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Addressing Parameters for Generative Spatial Design

Jonas Zukas[1*], Maksim Zuk[2], Lukas Misiunas[1]

[1] *Vilnius Gediminas Technical University, Vilnius, Lithuania*
[2] *European Humanities University, Vilnius, Lithuania*

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Abstract

This paper examines the integration of emotional responses and embodied cognition into AI-driven generative spatial design. It defines and validates parameters enabling AI systems to dynamically adjust spatial environments based on human emotions and behaviours. Employing embodied cognition theory, natural user interfaces, comparative software analysis, and machine learning, the authors identify methods to translate human interaction into generative design, laying the groundwork for responsive, emotionally adaptive environments.

Introduction

The integration of artificial intelligence (AI) into spatial and generative design methodologies presents transformative possibilities, particularly through the potential to create adaptive environments responsive to human emotional and behavioural dynamics [1], [2]. Despite significant technological advancements, current generative design practices frequently overlook the nuanced interactions between spatial forms, human emotions, and cognitive responses, leaving a notable gap in both theoretical understanding and practical applications [3], [4]. This research specifically targets this gap by defining, analysing, and testing critical parameters that connect AI-driven generative spatial design with embodied human interaction and emotional feedback.

The central subject of this research is the development and validation of adaptive emotional design (AED), an innovative methodology integrating emotional and behavioural responses into generative design processes [5]. AED leverages real-time data streams, including facial recognition, gesture recognition, and physiological signals, to dynamically adjust spatial configurations. Such adaptability represents a significant departure from conventional static design approaches, reflecting a paradigm shift toward spaces that actively engage with and respond to their occupants' evolving emotional states and behaviours.

This study's primary objective is to identify and evaluate the parameters required for the effective integration of AI with generative spatial modelling platforms. By systematically examining embodied cognition theories, spatial affordances, and user emotional responses, the research seeks to establish an empirical foundation for AI-driven generative modelling methods that prioritise emotional engagement and cognitive enhancement. Furthermore, it aims to delineate practical guidelines for implementing these parameters within existing spatial design workflows, ensuring usability, responsiveness, and intuitive user interaction.

Through comparative analysis of leading AI and modelling software platforms, supported by targeted case studies, this paper contributes concrete insights into how adaptive emotional parameters can be practically refined and applied. By clearly defining and validating parameters that link human interaction, emotional feedback, and generative design, this research aims to pave the way for broader adoption of adaptive, emotionally responsive design principles. Ultimately, it seeks to establish foundational methodologies capable of transforming static spatial environments into dynamic, interactive spaces tailored specifically to human experience and well-being.

I. Context of the Investigation

This research is grounded in the theoretical framework of embodied cognition, which proposes that human cognition is significantly influenced by physical interactions with the environment [6]. While the impact of spatial configurations on emotions and behaviours is established, the concept of adaptive spatial environments – spaces that respond dynamically to human inputs and

* Corresponding author. E-mail address: jonas.zukas@vilniustech.lt

actively influence behaviour – remains an emerging area of research [7]. To address this, AI technologies, employing data captured from sensors such as cameras, motion detectors, and biometric devices, offer promising methods for real-time adaptation and iterative learning from human-environment interactions.

Currently, a major limitation in spatial modelling approaches is the reliance on designers' intuitive expertise, which often lacks empirical validation and objective reasoning behind specific spatial modifications. Traditional methodologies tend to prioritise geometric surface adjustments without comprehensive consideration of contextual and/or functional relevance [8], [9]. This narrow scope restricts the systematic validation of spatial alterations and overlooks critical parameters influencing human behavioural responses.

Shape embodiment modelling [10], in contrast, provides a holistic approach by incorporating human spatial perception and isolating essential modification elements, such as surface curves and functional constraints, to evaluate their behavioural implications more objectively. By expanding the understanding of spatial functionality and integrating cultural and aesthetic factors, shape embodiment modelling facilitates the acquisition of tangible data and more meaningful insights into spatial modifications.

