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BEYOND EUCLIDEAN BOUNDARIES: ANALYZING NON-EUCLIDEAN SPACES IN GAMES

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Abstract: Game space is a reproduction of physical space; however, it is not constrained by the same limitations. We live in an Euclidean space, where geometry follows consistent rules: parallel lines never meet, angles in a triangle always sum to 180 degrees, and distances are fixed. However, non-Euclidean spaces break Euclid's fifth postulate with the result that parallel lines can converge or diverge, and distances may stretch or warp, as demonstrated in games like Portal and Antichamber. By going beyond these constraints, non-Euclidean spaces offer new possibilities for advancing a game's narration, aesthetics, and mechanics. The potential of non-Euclidean games has started to be discovered, but there has yet to be a definitive framework. Such a framework could unify the understanding of non-Euclidean mechanics, bridging theory and practical applications to enrich game design by stimulating innovativeness. The present work examines the possibilities of non-Euclidean spaces, particularly in relation to game mechanics. To this end, we analyzed ten games that feature diverse spatial qualities. Each game represents a different non-Euclidean space type. Schell's categories of mechanics are used as a conceptual structure for the analysis. The first category is space; the others are time, objects, actions, rules, skills, and chance. We examined the correlation between non-euclidean space and other categories to uncover the influence of non-euclidean spaces in games. Our findings show that non-Euclidean spaces offer new ways to build novel interactions and relations. It demonstrates the short comings of existing game space type classification and extends our understanding of spatial structures in games. This expanded knowledge has the potential to lead to richer gameplay experiences.

Keywords: game design, non-euclidean spaces, game mechanics, level design, game analysis

Introduction

Games have been a fundamental part of human culture and social life for thousands of years. Archaeological evidence suggests that ancient games date back 5000 years, such as Senet in ancient Egypt and the Royal Game of Ur in Mesopotamia (Bell, 1968). Huizinga (2014) proposed that play precedes culture, coining the term *homo ludens* to describe humans as “playing beings.” He defined games as voluntary activities within a “magic circle” that stays out of ordinary life, proceeds by rules and is not associated with material gains. According to Caillois (2001), play is also uncertain and representational. He categorized games into types such as *agon* (competition), *alea* (chance), *mimicry* (role-play), and *ilinx* (vertigo) to further emphasize

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their structural variety. Salen and Zimmerman (2003) assemble previous definitions and drop redundant parts to describe games as "a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome." From traditional board games to complex digital environments, games have grown into a multibillion-dollar industry. As of 2023, the global video game market generates $184 billion with more than 3.3 billion players worldwide and the figures are estimated to increase (Newzoo, 2024), solidifying games as a significant cultural and economic force.

Digital games are not only interactive entertainment but also a powerful form of media, contributing to mass communication in the 21st century. McLuhan (McLuhan, 1994) famously argued that "the medium is the message," which resonates with games as they mediate experiences, rules, and narratives through technological interfaces. Games and other new digital media are not foreign forces that disturb the existing culture. They come out from existing media (Bolter and Grusin, 2000). Digital games as a new media are a continuation of television, cinema, and literature (Juul, 2005). Digital Games, which provide entertainment, are nourished with the help of the internet and software programming and have become a major part of the media system (Castells, 2010). As a result, analyzing games and their impacts is critical for understanding their role in shaping the new media and its users.

Games, just like other media such as movies, music, and books, intend to create an emotional experience for the users (Isbister, 2016). Games and other entertainment media are different because the experience that games create can not be fully foreseen. The events in the game are generated when the players play the game, and those events are hard to predict at the time of design. Games are mainly divided into mechanics, dynamics, and aesthetics to understand their interaction with the players (Hunicke et al., 2004). New meanings for mechanics are used as the literature on game design is more advanced. According to Järvinen (Järvinen, 2007), a mechanic is a singular tool that describes the player's ability to interact with game elements with the intention of influencing the game state. The definition of Miguel Sicart (Sicart, 2008) is advantageous for game analysis. His definition is that "game mechanics are methods invoked by agents, designed for interaction with the game state." Space in games is a category of Mechanics (Schell, 2019).

