From Control to Contingency: Tolerance as a Generator of Digital Space

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This study repositions the concept of tolerance in XR-mediated digital space production from a narrow technical flexibility to a multi-layered principle of openness, uncertainty, and generative difference. In contrast to representational, form-centered, and deterministic design approaches, it advocates an understanding of space as a continuously emerging field of interaction and process. Drawing on Deleuze's concepts of becoming and difference and Parisi's account of speculative computation, the research conceptualizes XR space not as a fixed structure but as an evolving topology where deviations and contingencies are productive rather than erroneous. Experimental investigations extend from simulations, interpreted as agent-based systems, to sensor-driven embodied interaction in XR. These experiments reveal tolerance as an operative condition on behavioral, formal, and temporal levels: small parameter shifts or bodily variations generate qualitatively distinct outcomes, transforming unpredictability into creative potential. The findings demonstrate that tolerance is not a residual setting but a systemic bandwidth through which digital environments sustain novelty. The study contributes to architectural discourse by reframing tolerance as a missing conceptual link: an ontological, algorithmic, and experiential principle that sustains difference, enables co-authorship between human and machine, and positions XR-mediated design as an adaptive and processual mode of spatial production.

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Kontrolden Belirsizliğe:
Dijital Mekânın Üretiminde Tolerans

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Bu çalışma, XR aracılı dijital mekân üretiminde tolerans kavramını dar bir teknik esneklikten çok katmanlı bir açıklık, belirsizlik ve üretken fark ilkesi olarak yeniden konumlandırmaktadır. Temsile, biçim-merkezli ve deterministik tasarım yaklaşımlarına karşı, mekânın sürekli ortaya çıkan etkileşim ve süreç alanı olarak anlaşılmasını savunmaktadır. Deleuze'ün oluş ve fark kavramları ile Parisi'nin spekülatif hesaplama yaklaşımından yola çıkarak, XR mekânı sabit bir yapı olarak değil; sapmaların ve kontenjanların hata değil üretkenlik kaynağı olduğu evrimsel bir topoloji olarak kavramsallaştırmaktadır. Deneysel incelemeler, ajan-temelli sistemler olarak yorumlanan simülasyonlarından XR'de sensör tabanlı bedensel etkileşime uzanmaktadır. Bu deneyler, toleransın davranışsal, biçimsel ve zamansal düzlemlerde işleyen bir koşul olduğunu ortaya koymaktadır: küçük parametre kaymaları veya bedensel varyasyonlar, öngörülemezliği yaratıcı bir potansiyele dönüştüren niteliksel olarak farklı çıktılar üretmektedir. Bulgular, toleransın artık ikincil bir ayar değil, dijital ortamların yeniliği sürdürebilmesini sağlayan sistemik bir bant genişliği olduğunu göstermektedir. Çalışma, toleransı mimarlık söylemine eksik kalmış bir kavramsal halka olarak yeniden dahil ederek katkı sunmaktadır: farkı sürdüren, insan ile makine arasında eş-yazarlığı mümkün kılan ve XR aracılı tasarımı uyarlanabilir ve süreçsel bir mekân üretim biçimi olarak konumlandıran ontolojik, algoritmik ve deneyimsel bir ilke olarak konumlandırır.

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1. INTRODUCTION

Extended Reality (XR)—an umbrella term encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—has rapidly evolved as a medium that merges physical and digital environments into hybrid, immersive experiences. Unlike traditional architectural or screen-based digital models, XR-mediated spaces are not static representations but embodied environments that are continuously reshaped by user interaction, system feedback, and contextual conditions.

Despite this potential, many XR applications continue to reproduce physical environments as digital replicas or rely on conventional representational approaches. Such practices reduce XR to digital mimicry and overlook its capacity as a computational, process-driven, and interactive medium. This tendency reveals a methodological gap: the lack of design frameworks that fully exploit XR's immersive and dynamic affordances.

Within computational design, this gap becomes particularly evident in the treatment of the concept of tolerance. Often reduced to a technical "margin of error," tolerance has been framed as a constraint to be minimized rather than as a productive element of design. Yet in computational and adaptive systems, tolerance can be reinterpreted as openness to uncertainty, deviation, and difference—qualities that are central to the creative potential of XR-mediated environments.

This study therefore aims to reposition tolerance as a central design principle in XR-based digital space production. By shifting the discussion from tolerance as a technical parameter to tolerance as a creative and ontological condition, the paper articulates a conceptual and methodological framework grounded in agent-based modeling experiments. In doing so, it demonstrates how tolerance can be operationalized, visualized, and harnessed as a generative mechanism, offering new insights for the design of immersive and adaptive XR environments.

