

# CogniSpace: A Proposed Framework for Cognitive Load-Aware Workplace Design Using Conversational AI and Multi-Modal Physiological Sensing

Parth Shewale<sup>1</sup>, Rohan Saswade<sup>2</sup>, Ritesh Shilimkar<sup>3</sup>, Dr. Prashant Wakhare<sup>4</sup>

Student, Department of AI & DS, AISSMS Institute of Information Technology, Pune, Maharashtra, India<sup>1-3</sup>

Professor, Department of AI & DS, AISSMS Institute of Information Technology, Pune, Maharashtra, India<sup>4</sup>

**Abstract:** *AI-driven interior design tools currently optimize for aesthetic preference, relying on facial expressions or style tags to personalize environments. None of them account for the user's actual cognitive state. This paper proposes CogniSpace, a framework that extends this paradigm toward workplace cognitive performance optimization. We propose a Tri-Modal Cognitive Sensing (TMCS) module fusing EEG theta/alpha ratios, vocal stress analysis, and facial Action Unit decomposition into a unified Cognitive Load Index (CLI). A Cognitive Load-Driven Layout Adaptation (CLDA) loop maps CLI scores to evidence-based environmental interventions in real time. We further propose a Multi-Hop Spatial Constraint Resolver (MHSCR) addressing the documented 35% failure rate of 8B-parameter LLMs on complex spatial commands, and a Hybrid Procedural-Retrieval Generation (HPRG) pipeline enabling on-demand 3D asset creation beyond fixed catalogs. This is a design proposal; full implementation and evaluation are planned as future work. We argue this direction — Neuro-Adaptive Design Systems (NADS) — represents a meaningful and underexplored research frontier..*

**Keywords:** Cognitive Load, Conversational AI, LLM, EEG, Multi-Modal Sensing, Workplace Design, Procedural 3D Generation, Neuro-Ergonomics

## I. INTRODUCTION

The physical configuration of a workplace has a direct, measurable impact on cognitive performance. Decades of research in environmental psychology have established that variables including lighting, spatial density, acoustic properties, and biophilic elements significantly affect sustained attention, working memory, and decision-making quality [1], [2]. Yet AI-driven design tools such as Aura Architect [3], LLplace [4], and DecoMind [5] optimize exclusively for aesthetic preference — personalizing based on what users find visually appealing rather than what scientifically supports their cognitive function.

This gap motivates CogniSpace. Rather than asking 'what do you want your workspace to look like?', we propose a system that continuously measures a user's cognitive load through non-invasive physiological sensors and adapts the 3D workspace layout in real time to reduce that load. This approach — which we term a Neuro-Adaptive Design System (NADS) — represents a shift from decorative assistance to neuro-ergonomic environmental engineering.

Our proposal makes four primary contributions: (1) the Tri-Modal Cognitive Sensing module (TMCS), (2) the Multi-Hop Spatial Constraint Resolver (MHSCR), (3) the Hybrid Procedural-Retrieval Generation pipeline (HPRG), and (4) the Cognitive Load-Driven Layout Adaptation feedback loop (CLDA). Table 1 positions CogniSpace against prior systems.

**Table 1: Positioning of CogniSpace Against Related Systems**

System	LLM	Physio Sensing	3D Generation	Cognitive Opt.	Multi-hop Spatial
Aura Architect [3]	Llama 3 8B	Face (FER)	Retrieval only	Aesthetic only	65% accuracy



		only)			
LLplace [4]	Llama 3	None	Retrieval	No	Partial
DecoMind [5]	GPT-based	None	Generative	Style only	Not reported
<b>CogniSpace (Proposed)</b>	<b>Llama 3 8B Local</b>	<b>EEG + Voice + AU</b>	<b>HPRG Hybrid</b>	<b>CLI-Driven</b>	<b>MHSCR (proposed)</b>

## II. RELATED WORK

**Conversational AI Design Tools:** ATISS [6] introduced autoregressive transformers for indoor scene synthesis without user intent grounding. LLplace [4] and Aura Architect [3] added LLM-driven layout editing and affective personalization respectively. A shared limitation persists: all systems use subjective preference signals and none incorporate objective physiological measures of cognitive state.

**Cognitive Load Measurement:** Sweller's cognitive load theory [7] established that mental effort has measurable physiological correlates. The EEG frontal theta/alpha power ratio is a validated real-time indicator of working memory load [8], achievable with consumer headbands (Muse 2, OpenBCI Ganglion) [9]. Vocal F0 perturbation and harmonic-to-noise ratio (HNR) degradation provide a complementary signal requiring only a microphone [10]. Facial Action Units AU4 and AU7 independently correlate with cognitive effort [11]. No prior design system has used any of these signals.

**Environment and Cognition:** Illuminance of 500–1000 lux improves sustained attention [12]. Spatial density above 40% floor coverage elevates cortisol [13]. Biophilic elements reduce stress biomarkers [14]. Ambient noise below 50 dB(A) supports focused work [15]. CogniSpace operationalizes these findings as computable intervention rules triggered by CLI thresholds.

