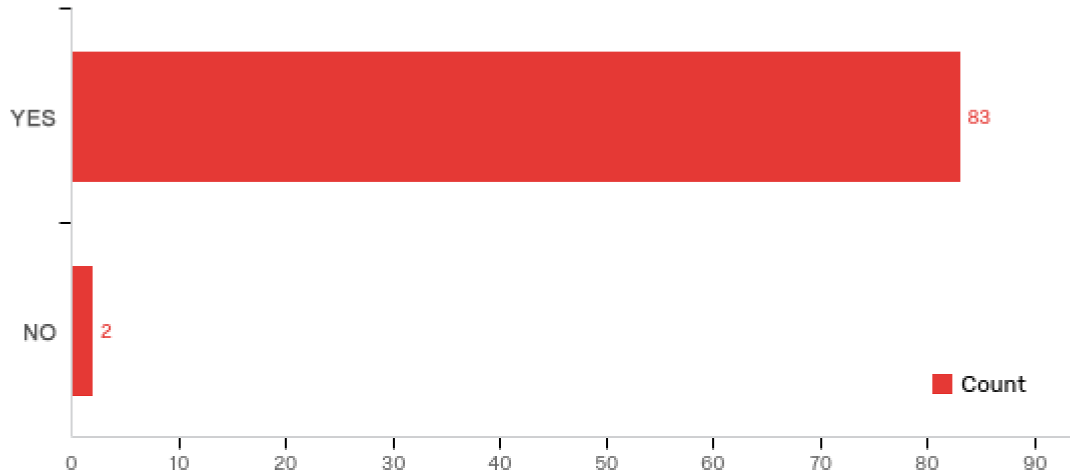


Figure A-6. Do you own or use a Smartphone

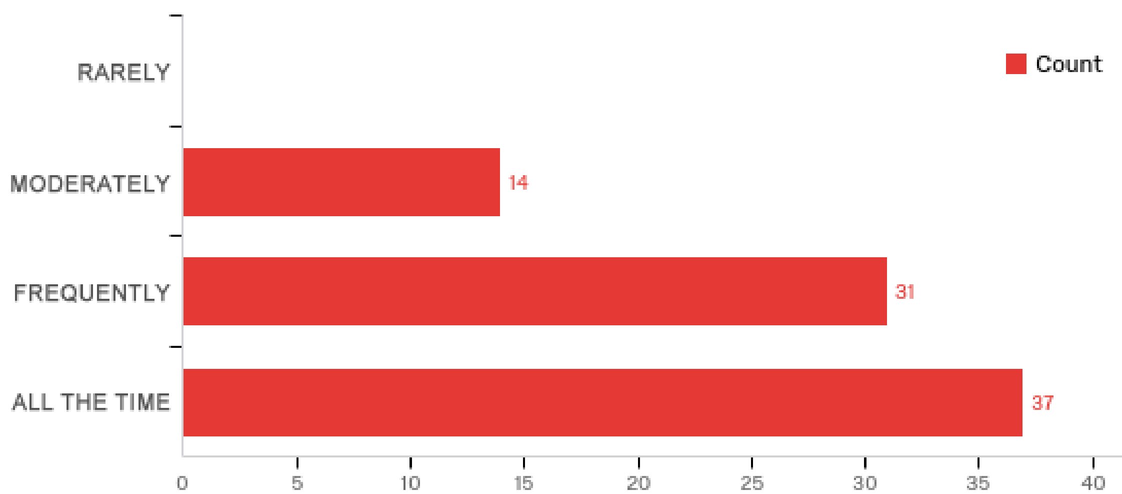


Figure A-7. Frequency of Smartphone usage

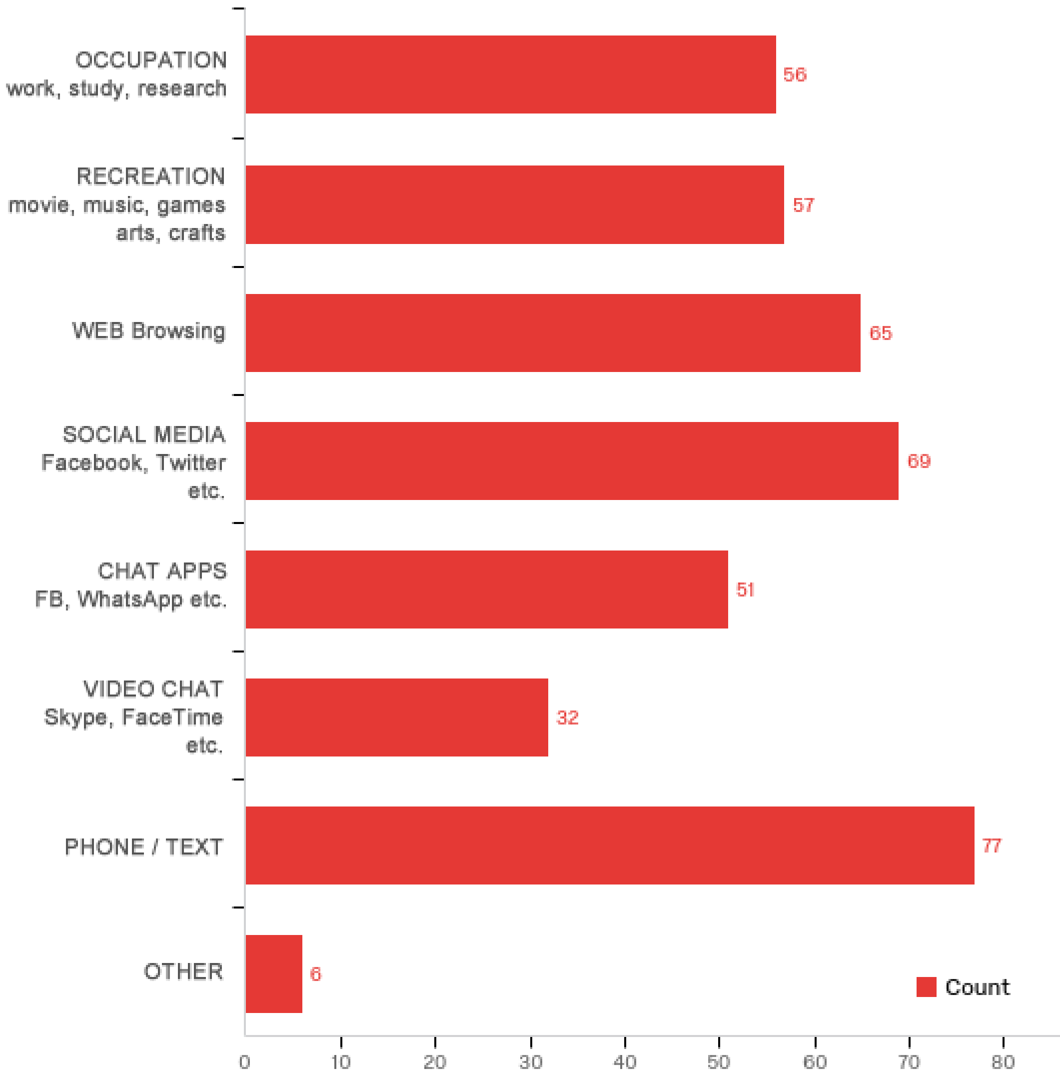


Figure A-8. Preferred types of activity on Smartphone

"Other" activities specified by respondents are as follows:
1. Photography and Graphic Design (Sort of)
2. Organizing, investing, shopping, services,
3. GoPro, OneWheel remote controls
4. Utility Apps (Tools, Health, Banking, House controls, etc)
5. Email

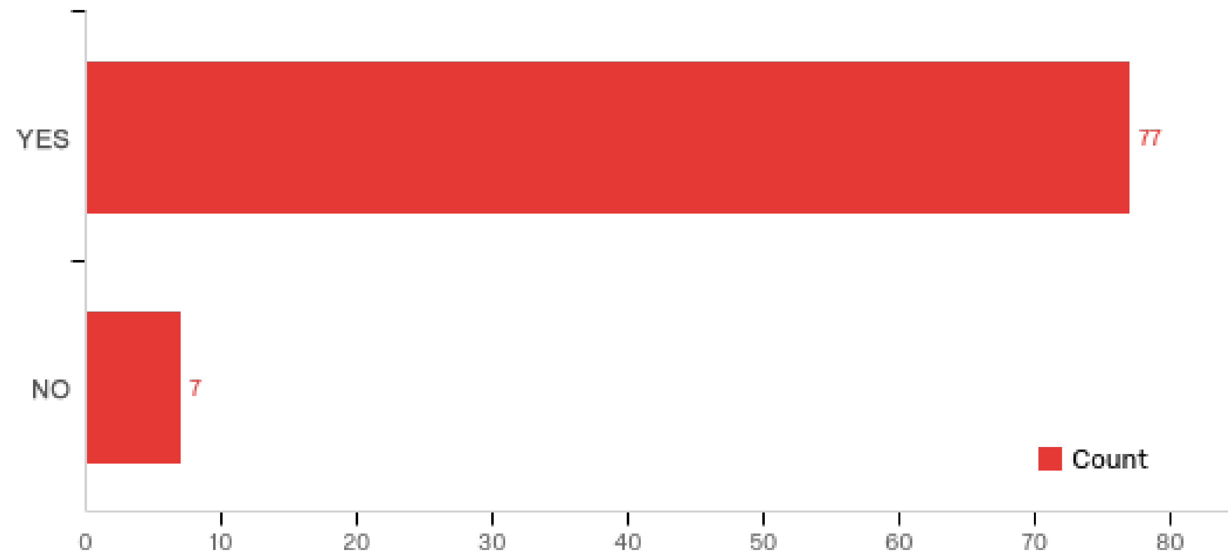


Figure A-9. Own portable computing device(s): Laptop, tablet, eBook reader, PDA, etc.

