PERCEPTUAL MATERIALIZATION FOR SPACE INTERFACE:

Exploring the Interactive Generation Design Method and Application of Space Interface via EEG Reveled Visual-Perception

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Abstract. The primary objective of this research is to elucidate how individuals are immersed in the spatial visual ambiance, leading to the elicitation of perceptual emotions and the establishment of a feedback mechanism between visual-perception and generative design, which serves as the critical intermediary linking human behavior and spatial geometry. To achieve this goal, Electroencephalogram (EEG) signals have been chosen as the preferred modality. By establishing the integrated EEG device system and real-time interactive visual perception platform, this research explores an interactive design methodology for space interface design, drawing insights from visual perception as revealed through EEG data. Next, the method of integrating hardware and software to establish a visual human-computer interaction platform is explored in detail, and the data characteristics of joint nodes are analyzed. Furthermore, the spatial interface was selected as the object for EEG interaction generation, applying Voronoi planar pattern controlled by noise functions for complex interface geometry generation and attempting to convert data from 2D pixels to 3D solid mesh models. This research demonstrates significant potential for further exploration and development within creating more personalized interactive spatial experience.

Keywords. Generative Design, Human-Computer Interaction, EEG, Space Interface

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1. Introduction

1.1. BACKGROUND

In the realms of architecture and space design, the ultimate measure of design success is the experience of the occupant. This philosophy, echoing the Renaissance humanist mantra "Man is the measure of all things" (Bailey et al., 2019), places the human who embodied in built environment at the forefront. This occupant-focused approach, deeply rooted in historical perspectives, continues to shape contemporary design practices and methodologies. The way individuals perceive an architectural space deeply influences their mental state, encompassing physiological, emotional, and cognitive responses. As a tangible reflection of these responses, ergonomic data, derived from quantifiable human bodily signals during the experience of space, plays a crucial role in evaluating and enhancing space design. This data forms the bedrock for assessing spatial effectiveness and offers key insights for its refinement.

Therefore, understanding the impact of spatial elements and their arrangement on human psychology is critically important. By deliberately designing these elements within architectural spaces, it's possible to create environments that fulfill both the physiological and psychological needs of individuals. This approach leads to the creation of spaces that not only align with but also enhance the human experience (Juan et al., 2022). During the development of parametric models for human-environment interaction, the electroencephalogram (EEG) emerges as a pivotal instrument. Functioning as a method to record brain activity through electrode-based measurements, EEG offers a quantifiable and direct indicator of subjective psychological states. This characteristic renders it apt for physiological evaluations of spatial forms in relation to defined parameter sets, thereby establishing its value in such assessments. As a result, EEG data can be effectively utilized to indirectly drive the parametric model, facilitating necessary adjustments and refinements to ensure congruence with human reactions.

1.2. RELATED WORKS

In environmental interaction, individual observers exhibit distinct physiological responses to material characteristics, encompassing a spectrum of somatic and psychological conditions which influence daily behavioral characteristics of space occupants (Guo et al., 2018). Concurrently, the perception of environmental attributes facilitates a predictive behavioral response, anticipating the interaction between environmental components and the human body, including aspects like spatial visual orientation and potential interactive behaviors. This predictive mechanism informs the strategic alteration of environmental elements, aiming to synchronize the ambiance with targeted experiential outcomes (Zhang et al., 2022). EEG measurements have been extensively adopted for analytical purposes in various studies. The correlation between EEG signals and psychological parameters, including human emotions and psychological stress, has been a focal point of discussion (Kim et al., 2004). Theoretically, this correlation provides a plausible basis for inferring individuals' emotional traits based on EEG data. Other researches focused on quantifying people’s degree of relaxation and stress through EEG signals

(Katmah et al., 2021). Specific EEG traits indicating mental states can significantly benefit human psychological and physiological health (Sanei et al., 2013). Current research has successfully identified a one-way link between ergonomics data and spatial environment assessment (Wu et al., 2020). Furthermore, Brain-Computer Interface (BCI) tool was already tested and developed as an design tool in the realm of architectural interior windows adjustment (Yang et al., 2023), immersive multi-media science-art installation system (Kovacevic et al., 2015), artistic expression by using EEG signal as painting controls (Kübler et al., 2019), yet the use of human-environment interaction feedback for complex spatial elements generation in architectural design remains largely unexplored.