The present study further enhances this method by integrating AI's analytical and learning capabilities, thereby making the spatial embodiment process more intuitive and robust. This methodological integration enables more efficient empirical data collection and comprehensive contextual analysis, ensuring more accurate and validated spatial design adaptations.

In the study by Pernot et al. [9], architectural shape descriptions relied on complex mathematical modelling without thorough investigation into the rationale or impacts of aesthetic and functional (spatial affordance) modifications. The study addresses the dangers of losing semantic content; therefore, it introduces a set of parameters to avoid an uncontrollably distorted shape. Although the approach reduced complexity by limiting shape parameters and providing functional constraints, it lacked explicit validation of design reasoning, placing significant reliance on designers' subjective evaluations.

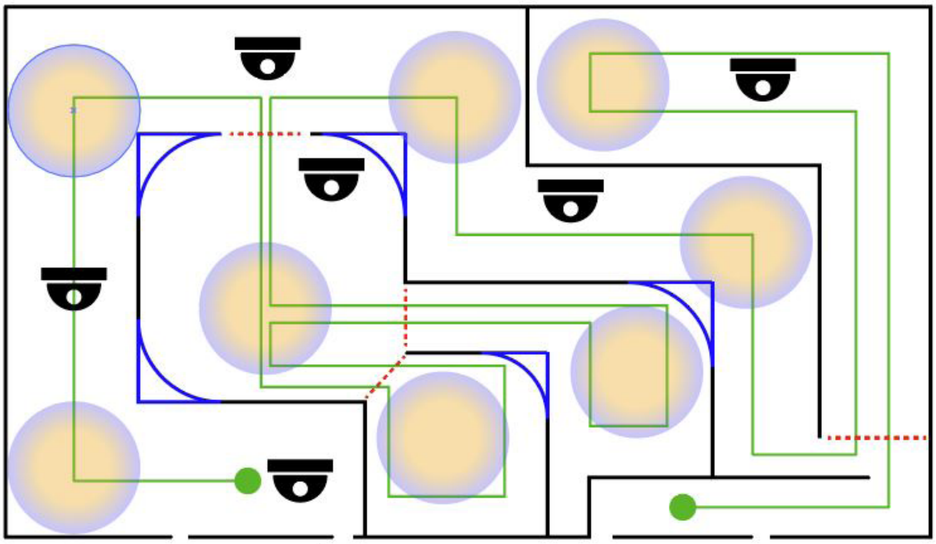
Another approach is the Kansei Engineering method, developed by Mitsuo Nagamachi. Closely related to the principles of emotional design, this method has found its greatest application in industrial design, although it can also be adapted to architectural design methods. The method involves the mathematical parameterisation of the desired attributes of an object or brand (e.g., cute, luxury, comfortable, cosy, etc.). Using this approach, it is possible to determine which object parameters (such as length, edge radius, etc.) are associated with certain expected user perceptions. A mathematical model is built that allows these desired properties to be controlled not qualitatively, but quantitatively. However, the method is extremely complex to apply and requires a certain level of statistical and mathematical proficiency, as well as in-depth research. It also relies on specialised software [11]. We believe it is far more promising to use AI methods to further develop this approach.

Our research addresses these limitations by combining embodied cognition theory and emotional responses with AI-driven modelling methods, ensuring the real-time validation and empirical testing of spatial design decisions.

Traditional spatial generative methods often rely on rigid geometry and manual input, significantly constraining their intuitiveness and adaptability. Modern parametric modelling tools facilitate rapid spatial form manipulations, yet they still require significant improvements to fully accommodate dynamic, real-time user interactions [12], [9]. Integrating AI methodologies, particularly those utilising emotional feedback and real-time adaptive responses, can significantly enhance the versatility and intuitive potential of spatial modelling processes. AI-driven methodologies are proposed to harmonise multiple parameters, systematically evaluating design modifications and ensuring predictable, behaviourally relevant outcomes.