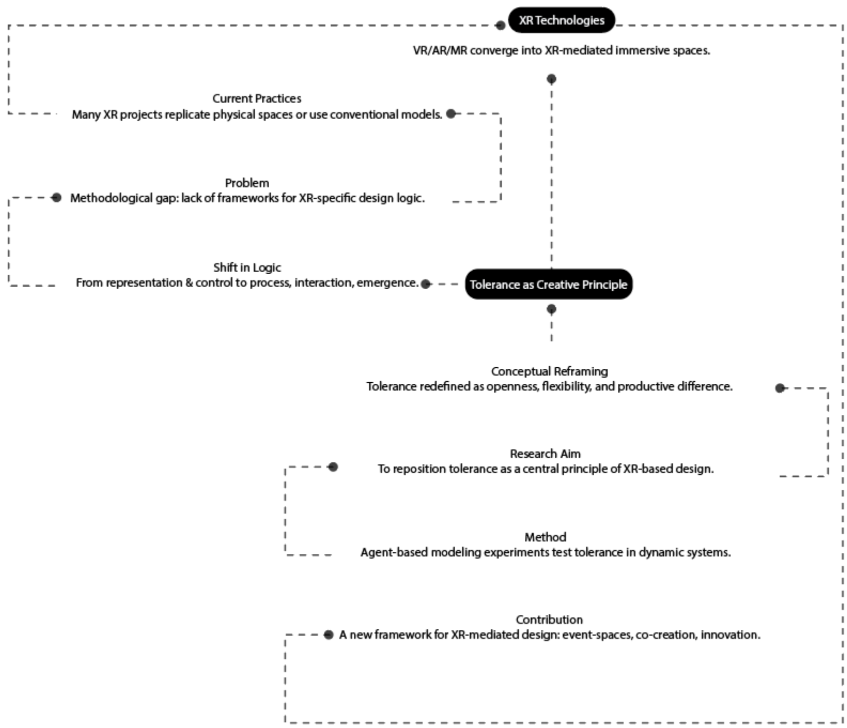


Figure 1: Conceptual cycle of the introduction: from XR technologies to tolerance as a creative principle in XR-mediated digital space.

In summary, the research problem addressed in this article is how tolerance can be repositioned from a marginal technical setting into a central creative principle of XR-mediated spatial experiences. To clarify this conceptual trajectory, **Figure 1** visualizes the logical flow of the study: starting from the emergence of XR technologies and their current practices, it highlights the methodological gap, the shift in design logic, and the reframing of tolerance. The cycle then connects the research aim and methodological choices to the broader contribution of the work, illustrating how tolerance functions not as a residual parameter but as the generative core of immersive digital design.

Building on this framework, the article proceeds in four stages. First, it outlines the philosophical foundations of XR-based digital space through concepts of difference, formation, and process. Second, it examines how tolerance operates within computational models such as agent-based systems. Third, it presents experimental studies that make tolerance visible through formal and spatial variations. Finally, it discusses how tolerance can be rethought as a creative design tool and ontological principle in XR-mediated environments.

2. TOLERANCE IN AGENT-BASED SYSTEMS: Algorithmic Flexibility and Distributed Generation

In XR-mediated digital environments, space can no longer be conceived as a visual surrogate of the physical world or as a symbolic vessel of cultural forms. When confined to representation, digital space is relegated to the circulation of images and the reproduction of identities, thereby neutralizing its most radical capacity: the generation of productive difference. By contrast, XR introduces a mode of spatiality that is immersive, relational, and processual, continuously reconfigured through embodied interaction, system feedback, and environmental contingencies. Within this horizon, tolerance must be redefined: no longer a narrow margin of technical error, it emerges as an ontological openness, the very condition through which deviation, uncertainty, and indeterminacy become productive forces rather than disruptive anomalies.

The difficulty of articulating such a shift lies in the long philosophical dominance of representational thought. From Plato's metaphysics of Ideas and Aristotle's logic of form and substance to Descartes' cogito, Kant's categorical schemata, and Hegel's dialectical totalities, Western philosophy has privileged the primacy of identity, resemblance, analogy, and opposition. Within this regime, difference has been subordinated to sameness, rendered either as deficiency or deviation. This lineage is broken decisively with the affirmation of difference in itself as a generative force of becoming (Deleuze, 1994). Thought, in this view, is not recognition but production; it does not ask "what is this?" but "what does this do?" In XR, this reversal is not merely conceptual but phenomenological: users encounter environments that do not present pre-coded forms to be recognized but relational systems of forces to be experienced. Tolerance is precisely the interval that sustains such openness, ensuring that variability manifests as creation rather than error.