2. Research Aim

Visual-perception serves as the critical intermediary linking human behavior and spatial geometry. This research aims to develop an interactive feedback mechanism between EEG data and space interface geometrical form. The objective is to establish a method for the generation and optimization of complex shape, driven by human-factors data. The study focuses on space interface elements within the human body's perceptible scale as the primary subjects for form generation. The study investigates the role of visual-perception in the built environment as a key driver and evaluative criterion for form generation. Furthermore, during the application research phase, this methodology examined for creating space interfaces with complex geometric forms that are conducive to material construction. The research aims of this study consists of the following three points:

- Establishment of an integrated human-computer design platform via EEG measurement system.
- Development of the EEG data-driven generative design method in the application for space interface design.
- Verification of complex geometric form materialization based on spatial visual-perception.

3. Methodology

3.1. WORKFLOW

In developing this visual-perception interactive generation design method, the data-flow is constructed via three parts, including brain-computer interactive tools system, graphic-based space interface form generative platform and target EEG data oriented form result materialization process. Among them, this research begins with a focus on the data-flow inherent to the methodology. The principle of data-flow is established as the fundamental and constant structure within this approach, forming the basis for subsequent research activities concerning tools platforms.

Within this methodology, the hardware system functions as a comprehensive tool for acquiring human EEG signals. The data captured reflects the psychological and cognitive states elicited by the visual-perception of geometric elements. Following this, the data derived from cognitive state calculations are relayed through numerical remapping transformations to a visualization platform capable of real-time geometric graphic processing. This data serves as a driving source for the ongoing transformation of planar geometric graphics, facilitated by EEG-based interaction.

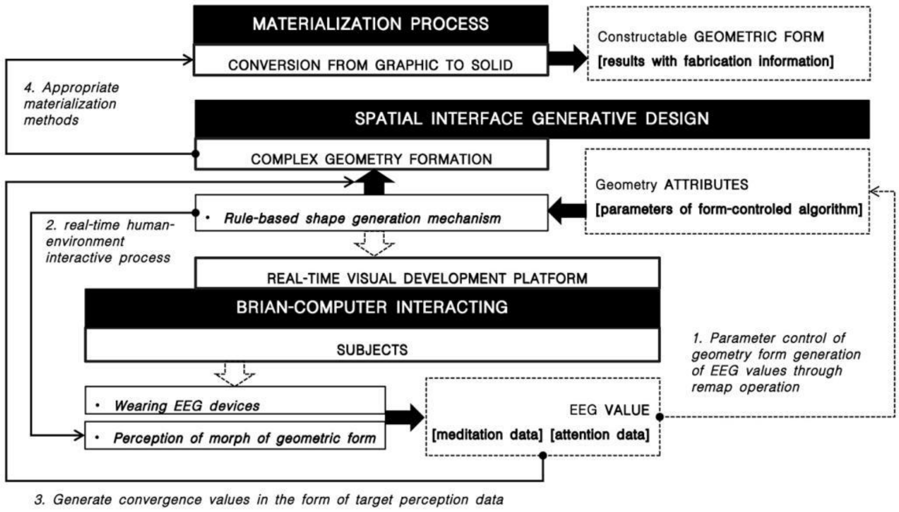


Figure 1. Workflow of visual-perception interactive generation design method

3.2. INTEGRATED TOOLS SYSTEM

On the establishment of tools system framework, EEG measurement equipment, visualization interaction platform and related auxiliary transmission kits are integrated on this system. Within this system, EEG signal data, manifested as Attention Values Data (AVD) and Meditation Values Data (MVD), are outputted and then remapped into geometric parameters. This remapped dataset is then fed in real-time into a visual interactive platform, facilitating the control of geometric graphic pattern generation and morph. Ultimately, the data undergoes a conversion from pixel formats to mesh geometric structures via modeling software.

