SpaceTimeCraft: A Strong Concept for Designing and Analyzing Embodied Movement in Virtual Environments

Constantinos Miltiadis
School of Arts, Design and Architecture
Aalto University
Espoo, Finland
c.miltiadis@gmail.com

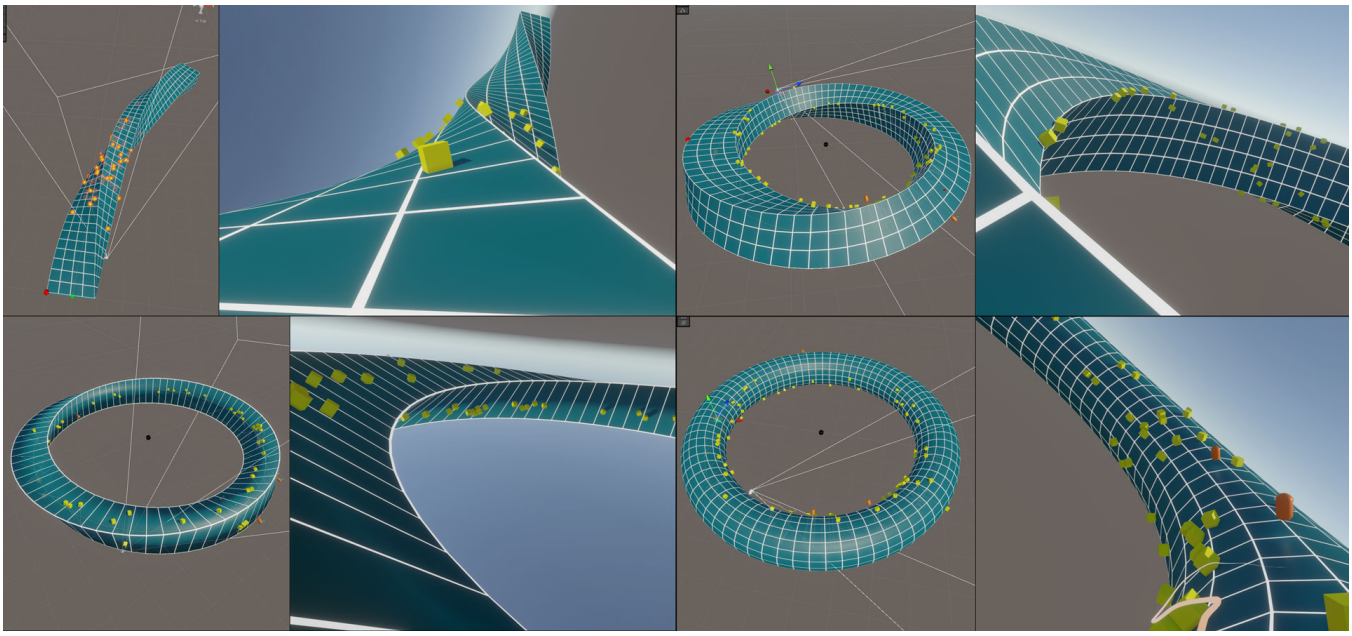

Figure 1: Prototype screenshots depicting four non-Euclidean navigable environment configurations: square-section contorted extrusion (top left), square-section Möbius surface (top right), triangular-section Möbius surface (bottom left), and torus (bottom right).

Abstract

Virtual navigation—embodied spatial movement in interactive digital environments—is a distinct interaction gestalt and a core aesthetic form of digital media, prevalent across videogames and VR applications. Despite its cultural ubiquity and the resurgence of movement-intensive gaming, unifying foundational research bridging theoretical analysis, empirical inquiry, and design practice remains scarce, leaving researchers without shared analytical frameworks and limiting actionable design knowledge available to practitioners. To address this, we implement exploratory gamemaking as a knowledge-generating method, integrating insights from diverse literature with the study of media artifacts, to probe the fundamental and invariant components of virtual navigable experience (VNX) through the edge case of non-Euclidean navigable environments. With SpaceTimeCraft, we contribute a "strong concept"—a form of intermediate-level knowledge that bridges theory with the design space. It frames virtual navigation as a *spatiotemporal enactive process* emerging from the synthesis of three heterogeneous components: *a spatial construction*, an *environmental simulation*, and a *vicarious phenomenological intentionality* (an interactive avatar). This minimally elegant model integrates diverse theoretical perspectives, providing a flexible framework for conceptualizing, analyzing, and comparing instances of VNX, and a generative design pattern for novel applications—a capacity we demonstrate through a configurable prototype.