Deleuze's concepts of repetition, multiplicity, and the virtual radicalize this framework. Repetition is never the return of the same but the inscription of difference in time; each recurrence is singular, irreducible to identity. Multiplicity designates a field of differences that cannot be subsumed into unity. The virtual is a reservoir of potentials whose actualizations are always partial, contingent, and incomplete. XR environments instantiate these dynamics directly: each gesture, gaze, or interaction actualizes different virtual potentials, generating singular spatial events that resist stabilization. Here, tolerance functions as the system's bandwidth, an elastic margin that allows the passage from the virtual to the actual without predetermination, enabling novelty to emerge as a systemic condition.

This rethinking extends into spatial ontology. Reality can be understood as a continuum of folds, where inside and outside endlessly inflect one another (Deleuze, 1993). Space ceases to be a homogeneous container and becomes a dynamic topology of curvature and transformation. XR environments operate within this register: minor parametric adjustments or behavioral perturbations fold spatial patterns into new configurations. Tolerance is what carries these folds; it is the threshold that allows infinitesimal differences to ramify into qualitative transformations, making instability a productive force rather than a system breakdown.

Luciana Parisi advances this line of thought into the computational domain. Algorithms are not inert mechanisms of calculation but speculative structures oriented toward incalculable possibilities (Parisi, 2013). Her notion of "parametric prehension" casts code as a selective and affective medium that senses, responds, and transforms in relation to data. Computation itself thus becomes a plane of becoming, resonant with the virtual (Deleuze, 1994): each execution condenses potential into actuality without exhausting it. In XR, such logics are rendered experiential, as environments mutate in real time according to the embodied inputs of users. Tolerance here is not error management but the operational latitude through which micro-variations in thresholds or parameters generate emergent, unforeseeable spatialities.

Digital design in this sense is grounded in an open, topological, and computational aesthetic (Parisi, 2013). Similar ambitions have been articulated within architectural practice by figures such as Marcos Novak, Greg Lynn, and Patrik Schumacher. Novak's notion of liquid architectures anticipated the idea that digital space should unfold as fluid, adaptive environments rather than as mimetic reproductions of physical structures (Novak, 1991). His work expanded the imagination of architecture into immersive, cybernetic, and speculative domains, foregrounding the capacity of the digital to construct entirely new spatial ontologies. Lynn's theorization of animate form reframed architecture as a temporal and process-driven entity, where geometry is not a fixed container but a continuously transforming material responsive to forces and contexts (Lynn, 1999). Schumacher's discourse on parametricism advanced this trajectory by proposing a systemic design paradigm in which variation, adaptability, and correlation between elements replace typological stability as the organizing logic of space (Schumacher, 2009). In parallel, reflections on digital tectonics highlighted the need to reconceptualize the structural and material dimension of architecture under digital conditions (Leach, Turnbull, & Williams, 2004), while Kolarevic emphasized the integration of design and manufacturing through algorithmic processes (Kolarevic, 2003), and Menges explored morpho-ecologies in which material performance and computational logic converge (Menges, 2007). Collectively, these contributions map the contours of a disciplinary shift: from architecture as representation and formal stability to architecture as dynamic, adaptive, and processual production.

Yet a critical tension remains. These contributions extend architectural thought beyond representation and formalism, but their emphasis often rests on stylistic novelty, formal proliferation, or aesthetic paradigms. The underlying question of tolerance—as the active negotiation of uncertainty and deviation—remains underdeveloped. In other words, computational design acknowledges emergence but rarely theorizes the systemic conditions that enable difference to become productive rather than accidental.

It is precisely here that this study turns toward agent-based systems. Unlike parametric or geometric frameworks, agent-based modeling foregrounds uncertainty, relationality, and decentralized decision-making as its operative logics. By generating difference as an inherent and irreducible quality, such systems provide a unique lens for examining tolerance not as a technical constraint but as a generative condition of spatial production.

As illustrated in **Figure 2**, the conceptual trajectory of this section moves from philosophical ontologies of difference, through computational mediation and architectural translation, toward the methodological operationalization of tolerance in agent-based systems, all within the lived horizon of XR environments. In the following section, agent-based approaches will therefore be introduced as the methodological ground for operationalizing tolerance. By moving from philosophical and theoretical arguments to computational experiments, the study demonstrates how tolerance can be both theorized and made visible as a systemic and creative quality of XR-mediated digital space.