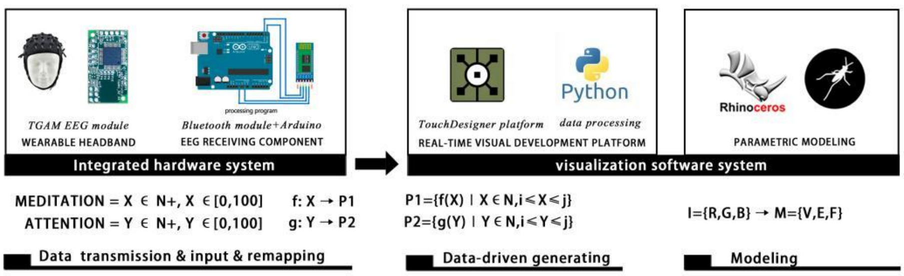


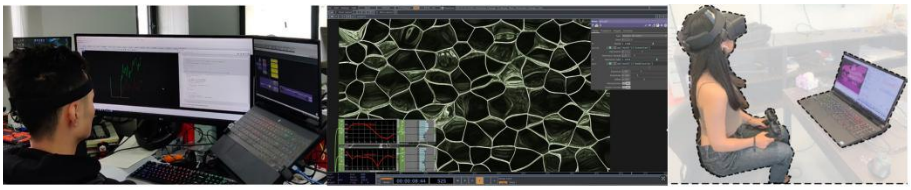
Figure 2. Framework of integrated tools platform with data-flow

3.2.1. TGAM module based EEG measurement device

Based on the context of selecting EEG monitoring and analysis equipment, this study emphasizes the need for contemporary EEG data, highlighting the significance of utilizing open-source equipment for comprehensive access. Therefore, the ThinkGear AM (TGAM) module developed by NeuroSky is chosen in this research, which can measurements EEG raw signals from subjects' frontal lobes, calculating into MVD and AVD , and then output those data ranging from 0 to 100 in every second. It involves converting hexadecimal data into binary format and then feeding it into the computer's serial port via Arduino development board. The telecommunication between TGAM module inserted onto wearable headband and Arduino board receiving is via Bluetooth module connected to master computer.

3.2.2. Real-time visual development platform

In the establishment of visual perception and generation system, the TouchDesigner platform is applied according to the goal of the real-tine visual interactive generation process (shows in Figure 3.b), which offers a node-based visual programming environment, allowing to create complex networks for graphics and multi-source data stream processing in a visually intuitive manner. Figure 3.a shows the real-time visualization interface of the master computer receiving EEG data via serial port. The whole experiments process shows in Figure 4.c, in which the additional VR display is able to affiliated set into the terminal interaction platform to create more immersive perceptional environment. VR setting is not necessary in some certain experimental scenarios, such as the perception of some flat planar patterns or insensitivity to immersive spatial experiences of solid matter.



a b c

Figure 3. Interactive visualization platform

4. Application in Space Interface Design

4.1. OBJECT GEOMETRY DEFINITION

In the exploration stage of design applications, the classic *Voronoi* polygon was selected as the geometric prototype for generating space interface patterns.Voronoi polygon, often referred to as Thiessen polygons, creating unique cell-like structures pattern find significant application in architectural digital design for elements like surface (Hua. 2016) and structural layouts (Coates et al., 2005). Digital designs for space interfaces derived from Voronoi polygon geometry have demonstrated extensive and mature applications includes building facades, interior partition panels, suspended ceilings, and decorative components. In this study, Voronoi diagram is the fundamental geometric prototype for interactive pattern generation.

4.2. INTERACTIVE GENERATION MECHANISM

4.2.1. Worley-noise based Voronoi pattern generation

Worley-noise is the core function that controls the generation of Voronoi geometry, generates patterns by randomly distributing points within a space and then calculating the distance of each location in the space to the nearest of these points. This process partitions the space into distinct grid cells (see Figure 4.c), each associated with a feature point. Subsequently, cells are partitioned based on the geometric partitioning principle of Voronoi diagram (the method shows in Figure 4.a and 4.b).