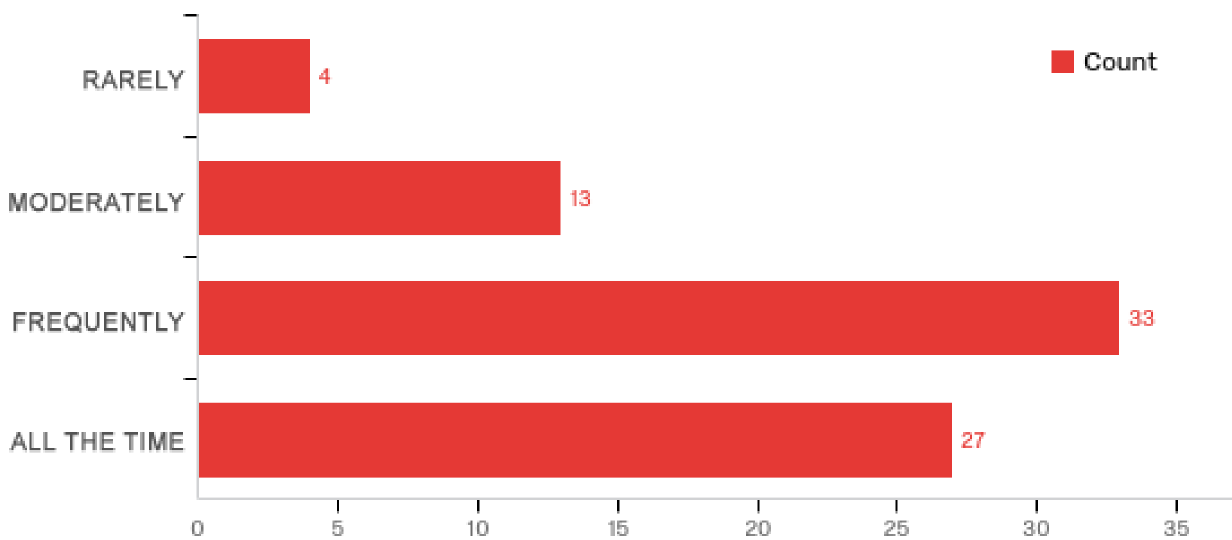


Figure A-10. Frequency of handheld or portable computing device usage

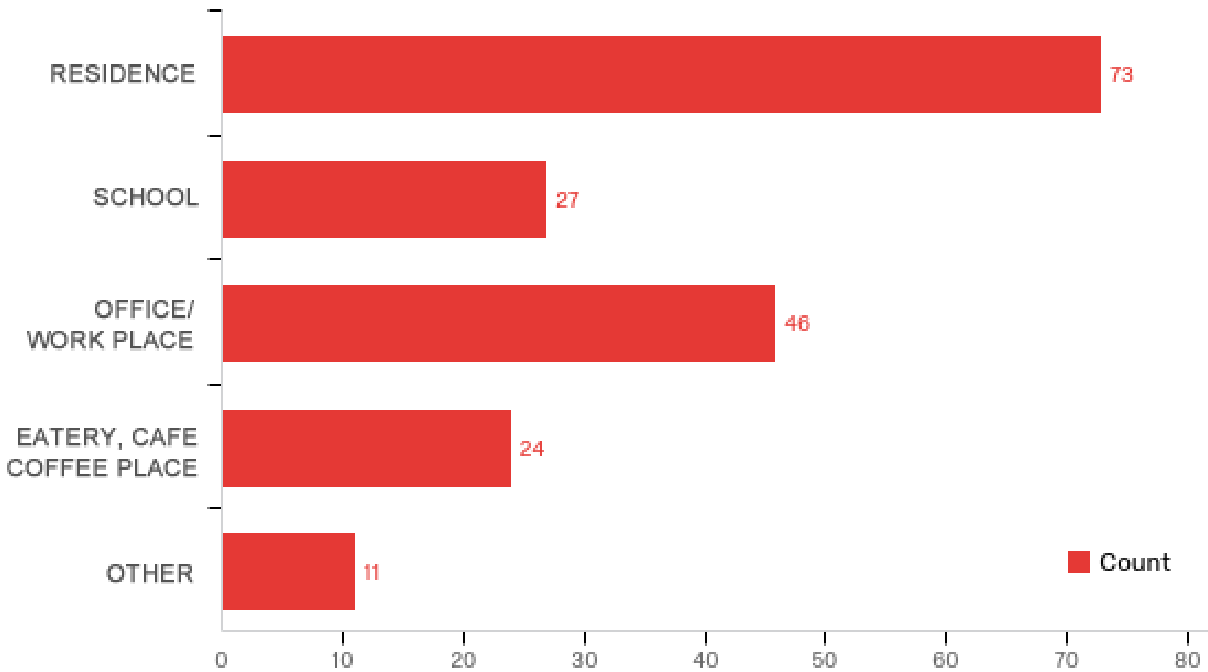


Figure A-11. Locations where handheld or portable computing devices are generally used

"Other" Locations specified by respondents are as follows:

1. Public Transportation
2. Travel
3. In traffic
4. Outdoor parks
5. Hotels when traveling
6. Car
7. Student center
8. Workshops, training, conferences
9. Meetings
10. Site
11. On Bus

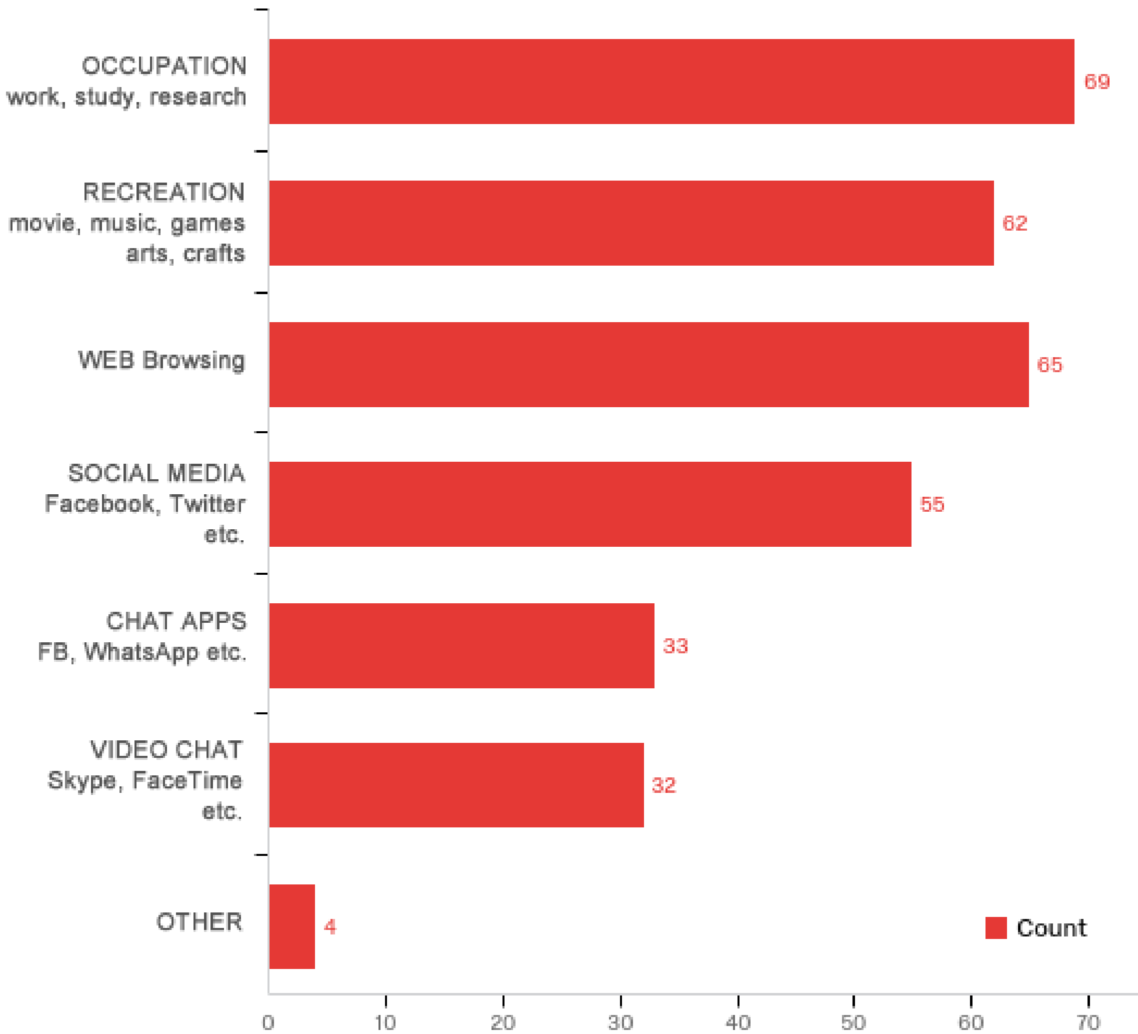


Figure A-12. Preferred types of activity for handheld or portable computing devices

"Other" activities specified by respondents are as follows:
1. Online shopping and banking
2. GPS
3. Email
4. Photo Editing