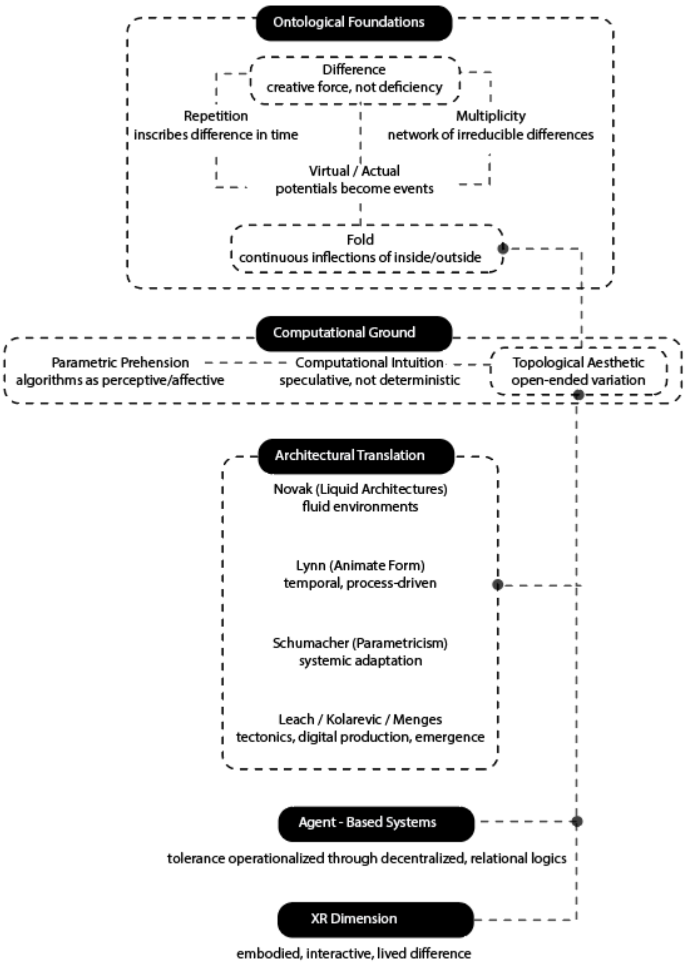


Figure 2: Conceptual Trajectory of Tolerance in XR-Mediated Digital Space.

3. TOLERANCE IN AGENT-BASED SYSTEMS: ALGORITHMIC FLEXIBILITY AND DISTRIBUTED GENERATION

In XR-mediated digital space production, the design is shaped not through predetermined forms but through interactive and plural processes; this causes design thinking to shift from static representation toward relational interaction, from precision toward openness, and from control toward emergence. This transformation is embodied through agent-based systems (Agent-Based Systems, ABS), which have emerged as an important methodological approach in the field of computational design. In such systems, tolerance is not a fixed margin of error but a range that enables the behavioral flexibility and evolutionary capacity of the system. More importantly, tolerance becomes the creative principle that allows unpredictable agent behaviors to produce novel spatial events in XR environments. In this section, the concept of tolerance will be analyzed through the basic features of agent-based models; the productive role of tolerance in distributed, local, and interaction-based space production will be discussed.

Agent-based systems are defined as decentralized structures that work on the behaviors of subcomponents and derive the whole from these local interactions. As defined by Macal and North, each agent is a unit that can perceive its environment, make decisions, and change its behavior according to the situation (Macal & North, 2010) . In these systems, integrity emerges not as a form imposed from above but through the micro-level relationships that agents establish with each other and their environments. Therefore, XR-based digital space is not an object produced by the designer; it is a process of formation resulting from the interactions of agents. In this process, tolerance comes into play as an openness that allows the system to differentiate and restructure rather than disintegrate when these interactions involve deviation, error, or unpredictability. From a methodological perspective, this means that system parameters (such as threshold values, behavioral rules, or probabilistic triggers) need to be explicitly defined and tested. In the following experimental section, these parameters will be detailed and visualized through step-by-step demonstrations to clarify how tolerance operates within the system.

In this context, tolerance becomes visible both in the way behavioral rules are defined and in the uncertainty of the agents' reactions to the environment. For example, an agent's not taking action when it passes a certain threshold value but showing different behaviors when it approaches the threshold value increases the tolerance capacity of the system. This enables the establishment of probabilistic systems based on openness instead of deterministic structures based on fixed rules. Thus, tolerance becomes a productive area that triggers behavioral diversity and differentiation, not a flexibility that only allows for error.