II. Role of Embodiment Principles in Data Collection on Shape Attributes

This study draws on the theory of embodied cognition, emphasising that human cognition is significantly influenced by bodily interactions with the surrounding environment [6]. While research extensively recognises how spatial environments affect human emotions and behaviours [1], the concept of adaptive spaces that respond dynamically to user input and behaviour remains relatively novel [13]. AI technologies, through the analysis of sensor data from devices such as cameras and biometric sensors embedded in environments [14], facilitate real-time adaptation of spaces. Current methodologies in shape modelling typically lack a comprehensive approach, frequently depending on designers' intuition without empirical validation of spatial modifications [9]. The shape embodiment modelling approach [10] fills this gap by systematically addressing spatial functionalities and their behavioural impacts, thereby enabling more precise and intuitive adjustments in spatial design processes (Fig. 1).



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Description	**Illustration**
Full path	
Shape variable	
Sensorial data capture	
Light variable	

Fig. 1. Adaptive spatial design usage of path, shape, and sensor data to enable AI-driven space adjustments [by the authors].

Parametric modelling tools offer faster manipulation of complex shapes but still lack adaptability to dynamic user input [12]. Moreover, mathematically representing spatial and emotional design parameters presents inherent challenges, particularly when managing high-dimensional data inputs common to advanced AI models [15]. While neural networks (CNN) and deep learning methods have improved spatial recognition capabilities, controlling variability and generating precise spatial adaptations remain complex. Recent advancements in generative models, such as StyleGAN and text-to-image diffusion models, offer potential avenues toward bridging gaps between rigid spatial modelling and truly adaptive, responsive designs. Thus, the integration of embodied cognition principles, AI-driven emotional feedback mechanisms, and advanced generative modelling techniques collectively forms the methodological foundation of this research (Fig. 2).

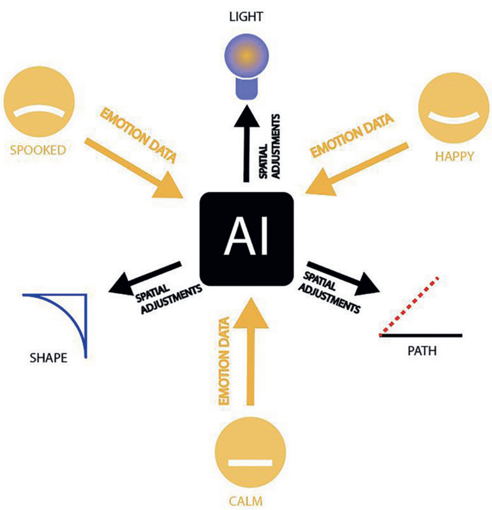

Fig. 2. Real-time AI space adaptation through light, shape, and path adjustments based on the user emotion data working process [by the authors].

To achieve the research objectives, authors employ a comprehensive methodological framework that integrates natural user interfaces (NUI), gesture recognition technologies, and AI-based decision-making processes. This approach is designed to systematically capture, analyse, and translate human emotional and behavioural data into dynamic design parameters.

III. Methodology

This study proposes a methodology to integrate emotional and cognitive feedback into generative spatial design tasks, utilising both real-time adaptive 3D software applications and AI learning. This approach is structured around a defined set of adaptive parameters (light, shape, path) and two primary methods of spatial adaptation: emotional enhancement and emotional target. The methodology is further distinguished by its dual application in both virtual and physical environments, ensuring versatility and scalability. On this basis, the authors propose a working model (Fig. 3).

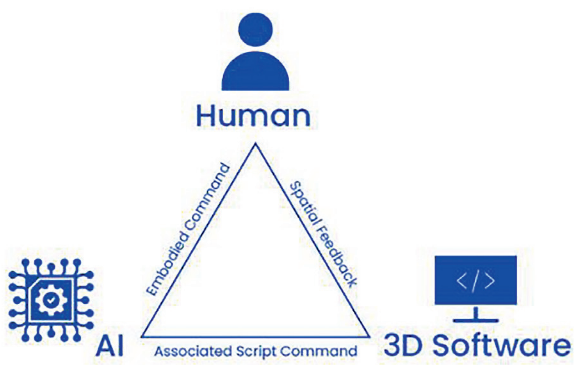

Fig. 3. Methodology of spatial embodiment connecting AI, 3D software, gesture recognition and real-time space adaptation [by the authors].