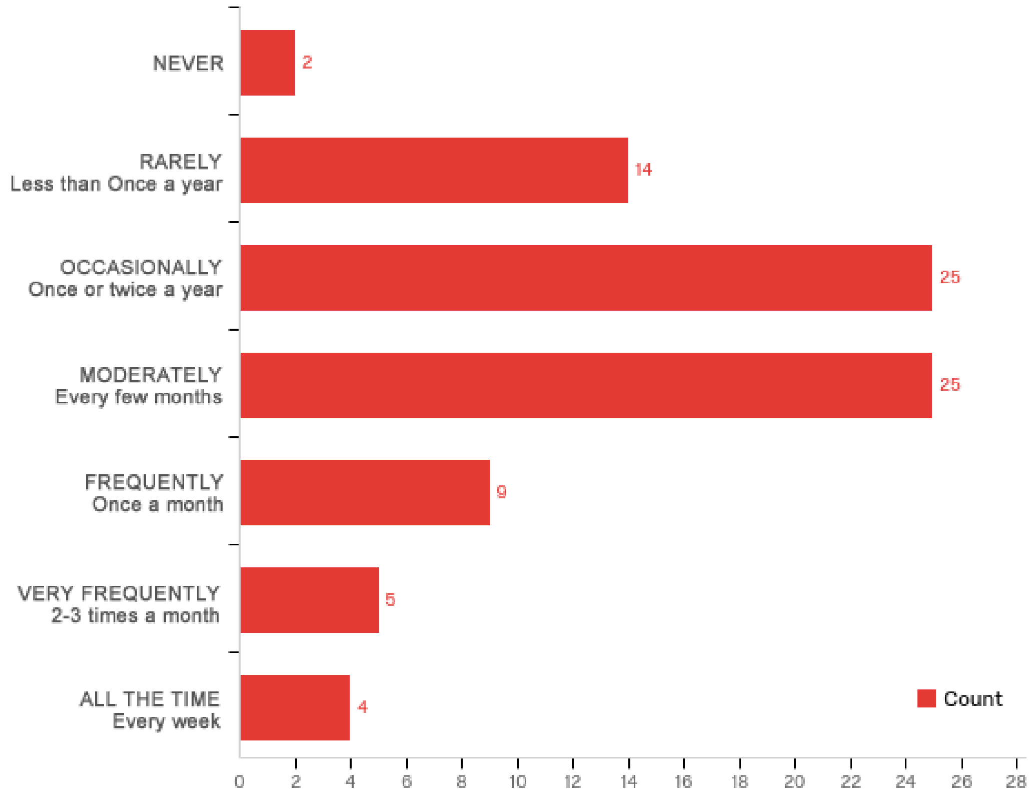


Figure A-13. Frequency of traveling outside city of residence, on average

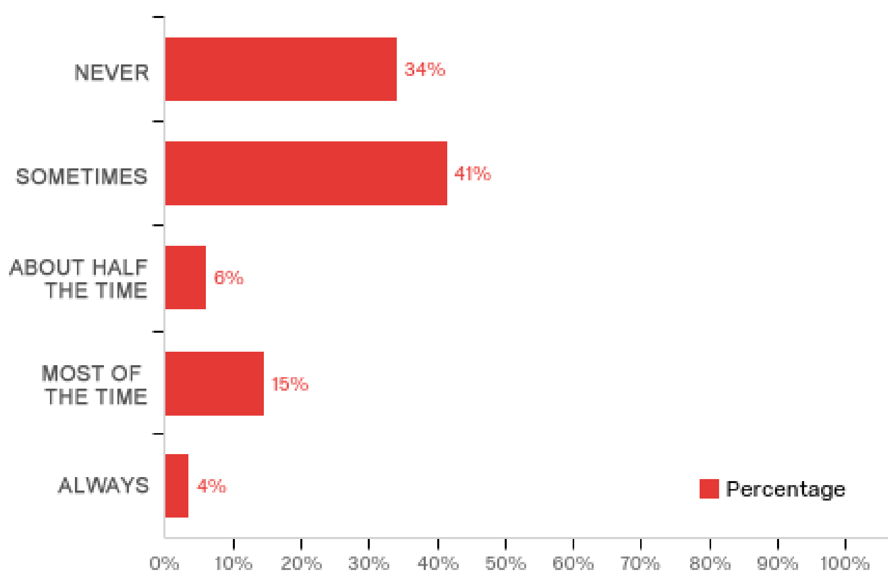


Figure A-14. Average % of travel that is occupation-related (work, research or studies)

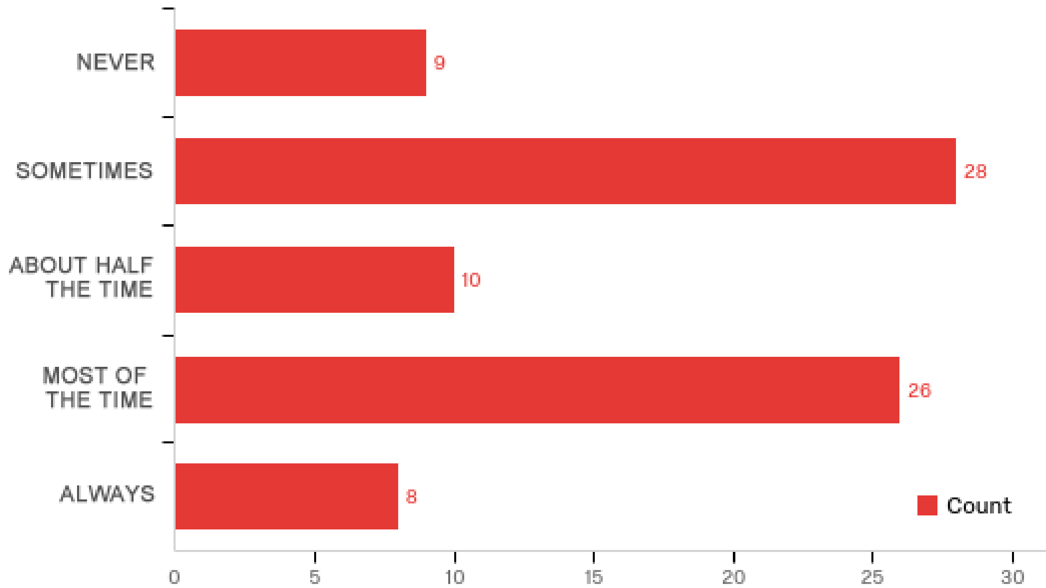


Figure A-15. Perform occupational responsibilities while traveling, using mobile technology

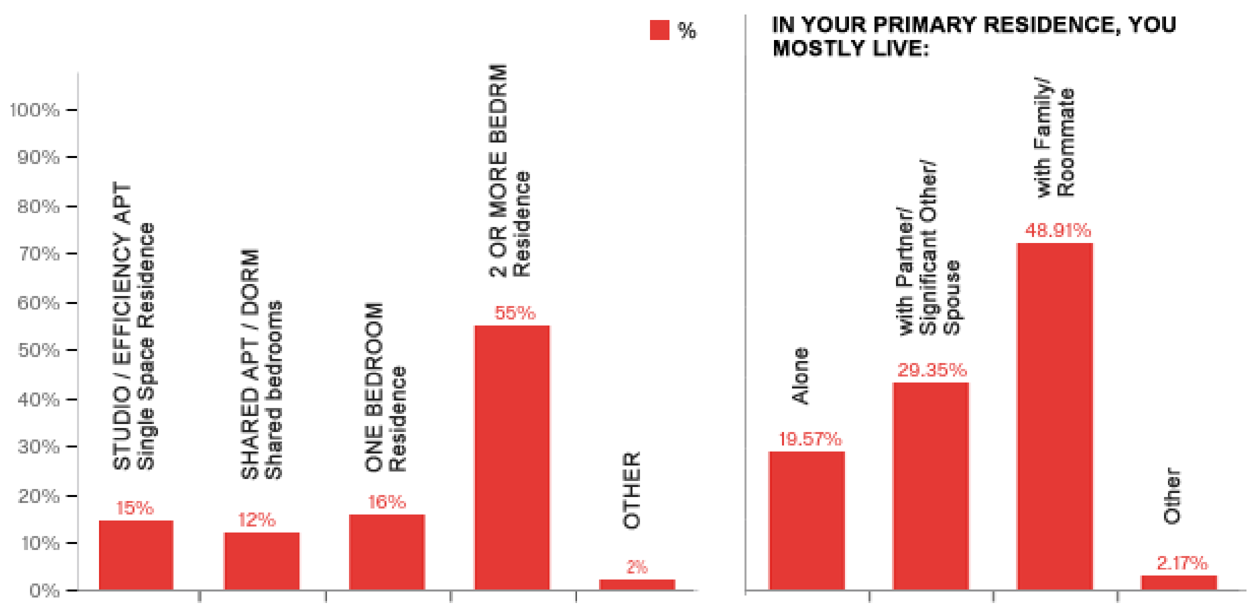


Figure A-16. Best description of primary living situation

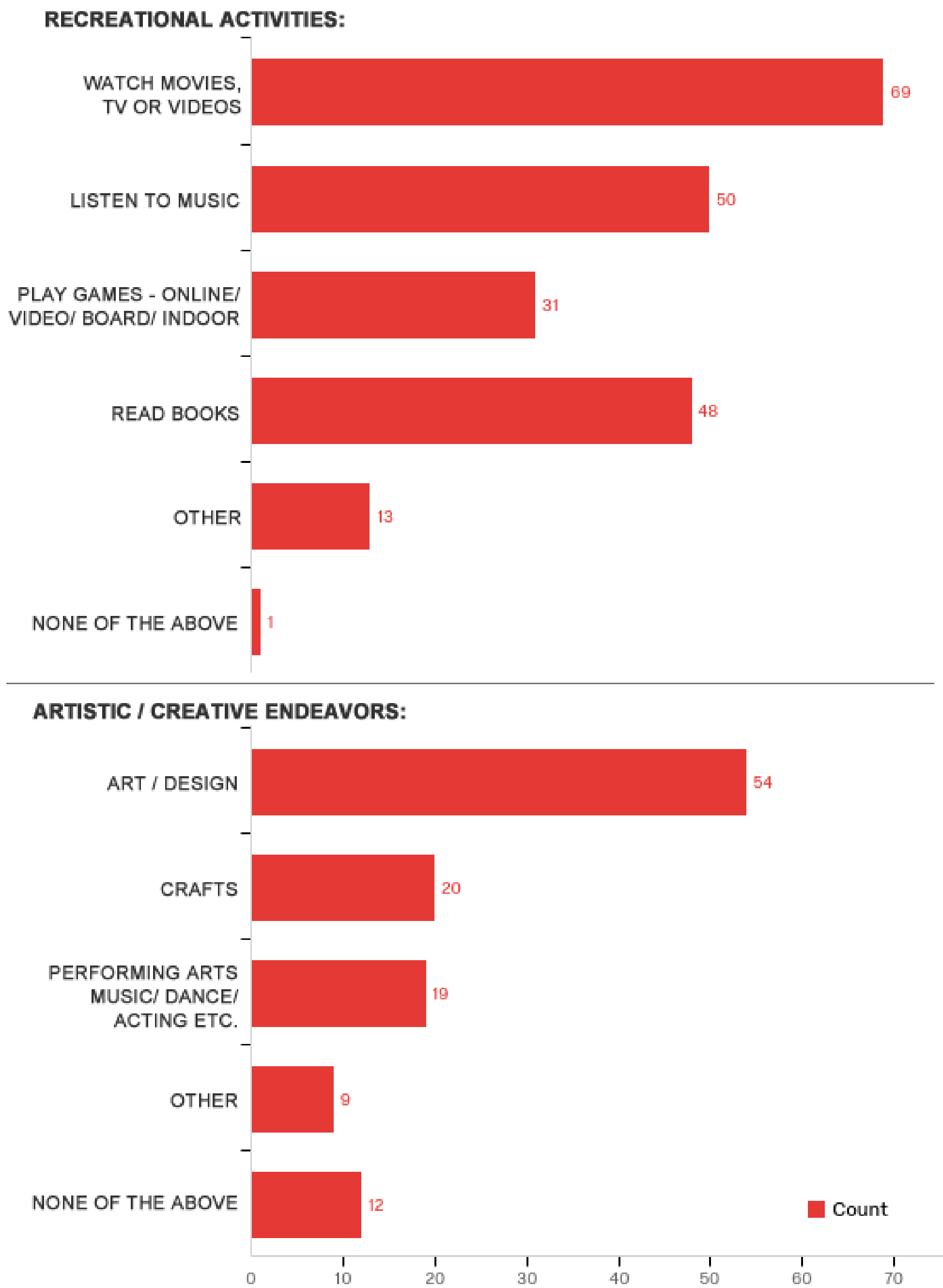


Figure A-17. Activities enjoyed in spare time

For the *Recreational Activities* category, the "other" activities specified by respondents:

1. Design and Drawing
2. Walking
3. Reading from web, cooking
4. Yoga, bouldering, culinary arts
5. Sports, outdoor activities
6. Frisbee
7. Outdoor activities - cycling, hiking etc
8. Crochet, cook, draw, write
9. Fishing, gardening
10. OUTDOORS! Beach or park w/ Dogs
11. Heavenly sleep
12. Hike, bike, ski, paddle boarding
13. looking at work of other photographers

For *Artistic/Creative Endeavors*, the "other" activities specified by respondents:

1. Parametric Architecture
2. Programming
3. Cooking
4. Watercolor
5. Woodworking
6. DIY Home Improvement, Gardening / Landscape
7. Photography
8. Painting
9. Photography

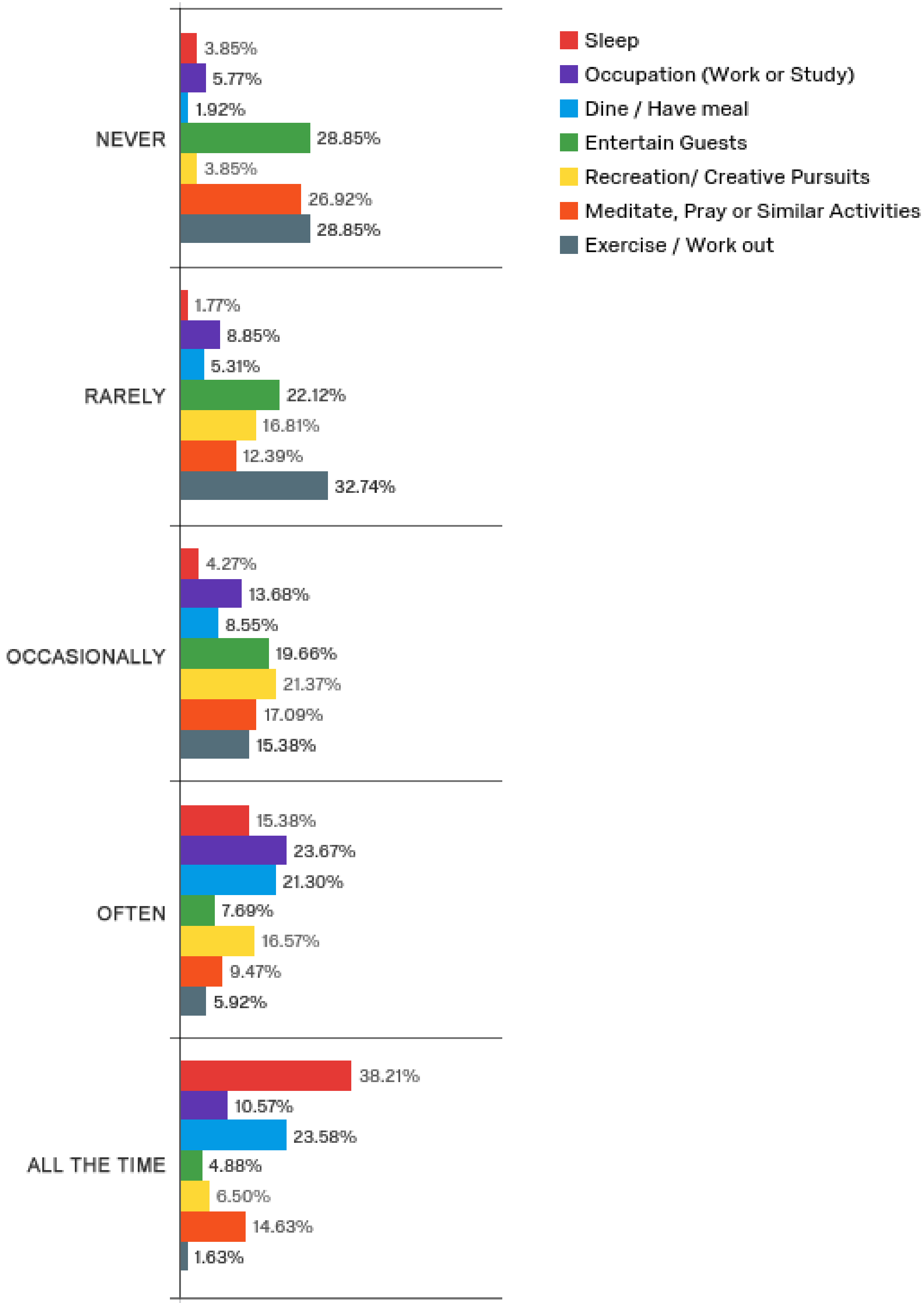


Figure A-18. Frequency of performing specific activities in primary living space/room

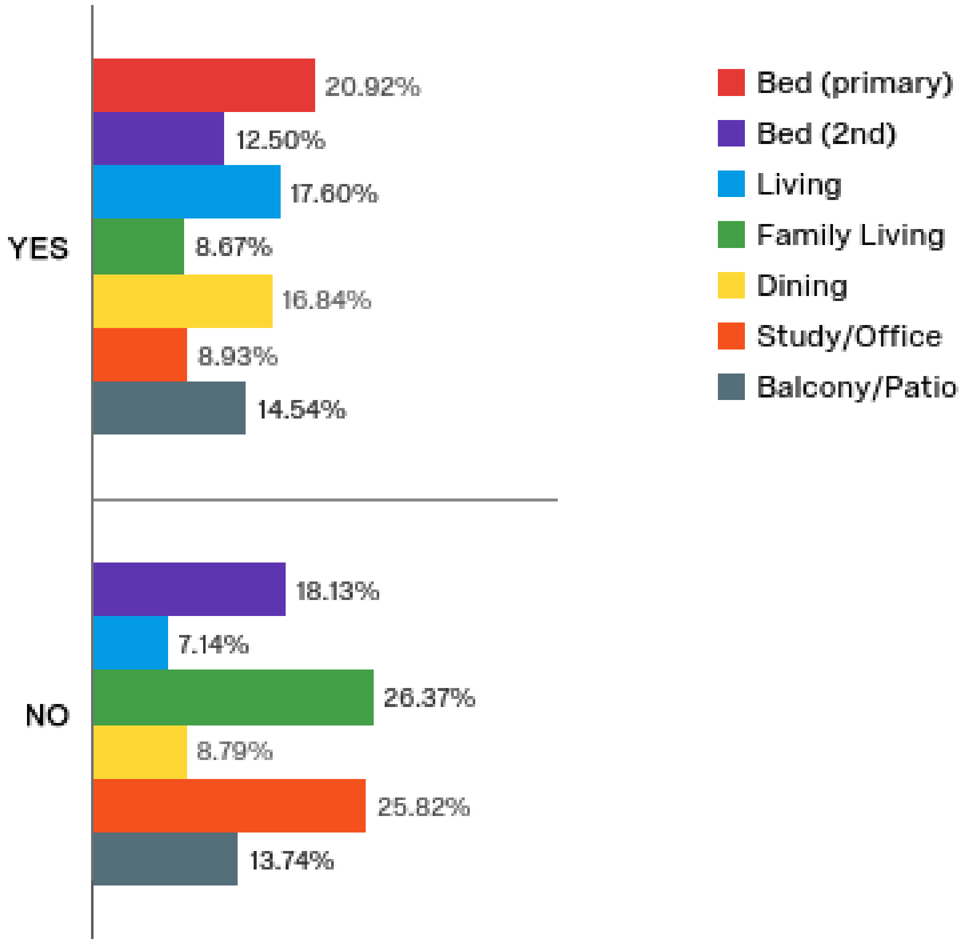


Figure A-19. Do you have these rooms or designated spaces in your residence?

