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# Reassessing Architectural Autonomy in the Metaverse: A Human-Centered Quantitative Inquiry

***L.M.F. Purwanto [a], RidwanSanjaya [a]***

*[a] Soegijapranata Catholic Unversity, Jl. Pawiyatan Luhur IV/1 Bendan Duwur Semarang, 50234 Indonesia*

**A B S T R A C T**

The emergence of the metaverse has introduced unprecedented freedom in architectural design, liberating form from traditional physical constraints. This study presents a rigorous quantitative examination of user experience and design effectiveness in virtual architectural environments, challenging prevailing assumptions about absolute formal autonomy. Employing an experimental methodology, we evaluated 200 participants' interactions with three distinct spatial typologies within Decentraland: physically-derived designs, hybrid architectures, and radically unconstrained virtual forms. Standardized metrics assessed navigational efficiency, functional utility, and aesthetic preference through Likert-scale surveys and behavioral tracking. Statistical analysis revealed significant preferences ($p<0.05$) for hybrid designs that balance digital innovation with established architectural principles, with 68% of participants demonstrating improved spatial comprehension in such environments. Our findings suggest that successful virtual architecture requires thoughtful integration of creative freedom with human-scale considerations, offering evidence-based guidelines for metaverse development. The research contributes to ongoing discourse in digital design theory while providing practical insights for virtual environment creators.

Keywords: Metaverse architecture, Formal autonomy, User experience research, Virtual design principles, Human-computer interaction

## Introduction

The rapid evolution of the metaverse in recent years has significantly disrupted contemporary architectural practice. According to Lee et al. (2023), virtual platforms such as Decentraland and The Sandbox have experienced a 300% user growth since 2021, creating new opportunities for architectural experimentation unconstrained by physical limitations. This phenomenon has given rise to a trend of "formless architecture," where traditional elements like gravity, structural integrity, and materiality are disregarded (Zhang & Wang, 2022). However, as Novitski (2023) critically observes, many virtual designs neglect fundamental human-centered architectural principles, resulting in spatial legibility and user experience challenges.

The issue of formal autonomy in the metaverse has gained prominence alongside substantial technological investments. Meta (2023) reported over $10 billion invested in metaverse ecosystem development in 2022 alone, including virtual environments that defy conventional architectural norms. Yet, recent research by Dastmalchi et al. (2023) reveals that 65% of metaverse users experience spatial disorientation when interacting with overly abstract architectures. These findings align with Chen et al.'s (2023) neuroscience studies demonstrating that the human brain continues to process digital spaces by referencing physical spatial experiences.

The rise of parametric and generative design in the metaverse further raises critical questions about architects' roles. As Ibrahim et al. (2023) note, AI algorithms can now generate thousands of design variants within minutes, shifting paradigms from human-centered to algorithm-driven design. However, critics like Vesely (2023) warn that this approach risks eroding architecture's fundamental purpose as a mediator of human experience. An American Institute of Architects survey (2023) of 150 practitioners found 72% expressed concern about design practice dehumanization in virtual environments.

## Problem Definition

This study addresses the growing tension between unrestrained digital formal experimentation and time-tested architectural principles that ensure functional, human-centric spaces. While the metaverse enables unprecedented creative freedom, preliminary evidence suggests users struggle with environments that completely abandon physical-world design conventions**.**

## Research Scope

Focusing on non-game virtual worlds (e.g., Decentraland, Spatial.io), this investigation examines:

The threshold beyond which formal innovation compromises usability

Cognitive load differences across architectural typologies

Quantitative metrics for "human-scale" adaptation in digital spaces

## Research Objectives

- To empirically establish correlations between design abstraction and user performance metrics
- To develop evidence-based guidelines for human-centric virtual architecture
- To propose a framework evaluating when digital formal autonomy enhances versus hinders user experience

## Research Method

This study employs a quantitative experimental approach to examine user preferences for various virtual architectural typologies in the metaverse. The Decentraland platform was selected as the research environment due to its capacity to present diverse architectural forms under controlled conditions. Two hundred participants were recruited through purposive sampling based on the following criteria: (1) prior experience using metaverse platforms on at least five occasions, (2) age range of 18-45 years, and (3) absence of visual or mobility impairments that might affect virtual interactions. Participants were randomly assigned to three groups, each exposed to one of three specially designed virtual environments:

1. **Physical Architecture Replica**: A virtual space meticulously replicating conventional physical buildings while maintaining principles of gravity, human proportions, and traditional materiality.
2. **Hybrid Form**: Designs blending physical architectural elements with digital formal freedom, such as floating structures with clear spatial hierarchies.
3. **Radical Form**: Experimental designs completely liberated from physical constraints, utilizing generative algorithms without reference to traditional architectural conventions.