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CCS Concepts

• Software and its engineering → Interactive games; **• Applied computing → Computer games**; **• Human-centered computing → HCI theory, concepts and models**; **Interaction design theory, concepts and paradigms**.

Keywords

movement, videogames, virtual environments, interactive navigation, virtual navigation, embodied movement, non-Euclidean geometry, research through design, game design, game development, design methods

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1 Introduction

Virtual navigation—embodied spatial movement in interactive digital environments—is a distinct paradigm of human-computer interaction and a core aesthetic form of digital media, best exemplified in videogames and VR applications [1, 49, 58]. This is a complex and dynamic form of interaction that can be understood as an "*interaction gestalt*" [56]: a unified composition of qualities greater than the sum of its parts. It involves real-time engagement with a digital artifact that affords vicarious embodied movement within an environmental simulation. We use the construct of virtual navigable experience (*VNX*) to describe the felt dimension of this interaction: the synesthetic, corporeal, non-verbal experience that unfolds through moment-to-moment vicarious spatial movement.

Despite its cultural prominence and ubiquity through videogames, fundamental unifying research into VNX remains scarce. Research on the topic comes primarily from game studies—a field that has discussed virtual navigation as an "unprecedented aesthetic form" and "central motif" of the medium [1, 58]—and from the cognitive sciences, where empirical research has documented significant cognitive benefits of virtual spatial navigation and action gaming [76, 101]. Beyond these, relevant discussions appear across other fields including architecture, media art, and HCI, though the literature as a whole has yet to develop a shared framework able to bridge these communities. Formal research from the orientation of design practice remains notably limited [18, 50, 57, 65], though relevant work has begun to emerge within HCI, particularly on embodied game design and embodied learning [45, 64].

The consequences of this lack of shared frameworks are increasingly evident. The resurgence of movement-intensive gaming—particularly through the sub-genre of 'boomer/movement shooters' [63]—demonstrates growing designer sophistication and audience attunement to increasingly intensive forms of virtual navigation, yet this phenomenon remains largely unexamined in scholarly literature. At the same time, mounting empirical evidence continues to attest to the cognitive significance of such gameplay [21, 67, 69, 73]. Yet without foundational models or shared terminology, analytical inquiry lacks the tools to examine such experiences beyond surface-level taxonomies, empirical findings remain disconnected from design knowledge, and practitioners lack adequate conceptual tools for advancing virtual navigation through design. Together, these developments underscore the need for a unifying framework capable of bridging these communities, examining existing instances of VNX, and guiding new ones.

To address this need, we contribute *SpaceTimeCraft*, a "strong concept" [44] for virtual navigation. A strong concept is a form of intermediate-level knowledge that bridges theory with a particular region of the design space concerning dynamic interaction. More abstract than a particular design instance yet more concrete than a general theory, it carries both explanatory and design-generative capacity. SpaceTimeCraft frames VNX as a *spatiotemporal enactive* process emerging from the synthesis of three heterogeneous components:

(1) a *spatial construction*—defined through geometry and topology and, at a higher level, through spatial layout and visual design;
(2) an *environmental simulation*—the set of laws and relationships governing the temporal-dynamic behavior of the environment (e.g. gravity, friction, simulation frequency); and
(3) a *vicarious phenomenological intentionality*—the interactive avatar, which prescribes a mode of being-in-the-world through a set of sensorimotor contingencies coupled to a user interface.

This tripartite model integrates partial perspectives—spatial, temporal-dynamic, embodied, and technological—into a coherent conceptualization of VNX that unites design, analytical, and experiential dimensions. It offers four modalities of inquiry: (1) isolation of individual components for focused examination; (2) an account of emergent qualities arising from their interaction; (3) qualitative modelling of interactive processes; and (4) a generative pattern language for design.