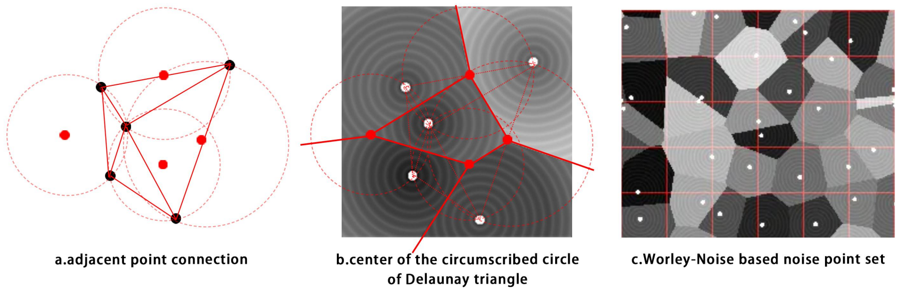


Figure 4. Voronoi pattern generation via Worley-noise

The process of Voronoi pattern geometric generation based on Worley-noise function, two parameters *Period* and *Harmonic-Gain* play crucial roles in shaping the characteristics of noise textures. The Period parameter determines the frequency of the base layer of noise; a lower value results in a noise pattern with more frequent changes, creating a finer texture, while a higher value leads to a more spaced-out, coarser pattern. On the other hand, Harmonic-Gain controls the impact of successive layers of noise, known as harmonics. Each harmonic adds complexity and detail to the noise. A higher Harmonic-Gain amplifies the effect of these additional layers, introducing more intricacy and finer details, whereas a lower value results in a smoother and less complex noise texture.

Subsequently, a constant noise array and a variable noise array, modulated by the aforementioned values, undergo real-time image blending through image subtraction algorithms. This process effectively combines the distinct noise patterns. Next, the *Slope* algorithm is employed to compute the gradient of each pixel in the input image. The gradient, indicative of the direction and magnitude of brightness change, is a critical tool for edge detection and image feature analysis. By applying this algorithm, the image's edges are precisely extracted, facilitating the generation of distinct borders. This methodological approach allows for the nuanced manipulation of image textures, enhancing both the visual depth and detail in the final output. This whole process shows in Figure 5.

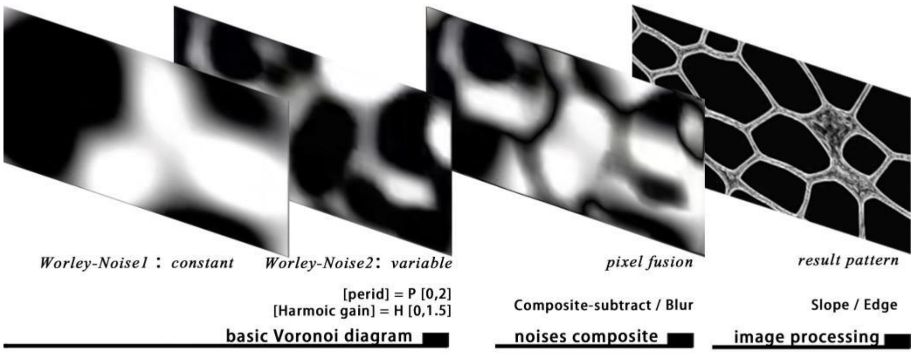


Figure 5. Method of generated pattern image processing

4.2.2. EEG-driven generation method

In the data remapping and association operation of EEG, AVD and MVD will correspond respectively to *Period* and *Harmonic-Gain,* the two parameters in the image processing process mentioned above. Based on our previous experimental results, a negative correlation between the AVD, which signify elevated attention levels in human cognitive states and the pattern density (Period value is negatively correlated with density). Specifically, the Voronoi cell density appears to elicit heightened attention. Conversely, the MVD demonstrates a positive correlation with pattern homogeneity. That is when the grayscale values of the Voronoi cells converge in similarity, this tends to facilitate a state of relaxation and meditation in the human psychology (see Figure 6).