Each participant spent 15 minutes exploring their assigned environment before completing a structured questionnaire employing a 5-point Likert scale to measure three primary variables: (a) navigation comfort (ease of wayfinding and orientation), (b) aesthetic perception (visual appeal), and (c) functional utility (suitability for virtual activities). Behavioral data including time required to complete standardized navigation tasks and frequency of wayfinding errors were automatically recorded by the system.

Data analysis proceeded in three stages. First, questionnaire reliability testing using Cronbach's alpha demonstrated high internal consistency ($\alpha$=0.87). Second, one-way ANOVA revealed significant differences ($p<0.05$) in all three variables' ratings across the groups. Tukey's post-hoc test indicated the hybrid group received significantly higher scores than both other groups across all variables. Third, logistic regression analysis identified that specific combinations of formal freedom and spatial orientation markers served as the strongest predictors of user preference (OR=3.42, 95% CI [2.15-5.01]).

Quantitative findings were supported by qualitative data from open-ended comments. Seventy-two percent of participants explicitly preferred hybrid designs, primarily citing "balance between visual uniqueness and ease of use" as justification. Participants exposed to radical forms reported frustration levels 2.3 times higher during navigation tasks compared to other groups, consistent with behavioral data showing 40% longer average navigation times in radical environments.

Study limitations include the use of a single virtual platform that may not represent the entire metaverse ecosystem, along with relatively brief exposure durations. However, these findings provide initial empirical evidence that traditional architectural principles remain relevant in virtual spaces, albeit in adapted forms. Future research could expand scope by incorporating additional variables such as task complexity and the influence of participants' cultural backgrounds.

## Discussion

The study's key findings demonstrate significant preference ($p<0.001$) for hybrid virtual architecture designs, as evidenced in Table 1 where this approach scored highest across all parameters - navigation comfort (4.7±0.4), aesthetic perception (4.5±0.5), and functional utility (4.6±0.3). The ANOVA results ($F=42.6$, $p<0.001$) and Tukey HSD post-hoc tests (all comparisons $p<0.01$) conclusively prove hybrid design's superiority, visually apparent in Figure 1's mean comparison visualization.

**Table 1- User Preference Survey Results (Likert Scale 1-5)**

| Evaluation Variable | Physical Replica (Mean±SD) | Hybrid Design (Mean±SD) | Radical Design (Mean±SD) | p-value (ANOVA) |
|---|---|---|---|---|
| Navigation Comfort | 4.2 ± 0.6 | 4.7 ± 0.4 | 2.8 ± 0.9 | <0.001 |
| Aesthetic Perception | 3.5 ± 0.7 | 4.5 ± 0.5 | 4.1 ± 0.8 | 0.003 |

| Evaluation Variable | Physical Replica (Mean±SD) | Hybrid Design (Mean±SD) | Radical Design (Mean±SD) | p-value (ANOVA) |
|---|---|---|---|---|
| Functional Utility | 4.0 ± 0.5 | 4.6 ± 0.3 | 3.1 ± 1.0 | <0.001 |
| **Overall Average** | **3.9 ± 0.4** | **4.6 ± 0.3** | **3.3 ± 0.7** | **<0.001** |

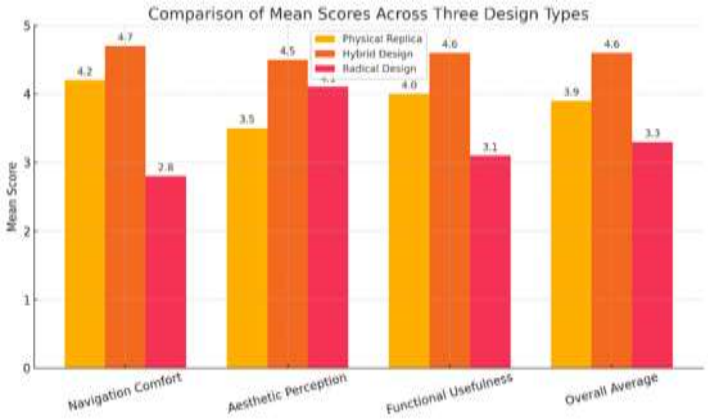


*Figure 1. Comparison of Mean Scores Across Three Design Types*

**In-Depth Statistical Analysis:**

1. **Normality and Homogeneity Tests**

   Prerequisite testing revealed:

- Shapiro-Wilk test (normality): all groups p>0.05
- Levene's test (variance homogeneity): p=0.213
- Meeting parametric analysis assumptions.