Spatial environments are divided into two main categories – closed spaces and open spaces. Closed spaces, such as offices, museums, and spas, offer greater control over environmental variables, making them more suitable for experimental adaptation [2]. Open spaces, including parks and beaches, present greater challenges due to dynamic environmental factors [16], but can still benefit from targeted emotional adjustments (Table I).

TABLE I

Functional Spaces Defined by Specific Emotional Targets [by the authors]

CLOSED SPACE	TARGET EMOTION	OPEN SPACE
SPA	CALM	Beach
Horror escape room	SPOOKED	Abandoned castle yard
Office	FOCUSED	Outdoor workspace
Gym	ENERGETIC	Sports field
Café	HAPPY	Festival ground
Bedroom	SLEEPY	Lakeside campsite
Amusement Park	EXCITED	Street fair

The adaptive parameters – light, shape, and path – are foundational to this methodology, representing the core spatial elements that can be dynamically adjusted to influence the user's emotions. These parameters were chosen due to their direct impact on human perception and spatial experience, aligning with the theory of embodied cognition [17]. Light affects visibility and ambience, shape influences embodied cognition, and path determines spatial affordability. These parameters are adaptable across a wide range of spatial contexts, making them universally applicable (Table II).

TABLE II

Definition of Set of Spatial Parameters for Emotionally Adaptive Design [by the authors]

	LIGHTING	SHAPE	PATH
CALM	Warm	Blunt	Clear/full
SPOOKED	Dim	Sharp	Uncertain
FOCUSED	Neutral	Geometrical	Direct
ENERGETIC	Bright	Emerging	Open
HAPPY	Warm	Conforming	Free-flowing
SLEEPY	Soft	Rounded	Smooth
EXCITED	Vivid	Stretching	Expansive

Data collection is achieved through a combination of technologies, including gesture recognition via natural user interfaces (NUI), emotion recognition using facial analysis and physiological sensors [18], and trend analysis from social media. These data sources provide a multi-dimensional understanding of user emotions, which are then processed by AI algorithms to identify the dominant emotional state of users within a space (Fig. 4).

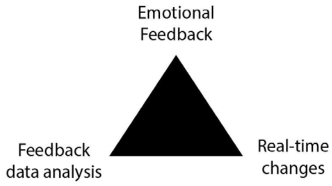

Fig. 4. Creating a natural user interface directly in adaptive space through real-time changes. Spatial modification and gesture/movement/emotion recognition technologies allow users to interact with the environment on an embodied cognition level (intuitively) [by the authors].

The AI system continuously analyses collected data, identifying the dominant emotional state and comparing it to the predefined emotional target of the space (such as CALM, FOCUSED, HAPPY, or SOOKED) (19). When the general user group has reached the emotional target but a significant portion has not, emotional enhancement is triggered. The AI adjusts one or more parameters (light, shape, path) to ensure that more users experience the target emotion. For example, if a space's target emotion is CALM but some users remain SPOOKED due to dim lighting, the AI increases light warmth to align with the calm emotion (Table III).

TABLE III

Definition of Set of Spatial Parameters for Emotionally Adaptive Design [by the authors]

TARGET EMOTION	LIGHTING	SHAPE	PATH
CALM	Dim	Blunt	Clear/full
SPOOKED	Dim	Geometrical	Uncertain
FOCUSED	Warm	Stretching	Direct
ENERGETIC	Bright	Emerging	Closed
HAPPY	Sharp	Sharp	Free-flowing
SLEEPY	Soft	Sharp	Hard
EXCITED	Cool	Stretching	Expansive

Emotional climb is a method within emotional enhancement [20], designed to help users gradually or suddenly reach the target emotional state when the public majority's emotion does not match the target emotion. The authors propose two distinct approaches:

- Soft emotional climb: Gradual adaptation through complementary emotions. If the target emotion is CALM but users are currently SLEEPY, the system may first create a HAPPY atmosphere, transitioning smoothly to CALM. This approach minimises emotional shock, ensuring a natural progression.
- Hard emotional shock: Sudden adaptation through opposing emotions. If the target emotion is FOCUSED but users are currently SLEEPY, the system may create a SPOOKED atmosphere briefly, jolting users toward FOCUSED. This approach is direct and is used when rapid emotional adaptation is needed.