As Eric Bonabeau points out, agent-based modeling allows the system to operate in a way that is based on heterogeneity and local decisions (Bonabeau, 2002). This situation offers a radical alternative to the long-standing top-down modeling practices common in digital modeling traditions. In traditional modeling approaches, all components of the system are defined centrally, and each unit is obliged to comply with this definition. However, in agent-based approaches, the components (agents) are independent; they shape their behaviors according to the micro-scale interactions they enter with the environment. Here, tolerance becomes indispensable for the system to maintain its decentralized structure: even when the behavior of each agent is not completely predictable, the system has the capacity to develop new patterns instead of collapsing.

In agent-based systems, space is not just a background; it is an interaction surface for agents. Agents are both affected by this environment and change it by affecting it. This two-way relationship transcends classical understandings of space and transforms digital space into a "behavior area". Within this behavior area, tolerance shapes the dynamics of space depending on how agents read environmental data, how they react, and what deviations these reactions may contain. Here, the designer constructs the agent's area of action, decision mechanism, and interaction protocol, not the form. Tolerance operates in space between these decisions. In creative terms, this means that the designer shifts from authoring forms to co-authoring conditions for emergence. Tolerance provides the necessary openness for this co-authorship between designer, agent, and user.

4. EXPERIMENTAL APPLICATIONS: VISIBILITY AND PRODUCTIVE EFFECTS OF DIGITAL TOLERANCE

Tolerance in XR-mediated digital space production is not only a technical margin of flexibility but a principle that enables behavioral diversity and formal differentiation. To explore this, initial experiments employed a simple metaball algorithm. Although often treated as a basic modeling tool, metaballs can be read as an agent-based system, since each metaball acts as an agent generating a field and interacting locally with others. The focus here was not the final form but the dynamics of the system.

By varying parameters such as population count, seed, and threshold, it became clear that tolerance functions as a systemic condition: small shifts in thresholds produced radically different densities and connections, revealing that space emerges as a relational field rather than a predetermined geometry. These experiments established tolerance as the bandwidth through which uncertainty becomes generative.

The system used in experimental productions is based on a simulation in which interactive agents create a certain gravitational field, and these fields approach each other to form a superficial space. In this context, the basic inputs of the system were controlled with three parameters:

- Population Count: Number of agents
- Seed: Random value that determines the initial distribution
- Threshold: Interaction distance between agents, that is, tolerance range that determines whether the form will merge or not

To move beyond abstract simulation, the system was extended through visual analyses and embodied experiments in which the designer entered the network via sensor data. In this setting, tolerance became directly perceptible: deviations from bodily movement were absorbed by the algorithm and transformed into new spatial formations. The diagrams and video stills thus demonstrate that tolerance operates not only technically but also formally and experientially, sustaining novelty as the core condition of XR-mediated design.

4.1. Visual Analysis: Formal Expansion of Tolerance

As represented visually in the diagram in **Figure 3**, the presence of a single agent and a high threshold value caused the system to remain unsolved without creating any surfaces. This shows that the system loses its productivity in the absence of tolerance. When the number of agents is zero or the interaction thresholds are reduced to zero, no connection can be established between the parts, and the system remains in the void without producing forms.

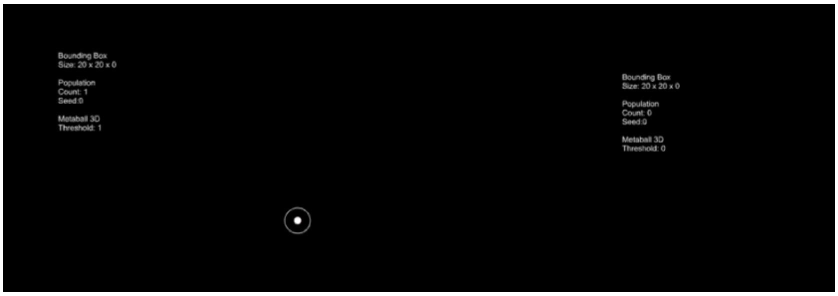


Figure 3: Left Image: Population Count: 1, Seed: 0, Threshold: 1 & Right Image: Population Count: 0, Seed: 0, Threshold: 0.

As represented visually in the diagram in **Figure 4** and **Figure 5**, it was observed that with the increase in the population number, the points surfaced, connected, and formed more holistic structures depending on the threshold value. The fact that the same number of agents produced completely different results only when the threshold value was different confirms that tolerance is a dynamic determinant in the production of digital space. This variability demonstrates tolerance as a mechanism of creative differentiation, where the system explores multiple possible outcomes instead of converging on a single solution.

Figure 4: Left Image: Population Count: 20, Seed: 0, Threshold: 0.5. & Right Image: Population Count: 20, Seed: 0, Threshold: 0.