We develop this concept via an integrative mode of research *through* design (RtD) applied to experimental and exploratory gamemaking. This approach builds on cursory discussions of gamemaking as a research method [29, 62, 99], employing prototyping as a primary knowledge-generating method rather than as a vehicle for evaluation. Our aim, thus, is not to test hypotheses about user experience but to investigate the fundamental components of VNX through the constructive act of design itself. To this end, we construct a configurable videogame prototype that abstracts from videogame-specific elements (narrative, characterization, goals) to focus on the elementary components of movement-based spatial interaction.

We probe this design space through the edge case of non-Euclidean virtual environments, an often discussed yet rarely implemented design scenario. This scenario necessitates a paradigm shift in environmental construction akin to relativistic physics, that goes against the grain of the Euclidean-Newtonian conventions embedded in contemporary game engines. As a probe, this edge case serves to reveal the fundamental and invariant components of VNX that would otherwise remain obscured, while also expanding the design space into a largely unexplored region of navigable media. Yet as a paradigm shift rather than a niche exploration, the resulting framework is generalizable to conventional spatial constructions as well.

In what follows, we situate this work by integrating insights from the wider research landscape and identifying key gaps that motivate our approach. We formulate three research questions, and outline our integrative methodology, theoretical framing drawing from enactive cognition, and design project construction. We then

discuss the outcomes of the project and elaborate on SpaceTimeCraft as a strong concept, situating it in relation to established frameworks (such as MDA [43] and "game feel" [93]) and defending its validity as a contribution that is grounded in both literature and design practice, generative of new applications, and open to further elaboration.

2 Research Area Synthesis and Gaps

Virtual navigation as a form of movement-based human-computer interaction has attracted attention from multiple distinct traditions, including game studies, the cognitive sciences, architecture, media art, and HCI. Each of these communities engages the subject through its own paradigms, conceptual language, and research methods [20], resulting in a rich yet dispersed body of literature with limited overlap between domains. This fragmentation also extends across technologies and time periods—from the first wave of VR (ca. 1987–1997), through the onset of formal videogame research (since ca. 2000), to contemporary VR (since ca. 2014). While this breadth reflects the genuine complexity of the phenomenon, the literature as a whole has yet to produce shared frameworks capable of bridging these communities or generating knowledge that is actionable across both research and design practice.

At the same time, virtual navigation amounts to a dynamic and culturally pervasive phenomenon, most prominently expressed in videogames. It is an aesthetic form in constant evolution, shaped by technological advancements, design innovations, and the emergent practices of player communities (e.g., modding, speedrunning, esports). The cultural fascination with virtual navigation has been discussed as part of the long-standing preoccupation of Western culture with spatiality and embodied experience [1, 58].

2.1 Virtual Navigation in Game Studies

Game studies has produced a rich body of work on virtual navigation, and provides the primary scholarly context for this research. Early scholarship acknowledged navigable space as a "genuinely original and historically unprecedented aesthetic form" [58], with Aarseth describing it as the "defining element" and "raison d'être" of the videogame medium [1]. Interactive spatiality was subsequently discussed as a mode of engagement distinct for its reliance on kinesthetic performance and spatial practice [32, 47, 92], and Günzel's "spatial turn" [38] proposed it as a paradigmatic shift in the study of videogames. In parallel, some scholars have underscored the synesthetic and embodied experiential qualities central to the appeal and aesthetic language of the medium [49, 88, 89], while a significant body of work has engaged with phenomenological dimensions of gameplay [19, 31, 52]. Together, these contributions establish virtual navigation as a fundamental aspect of the medium's aesthetic language.

However, several important dimensions remain understudied. As Keogh [49] argues, research has focused predominantly on how videogames produce meaning through their systems and mechanics, while neglecting the corporeal dimension of gameplay through which videogames are perceived and felt, an approach that accounts for only part of the medium's aesthetic language. Shinkle [88] has similarly criticized the focus on visual, semiotic, and taxonomic approaches that overlook embodied perception and physiological response. The topic of interactive spatiality, despite its early recognition, also remains undertheorized. More than a decade after the "spatial turn," discourse on videogame space has largely stagnated, with no unifying framework to integrate spatial constructions with the embodied and temporal-dynamic dimensions of gameplay experience.