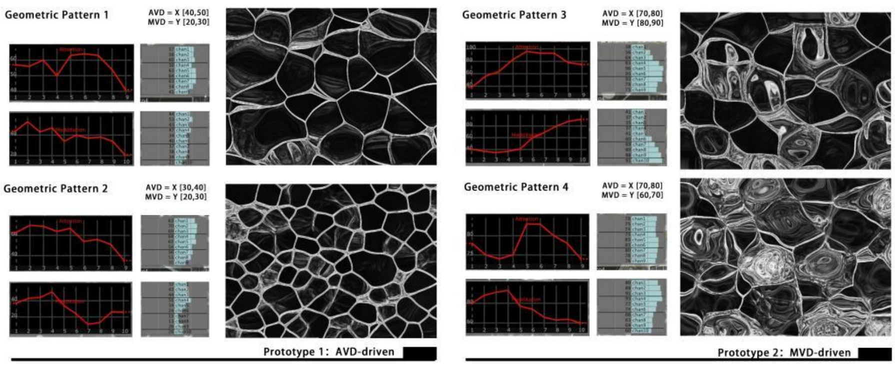


Figure 6. Relationship between EEG and pattern characteristic

The output values of AVD and MVD have a range of positive integer from 0 to 100, while the definition ranges of *Period* and *Harmonic-Gain*, in a well generated pattern image state, are float decimals from 0 to 2 and from 0 to 1.5, respectively. The next manipulation is remapping the range of AVD to the domain of Period parameters positively and remapping the range of MVD to the domain of Harmonic-Gain parameters. A comprehensive interaction mechanism utilizing EEG signals for the generation of pattern geometry has been successfully established.

Utilizing this methodology, our study conducted several experiments wherein participants were equipped with EEG devices to observe and perceive pattern generated dynamically in real-time. Concurrently, EEG data waveforms, redrawn based on segments of 10-second EEG data, were displayed on the terminal screen. In this setup, the AVD and MVD were instrumental in influencing the formation of pattern geometries, specifically modulating the density and grayscale distribution of Voronoi cells (see Figure 7). This approach effectively integrates EEG signals into the interactive process of pattern formation, demonstrating the potential of biofeedback in design and visualization fields. Furthermore, by adjusting the parameter values of the *Slope, Blur, Edge* image processing algorithm, more diverse and complex pattern morph can be obtained. The series of results shows in Figure 8.