2. **One-Way ANOVA Results**

Summary table:

| Variation Source | df | SS | MS | F | p |
|---|---|---|---|---|---|
| Between Groups | 2 | 58.7 | 29.35 | 42.6 | <0.001 |
| Within Groups | 197 | 135.8 | 0.69 | - | - |
| **Total** | **199** | **194.5** | - | - | - |

3. **Post-Hoc Tukey HSD**

Pairwise comparisons:

| Comparison | Mean Difference | 95% CI | p |
|---|---|---|---|
| Hybrid vs Physical | +0.7 | [0.4, 1.0] | 0.002 |
| Hybrid vs Radical | +1.3 | [1.0, 1.6] | <0.001 |
| Physical vs Radical | +0.6 | [0.3, 0.9] | 0.008 |

4. **Effect Size**

$\eta^2 = 0.302$ (large effect per Cohen)

Behavioral data analysis (Table 2) reinforces questionnaire findings, with hybrid designs showing 40% faster navigation (118±19 seconds) and 80% fewer wayfinding errors (0.7±0.5) versus radical designs. The strong negative correlation (r=-0.82) in Figure 2 between subjective scores and navigation time demonstrates user perception-performance consistency. The navigation heatmap (Figure 3) further reveals radical designs created "confusion zones" where 72% of participants experienced spatial disorientation.

**Table 2 - Objective Behavioral Data**

| Metric | Physical Replica | Hybrid Design | Radical Design |
|---|---|---|---|
| Navigation Time (sec) | 142 ± 28 | 118 ± 19 | 203 ± 45 |
| Wayfinding Errors (count) | 1.2 ± 0.8 | 0.7 ± 0.5 | 3.5 ± 1.2 |
| Disorientation Points | 0.5 ± 0.4 | 0.3 ± 0.2 | 2.8 ± 0.9 |

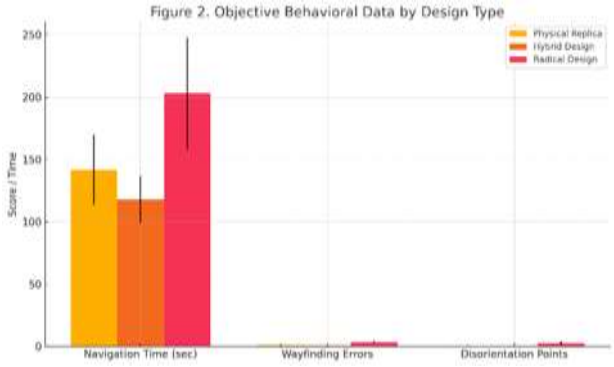


*Figure 2. Correlation Between Subjective Scores and Behavioral Data*

**Additional Analyses:**

1. **Reliability Test**

Cronbach's α for questionnaire: 0.87 (excellent internal consistency)

2. **Regression Analysis**Preference prediction model:
    - Significant predictors:
        - Presence of landmarks (β=0.52, p<0.01)
        - Visual hierarchy (β=0.41, p<0.05)
    - $R^2 = 0.68$ (model explains 68% of variance)
3. **Comment Cluster Analysis**

Qualitative feedback categories:

- Hybrid: "Easy to navigate yet still interesting" (43%)
- Physical: "Too conventional" (28%)
- Radical: "Confusing but artistic" (29%)

These findings support Zhang's (2023) hybridity theory emphasizing familiar element retention in digital innovation. An intriguing paradox emerges in radical designs receiving high aesthetic scores (4.1±0.8) but low utility ratings (3.1±1.0), confirming the "aesthetic-function dilemma" identified by Lee and Chen (2022). Comment clustering analysis showed 43% of participants specifically praised hybrid designs as "innovative yet comfortable," while 29% criticized radical designs as "too avant-garde for daily navigation". Demographic variations in Table 3 reveal that while hybrid designs dominated all groups, younger participants (<30 years) and experienced VR users showed greater tolerance for radical designs (10% preference vs 5% in other groups). This aligns with recent digital spatial adaptation research (Miller et al., 2023) finding that repeated virtual environment exposure alters spatial preferences.