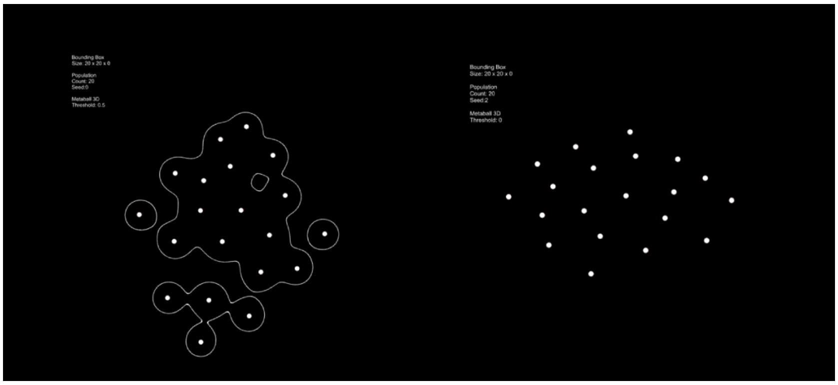
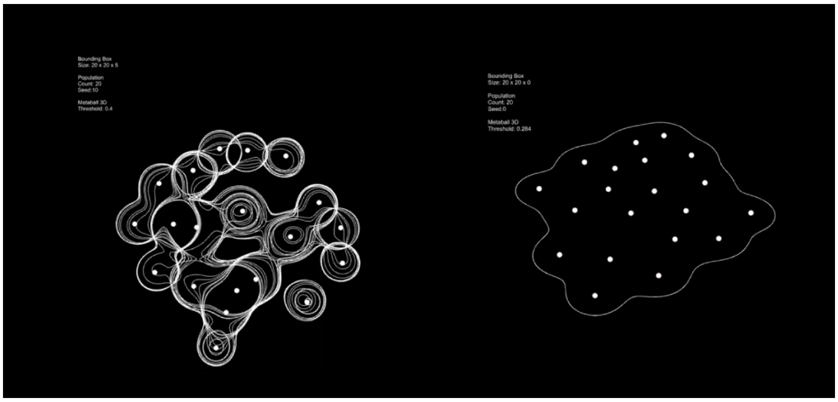


Figure 5: Left Image: Population Count: 20, Seed: 10, Threshold: 0.4. & Right Image: Population Count: 20, Seed: 20, Threshold: 0.284.



As represented visually in the diagram in **Figure 6** and **Figure 7**, it is seen that the system started to produce both denser and more complex surfaces; the form is no longer only connected but also layered, curved, and multi-centered. This situation shows that tolerance has the potential to create not only connection but also topological complexity. Especially when the threshold value is kept within certain ranges, the transitions between surfaces become softer and more discontinuous, while when this value is increased, the boundaries of the space become sharper, denser, and more organic.

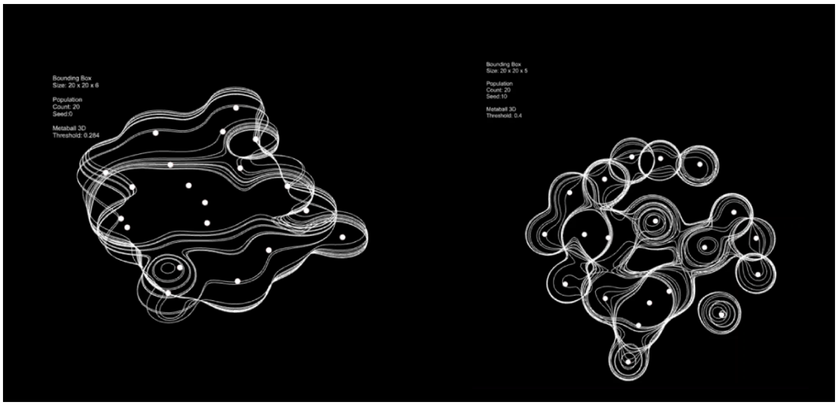


Figure 6: Left Image: Population Count: 20, Seed: 10, Threshold: 0.284. & Right Image: Population Count: 20, Seed: 10, Threshold: 0.4.