These gaps are compounded by the nature of VNX itself. The felt dimension of virtual navigation is tacit and pre-reflective, appealing to aesthetic registers and cognitive capacities that are incongruent with natural language and analytical reasoning [32, 47, 92]. Multiple scholars have framed this as an affective experience, rooted in dynamic corporeal sensations that operate below the threshold of conscious reflection and resist conventional modes of analysis [4, 49, 88]. *Super Mario Bros.* (Nintendo, 1985) offers a concrete illustration. While the pleasure of making Mario move is immediately felt by the player, communicating that experience to another person or conveying one's knowledge of the game proves elusive. This sensation resists analytical articulation, qualification through emotional categories, or rationalization through performance metrics. As Karhulahti describes it, kinesthetic gaming is a "sensation-seeking performance" that is "not primarily intellectual, not reflective or interpretative in character, but rather sensual" [47].

The difficulty of examining VNX through conventional analytical tools is especially evident in the limited scholarly discourse on movement-intensive action gaming, and particularly first-person shooters (FPS). FPS games represent one of the most popular, persistent, and culturally significant genres since their emergence in the early 1990s. They stand out for their primary appeal to intensive spatial navigation and moment-to-moment action, often at the expense of the narrative dimension. Yet despite this significance, scholarly attention to the aesthetic and design dimensions of FPS games remains remarkably scarce. This gap appears largely owed to the challenges such games present to formal analysis, since they center on dynamic corporeal experience that resists conventional scholarly methods. A survey of the DiGRA conference library (searching "FPS" and "shooter"), for instance, returns only 20 results, with only two directly relevant to mechanics and experience.

Most notably, the recent emergence of "boomer/movement shooters" [63]—a sub-genre inspired by fast-paced FPS games of the 1990s—marks a significant evolution in virtual navigation. Titles such as *DOOM* (2016), *Doom Eternal* (2020), and *ULTRAKILL* (2020), as well as more experimental examples like *Boomerang X* (2021) and *Neon White* (2022), demonstrate a progressive intensification of movement-based interaction. Such games foreground speed and sensorimotor precision through complex mechanics tuned to incentivize fast-paced, high-mobility gameplay. This wave suggests not only growing design sophistication but also increasing audience attunement to cognitively and physically demanding forms of interaction. However, this phenomenon has received virtually no scholarly attention. At present, researchers lack the analytical tools to examine such forms of gameplay, or even to distinguish between qualitatively different forms of experience—for example, slow-paced military shooters such as *Counter-Strike* (1999) from fast-paced movement-intensive games like *Doom Eternal* (2020).

2.2 Videogame Play and Cognitive Skill Development

Over the past decades, videogame play has attracted significant empirical attention for its cognitive benefits. Research has demonstrated that playing videogames can induce neuroplasticity and support the development of perceptual, attentional, and complex skills transferable to real-world applications [28, 36, 53, 76, 83]. An area of particular interest is that of spatial skills, a subset of cognitive abilities predictive of success in STEM fields [25, 98, 101]. A growing body of empirical work has demonstrated the potential of both virtual spatial navigation [53, 82] and "action videogames" [11, 21, 100, 101] to advance such skills. FPS games involving intensive action and spatial navigation have shown especially strong correlations with cognitive skill development, including evidence of long-lasting neurological adaptation [16, 48, 67–69, 73].

However, empirical studies typically rely on commercial videogames identified by loose genre terms such as "action games," with researchers reporting uncertainty as to which specific gameplay qualities correspond to which cognitive outcomes [76, 101]. Recent work by Dale et al. [21] sought to qualify "action videogames" as compound cognitive tasks that involve fast-paced action, focused and distributed attention, and sufficient variability to prevent task automatization. Yet, such definitions remain broad and lack reference to specific design properties. Design-oriented research capable of identifying those qualities and translating empirical findings into actionable guidelines remains limited, as discussed in the following section. This disconnect underscores the need for integrative approaches that bridge empirical evidence with design expertise, to advance both empirical inquiry and design practice.