In the evolution of mathematical understanding, the journey from Euclidean to non-Euclidean spaces marks a deep paradigm shift in how with spatial dimensions are perceived and interacted. Euclidean geometry is established by Euclid over two millennia ago. Their work is considered a foundation because he codified all known geometry in a systemic way, starting with very simple concepts such as identicalness, points, and lines (Hofstadter, 1979). Euclidean geometry assumes a space where familiar concepts prevail; parallel lines never meet, and the sum of the angles in a triangle is always 180 degrees. Mathematicians first discussed the possibility of non-Euclidean geometry in the 19th century. New possibilities for mathematics and physics were opened by proving that geometries could exist beyond Euclidean postulates that are no longer necessarily applied. Non-Euclidean geometry allows for spaces where parallel lines could diverge or converge, among other properties (Capecchi and Ruta, 2016). The relevancy of non-Euclidean geometry in recent research cannot be understated, specifically in the fields that can incorporate digital calculations to produce spatial mechanisms. For example, Wang et al. (2021) state that studying non-Euclidean objects could be difficult and might involve the embedding of non-Euclidean data into Euclidean frameworks. It usually leads to challenges demanding new statistical techniques.

Even though games like Chants of Senaar (Rundisc, 2023) only use non-Euclidean spaces for aesthetic appeal, the significance of space in video games extends beyond just aesthetic appeal. Better game space design is important for player experience and gameplay (Si et al., 2017). Furthermore, Korkmaz and Kim study how players move in virtual landscapes, indicating that spatial design is also essential for player immersion (Korkmaz and Kim, 2022). Complexities of non-Euclidean space enriches within game environments. For instance, Osudin et al. claims that non-Euclidean spaces in games can yield innovative gameplay experiences that challenge players to plan and think differently and produce fun, interesting, enjoyable, and weird experiences (Osudin et al., 2025). One of the earliest games with a non-Euclidean space is Asteroids (Atari, 1979). The space in Asteroids is a torus, so the objects at the edge of the screen reappear at the opposite edge. Torus space allows players to dodge asteroids by moving to the other side of the screen. The spatial design of the games affects the game mechanics. Osudin et al. (Osudin et al., 2025) developed curvier versions of Asteroids. they found that curvier space reduces the mastery and control of the players but does not affect the immersion or the challenge.

While non-Euclidean spaces have been used in games to create novel experiences, there is still inadequate groundwork to understand their mechanical impacts on the game. This lack of structured understanding limits the potential for designers to exploit non-Euclidean spaces for creative and interactive innovation fully. This study explores how non-Euclidean spaces are used in game levels. It examines how different non-Euclidean spatial structures influence or interact with various game mechanics by applying content analysis to a selection of games that employ diverse non-Euclidean spatial structures.

Materials and Methods

A Case study is an empirical study that investigates a contemporary phenomenon within its real-life context (Yin, 2002). Quantitative or Qualitative methods can be utilized in case studies. Content analysis is usually described as quantitative, but it can also be used as a qualitative method (Neuendorf, 2002). In this study, content analysis was used to identify recurring patterns and themes across the selected cases. Content analysis is a research technique for making replicable and valid inferences from texts (or other meaningful matter) to the contexts of their use (Krippendorff, 2004). A concern about the reliability of content analysis is reproducibility, which is the concurrence of the analysis done by different researchers (Weber, 1990).

To ensure reliability, we used Schell's (2019) types of mechanics as a guideline. These types of game mechanics are space, time, objects, actions, rules, skill, and chance. Each type explains gameplay from a distinct point of view. Space defines the structure where gameplay happens, whether in grids, 3D environments, or nested areas that reflect how players mentally organize game worlds. Time can be discrete (turn-based) or continuous (real-time), and its manipulation, such as pausing or rewinding, can boost strategy and pacing. Objects, for example, characters, props or tools, are the nouns of gameplay. Objects have attributes that change during play and can be public or private, influencing how players interpret the game state. Actions are player behaviors, ranging from basic moves to complex strategic decisions, with emergent gameplay, which is formulated by the ratio of strategic actions to basic actions. Rules provide the framework for all interactions, including operational (how to play), behavioral (fair play), and structural rules enforced by digital systems. Skill connects challenge to player ability predominantly across physical, mental, or social dimensions. It should be designed to maintain the engagement of the target audience.

Lastly, chance introduces uncertainty, adding surprise and strategic variability, often calculated through expected value but shaped by the player‘s perception. Together, these mechanics provide a comprehensive, meaningful and dynamic game experience.

Non-probability sampling is used when the researchers are not able to ensure that each member of the population will be presented (Leedy and Ormrod, 2016). Judgemental or Purposive sampling is a non-probability sampling in which researchers deliberately select a sample on the basis of knowledge of the purpose of the research, population, and its elements (Babbie, 2013). Judgemental sampling is usually used in content analysis. This sampling method can elucidate the research questions being examined (Zhang and Wildemuth, 2009). We aim to select a wide range of non-euclidean games to diminish the shortcomings of purposive sampling. At least one game from each non-Euclidean space type has been selected. Loukakis *et al.* (2022) define these space types in games as Wrapped Space, Wormhole, Spiral Spaces, Fractal Spaces, 4th Space dimension, Impossible Spaces, Escherlike Spaces, Perspective Manipulation, and Hybrid Spaces.