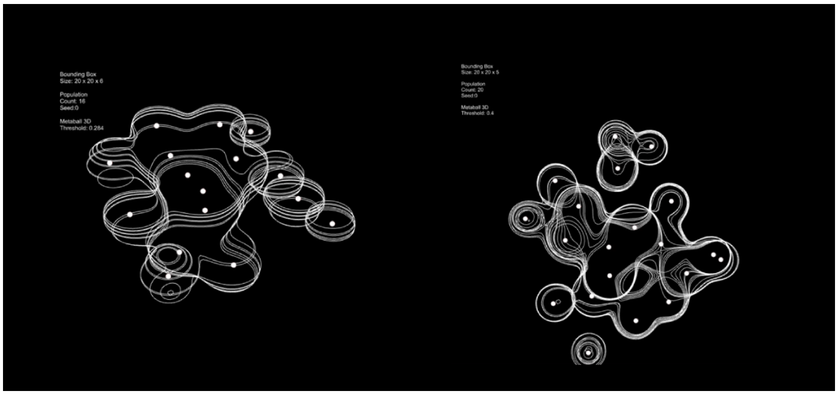


Figure 7: Left Image: Population Count: 16, Seed: 10, Threshold: 0.284. & Right Image: Population Count: 20, Seed: 20, Threshold: 0.4.

The diagrams above outline the algorithmic logic of the system, illustrating how agents interact through thresholds, densities, and probabilistic rules. Variations in parameters such as population, seed, and threshold determine whether surfaces merge, remain disconnected, or evolve into layered and multi-centered topologies. These visualizations confirm that tolerance is not simply a static parameter but the condition that governs how differences become spatially perceptible. Minor shifts in threshold values generate qualitatively different structures, demonstrating that tolerance operates as a dynamic determinant in the production of digital space. In Deleuzian terms, what emerges is not the suppression of error but the affirmation of difference as a productive force of becoming (Deleuze, 1994).

Yet the system becomes fully legible only when embodied interaction is introduced. In the second set of experiments, the designer entered the system through sensors, effectively becoming one of the agents. Using the Fologram app, smartphone sensor data (orientation, movement, and rhythm) was streamed into Grasshopper 3D, where it directly modulated agent parameters. Each gesture, shift in orientation, or variation in cadence altered the interaction thresholds, producing outcomes that could not be predicted in advance. In this configuration, tolerance expands beyond technical flexibility into an embodied principle: it is the bandwidth within which the system absorbs the unpredictability of human action and transforms it into generative spatial variation.

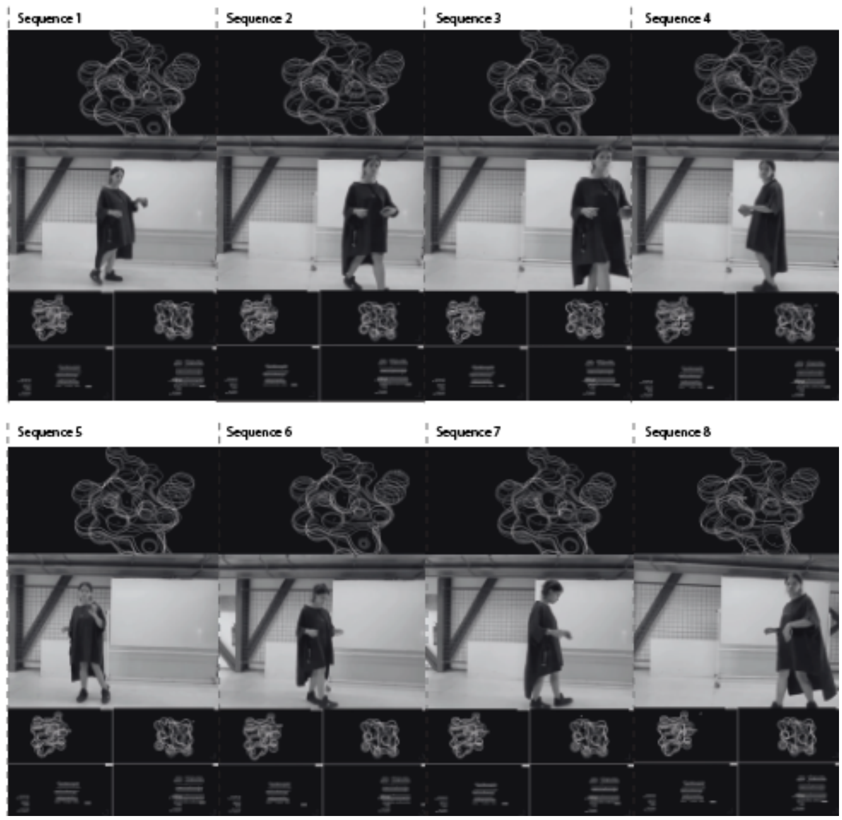


Figure 8: Sequential visualization of embodied interaction within the agent-based system.