2.3 Absence of Design-Oriented Research

Despite the cultural prominence of virtual navigation and the proliferation of gamemaking, formal research from the orientation of design practice and design thinking remains notably scarce [18, 50, 55, 57, 65]. This scarcity reflects a broader tension between academic research and practice [9, 55], leaving research and practice as largely distinct communities with separate methodologies and forms of knowledge. Although the importance of practice-based research has been widely acknowledged [14, 18, 57, 91], the community has yet to establish such an orientation. Formal methods remain underdeveloped [50, 51], and scientific venues and accreditation frameworks for design practice contributions are largely absent [18, 57]. This absence represents a significant gap in the methodological foundations of videogame research, and is particularly consequential for inquiry into VNX, where design knowledge and practice are intrinsic to understanding and advancing the phenomenon under study.

Gamemaking practitioners have long expressed the need for shared conceptual tools and vocabularies to support knowledge exchange and inform design [2, 15, 17]. The most significant responses to this need have come in the form of intermediate-level knowledge bridging design thinking with the experiential dimensions of gameplay. Two prominent examples are the Mechanics-Dynamics-Aesthetics (MDA) framework [43], and the concept of "game feel" [93]. The first offers a foundational ontology for videogame experience, articulating the relationship between designed rules, emergent system behavior, and the resulting player experience. The second addresses the elusive felt dimension of gameplay, discussing it as the sensation of "real-time control of virtual objects in a simulated space, with interactions emphasized by polish", and providing a designerly perspective on matters including aesthetic experience, skillful interaction, and sensory extension. Both have been instrumental in establishing a shared vocabulary for discussing dynamic aspects of gameplay, yet neither was intended to address virtual navigation as a distinct gestalt—its spatial constructions, the dynamics of its environmental simulation, or the embodied dimension of movement-based interaction.

In parallel, recent work within HCI has begun to address related concerns through theoretical taxonomies of movement-based interaction [8], guidelines for embodied game design [45, 101], and design frameworks for embodied learning [64], though these contributions remain focused on broader questions of embodied interaction rather than on the specific gestalt of virtual navigation. A comprehensive foundational framework integrating the spatial, temporal-dynamic, and phenomenological dimensions of virtual navigation remains absent. This work aims to build on and extend these contributions by providing such a framework.

2.4 Non-Euclidean Geometry and the Conventions of Design Software

Virtual navigation also intersects with a longer cultural preoccupation with spatiality and embodied experience, particularly due to its potential to render experienceable spatial forms that transcend the conventions and constraints of the physical world. The hypothesis that embodied spatial experience offers a distinct epistemological framework can be traced to the mid-19th-century discovery of non-Euclidean geometry, which challenged the Euclidean-Cartesian model of space underpinning Western epistemology [84, 97]. Such ideas found expression around the turn of the 20th century in explorations of non-Euclidean space in modern art [42], and in the Bauhaus pedagogy of experiential, "kinaesthetic" knowledge which subsequently became foundational to architectural education [109].

In computing, similar speculations flourished during the first wave of VR (ca. 1987–1997), when "cyberspace" was mythologized as an 'electronic psychedelic'—a means to transcend the limitations of physical reality and expand human consciousness [13, 24, 35, 70, 78]. Among the more sober and elaborate investigations of this vision were the works of pioneering artists Char Davies [22, 23] and Marcos Novak [41, 74, 75], who saw VR as a medium for challenging lived assumptions of Euclidean-Cartesian space through embodiment in synthetic spatiotemporal constructions [66, 71]. However, this wave of experimentation dissipated following the mid-1990s disinvestment in VR technologies. As several scholars noted, despite its radical early promise, digital space largely conformed to the Euclidean-Cartesian framework it sought to displace [37, 77].

This remains true today. Virtually all digital design tools operate within the paradigm of Euclidean-Cartesian space and Newtonian physics—a model superseded in physics by the theory of relativity. This analytical simplification of physical space is well-suited to conventional applications such as engineering and architectural design,

where the aim is to approximate the physical world. Contemporary game engines inherit the same framework as a default context for environmental design, despite the fact that videogames—unlike engineering or architectural applications—need not model the physical world. Although videogames have been widely discussed as a celebration of spatial concepts [6, 39, 104], the result, as Backe [7] observes, is a "great conventionalization" governing spatial design in videogames. This conventionalization insists on foregrounding similarities with real-world environments rather than exploring spatial constructions specific to digital materiality.