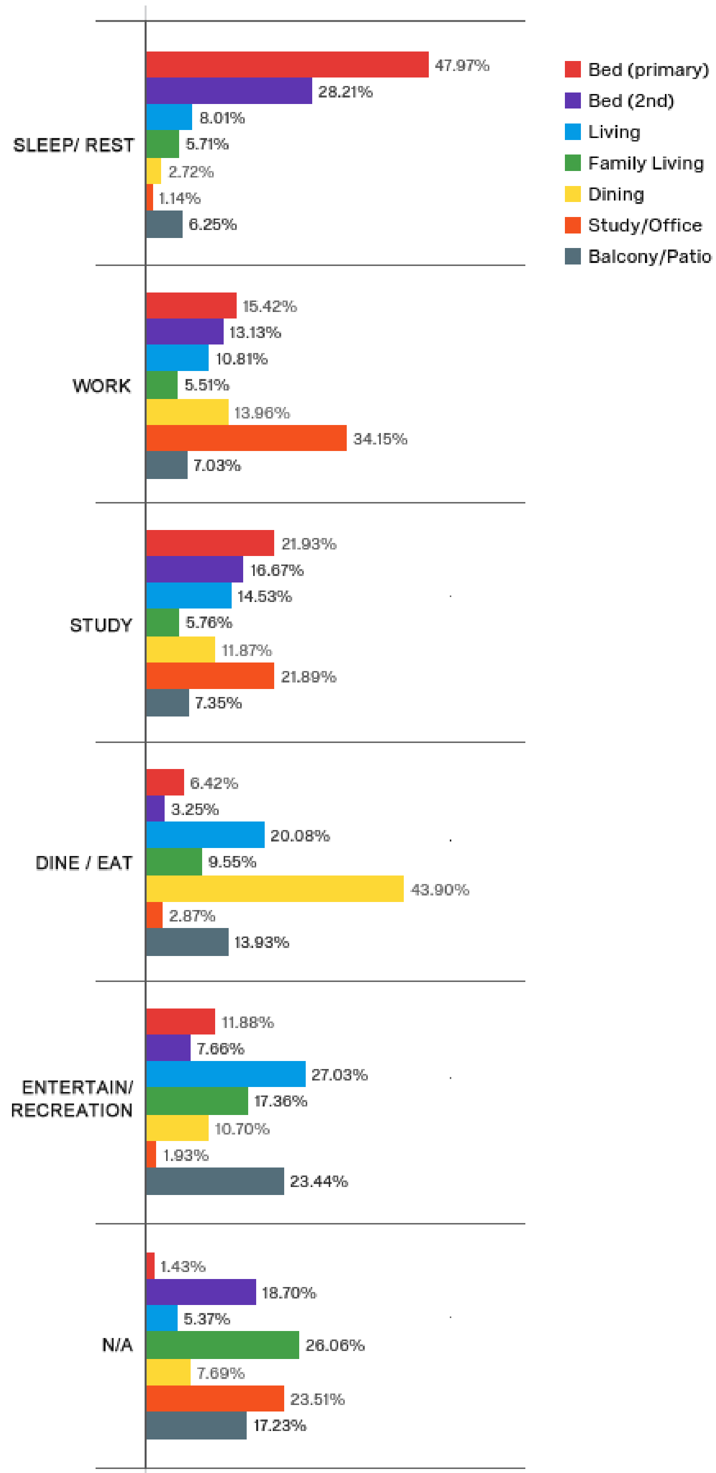


Figure A-20. Activities typically conducted in the listed rooms

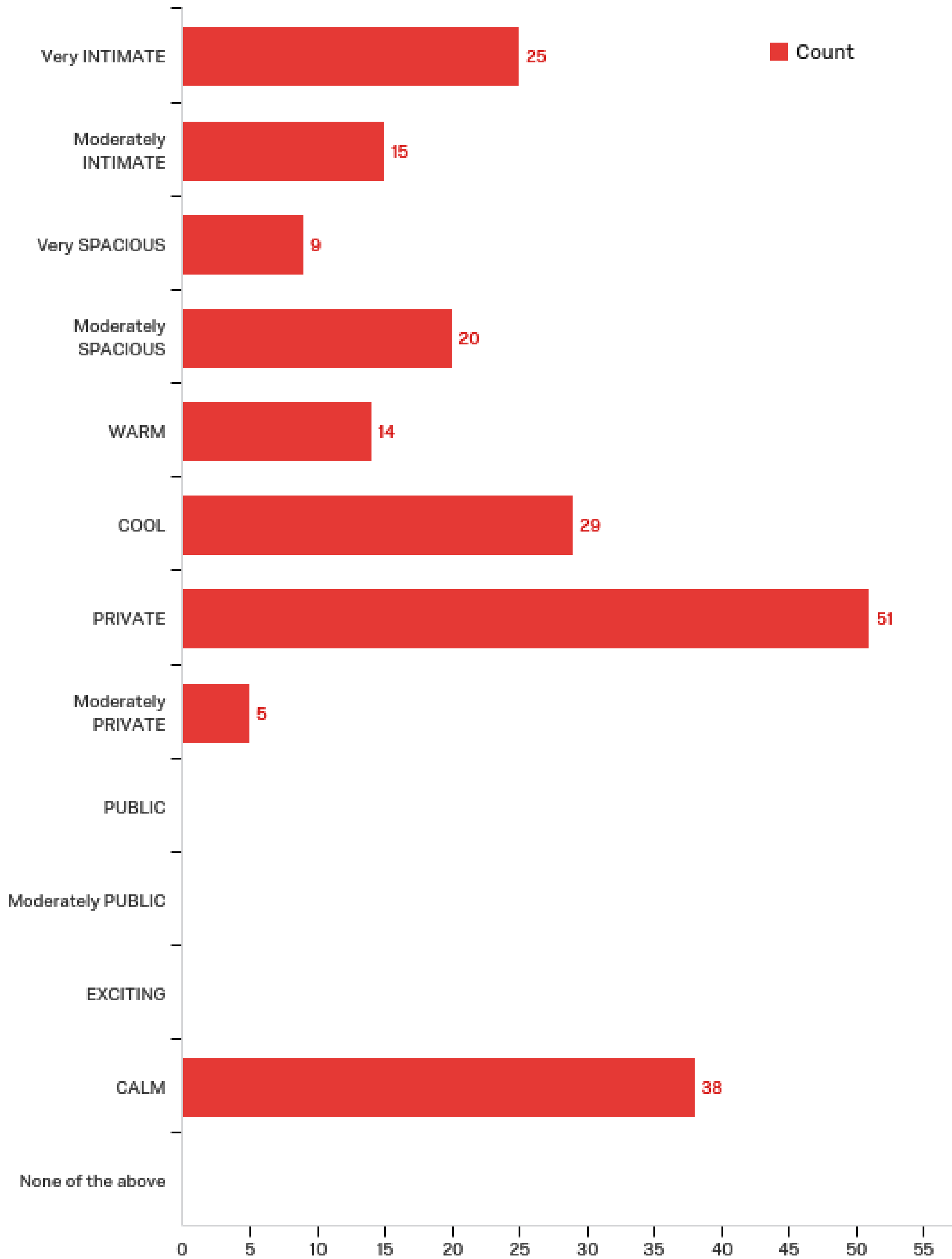


Figure A-21. Preferable environments for sleeping

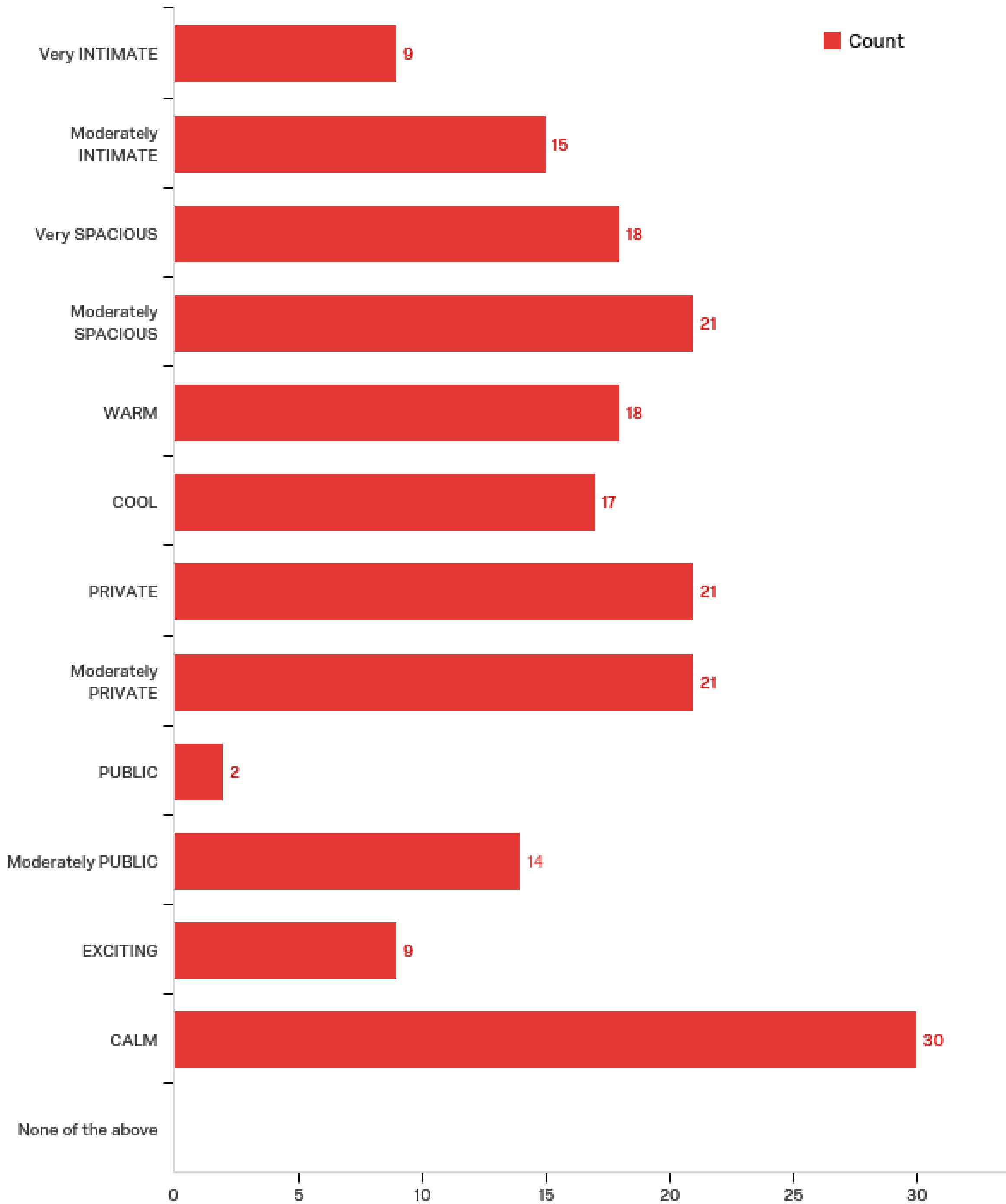


Figure A-22. Preferable environments for work or studies

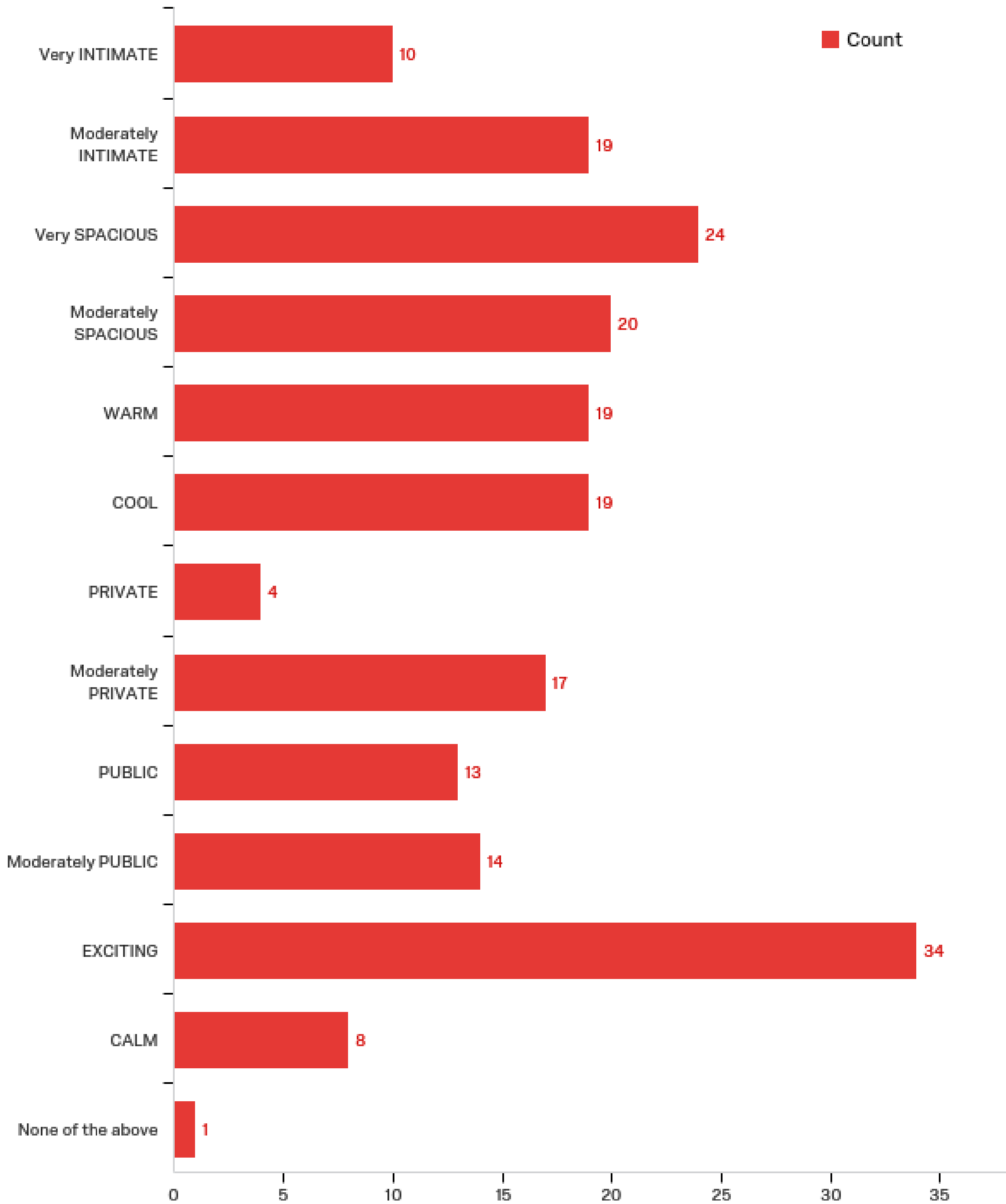


Figure A-23. Preferable environments for recreation or entertainment

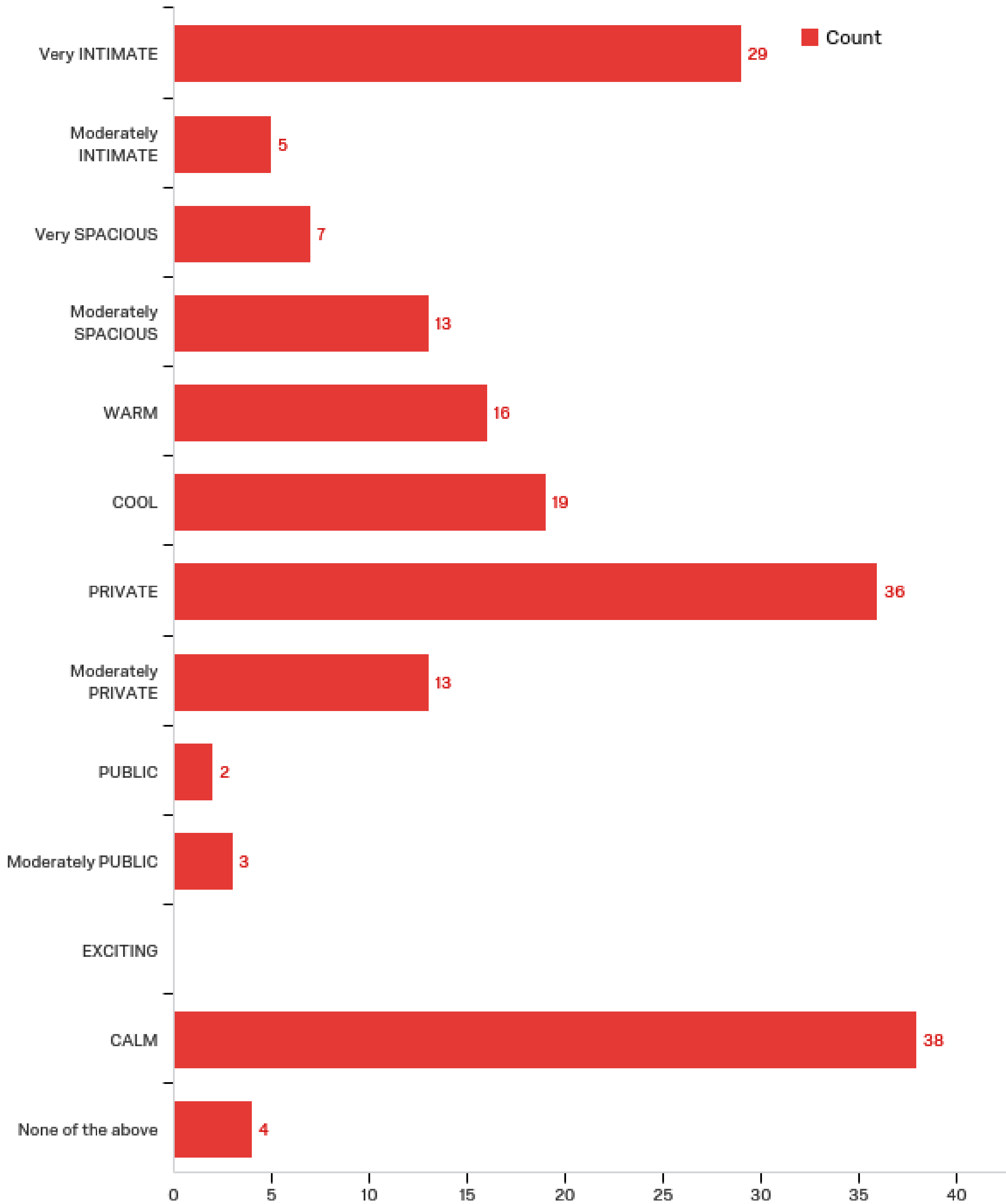


Figure A-24. Preferable environments for contemplation, meditation, prayer or similar activities

APPENDIX B

USER STUDY PARTICIPANTS: DEMOGRAPHIC INFORMATION

Table B.1. Demographic Data of Participants

	Total	Percentage (%)
Gender:		
Female	15	47
Male	17	53
Occupation:		
Student	27	84
Professionals	5	16
UnderGrad	5	16
Graduate	13	40
Doctoral	14	44
Native Language:		
Chinese	3	9
French	3	9
English	15	47
Turkish	1	3
Hindi	3	9
Spanish	5	16
Russian	1	3
Nepali	1	3
Race:		
Caucasian	18	56
East Asian	3	9
South Asian	5	16
Hispanic of any race	4	13
African American	1	3
2 or more races	1	3

Table B.1. Demographic Data of Participants (contd.)

	Total	**Percentage (%)**
Will you be wearing glasses or contacts during the study?		
Glasses	14	44
Contacts	6	19
None	12	37
Do you play video games? (e.g. computer, console, arcade, tablet, smart phone)		
Never	6	19
Rarely	13	40
Sometimes	8	25
Frequently	5	16
Have you ever experienced an Immersive Virtual Reality System?		
Never	18	56
Once or twice	10	31
Quite a few times	4	13

APPENDIX C

QUESTIONNAIRE: QUANTITATIVE STUDY

On a scale of 1-10:

1. How spacious is this space?
2. How exciting is this space?
3. How warm is this space?
4. How calm is this space?
5. How intimate is this space?
6. How cool is this space?
7. How comfortable is this space?

On a scale of 1-10:

8. How would you rate this space for working?
9. How would you rate this space for resting?

On a scale of 1-10, what is your overall satisfaction with this space?

APPENDIX D

QUESTIONNAIRE: QUALITATIVE STUDY

"Take a minute and think how you would want to change the appearance of this space—its size, color, material, texture, brightness, scale, lighting or any other visual features to make it an ideal space for you to live in.