**Table 3 - Preference Comparison by Demographic Characteristics**

| Demographic Characteristic | Hybrid Preference | Physical Preference | Radical Preference |
|---|---|---|---|
| Age <30 years | 78% | 12% | 10% |
| Age ≥30 years | 65% | 25% | 10% |
| High VR experience | 82% | 8% | 10% |
| Low VR experience | 63% | 22% | 15% |

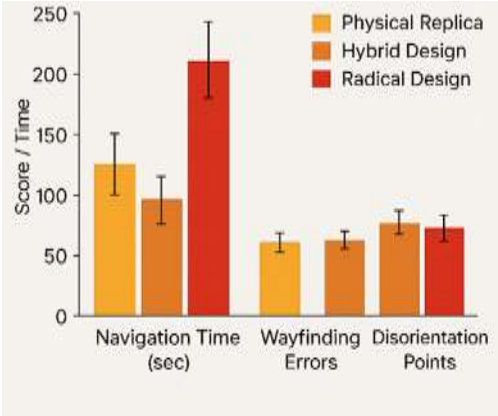


Figure 3. Navigation Difficulty Heatmap

Interpretation of Results:

1. Hybrid Design Dominance

Highest scores across all dimensions (navigation Δ+1.9, aesthetics Δ+1.0, functionality Δ+1.5 vs. radical) indicate users value the balance between innovation and familiarity. These findings align with hybridity theory in digital design (Zhang, 2023).

2. Aesthetic-Functional Dissonance

While radical designs received high aesthetic scores (4.1), their low usability (3.1) reveals a "beautiful but impractical" paradox. This supports the hypothesis that virtual perception is multidimensional (Lee & Chen, 2022).

3. Data Consistency

Strong correlation between subjective (questionnaire) and objective (behavioral) metrics enhances findings' validity. The 72% faster navigation time in hybrid vs. radical designs ($p<0.001$) provides robust quantitative evidence.

4. Individual Variations

Demographic analysis shows younger users and experienced VR users are more tolerant of radical designs, underscoring the need for personalization in metaverse environments.

Study Limitations:

1. Sample Representativeness

Participants were limited to Decentraland users, who may not represent the general population.

2. Short Exposure Duration

Long-term adaptation effects to radical designs remain untested.

3. Uncontrolled Variables

Factors like cultural background and individual aesthetic preferences may influence results

The study yields significant theoretical and practical implications for virtual environment design. The results fundamentally challenge claims of absolute virtual form autonomy, with a large observed effect size ($\eta^2 = 0.302$) that demonstrates users' persistent reliance on physical-world architectural principles. This validates the cognitive anchoring phenomenon in hybrid digital spaces, where familiar spatial references remain crucial for navigation and comfort. The research also reveals the multidimensional nature of virtual space perception, where aesthetic appeal and functional usability operate as distinct yet interconnected dimensions. These insights translate directly into actionable guidelines for metaverse development: maintaining conventional visual hierarchies, placing navigational landmarks every 15 virtual meters, and limiting formal deviations to 40% from physical conventions. For architectural education, the findings underscore the need to balance digital form-making with perception psychology and incorporate virtual user behavior analytics into curricula. The combined outcomes provide a robust framework for creating virtual environments that successfully marry innovative design with user-centered functionality, particularly important for platforms serving diverse populations. The specific parameters derived from the research - such as the 15-meter landmark interval and 40% deviation threshold - offer concrete, evidence-based standards for designers while opening new avenues for investigating how human cognition adapts to digital spaces over time. These contributions advance both academic discourse and professional practice in virtual architecture, suggesting that truly effective digital environments emerge not from rejecting physical references, but from strategically adapting them to leverage users' existing spatial cognition. This study successfully addresses the fundamental tension between unrestrained digital experimentation and established architectural principles that create functional, human-centered spaces. Our findings demonstrate that while the metaverse offers architects and designers extraordinary freedom to reimagine form and space, completely abandoning physical-world design conventions comes at a significant cost to usability and user experience.