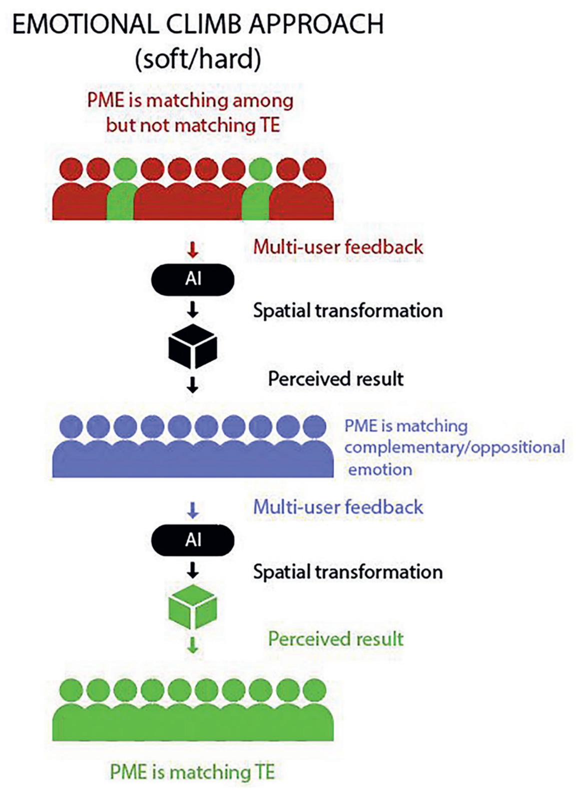

Fig. 5. Real-time emotional enhancement of spatial design and limitations to overcome through parameter discrepancy [by the authors].

These approaches are illustrated in the emotional climb diagram (Fig. 5), demonstrating how the system navigates user emotions toward the target state. This methodology is designed to operate in two primary contexts:

3D software application: In virtual environments, AI uses data from user feedback to dynamically adjust 3D spatial designs, ensuring they match the target emotional state. These adjustments are visible in real-time, providing immediate design feedback.

Real-world application: In physical spaces, AI directly modifies environmental parameters (light, shape, path) to match the target emotion for users present in the space.

A practical simulation of the methodology was conducted using 3D software (Blender) to dynamically adapt a museum room environment based on user feedback and target emotions. The initial state was designed to evoke a CALM mood, followed by adjustments to match the target emotions of HAPPY and SPOOKED. The simulation demonstrated how the adaptive parameters, in this particular case, lighting, were modified in real-time by AI to achieve the desired emotional states, directly reflecting the methodology's principles (Fig. 6).

The lighting colour temperatures were adjusted based on established empirical findings from the study on non-image-forming (NIF) [23] effects of light on emotional perception:

- CALM: 2700K (warm white), creating a soothing atmosphere that reduces negative emotional bias.
- HAPPY: 3500K (warm white), maintaining a warm, inviting ambience.
- SPOOKED: 6500K (cool white), enhancing the perception of negative emotional stimuli, creating tension.

These values were directly derived from the study, ensuring scientifically valid emotional impact through lighting.

Fig. 6. Simulation in Blender of real-time data feedback in spatial design [by the authors].

Using, for example, the OpenCV DNN Module [21], it is possible to obtain real-time data on user emotion and gesture recognition. Moreover, this data can immediately be represented in a parameterised quantitative form. In this case, unlike the Kansei Engineering methods, the resulting parameters can be used directly without the need for deep sociological research, which often presents difficulties in accurately correlating verbal data with numerical parameterisation. The data obtained through this methodology can then be transferred to Blender (or CAD software) to modify the selected properties of the object, using scripts. There is a possibility to generate novel objects with AI (like ChatGPT) directly, but for now, the transition gap is too wide, and results could be suboptimal.