The selected games are Manifold Garden (William Chyr Studio, 2020), Portal (Valve, 2007), Classic Marathon (Aleph One Developers, 2004), Game Inside a Game (Hogan, 2020), Tetraspace (Antonelli, 2015), AAAAXY (Divverent, 2021), Monument Valley (ustwo games, 2022), Superliminal (Pillow Castle, 2020), Fragments of Euclid (Zanuttini, 2017), and Knossu (Whiting, 2015). Specifications of the selected games are shown in Table 1. The games were published between 2004 and 2022. Five games are published on Steam, and four games are published on Itch.io. Games published on Steam have either “Very Positive” or “Overwhelmingly Positive” reviews. Games published on Itch.io have ratings between 4.5 and 4.7. Games with high appraisal were selected because well designed games are better at reflecting their features. Puzzle is the most common genre in the selected games. First Person, Platformer, and Surreal genres are also recurrent.

Table 1: Descriptive information about the selected games

Game Name	Space Type	Release Date	Steam Review	Itch.io Rating	Platform	Genre 1	Genre 2	Genre 3
Manifold Garden	Wrapped Space	30 October, 2020	Overwhelmingly Positive		Steam	Puzzle	Surreal	Abstract
Portal	Wormhole	10 October, 2007	Overwhelmingly Positive		Steam	Puzzle	Puzzle Platformer	First Person
Classic Marathon	Spiral Spaces	10 May, 2024	Very Positive		Steam	FPS	Shooter	PvP
Game Inside a Game	Fractal Spaces	6 December, 2020		4.5	Itch.io	Puzzle		
Tetraspace	4th Space dimension	9 August, 2015		4.5	Itch.io	Puzzle		
AAAAXY	Impossible Spaces	24 November, 2021		4.5	Itch.io	Platformer		
Monument Valley	Escher like Spaces	12 July, 2022	Overwhelmingly Positive		Steam	Puzzle	Relaxing	Adventure
Superliminal	Perspective Manipulation	5 November, 2020	Very Positive		Steam	Puzzle	First Person	Surreal
Fragments of Euclid	Hybrid Spaces	26 February, 2017		4.7	Itch.io	Puzzle		
Knossu	Wormhole	12 October, 2015			Stand-alone	Horror		

Results and Discussion

Space

Space is the first type of game mechanic we analyzed. Namely, it is also the most related one. In games such as Manifold Garden, the navigation through the space is intentionally difficult, integrated directly into the gameplay loop. Similarly, AAAAXY and Knossu employ spatial difficulty not as an obstacle but as an essential gameplay mechanic, where mastering way-finding becomes part of the gameplay.

In Fragments of Euclid, non-Euclidean mechanics are used as spatial separators to structure these complex spaces, so they introduce distinct zones or levels without relying on traditional boundaries. In games such as Portal and Superliminal, space is divided by puzzle separators and teleportation. Both techniques serve to create transitions across levels of otherwise incompatible spaces. Separating levels facilitates easier navigation, relieving the cognitive load that is caused by non-Euclidean environments. In terms of navigational assistance, games like AAAAXY and Classic Marathon implement mapping systems to help players manage the complexity of non-Euclidean worlds, although it is acknowledged that designing effective maps for such spaces is notoriously challenging.

Space manipulation is not just a visual effect but the main puzzle mechanic in Monument Valley, where the perception of the player directly affects problem-solving strategies. Non-Euclidean properties like axis shifting allow spaces to become more complex than their physical dimensions would suggest. Moreover, the spaces in Superliminal forge a link between environmental design and object interactions, and spaces in Monument Valley and Superliminal forge a link between space and player actions, thus creating systems where the layout of the world is strongly connected with the behaviors it contains.

In selected games, even Euclidean spaces have unusual features, such as illusory walls in Superliminal. The uncertainty challenges players' spatial assumptions. Multiple space types can coexist within a single game. Superliminal, Valley, and AAAAXY contain different types of non-Euclidean spaces. Additionally, the introduction of a fourth spatial dimension in Tetraspace creates a challenge to rethink the space itself. Finally, Classic Marathon uses simple space-overlapping tricks that reduce the spatial strain on designers while developing the game, but their effect on gameplay is limited, so not all non-Euclidean spatial elements equally impact player experience.