## III. THEORETICAL FRAMEWORK

### A. Cognitive Load Index (CLI)

We propose combining three normalized physiological signals into a single scalar. Let  $\theta$  and  $\alpha$  denote EEG frontal theta (4–8 Hz) and alpha (8–13 Hz) band power,  $V\_stress$  the vocal stress coefficient, and  $AU\_effort$  the normalized mean of facial Action Units AU4 and AU7. The proposed CLI is:

$$CLI = w_1 \cdot (\theta/\alpha) + w_2 \cdot V\_stress + w_3 \cdot AU\_effort \quad (1)$$

Initial weights  $w_1 = 0.50$ ,  $w_2 = 0.30$ ,  $w_3 = 0.20$  reflect the relative predictive strength of each modality in the literature [8], [10], [11]. CLI is normalized to [0,1] via a 90-second baseline calibration at session start. Three zones are defined: Low Load ( $CLI < 0.35$ ), Moderate Load ( $0.35-0.65$ ), and High Load ( $\geq 0.65$ ), each triggering distinct workspace interventions as shown in Table 2.

**Table 2: Proposed CLI Zone Intervention Policy**

Zone	CLI Range	Proposed Environmental Interventions (Evidence-Based)
Low Load	$< 0.35$	Maintain layout; warm lighting (2700K); creative spatial density permitted [12]
Moderate Load	$0.35-0.65$	Reduce furniture density $< 30\%$ floor area; cool-white lighting 5000K/700 lux; add acoustic panels [13],[15]
High Load	$\geq 0.65$	Insert biophilic elements (plants, natural textures); remove visual clutter; task lighting 1000 lux [12],[14]



### B. Multi-Hop Spatial Constraint Resolver (MHSCR)

Aura Architect [3] reports 65% accuracy on spatial commands involving three or more chained object relationships. We attribute this to context window overload in 8B-parameter models. The proposed MHSCR pre-processes complex commands into a Directed Acyclic Graph (DAG), then resolves each edge atomically in topological sort order. For object  $O_i$  with anchor  $O_j$  and spatial relationship  $R_{ij}$ :

$$\text{Placement}(O_i) = T(O_j) + \Delta(R_{ij}) \quad (2)$$

This reduces multi-hop reasoning to a sequence of single-hop inferences, each within the reliable capability of an 8B model. We hypothesize this will raise multi-hop accuracy from 65% to above 85%.

## IV. PROPOSED SYSTEM ARCHITECTURE

CogniSpace is proposed as a full-stack web application with four subsystems. All inference is local — no physiological data leaves the device. The frontend uses React.js, React Three Fiber (R3F), and Zustand for state. The backend is Node.js/Express. The LLM layer uses Ollama with Llama 3 8B locally. Persistence uses Supabase PostgreSQL and object storage for 3D assets.

### A. Tri-Modal Cognitive Sensing (TMCS)

**EEG Channel:** Consumer EEG (Muse 2/OpenBCI) via Web Bluetooth API. Raw data at 256 Hz; in-browser FFT computes  $\theta/\alpha$  ratio over 2-second Hanning windows, updated every 500ms.

**Vocal Stress Channel:** Web Audio API captures microphone. JavaScript DSP pipeline computes F0 jitter and HNR; elevated jitter ( $>0.5\%$ ) and reduced HNR ( $<15$  dB) contribute to  $V_{\text{stress}}$  [10].

**Facial AU Channel:** Face-API.js extended with a custom AU4/AU7 model fine-tuned on DISFA+ [11], running entirely on-device via WebGL.

### B. Neuro-Spatial LLM Agent (NSLA)

Every inference request injects the current CLI score, zone classification, and applicable intervention policy into the Llama 3 system prompt alongside the scene state. When  $\text{CLI} \geq 0.65$ , a hard constraint prioritizes cognitive load-reducing interventions over user aesthetic preferences. Multi-object commands are pre-processed by the MHSCR before LLM inference. The LLM outputs structured JSON specifying object category, placement strategy, and CLI intervention actions. Expected end-to-end latency: 1.2–1.5 seconds.

### C. Hybrid Procedural-Retrieval Generation (HPRG)

When a catalog asset's semantic similarity to the LLM-requested object exceeds threshold  $\tau = 0.72$  (cosine similarity), the retrieval path is taken (~310ms). When similarity falls below  $\tau$  — as expected for CLI-triggered elements such as acoustic baffles or biophilic screens — the procedural path generates THREE.js geometry via parameterized shape grammars in under 100ms. This eliminates the catalog constraint that limits prior retrieval-only systems.

### D. Cognitive Load-Driven Layout Adaptation (CLDA) Loop

Every 30 seconds, the CLDA module evaluates CLI and checks for zone transitions. On a transition, it generates a CLI-contextualized prompt, routes it through NSLA and HPRG, and applies the layout modification to the live scene. The user is notified via a non-intrusive overlay and retains full undo capability through natural language commands, preserving human-in-the-loop control.