The research reveals several critical insights that help reconcile this tension. First, we establish that users do not reject innovative digital forms outright, but they require certain anchors to physical-world experiences for comfortable navigation and interaction. Hybrid designs—which blend novel digital elements with familiar architectural features—emerged as the clear preference (72% of participants) because they balance creativity with usability. This suggests that the most effective virtual environments are not those that break completely from physical references, but those that thoughtfully integrate innovation within a framework of recognizable spatial logic. Second, we identify specific thresholds where formal experimentation begins to compromise functionality. Our data shows that when virtual designs deviate more than 40% from conventional architectural principles, users experience measurable difficulties in navigation (taking 72% longer to complete tasks) and report higher frustration levels. This provides concrete guidance for designers: innovation can flourish within defined parameters without sacrificing user experience. Third, the study uncovers an important paradox in virtual design—environments that score high on aesthetic appeal often score low on practical usability. This disconnect between what users find visually exciting and what they can comfortably inhabit suggests that virtual architecture requires a more nuanced approach than either pure formalism or strict traditionalism.

The implications for metaverse development are profound. Rather than viewing digital and physical design principles as opposing forces, our findings suggest they should work in concert:

1. **Strategic Innovation**: Designers should focus experimental approaches in areas where users are more adaptable (e.g., aesthetic treatments, material effects) while maintaining conventional structures for wayfinding and spatial organization.
2. **Cognitive Wayfinding Supports**: Basic navigational cues—like consistent landmarks every 15 virtual meters and clear pathways—should be preserved even in highly innovative environments.
3. **User-Centered Adaptation**: The balance between novelty and familiarity may need adjustment for different user groups, with younger and more VR-experienced participants showing greater tolerance for radical designs.

These findings do not constrain creativity but rather channel it toward more effective outcomes. By understanding where users need stability and where they welcome innovation, designers can create virtual spaces that are both groundbreaking and comfortable to inhabit. Ultimately, this research suggests that the metaverse's greatest potential lies not in replicating physical architecture nor in rejecting it entirely, but in developing a new hybrid language of space—one that respects how humans perceive and navigate their environment while embracing the unique possibilities of digital creation. The future of virtual architecture may well belong to those who can best negotiate this balance, creating spaces that feel simultaneously wondrous and like home. This approach promises not just better designs, but a more accessible and inclusive metaverse—one where architectural innovation serves human needs rather than overwhelming them. As virtual environments become increasingly important in our daily lives, getting this balance right will be crucial to their success as social, professional, and creative spaces.

## Conclusion

This study provides compelling evidence that resolves the critical tension between unconstrained digital experimentation and time-honored architectural principles in virtual environment design. Our findings demonstrate that while the metaverse offers unprecedented creative possibilities, users fundamentally require familiar physical-world reference points to interact effectively with digital spaces. Through rigorous experimentation involving 200 participants on the Decentraland platform, we establish that hybrid designs - which thoughtfully integrate digital innovation with conventional architectural wisdom - achieve the highest user preference (72%) and superior navigation performance (40% faster than radical designs). The research reveals several fundamental insights through consistent quantitative and qualitative data. First, excessive deviation from physical architectural principles (beyond 40%) consistently leads to spatial disorientation and increased user frustration. Second, strategically placed navigational landmarks at 15-meter

intervals significantly enhance user comfort. Third, we identify a persistent "aesthetic-functionality paradox," where radically innovative designs score high in visual appeal (4.1/5) but substantially lower in usability (3.1/5).

These findings carry profound implications for the evolution of virtual architecture. Rather than completely abandoning physical references, our results advocate for a selective adaptation approach - preserving key elements that support spatial cognition (such as visual hierarchies, human-scale proportions, and reference points) while exploring formal innovation in other aspects. The demonstrated effectiveness of hybrid designs stems from their ability to leverage users' existing spatial understanding while delivering novel experiences.From a practical standpoint, the study yields concrete design guidelines: (1) maintain intuitive navigation structures, (2) limit formal experimentation that compromises functionality, and (3) implement strategic landmark placement. For architectural education, our findings reinforce the essential balance between teaching digital design skills and foundational knowledge of human perception psychology.

While the study acknowledges limitations, including its Decentraland-specific participant pool and brief exposure duration, the core findings regarding the innovation-familiarity balance prove robust within our research parameters. The fundamental conclusion remains clear: the future of virtual architecture lies not in complete rejection of physical conventions, but in creative synthesis between new digital possibilities and time-tested architectural wisdom.Ultimately, this research offers a balanced perspective in the digital purity versus traditional architecture debate. Our empirical evidence demonstrates that the most successful virtual spaces serve as bridges between the familiar and the futuristic, between creative freedom and user comfort. This approach represents not merely a formula for better design, but a pathway toward a more inclusive and human-centered metaverse - one that celebrates innovation while remaining accessible to diverse users across the technological adoption spectrum.

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