Time

Time mechanics in non-Euclidean games are similar to regular games. However, they are used to manipulate player expectations and introduce pressure within the gameplay experience. Knossu introduces a randomly generated destruction zone that teleports players outside the level boundaries and recreates the level from scratch, which challenges players' sense of temporal and spatial stability. This unpredictable event acts as a temporal hazard directly influenced by non-Euclidean space and its collapsing and reformation. Additionally, the implementation of time loops in Superliminal offers a distinct temporal manipulation where players repeatedly replay the same or similar sequences. This cyclical experience disorients players and redefines progression by breaking linear time expectations. These strategies in

temporal design highlight how non-Euclidean principles are extended beyond spatial structures, but most of the games have regular time structures. Even though Portal has a regular time structure, the use of falling from portals creates race conditions, which introduces an element of urgency in a non-Euclidean manner.

Object

In non-Euclidean games, objects go beyond their traditional roles and often become an extension of the spatial environment itself. In Superliminal, for example, objects transform into a room through scaling, so it blurs the boundaries between the environment and interactive elements. Across all the games studied, objects possess limited attributes yet follow non-Euclidean rules. These objects are frequently central to puzzle design, as seen in Portal, Game Inside a Game, Tetraspace, Valley, Superliminal, and Fragments of Euclid. Changing the attributes of game objects, such as gravity direction in Fragments of Euclid, becomes a core mechanic for solving certain puzzles, which demonstrates the relationship between objects and rules. The non-Euclidean mechanic of Superliminal is changing the scale of objects on the basis of the player's perspective. This mechanic creates an interaction between space and objects, disturbing classical fixed size and position concepts.

The attributes of game objects are occasionally hidden through visual deception. In Superliminal, players cannot fully perceive the state of some objects until they stand in a specific location and look in a specific direction; this leads to a reassessment of the environment. Although the attributes of the objects are not explicitly hidden in Tetraspace, their complexity makes them difficult to comprehend. Thus, it resembles a concealment of the attributes of game objects. AAAAXY has a fog that limits the avatars' vision, so game objects in the levels become concealed from the player. Experimentation and discovery become more important in this game. Overall, objects in these games function not just as tools or props but as dynamic extensions of the non-Euclidean world, significantly shaping both puzzle design and player experience.

Action

The analyzed games feature a set of basic actions, such as holding a box, moving, and jumping, providing players with a familiar base knowledge for interaction. However, a few non-Euclidean actions significantly change the gameplay experience in titles like Fragments of Euclid, Portal, Monument Valley, Superliminal, Tetraspace, and Manifold Garden. These non-Euclidean actions usually involve manipulating space or objects in ways that would be impossible under Euclidean rules. For instance, the only non-Euclidean action in Portal is opening a portal, which suffices to change the status of the game.

Strategic actions in these games primarily emerge through combinations of basic mechanics rather than emerging completely new behaviors. For example, players must combine movement, object manipulation, and spatial awareness to solve puzzles in Portal, Monument Valley, Game Inside a Game, Superliminal, Tetraspace, and Manifold Garden. These strategic actions are a combination of basic actions, and the combination does not evolve into abstract actions, so the degree of emergent gameplay remains relatively low. The complexity arises more from the spatial conditions than from unexpected player-devised solutions, marking a clear distinction from high-emergence systems seen in simulation games.

Interestingly, while the actions are Euclidean, their behavior shifts according to the behavior of the space. In Game Inside a Game, the object multiplies by jumping out of the box because the box is in a fractal space, and multiple boxes are nested in one box. The space alters the outcomes of standard actions and transforms standard actions into strategic challenges. Other examples are teleporting or rotating by passing through doors, changing scales by grabbing and dropping, and moving into the fourth space dimension. This relationship between action and spatial context illustrates how non-Euclidean design can subvert traditional mechanics without overwhelming the player's basic toolset.

Rules

Rules in non-Euclidean games often present challenges for players to understand spatial behaviors that differ from the real world. In most of the studied games, the integration of non-Euclidean properties into rules makes those game mechanics less intuitive and more dependent on player exploration. Some of the analyzed games incorporate ambiguous rules into their gameplay and expect players to discover the rules by themself. In contrast, the developer's Portal designs an extensive tutorial to gradually teach players new mechanics to minimize the frustration of learning complex rules. On the other hand, Monument Valley was developed with simple aesthetics and a low difficulty level. Hence, the burden of learning non-Euclidean rules is diminished.