IV. Results

To effectively simulate user interaction without direct user participation, 100 virtual respondents were simulated to ensure statistically reliable results while maintaining computational efficiency. This sample size provides a balanced representation of diverse user emotions without overloading the system. These virtual respondents were computationally generated user profiles, each assigned an initial emotional state (NEUTRAL, HAPPY, SPOOKED) based on a balanced probability distribution reflecting a realistic user base: 33 % – NEUTRAL, 34 % – HAPPY, 33 % – SPOOKED. This distribution was chosen to ensure a diverse range of emotional responses, simulating a realistic public space scenario.

Dominant adjusted shapes were defined based on their direct psychological influence on user perception [24], [25]. Rounded, smooth shapes were used for CALM to promote a sense of safety and comfort, chosen because previous studies indicate such forms reduce cognitive tension. Playful geometric shapes for HAPPY were selected to encourage exploration, and sharp, angular shapes for SPOOKED were applied to induce caution, reflecting the psychological impact of sharp edges as threatening. These shapes were consistently applied to maintain visual coherence with the target emotions.

User movement data were simulated using Python, leveraging scientific libraries such as NumPy, Pandas, and SciPy. The observed values represented the actual number of users in each category (CALM, HAPPY, and SPOOKED) after adaptive adjustments (Table IV), while the expected values were calculated based on the initial distribution of user responses before adaptation. The analysis used a chi-squared test, comparing observed and expected values to determine whether the adaptive adjustments significantly impacted user movement. Python's SciPy library performed the test, calculating statistical values for each category, while NumPy managed data arrays and Pandas organised the results in a tabular format. This approach ensured precise, reproducible calculations, directly demonstrating the system's ability to influence user behaviour.

TABLE IV

Chi-Squared Test Table (Movement Change) [by the authors]

EMOTION TYPE	OBSERVED (AFTER)	EXPECTED	DIFFERENCE	CHI-SQUARED VALUE
CALM	33	89	–56	35.24
HAPPY	34	20	14	9.80
SPOOKED	33	73	–40	21.92
TOTAL	**100**	**182**	**–82**	**66.96**

The expected movement values (89 for CALM, 20 for HAPPY, and 73 for SPOOKED) were randomised within a range of ± 50 % of the baseline user count, reflecting natural user variability. This ensured that expected values influenced observed changes, not the other way around (Table IV).

The simulation outcomes demonstrate the efficacy of the proposed adaptive emotional design (AED) methodology in effectively integrating emotional feedback into generative 3D spatial design. The tested spatial environments dynamically responded to in-Python simulated user emotional states, significantly influencing both spatial functionality and user engagement (Table V). By actively adjusting shapes, these environments effectively influence the user's behaviour. Nevertheless, it was recognised that while these results are promising, initial testing was confined to controlled simulated scenarios.

TABLE V

Simulation in Python with core libraries: NumPy, Pandas, Matplotlib, OpenCV [by the authors]

SIMULATED EMOTIONAL STATES AND SPATIAL RESPONSE (N – 100 VIRTUAL PEOPLE)				
Sample	Target emotion (user count %)	Light colour temperature (K)	Dominant adjusted shape	User movement change (%)
1.	CALM (33 %)	2700	Rounded, smooth	–63 % (relaxed)
2.	HAPPY (34 %)	3500	Playful, geometric	+68 % (explored)
3.	SPOOKED (33 %)	6500	Sharp, dark	–55 % (hesitated)

The table shows how simulated user behaviours dynamically responded to spatial adjustments.

Broader real-world applications, particularly in complex, public environments, will require further advancement in AI methods to reliably interpret and respond to the complexities of human emotional and behavioural interactions [22].

Through testing in virtual environments using software tools such as Blender, Davinci, Python and ChatGPT, the study validated the ability of the system to dynamically and accurately adjust spatial parameters in real-time, corresponding with predetermined emotional targets (e.g., CALM, HAPPY, SPOOKED). Platforms such as Mediapipe and OpenCV further emphasise the importance of combining emotion and gesture recognition for autonomous spatial control.