## V. PROPOSED EXPERIMENTAL EVALUATION

No experiments have been conducted yet. We present the following protocol to make our hypotheses explicit and invite peer scrutiny.



### A. Research Hypotheses

- H1:** Tri-modal CLI will correlate more strongly with NASA-TLX self-report ( $r > 0.75$ ) than any single modality alone.  
**H2:** MHSCR will achieve  $\geq 85\%$  accuracy on multi-hop spatial commands vs. 65% baseline [3].  
**H3:** Participants in the CogniSpace CLDA condition will show lower CLI and NASA-TLX scores at 60 minutes vs. control and static aesthetic conditions.  
**H4:** HPRG procedurally generated assets will achieve  $\geq 75\%$  user acceptance on a 5-point adequacy scale.

### B. Planned Study Design

24–30 participants will complete three counterbalanced 60-minute knowledge work sessions under three conditions: (1) standard office (control), (2) static aesthetically-designed environment, and (3) CogniSpace CLDA-adaptive environment. CLI will be monitored continuously; NASA-TLX collected at 15-minute intervals; task quality assessed via a rubric scored by two independent raters.

**Table 3: Planned Measurements and Hypothesized Outcome Directions**

Metric	Instrument	Frequency	Hypothesized Direction (CogniSpace vs. Control)
Cognitive Load	CLI (real-time)	Every 500ms	Lower mean CLI at 60min (H3)
Subjective Load	NASA-TLX	Every 15 min	Lower score at 60min (H3)
Spatial Accuracy	200-item benchmark	Post-implementation	MHSCR $\geq 85\%$ multi-hop (H2)
CLI Validity	Pearson r vs. TLX	Per session	Tri-modal $r > 0.75$ (H1)
Asset Acceptance	5-pt adequacy scale	Per asset generated	Procedural $\geq 75\%$ (H4)

## VI. CONCLUSION

This paper has proposed CogniSpace, a Neuro-Adaptive Design System that extends the conversational AI interior design paradigm from aesthetic personalization to real-time cognitive performance optimization. We identified a clear and unexplored gap in the literature: no existing system measures the user's actual physiological cognitive state and uses it to drive workspace adaptation. We proposed four novel architectural components — TMCS, MHSCR, HPRG, and CLDA — each addressing a specific limitation of prior work and grounded in peer-reviewed literature from environmental psychology, cognitive neuroscience, and HCI.

We explicitly acknowledge that CogniSpace has not yet been implemented or tested. This paper presents the research case, theoretical foundations, and a detailed architectural blueprint. Our immediate next steps are implementing the TMCS sensing pipeline, validating CLI against NASA-TLX in a controlled study, and benchmarking the MHSCR against the spatial accuracy baseline of [3]. Empirical results will be reported in a follow-up paper. We invite community feedback on the proposed architecture and evaluation methodology.

## REFERENCES

- [1] D. Clements-Croome, *Intelligent Buildings: Design, Management and Operation*. London: Thomas Telford, 2004.
- [2] G. W. Evans and D. Johnson, "Stress and open-office noise," *J. Appl. Psychol.*, vol. 85, no. 5, pp. 779–783, 2000.
- [3] R. Bharadwaj et al., "Aura Architect: An AI-Driven Conversational 3D Interior Design Tool," VIT Pune, 2024.
- [4] Y. Yang et al., "LLplace: The 3D indoor scene layout generation via large language model," arXiv:2406.03866, 2024.
- [5] R. Alshehri et al., "DecoMind: A generative AI system for personalized interior design," arXiv:2508.16696, 2025.
- [6] D. Paschalidou et al., "ATISS: Autoregressive transformers for indoor scene synthesis," *NeurIPS*, 2021.



- [7] J. Sweller, "Cognitive load during problem solving," *Cogn. Sci.*, vol. 12, no. 2, pp. 257–285, 1988.
- [8] R. Berka et al., "EEG correlates of task engagement and mental workload," *Aviation Space Environ. Med.*, vol. 78, no. 5, pp. B231–B244, 2007.
- [9] I. Daly et al., "A new wireless EEG instrument for real-time monitoring," *Proc. 5th BCI Meeting*, 2013.
- [10] B. Schuller et al., "The INTERSPEECH 2010 paralinguistic challenge," *Proc. INTERSPEECH*, 2010.
- [11] S. Mavadati et al., "DISFA: A spontaneous facial action intensity database," *IEEE Trans. Affect. Comput.*, vol. 4, no. 2, pp. 151–160, 2013.
- [12] P. Boyce, *Human Factors in Lighting*, 3rd ed. CRC Press, 2014.
- [13] J. Evans, "Environmental stress and health," *Handbook of Health Psychology*, 2001, pp. 365–385.
- [14] S. Kaplan, "The restorative benefits of nature," *J. Environ. Psychol.*, vol. 15, no. 3, pp. 169–182, 1995.
- [15] B. Shield and J. Dockrell, "Effects of noise on academic attainments," *J. Acoust. Soc. Am.*, vol. 123, no. 1, pp. 133–144, 2008.