Figure 8 demonstrates this embodied dimension through a sequence of stills **(1–8).** As the participant's body enters the system as an agent, movement data perturbs the interaction rules, producing visible shifts in density, curvature, and connectivity. Each sequence reveals how tolerance mediates between bodily unpredictability and computational logic: rather than filtering out deviations, the system incorporates them, transforming gestures into new spatial configurations. These sequential frames make perceptible how difference itself is repeated—not identity—so that novelty is sustained across events.

This transformation resonates with accounts of computation as speculative rather than deterministic (Parisi, 2013). Code does not merely execute fixed instructions but folds external contingencies into its ongoing operations, opening new potentials. In the XR setting, the human body's entrance as an agent exemplifies this logic: tolerance mediates between the indeterminacy of movement and the responsiveness of algorithms, converting deviations into new spatial organizations. The notion of the fold is equally operative here (Deleuze, 1993): each embodied action inflects the system, folding external gestures into internal variations so that space is constantly rewritten.

As the diagrams and video sequences together illustrate, the system is not a closed machine but a relational field in which human and computational agents co-produce outcomes. The density, curvature, and connectedness of forms shift in real time with embodied input, making tolerance directly experiential. It is not hidden in the code but becomes perceptible as the very quality that sustains novelty across successive events. In this sense, tolerance mediates between algorithmic rules and lived immersion, ensuring that uncertainty is not eliminated but harnessed as the driver of creative difference in XR environments.

4.2. Visual Consideration of Tolerance:

As observed in the images, low threshold values generated sparse and discontinuous configurations, while high threshold values produced denser and more cohesive surfaces. This variation demonstrates that tolerance is operative not only as a functional parameter but also as a formal determinant in the digital production process. The behavioral logic of the system directly shapes its spatial articulation: tolerance does not prescribe how space should appear, but conditions how it comes into being. Deviations that might conventionally be dismissed as "errors" instead operate as productive variations, enabling the system to evolve into new spatial modalities.

The metaball experiment confirms that even the simplest agent-based simulations disclose the creative potential of tolerance. Spatial novelty here does not emerge from pre-determined formal intentions but from the relational protocols of interaction and from the tolerance ranges inscribed within them. In this sense, tolerance resonates with the affirmation of difference (Deleuze, 1994) and with the account of speculative computation (Parisi, 2013): it is the operative openness that allows systems to absorb contingency and transform it into generative spatial complexity.

The results of these experiments thus support an understanding of XR-based digital environments not as representational projections but as emergent formations. Tolerance proves to be intrinsic not only to physical fabrication but also to the very logic of algorithmic production. Systems that suppress tolerance lapse into determinism, producing fixed and predictable outcomes; systems that embrace tolerance remain adaptive, enabling differentiation, transformation, and deviation. These differences should not be understood merely as technical artifacts but as aesthetic and ontological potentials that expand the horizon of what digital space can become.

5. CONCLUSION

This study has repositioned tolerance in XR-mediated digital space production from a narrow technical margin of error to a multi-layered principle of openness, uncertainty, and generative difference. Tolerance was reframed as the condition that affirms discontinuities and transforms them into productive variations, drawing on concepts of becoming and difference (Deleuze, 1994) and on the notion of speculative computation (Parisi, 2013). While architectural discourses have advanced the field toward dynamism and adaptation (Novak, 1991; Lynn, 1999; Schumacher, 2009; Leach, 2004; Kolarevic, 2003; Menges, 2007), this study makes explicit that tolerance is the missing conceptual link that sustains creativity in immersive systems.

Experiments with agent-based modeling demonstrated how small deviations in thresholds or initial conditions generate qualitatively distinct spatial outcomes, while embodied interaction experiments Figure 8 showed how sensor-driven movements directly perturb and co-shape computational dynamics. Together, these results revealed tolerance as a principle that mediates between algorithmic rules and lived immersion, turning unpredictability into creative potential.

In conclusion, tolerance enables XR-mediated digital environments to move beyond representation and control, establishing them as adaptive, relational, and processual spaces. Rather than suppressing deviation, tolerant systems embrace difference as the driver of novelty. In doing so, tolerance emerges not only as a systemic bandwidth but as the creative principle that enables co-authorship, experimentation, and continuous invention in XR-based design.

Conflict of Interest Statement

The manuscript is entitled “From Control to Contingency: Tolerance as a Generator of Digital Space" has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere.

Author Contribution

All authors contributed equally to this article.

AI Use Disclosure

The authors declare that generative AI and AI-assisted tools were used for language editing and grammar correction in the preparation of this manuscript. The authors carefully reviewed and approved all AI-assisted suggestions and take full responsibility for the accuracy, integrity, and originality of the final manuscript.

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