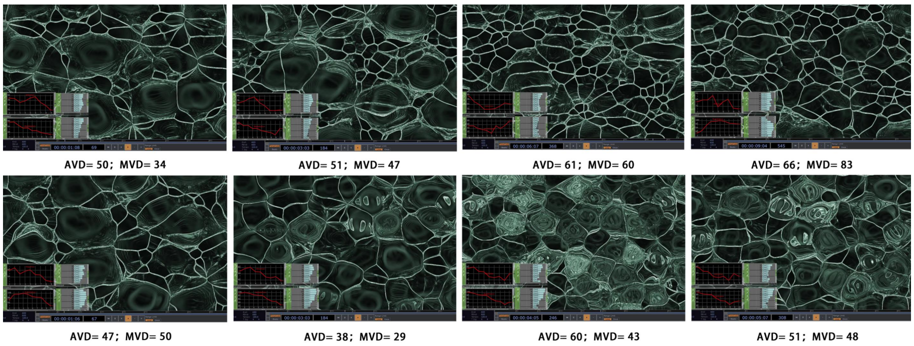


Figure 7. EEG-driven Voronoi pattern morph

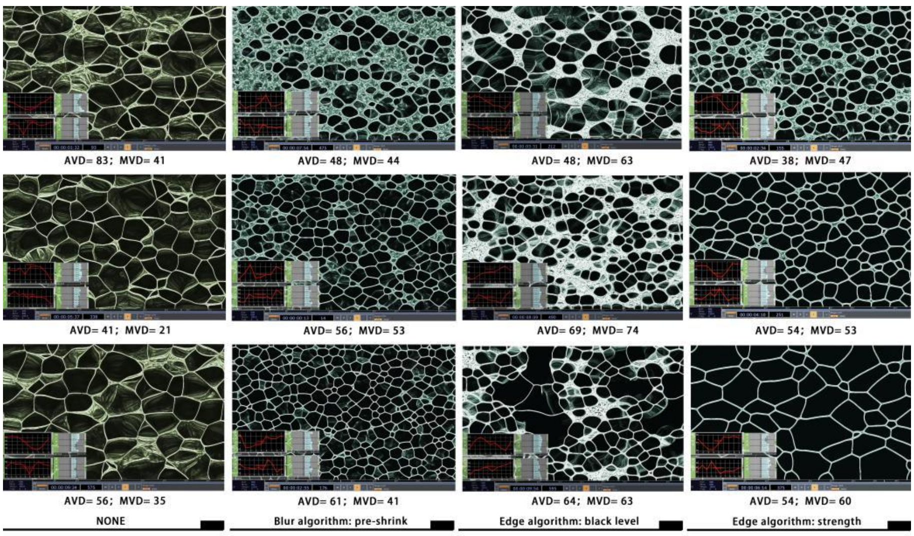


Figure 8. Parameter adjustment of image processing functions

4.3. MATERIALIZATION MODELING PROCESS

During the materialization of interfaces from planar patterns, the grayscale value of the image is employed as a depth parameter for three-dimensional modeling. This approach is integral to the transition from pixel-based pattern to mesh models, where the varying grayscale intensities are mapped as depths value, thereby facilitating the conversion of a two-dimensional image into a three-dimensional structure, shows in Figure 9.

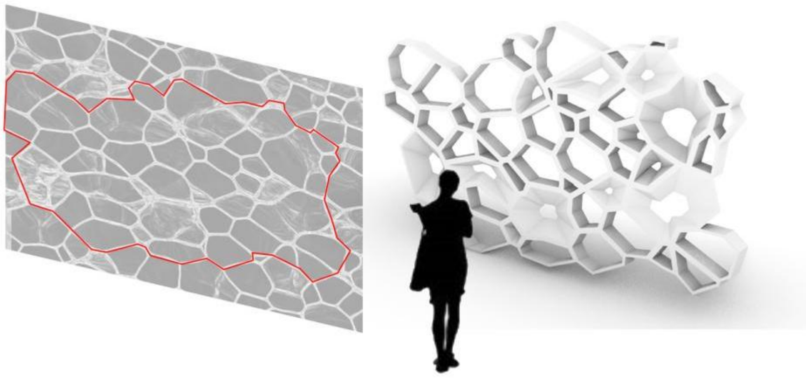


Figure 9. Space interface design application

5. Conclusion

This research signifies an investigation into an interactive design methodology and its implementation for space interface design, informed by visual perception insights derived from Electroencephalography (EEG) data. The method established based on integrated EEG device system and real-time interactive visualization platform, encompasses the utilization of EEG technology to measure and interpret human visual perception, which then guides the creation and enhancement of interactive spatial interfaces. To elaborate, this approach involves measuring EEG signals with Attention value and Meditation value to gain an understanding of how individuals perceive and interact with certain geometry pattern-designed spatial interface surroundings. Voronoi polygon pattern is tested in this research. By analyzing the generation result via human-computer interaction process, the insights obtained from EEG data, which reflect the brain's response to visual stimuli, can be instrumental in designing space interface geometric patterns that are not only more intuitive and engaging but also tailored to the user's perceptual and cognitive preferences. Finally, with the application of transforming planar patterns into space interfaces, image grayscale values are utilized to define depth in three-dimensional modeling, proves the feasibility of applying the visual-perception based generative design method proposed in this study to complex space interface design.

Furthermore, this methodology is also applicable to intricate generative designs, where it facilitates the direct parameterization of three-dimensional geometric elements based on feedback derived from EEG data. Essential principles guiding the application of this method for target objects include:

- Comprise a variety of design elements, such as planar or three-dimensional geometries.
- Be capable of offering direct visual stimuli or possess attributes that are closely related to human visual perception experiment.
- Non-intrusive to core structural integrity

For instance, this method could be applied in architectural complex digital design, where EEG-informed insights directly shape the aesthetics and functionality of building elements, or in interactive installations, where user engagement is maximized through EEG-driven adaptive interfaces. Additionally, in virtual reality (VR) and augmented reality (AR) applications, this approach could also be applied to enhance user experience by aligning virtual environments with the user's natural visual processing patterns, as revealed by EEG.

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