Successfully explaining the goals of the games to the players varies across the games studied. In Knossu, Portal, and Tetraspace, long-term objectives are clearly articulated, allowing players to navigate complex spaces with a consistent sense of purpose. Short-term goals are apparent in Game Inside a Game. On the contrary, Fragments of Euclid and Superliminal have clear long-term narratives to guide player progress but lack short-term goals. AAAAXY deliberately uses ambiguous goals to stimulate players to explore. Games such as Superliminal and AAAAXY modify mechanics between levels, resulting in adaptive problem-solving.

Chance

Even though some games incorporate chance mechanics, they are not associated with non-Euclidean mechanics.

Skill

Skills demanded by non-Euclidean games predominantly engage the cognitive faculties of players. Players must navigate unfamiliar spaces and resolve challenges opposing real-world logic across the selected cases, including Portal, Fragments of Euclid, Game Inside a Game, AAAAXY, and Manifold Garden. Although the primary emphasis remains on mental capacities, a minor degree of physical skill, particularly dexterity and precision in movement, is also necessary for certain instances, such as those encountered in Portal and Fragments of Euclid.

A consistent theme observed among these games is the prominence of way-finding and three-dimensional thinking as essential competencies. Titles such as Fragments of Euclid, Knossu, Monument Valley,

AAAAXY, and Manifold Garden require players to navigate with new means, such as wall walking and teleportation and the ability to reinterpret virtual spaces dynamically. In particular, Knossu and Tetraspace necessitate the development of novel navigation strategies that surpass experiences available within the physical world. Virtual skill development within these games is often limited. Only Portal among the studied games has a virtual skill progression. The game provides a portal gun and its upgrades to the player, resulting in increasing puzzle difficulty.

Discussion

Our work finds that chance and time mechanics are mostly irrelevant for non-Euclidean spaces. Non-Euclidean games have many properties that are similar to Euclidean games, but small changes in game rules and game space are enough to produce novel gameplays. Game objects, actions, and rules are strongly connected to each other, so when one of them carries non-Euclidean properties, it also affects others.

Osudin *et al. (2025)* conducted a study that uses both qualitative and quantitative methods. The quantitative part of their research found that challenges are the same in both games, but their qualitative part shows that the players think they face more challenges in non-Euclidean games. We also confirm that non-Euclidean games are more difficult. Even though it is more difficult than regular spaces, games are playable. Pisani *et al.* (2019) also think that human spatial reasoning is flexible and can adapt to non-Euclidean spaces.

Loukakis *et al.* (2022) categorize non-Euclidean spaces and assign games to a type. Selected games embody many non-Euclidean space types at the same time. For example, a Manifold Garden is a wrapped space and an Escher-like space. AAAAXY also has different space types, such as impossible, wrapped, elliptic and hyperbolic spaces. Assigning games into space types results in assigning most games to the hybrid spaces. Listing each space type the game holds is more suitable for game spaces. This type of grouping is called a tag system. Tags are keywords that are assigned to a resource (Thomas et al., 2009). Non-Euclidean space tags could explain games better to players or other professionals.

Conclusion

This study demonstrates that even minor changes in the spatial structures and rule systems can significantly impact gameplay experiences in non-Euclidean games. Mechanics such as objects, actions, and rules are influenced by the Euclidean or non-Euclidean environments and affect each other. Chance and time mechanics are generally less significant within the non-Euclidean. Non-Euclidean generates unique challenges and novel forms of plays. The findings show that non-Euclidean spaces are more challenging but do not exceed human cognitive abilities.

Our study reveals design recommendations. Non-Euclidean mechanics already puts a cognitive load on the players, so the designers should be clear about the distinction between Euclidean and non-Euclidean game elements, pay additional attention to teaching the game, and be cautious about adding multiple non-Euclidean mechanics. Games with non-Euclidean spaces can be successful without strategic action, so simple actions are sufficient. Getting lost is easy on large levels, and non-Euclidean space feels larger, so it is suggested to avoid large levels. These games can aim to disorient and confuse the player; in that case, the opposite of these recommendations is true, but in any case, the players need to know what to do next.

A significant limitation of the current analysis is the reliance on a finite selection of games, which may not fully capture the diversity of games. Another limitation is the lack of inter-coders. The future studies could include multiple coders, or incorporate triangulation methods by gathering data from numerous sources such as players, developers or gameplay telemetry. We analyzed the games from the point of view of mechanics; other aspects of the games, such as aesthetics and narratives, can be used to analyze them in the future. Future research and games would benefit from expanded case studies and refined taxonomy. Overall, the study reaffirms the relevance and potential of non-Euclidean design in advancing experimental game design.

Declaration of Interest Statement

The authors declare that they have no conflict of interests.

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