V. Discussion

This research presents pioneering steps in bridging the fields of embodied cognition, emotional design, and generative AI, revealing far-reaching implications and innovative applications that extend beyond traditional spatial design boundaries. While the current discussion emphasises practical applications within architectural and interior spaces, the potential of this methodology is significantly broader, warranting exploration across disciplines such as psychology, healthcare, education, urban planning, entertainment, and neuroscience.

A major strength of the proposed methodology lies in its flexibility, demonstrated effectively through both 3D software simulations and real-time adaptive space applications. The system is capable of integrating diverse emotional responses and adjusting environmental parameters accordingly. Nonetheless, limitations persist, particularly concerning the accurate interpretation of complex human emotions in multi-user environments, where conflicting emotional responses may complicate adaptive interventions. Overcoming this challenge will require advanced AI systems with deep contextual awareness and sophisticated emotion recognition capabilities.

The implications in healthcare are particularly transformative. The integration of adaptive emotional design (AED) could redefine therapeutic environments, dynamically adjusting parameters such as lighting, acoustics, aromatherapy, colour therapy, and personalised environmental cues based on biometric data. Hospitals and care facilities could implement responsive systems to reduce anxiety, accelerate patient recovery, and improve overall well-being. Further exploration could involve integrating AED with medical IoT devices, creating environments responsive to patient health metrics, thereby offering unprecedented customisation and care.

In educational contexts, AED systems have the potential to significantly enhance learning efficiency by dynamically modifying classroom environments to maintain optimal cognitive and emotional states. By leveraging real-time neurofeedback, such as EEG signals, educational spaces could adapt factors including ambient noise, room temperature, and visual stimuli to support improved concentration and emotional regulation among students.

The entertainment and leisure industries could similarly benefit from adopting AED methods. Dynamic adjustments to spatial configurations, sensory atmospheres, and narrative experiences could create immersive environments that respond in real-time to visitor emotions, greatly enhancing storytelling and visitor satisfaction in interactive museums, theme parks, and entertainment venues.

Urban planning and public spaces also stand to benefit substantially from AED integration. Emotionally intelligent public spaces could actively respond to real-time community emotions and needs, enhancing social cohesion and public well-being. Such smart urban environments could utilise crowd-sourced emotional data to manage pedestrian flow, reduce stress hotspots, and dynamically adjust public spaces during large-scale events or emergencies.

From a neuroscientific perspective, this research offers unique insights into the interplay between spatial design, emotional processing, and cognitive function. Investigating neurophysiological responses to adaptive spatial adjustments could significantly expand understanding within neuroarchitecture, potentially informing the design of spaces that proactively enhance cognitive and emotional health. Cross-disciplinary collaboration among architects, neuroscientists, and psychologists would facilitate ground-breaking developments in cognitive ergonomics and spatial cognition.

Despite its significant potential, the widespread implementation of AED systems introduces several potential dangers. One key aspect addressed by this research is the psychological impact of continuously adapting environments. While adaptive spaces can significantly enhance comfort and well-being, they also present a genuine risk of over-reliance on technology, potentially diminishing personal control and autonomy. This raises philosophical questions about the delicate balance between automation and human control, touching upon broader concepts within human-computer interaction and autonomy. Furthermore, psychological manipulation through emotionally adaptive environments represents a significant ethical concern. Robust privacy measures and stringent data protection protocols must be developed to prevent misuse or unauthorised access to sensitive emotional and biometric data, providing users with clear control over their environments. This could inform public policy decisions regarding the ethical deployment of emotionally intelligent AI technologies across both private and public sectors.

Future research should explore the connection between machine learning and design methodologies. Also, it could include more parameters to encompass multisensory variables such as texture, aroma, temperature, and haptic feedback. The integration of advanced neuro-responsive technologies, including EEG and biofeedback mechanisms, could further enhance system adaptability. Additionally, long-term studies on the psychological impact and user acceptance of continuously adaptive environments are essential to ensuring sustained comfort and well-being.

In conclusion, by considering these innovative, cross-disciplinary implications and carefully addressing associated risks and ethical concerns, this research lays a foundation for transformative advancements across multiple fields, fundamentally reshaping our interaction with spatial design and technologies.