Today, several videogames attempt to transcend such design conventions and produce seemingly impossible environments, yet very few implement genuinely non-Euclidean environments—where the space is curved and Euclid's parallel postulate does not hold. Examples such as *Portal* (2007), *Antichamber* (2013), and *Manifold Garden* (2019), frequently misidentified as non-Euclidean, employ perceptual tricks within a conventional spatial framework [105]. Actual non-Euclidean geometry has been implemented in only a handful of titles, including *Super Mario Galaxy* (2007) and *Outer Wilds* (2019) that implement spherical space, and *Hyperbolica* (2022) set in hyperbolic space. A small body of research and artistic prototypes has also explored navigation in non-Euclidean virtual environments [40, 46, 102, 103]. This scarcity attests to the difficulty of departing from existing conventions, which requires working against the grain of the tools themselves. Yet it also points to a vast and largely untapped region of the design space, concerning the capacity of navigable media to render experienceable spatial forms that have no counterpart in the physical world.

3 Research Questions

Drawing on the gaps identified above, we formulate three research questions to guide this work:

RQ1: How can exploratory design prototyping advance the understanding and design space of virtual navigable experience?

RQ2: How can alternative design approaches overcome the limitations concerning spatial constructions ingrained in contemporary game engines?

RQ3: What are the components of a minimal unifying framework capable of describing the gestalt of virtual navigation, both for analyzing existing instances and for generating novel applications?

4 Methodology, Theoretical Framing, and Design Project Construction

We implement an *integrative* mode of research *through* design applied to experimental and exploratory gamemaking, aimed at contributing a "strong concept" [44] for the gestalt of virtual navigation. As outlined in the introduction, a strong concept is a form of intermediate-level knowledge that bridges theory with a particular region of the design space, carrying both analytical and design-generative capacity. Our approach involves three interrelated components: (1) an integrative review of relevant knowledge across literature, gray sources, media artifacts, and technologies; (2) the construction of an exploratory design project pursued as a primary knowledge-generating method to probe the fundamental and invariant components of VNX; and (3) the case study of non-Euclidean navigable environments as a design scenario to focus this inquiry. We frame VNX theoretically through the lens of enactive cognition [94, 95], and delimit the scope of our investigation through a set of heuristics that focus on particular forms of VNX.

4.1 Integrative Research

The integrative component of this approach draws from the model of "generic epistemology" [85, 87], developed for the study of contemporary phenomena that are inherently polyvalent in nature—taking multiple expressions simultaneously—and thus present a challenge to conventional disciplinary and interdisciplinary approaches. Our approach is further informed by discussions of integrative research in the context of design inquiry [33, 72, 86], as well as the method of "integrative literature reviews" [20, 81] for inquiry into fragmented research areas. Beyond academic literature, we evaluate a wide range of gray sources, media artifacts, and related technologies.

The integrative review and examination of sources was facilitated through a hypertextual Research Notebook (elaborated in Appendix). The notebook presents a structured web of interconnected annotations that offers a hypertextual elaboration of the concept of "annotated portfolios" [10, 34], a format proposed for communicating knowledge produced through RtD projects. Its construction was instrumental for tracing connections across the different dimensions of the phenomenon—videogames, technologies, and discourses—allowing us to identify recurring themes, extract and examine shared attributes such as game mechanics and design patterns, reveal research gaps, and substantiate directions for inquiry. An Interactive Timeline Visualizer (also in Appendix) complements this by mapping entries along the temporal dimension, facilitating a historical overview of VNX.

4.2 Theoretical Framing

We frame VNX as an affective form of experience emerging through an enactive process.

With the concept of affect [60] we describe the felt dimension of virtual navigation: the pre-conscious, corporeal, multisensory intensities that arise during interactive movement. Affect theory has been previously used to discuss proprioception [61] and to examine aesthetic qualities of videogames in relation to virtual kinesthetics and interactive spatiotemporal embodiment [4, 5, 8, 47, 88, 89]. We draw on this tradition to conceptualize VNX as a form of experience that is difficult to externalize, communicate, or measure.