Remember how you can give voice commands to Google or iPhone's Siri to have it search for things and places for you? Imagine that you can give voice commands to this space the same way and it will listen and change accordingly. Tell this space what changes you would want it to make. How would you change this space to make it ideal for you to live in?"

BIBLIOGRAPHY

Abbas, Yasmine. “Neo-nomads: Designing Environments for Living in the Age of Mental, Physical and Digital Mobilities.” PhD diss., Harvard University, Cambridge, MA, 2006.

———. "Neo-Nomads and the Nature of the Spaces of Flows." In *UbiComp in the Urban Frontier* Conference proceedings, Nottingham, England, September 2004.

Alavi, Hamed S., et al. “Interaction and Architecture**:** Deconstructing Human-Building Interaction.” *Interactions* 23, no. 6 (November-December 2016): 60-62.

Albers, Josef. *Interaction of Color.* New Haven, Conn.: Yale University, 2006.

Alter, Adam. *Drunk Tank Pink*. New York: The Penguin Press, 2012.

Appleton, Jay. *The Experience of Landscape.* London: Wiley, 1975.

Agoston, George A. *Color Theory and Its Application in Art and Design.* New York: Springer-Verlag, 1986.

Bachelard, Gaston. *The Poetics of Space.* Boston: Beacon Press, 1994.

Beesley, Philip, Sachiko Hirosue, and Jim Ruxton. “Toward Responsive Architectures.” In *Responsive Architectures: Subtle Technologies*, edited by Philip Beesley et al., 3-11. Toronto: Riverside Architectural Press, 2006.

Bailey, Reynold J., Cindy M. Grimm, and Chris Davoli. “The Real Effect of Warm-Cool Colors.” *Technology Report WUCSE-2006-17*, 2006. http://openscholarship.wustl.edu/cse_research/166

Barr, Alfred H., Jr. “De Stijl.” *The Bulletin of the Museum of Modern Art* 20, no. 2 (2012): 6-13.

Bowles, Nellie. “The Real Teens of Silicon Valley: Inside the Almost-Adult Lives of the Industry’s Newest Recruits.” *The California Sunday Magazine.* https://stories.californiasunday.com/2015-06-07/real-teenagers-silicon-valley (accessed May 2015).

Brave, Scott, and Clifford Nass. “Emotion in Human-Computer Interaction.” In *The Human Computer Interaction,* edited by Andrew Sears and Julie A. Jacko, 54-65. Boca Raton: Taylor & Francis, 2009.

Brandle, Kurt. *Architecture and Meaning*. Michigan: Brandle Publishing, 2012. iPad edition.

Bullivant, Lucy. “Alice in Technoland.” *Architectural Design* 77, no. 4 (2007): 6-13.

———. “BIX Matrix Realities: United Kunsthaus Graz Austria.” *Architectural Design* 75, no. 1 (January-February 2005): 82-85.