CONCLUSIONS

This study has demonstrated the transformative potential of integrating artificial intelligence (AI) into generative spatial design through the innovative approach of adaptive emotional design (AED). The study successfully achieved its primary objective of identifying and validating essential parameters for integrating AI-driven generative embodied modelling and emotional feedback.

The findings from simulations confirmed the effectiveness and practical applicability of AED. Target emotional states were consistently achieved by strategically adjusting spatial parameters, highlighting the robustness and adaptability of the proposed methodology. The flexibility inherent in this approach underscores its broad applicability across diverse contexts, including healthcare, educational programs and entertainment.

Nevertheless, several limitations and challenges were identified, particularly regarding the accurate interpretation of complex emotional states in multi-user environments, where conflicting or nuanced emotional reactions pose difficulties for real-time AI responsiveness. Enhancing AI capabilities for more precise emotional recognition and human response monitoring technologies represents further promising avenues for advancing this field. Additionally, the ethical dimensions related to adaptive environmental systems were recognised as critically important, notably concerning user consent, autonomy, and data privacy, especially in public or commercial settings.

The implications of this research are particularly significant for design, architecture, and art, where adaptive emotional responsiveness can profoundly influence user experiences and interactions. Designers and architects can leverage AED principles to create environments that dynamically evolve, enhancing aesthetic engagement and functional efficiency. In the realm of art, artistic tools are expanded and can be enhanced using real-time emotional feedback, allowing artists to create unique, deeply personalised and emotionally resonant experiences for the audience.

The next step would be the experimental applications to validate and further refine the proposed AED methodology. Implementing these adaptive systems in actual environments will enable researchers to comprehensively assess their effectiveness, examine user responses in authentic contexts, and identify practical challenges and opportunities for further development.

Ultimately, this research advances the understanding of AI's potential role in bridging human emotional experiences with spatial design practices. By laying the groundwork for responsive, user-centred environments, it contributes to a new generation of adaptive spaces designed explicitly to enhance human emotional well-being and cognitive engagement.

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Jonas Zukas was born in 1979. He obtained a BA (2001) and MA (2004) in Sculpture from the Vilnius Academy of Arts. In 2021, he received a PhD degree in History and Theory of Arts from Vilnius Tech University. Jonas is working in the field of universal design. In 2011, Jonas Žukas became a lecturer of Product Design at Raffles Education Corporation (Singapore). Since 2015, he has been teaching at the Department of Design of the Vilnius Tech Faculty of Architecture. Currently, he is an Associate Professor, and his research interests are the intuitiveness of the material environment.

Maksim Zhuk was born in 1989. He obtained a BA (2011) and MA (2013) in Visual Arts and Sociology from the European Humanities University. Maksim works in the fields of graphic design, generative art and teaching. In 2011, Maksim Zhuk became a lecturer of Graphic Design and 3D at EHU.

Lukas Misiunas holds a Bachelor of Industrial Design (2022) from the Academy of Arts, Vilnius, Lithuania and a Master of Strategic Design and Innovation (2023) from Istituto Europeo di Design, Milano, Italy. Currently, he is a Senior Product Designer in JSC "PLAGA", owner and CEO of SP "Nokturna", and Lecturer of Seamless Design and Design Evolution at Vilnius Gediminas Technical University. He has participated in local and international conferences. His research interests are AI integration in spatial design, seamless product design methodologies, and sustainable product design.

Contact Data

Gintaras Stauskis
Vilnius Gediminas Technical University,
Faculty of Architecture, Design Department
1 Traku St., 01132 Vilnius, Lithuania
E-mail: *jonas.zukas@vilniustech.lt*
ORCID iD: https://orcid.org/0000-0003-2500-3163

Maksim Zhuk
European Humanities University,
Department of Humanities and Arts
17 Savičiaus St., Vilnius, Lithuania
E-mail: *maksim.zhuk@ehu.lt*

Lukas Misiunas
Vilnius Gediminas Technical University,
Faculty of Architecture, Design Department
1 Traku St., 01132 Vilnius, Lithuania
E-mail: *lukas.misiunas@vilniustech.lt*