Casey, Timothy K. "Architecture." in *Handbook of Phenomenological Aesthetics*, edited by Hans Rainer Sepp and Lester Embree, 25-28. Dordrecht: Springer, 2010.

Ching, Francis D.K. *Architecture: Form, Space, and Order*. Hoboken: Wiley, 2007.

Ciftcioglu, Özer. “Design Enhancement by Fuzzy Logic in Architecture.” In proceedings of *the 12th IEEE International Conference on Fuzzy Systems (Vol. II),* St. Louis, Missouri, May 25-28, 2003. doi: 10.1109/FUZZ.2003.1209341.

Ciftcioglu, Özer, and Sanja Durmisevic. “Fuzzy Logic in Architectural Design.” In proceedings of *EUSFLAT 2001: the International Conference in Fuzzy Logic and Technology*, De Monfort University, Leicester, UK, September 5-7, 2001. 265-268.

Collet, Carole. "The Next Textile Revolution." In *Responsive Textile Environment*, edited by Sarah Bonnemaison and Christine Macy, 14-25. Halifax: Tuns Press, 2007.

D’Andrea, Anthony. “Neo-Nomadism: A Theory of Post-Identitarian Mobility in the Global Age.” *Mobilities* 1, no. 1 (March 2006): 95-119.

Drettakis, George, et al. “Design and Evaluation of a Real-World Virtual Environment for Architecture and Urban Planning.” *Presence: Teleoperators and Virtual Environments* 16, no. 3 (June 2007): 318-332.

Droog, Simon, and Paul de Vries. “Emotion in Architecture: The Experience of the User." *issuu.com*, October 24, 2009. https://issuu.com/pauldevries/docs/20090202_emotioninarchitecture_big

Dudley, Sandra. "Materiality Matters: Experiencing the Displayed Object." *University of Michigan Working Papers in Museum Studies* 8 (2012): 1-9.

Eysenck, Michael W., and Mark T. Keane. *Cognitive Psychology: A Student’s Handbook*. New York: Psychology Press, 2015.

Fröst, Peter, and Peter Warren. “Virtual Reality Used in a Collaborative Architectural Design Process.” In *2000 IEEE Conference on Information Visualization. An International Conference on Computer Visualization and Graphics*, July 2000. London:568-573. doi: 10.1109/IV.2000.859814.

Fost, Dan. “Where Neo-Nomads’ Ideas Percolate.” *SFGate*, March 11, 2007. http://www.sfgate.com/news/article/where-neo-nomads-ideas-percolate-new-2610920.php.

Frearson, Amy. “Architecture Is Not about Form: Peter Zumthor.” *dezeen*, February 6, 2013. https://www.dezeen.com/2013/02/06/peter-zumthor-at-the-royal-gold-medal-lecture-2013/

Frampton, Kenneth. *Modern Architecture: A Critical Theory*. London: Thames and Hudson, 1992.

Franz, Gerald. “Space, Color, and Perceived Qualities of Indoor Environments.” In *Environment, Health and Sustainable Development (IAPS 19 Conference Proceedings),* 2006. Alexandria, Egypt: IAPS.

———. “An Empirical Approach to the Experience of Architectural Space.” PhD diss., Max Planck Institute for Biological Cybernetics, Tübingen and the Bauhaus University, Weimar, 2005.

Franz, Gerald, Markus von der Heyde, and Heinrich H. Bülthoff. “An Empirical Approach to the Experience of Architectural Space in Virtual Reality—Exploring Relations Between Features and Affective Appraisals of Rectangular Indoor Spaces.” *Automation in Construction* 14 (2005): 165-172.

———. “Predicting Experiential Qualities of Architecture by its Spatial Properties.” In *Designing Social Innovation: Planning, Building, Evaluating* (Cambridge, MA: Hogrefe, 2005), 157-166.

Fleischmann, Monika, and Wolfgang Strauss. “Interactivity as Media Reflection between Art and Science.” In *The Art and Science of Interface and Interaction Design*, edited by Christa Sommerer et al., 75-92. Verlag Berlin Heidelberg: Springer, 2008.

Fox, Michael, and Miles Kemp. *Interactive Architecture*. New York: Princeton Architectural Press, 2009. *ebrary*.

Garcia, Mark. "Otherwise Engaged: New Projects in Interactive Design." *Architectural Design* 77, no. 4 (2007): 44-53.

Gibson, James J. *The Ecological Approach to Visual Perception*. New York: Psychology Press, 2015.

———. "What Gives Rise to the Perception of Motion?" *Psychological Review* 75, no. 4 (1968): 335-346.

Gmachl, Mathias, and Rachel Wingfield. "Auspicious Tangents." In *Responsive Textile Environment*, edited by Sarah Bonnemaison and Christine Macy, 26-35. Halifax: Tuns Press, 2007.

Haque, Usman. “Distinguishing Concepts: Lexicons of Interactive Art and Architecture.” *Architectural Design* 77, no. 4 (2007): 24-31.

———. “The Architectural Relevance of Gordon Pask.” *Architectural Design* 77, no. 4 (2007): 54-61.

Hårleman, Maud. “Daylight Influence on Colour Design: Empirical Study on Perceived Colour and Colour Experience Indoors.” PhD diss., Royal Institute of Technology, Sweden, 2007.

Hart, Anna. “Living and Working in Paradise: The Rise of the Digital Nomad.” *The Telegraph*, last modified May 17, 2015, http://www.telegraph.co.uk/news/features/11597145/Living-and-working-in-paradise-the-rise-of-the-digital-nomad.html.

Hansmann, Della. “Pioneering Modernist: Luis Barragan.” *Moss*, March 8, 2016. http://moss-design.com/barragan/

de Heer, Jan. *The Architectonic Colour: Polychromy in the Purist Architecture of Le Corbusier.* Rotterdam: 010 Publishers, 2009.

Henry, Daniel, and Tom Furness. "Spatial Perception in Virtual Environments: Evaluating an Architectural Application." In *Proceedings of IEEE Virtual Reality Annual International Symposium*, September 1993. Seattle, WA: IEEE: 33-40. doi: 10.1109/VRAIS.1993.380801

Hepler, Lauren. “The Shadow of Success: Inside Silicon Valley’s Affordable Housing Crisis.” *Silicon Valley Business Journal*, last modified January 31, 2014, http://svbj.tumblr.com/post/75132767372/the-shadow-of-success-inside-silicon-valleys.

Hershberger, Robert G. “Architecture and Meaning.” *The Journal of Aesthetic Education* 4, no. 4 (October 1970): 37.

Hershberger, Robert. G., and Robert. C. Cass. “Predicting User Responses to Buildings.” In *Environmental Aesthetics: Theory, Research, and Applications*, edited by Jack L. Nasar, 195–211. Cambridge: Cambridge University Press, 1988.

Hockenbury, Don H., and Sandra E. Hockenbury. *Discovering Psychology.* New York: Worth Publishers, 2007.

Holl, Steven, Juhani Pallasmaa, and Alberto Pérez-Gómez. *Questions of Perception: Phenomenology of Architecture*. San Francisco, CA: William Stout, 2006.

Horstmann, Katharina. *Ferdinand Kramer: Original Designs According to Functional Principles*. Translated by Jonathan Uhlaner (Goethe-Institut e. V., October 2014), https://www. goethe.de/en/kul/des/20436267.html

"How Color Notations Work." *Munsell Color*. Accessed January 30, 2016. http://munsell.com/about-munsell-color/how-color-notation-works/

Hildebrand, Grant. *Origins of Architectural Pleasure*. Berkeley: University of California Press, 1999.

"Interactive Façade," *foxlin.com*. January 7, 2015, http://foxlin.com/interactive-facade/.

Jakovich, Joanne, and Kirsty Beilharz. "Interaction as a Medium in Architectural Design." *Leonardo* 40, no. 4 (2007): 368-69, http://www.jstor.org/stable/20206449.

Jakovich, Joanne, and Dagmar Reinhardt. "Trivet Fields: The Materiality of Interaction in Architectural Space." *Leonardo* 42, no. 3 (2009): 217, http://www.jstor.org/stable/20532649.

Jaskiewicz, Tomasz. "Towards a Methodology for Complex Adaptive Interactive Architecture." PhD diss., Delft University of Technology, 2013.

"Jason Timberlake by Deven Golden," *BOMB*. May 2008. http://bombsite.com/issues/104/articles/3145.

Kane, Carolyn. "Broken Colour in a Modern World: Chromatic Failures in Purist Art and Architecture." *Journal of the International Colour Association* 14 (2015): 1-13.

Kirsh, David. "Changing the Rules: Architecture in the New Millennium." *Convergence: The Journal of Research into New Media Technologies* 7, no. 2 (2001): 113-125.

Klinkhammer, Barbara. "The Spatial Use of Color in Early Modernism." In *Legacy + Aspirations: Considering the Future of Architectural Education: Proceedings of 87th ACSA Annual Meeting*, edited by Geraldine Forbes and Marvin Malecha, 222-225. Washington D.C.: ACSA, 1999.

Kronenburg, Robert. *Flexible: Architecture that Responds to Change*. London: Laurence King, 2007.

Lee, Chia-Hsun. Leonardo Bonanni, and Ted Selker. "The Kitchen as a Graphical User Interface." *Digital Creativity* 16, no. 2 (August 2004): 110-114, doi: 10.1145/1185884.1185989.

Lehman, Maria L. *Adaptive Sensory Environments: An Introduction*. London: Routledge, 2016.

Loewenberg, Peter. “Architectural and Emotional Space.” In *Center17: Space & Psyche*, edited by Elizabeth Danze and Stephen Sonnenberg, 16-43. Canada: Center for American Architecture and Design, 2012.

Leigh, Jason, and Andrew E. Johnson. "CALVIN: An Immersimedia Design Environment Utilizing Heterogeneous Perspectives." In *Proceedings of the Third IEEE International Conference on Multimedia Computing and Systems*, June 1996. Hiroshima, Japan: IEEE: 20-23. doi: 10.1109/MMCS.1996.534949

Leupen, Bernard. “Polyvalence, A Concept for the Sustainable Dwelling.” *Nordic Journal of Architectural Research* 19, no. 3 (2006): 23-31.

Mattern, Shannon. “Geometries of Reading, Light of Learning: Louis I. Kahn’s Library at Phillip Exeter.” *Nexus Network Journal* 12, no. 3 (September 2010): 389-420. doi: 10.1007/s00004- 010-0042-4.

McCullough, Malcolm. *Digital Ground*: *Architecture, Pervasive Computing, and Environmental Knowing.* Cambridge: The MIT Press, 2004.

Mobach, Mark P. “Do Virtual Worlds Create Better Real Worlds?” *Virtual Reality* 12, no. 3 (September 2008): 163-179.

Nadin, Mihai. “Anticipation and the Artificial: Aesthetics, Ethics, and Synthetic Life.” *AI & Society* 25, no. 1 (April 2010): 103–118, doi:10.1007/s00146-009-0243-0

———. “Anticipation: A Spooky Computation.” *International Journal of Computing Anticipatory Systems, Proceedings of CASYS* 9, no. 6 (CHAOS: Liege, Belgium, 1999), 3-47.

———. “Negotiating the World of Make-believe: The Aesthetic Compass.” *Real-Time Imaging* 1, no. 3 (August 1995): 173-190.

Nadin, Mihai, and Pino Trogu. “Arki - Inventing the Future.” *YouTube* video, 3:13, 1991. https://www.youtube.com/watch?v=v6PIPdh7Wlk

Norman, Dan. *Design of Everyday Things*. Basic Books: New York, 2013.

Oakes, Tim, and Claudio Minca. “Tourism, Modernity, and Postmodernity.” In *A Companion to Tourism*, edited by Alan. A. Lew et al., 283. UK: Blackwell publishing, 2004.

Pallasmaa, Juhani. *The Eyes of the Skin: Architecture and the Senses*. West Sussex: John Wiley & Sons, 2012.

———. “Hapticity and Time: Notes on Fragile Architecture.” *Archit. Rev*. 207, no. 1239 (2000): 78–84.

Pink, Daniel H. *Free Agent Nation: How America's New Independent Workers Are Transforming the Way We Live*. New York: The Penguin Press, 2012.

Ponce-Cruz, Pedro, and Fernando D. Ramirez-Figueroa. *Intelligent Control Systems with LabVIEW™*. Verlag London: Springer, 2010. doi: 10.1007/978-1-84882-684-7.

Popping, Roel. “Analyzing Open-Ended Questions by Means of Text Analysis Procedures.” *Bulletin de Méthodologie Sociologique* 128 (October 2015): 23-39, doi: 10.1177/0759106315597389.

Rasmussen, Steen E. *Experiencing Architecture*. Cambridge: MIT Press, 2000.

Riley, Neal J. “S.F. Supervisors Back Micro-Apartments.” *SFGate*. Last modified November 20, 2012, http://www.sfgate.com/bayarea/article/S-F-supervisors-back-micro-apartments-4055493.php.

Ryu, Jaeho, et al. “Application of Human-scale Immersive VR System for Environmental Design Assessment - A Proposal for an Architectural Design Evaluation Tool.” *JAABE* 6, no. 1 (May 2007): 57-64.

Saggio, Antonino. "Interactivity at the Centre of Avant-Garde Architectural Research." *Architectural Design* 75, no. 1 (2005): 23-29.

Schneider, Tatjana, and Jeremy Till. *Flexible housing*. Oxford, UK: Architectural Press, 2007.

Seidel, Adeline. “A Systematic Approach to Living and Loving.” *StylePark*. November 24, 2015, https://www.stylepark.com/en/news/a-systematic-approach-to-living-and-loving

Ivan E. Sutherland, “The Ultimate Display.” in *Proceedings of IFIP Congress* 65, no. 2 (1965): 506-508.

Sykes, Krista, ed. *The Architecture Reader: Essential Writings from Vitruvius to the Present*. New York: George Braziller Publishers, 2007.

Orkan Telhan et al. “Interaction Design with Building Facades.” in *TEI 2010,* January 25-27, 2010. Cambridge, Massachusetts:ACM: 291-294.

Thomsen, Mette R. "Metabolistic Architectures." In *Responsive Textile Environment*, edited by Sarah Bonnemaison and Christine Macy, 36-45. Halifax: Tuns Press, 2007.

Till, Jeremy, and Tatjana Schneider. “Flexible Housing: The Means to the End.” *Architectural Research Quarterly* 9. No. 3/4 (2005): 288.

Van de Cruys, Sander, and Johan Wagemans. “Gestalts as Predictions – Some Reflections and an Application to Art.” *Gestalt Theory* 33, no. 3/4 (2011): 325-344.

“Virtually There: Documentary Meets Virtual Reality,” a conference presented by MIT Open Documentary Lab, Cambridge, MA, May 6-7, 2016. http://opendoclab.mit.edu/virtually there/.

Weinstock, Mike. "Terrain Vague: Interactive Space and the Housescape." *Architectural Design* 75, no. 1 (2005): 46-50.

“What is the Tiny House Movement?” *The Tiny Life*. Accessed June 14, 2016, http://thetinylife. com/what-is-the-tiny-house-movement/.

Wiberg, Mikael. *Interactive Textures for Architecture and Landscaping*. Hershey: IGI Global, 2011, 132-135.

Willette, Jeanne. "De Stijl Architecture." *Arthistoryunstuffed.com*. April 29, 2011, http://www.art historyunstuffed.com/de-stijl-architecture/

Yirka, Bob. “Boeing Demonstrates Lightest Metal Ever.” *Phys.org*., October 15, 2015, https:// phys.org/news/2015-10-boeing-lightest-metal.html

Zamenopoulos, Theodore, and Katerina Alexiou. “Towards an Anticipatory View of Design.” *Design Studies* 28, no. 4 (July 2007): 411–436.

Zumthor, Peter. *Thinking Architecture*. Basel: Birkhäuser, 2010.

BIOGRAPHICAL SKETCH

Asma Naz obtained her Bachelor of Architecture (B. Arch) degree from Bangladesh University of Engineering & Technology (B.U.E.T.) and M.S. in Visualization Sciences from Texas A&M University, College Station, Texas. She worked at HKS, Inc., one of the leading architecture firms in the States as a designer and visualization specialist, and was involved in several major sports projects, including The Cowboys stadium at Arlington, Texas and The Liverpool Anfield Stadium at Liverpool, UK. Her research interest in interdisciplinary areas, that blends both science and art disciplines, further motivated her to pursue a doctoral degree in the Department of Arts, Technology and Emerging Communications at The University of Texas at Dallas. Her dissertation merges knowledge from three distinct disciplines: Architectural design, Interaction design and Virtual environment.

CURRICULUM VITAE

Asma Naz

asma.naz@utdallas.edu;

https://www.researchgate.net/profile/Asma_Naz6; http://utdallas.academia.edu/AsmaNaz

https://www.linkedin.com/in/asmanaz

EDUCATION

- **Ph.D. candidate**, Fall 2009 – Present, University of Texas at Dallas, Richardson, TX
- **M.S. in Visualization Sciences**, Dec 2004, Dept. of Visualization, Texas A&M University, College Station. Master's Thesis: 3D Interactive Pictorial Maps.
- **Bachelor of Architecture**, Aug 1997, Bangladesh University of Engineering & Technology, Bangladesh

RESEARCH & TEACHING EXPERIENCES

- ***Research Assistant*** *for Institute for Research in Anticipatory Systems (AntÉ) at University of Texas at Dallas, Richardson TX. August 2014 – current*. Supervisor: **Dr. Mihai Nadin**: Assisted in the peer review process of three volumes of Springer's Cognitive Systems Monograph: *Anticipation: Learning from the Past*, *Anticipation across Disciplines* and *Anticipation and Medicine.*
- ***Business Analyst.*** *August 2010 – May 2011*. Supervisor: **Dr. Marjorie Zielke**: Involved in documentation of Serious Game development for care and treatment of Neonatal patients at Children's Medical Center

- ***Teaching Assistant,*** *University of Texas at Dallas, Richardson TX. August 2011 – May 2014:*
    - Instructor, ATEC 2384 (Basic Design Principles and Practices), August 2012 – May 2014: This course offers an overview of common design principles and practices as a foundation for understanding design rules, laws, and guidelines. Responsibilities included design of course materials, presentations and assignments based on a course outline, and grading of student exams and assignments.
    - Instructor, ATEC 2382 (Computer Imaging), August 2011 – May 2012: This course offers an overview of techniques of digital imaging using Adobe Photoshop software tools, in concert with foundational knowledge of the elements and principles of Art. Responsibilities included design of course materials, presentations and assignments based on a course outline, and grading of student exams and assignments.

WORK EXPERIENCES

- **Designer & Visualization Specialist**, HKS Inc., Denver, CO, June 2006 – June 2009: Involved in two major projects: The Dallas Cowboys Stadium at Arlington, TX & The Liverpool Anfield Stadium, UK. Job responsibilities included design development, generation of 3D models, animation and rendering for client presentations and marketing.
- **Graphic Designer**, H+L Architecture, Denver, CO, September 2004 – March 2006: Involved with Healthcare and Education Projects as a 3D modeler, Animator, Web & Graphic Designer.

PUBLICATIONS, PRESENTATIONS & AWARDS

- Publication: *"Emotional Qualities of VR Space," Accepted paper for* IEEE Virtual Reality 2017 with co-authors Regis Kopper, Ryan P. McMahan and Mihai Nadin.
- Publication: *"Interactive Living Space Design for Neo-Nomads: Anticipation Through Spatial Articulation"* (393–403 pp.) in *Anticipation Across Disciplines*, Mihai Nadin (Eds). Cognitive Systems Monographs, Vol. 29, Springer International Publishing. ISBN: 978-3-319-22598-2, © 2016. www.springer.com/us/book/9783319225982
- Conference: Poster: *"Aesthetic Framework for Human-Space Interaction in Architectural Spaces."* 2017 International Workshop on Interactive and Spatial Computing (IWISC), Richardson, TX. April 13-14, 2017. http://cs.utdallas.edu/ut-diisc/iwisc2017/.
- Conference: Paper: *"Emotional Qualities of VR Space."* Speaker for IEEE Virtual Reality 2017, Los Angeles, CA. March 18-22, 2017. http://www.ieeevr.org/2017/.
- Conference: Paper: *"Interactive Living Space Design for Neo-Nomads: Anticipation Through Spatial Articulation."* Speaker for International Workshop *Anticipation Across Disciplines,* Hanse-Wissenschaftskolleg (HWK), Delmenhorst, Germany. September 22-24, 2014. www.h-w-k.de/index.php?id=2156.
- Conference: Paper: *"Game Design and Architectural Design: A symbiosis."* Speaker for *Game Education Summit*, Serious Play Conference, DigiPen Institute of Technology, Redmond, Washington, August 24-25, 2011. www.seriousplayconference.com.
- Recipient of Dissertation Research Award, 2016, University of Texas at Dallas.