Following the theory of enactivism, we frame virtual navigation as a process of *situated embodied action* [94, 95]. Enactivism bridges phenomenology with cognitive science, proposing that cognition is not confined to the brain but is a situated, embodied sense-making activity that "cuts across the brain-body-world divisions" [96]. In this view, cognition is something we actively do as autonomous agents, making sense of our environment through our body, sensorimotor contingencies, and perceived capacities for action.

This perspective is particularly valuable for three reasons. First, it provides a theoretical framework that is directly actionable in design research: as an enactive process, virtual navigation is constituted by environmental parameters and embodied sensorimotor contingencies, all of which are controlled by a digital artifact and can therefore be manipulated through design to explore different

configurations of enactive contexts. Second, enactivism treats cognition and emotion as "thoroughly integrated at biological, psychological, and phenomenological levels" [95], supporting an understanding of virtual navigation as a dynamic process where action, perception, emotion, and experience are intertwined aspects of the same phenomenon. Third, enactivism asserts the individual's autonomy to "bring forth its own cognitive domain" [95] in the dynamic interaction with an environment based on situated embodied capacities. This accounts for the inherently subjective nature of the experience, as well as emergent behaviors that manifest only in specific contextual interactions. It also accounts for the extension of cognitive capacities through tools, and the perceptual transparency of interfaces that are incorporated through habituation [3, 80, 95], as is the case with gaming interfaces.

This framing allows us to view VNX as an aesthetic form not dissimilar to physical activities grounded in situated embodied action. Activities such as dancing, skateboarding, or skydiving orient the body in particular proprioceptive conditions, requiring intuitive skillful action and eliciting intensive multisensory forms of non-symbolic experience. Virtual navigation presents a similar enactive process that, however, takes place vicariously—through the sensorimotor contingencies of an interactive avatar—within a synthetic environment where the avatar is embedded.

4.3 Design Project Construction

Integrating the above insights, we construct a design project in experimental and exploratory gamemaking, aiming to develop an "ultimate particular" [72]—a design instance that best addresses our research questions and generates knowledge bridging theory with design practice. Our approach is informed by literature on RtD [27, 34, 54, 90, 107, 108] as well as cursory discussions of research through gamemaking [29, 62, 99, 106]. Rather than developing a fixed artifact or polished videogame, we set out to produce a modular and configurable prototype. This decision reflects our aim to contribute fundamental knowledge concerning a dynamic interaction gestalt [44, 99] rather than to investigate a particular application, and is inspired by the configurable platformer prototype developed by Brown [12].

4.3.1 Scope. We delimit the scope of this investigation to forms of experience that are both *specific* to digital environments and *relatable* to real-world activities. This focus enables the examination of enactive processes that engage skills and capacities akin to those used in physical activities (relatable), while extending beyond the constraints of the physical realm into expanded registers of cognitive and sensory experience (specific).

To refine this scope, we introduce a set of heuristics focusing on enactive processes that are embodied, relatable, movement-focused and intensive, interface-transparent, and medium-specific (defined in Appendix). Together, these heuristics highlight forms of VNX that rely on intuitive and immediate movement as a dynamic skill-based activity, best exemplified in movement-intensive action videogames, which have also been shown to support cognitive skill development [21, 67, 68, 100, 101].

Accordingly, we center the investigation on intensive navigation in 3D environments from an embodied first-person perspective, as well as design patterns that enable and incentivize intuitive, skillful movement-based interaction. This excludes 2D navigation (e.g. side-scrolling videogames), third-person perspectives, and non-intensive forms of navigation such as wayfinding. We also abstract from elements not directly related to movement, including narrative, characterization, and environmental design.

4.3.2 Case Study: Non-Euclidean Navigation. We examine the case of non-Euclidean virtual navigable environments, implementing a relatively simple form of non-Euclidean geometry through 2D locally-Euclidean curved manifolds embedded in 3D space. This is to investigate forms of spatial experience that are specific to digital navigable media and inconstructible in the physical realm.

This case study is motivated by several considerations. First, it provides a scenario that challenges prevailing conventions in gamemaking, where spatial design is largely constrained by analytical simplifications of physical space and oriented towards reproducing its visual appearance. To pursue this scenario, we develop a design approach that, akin to relativistic physics, entails a paradigm shift from a Euclidean-Newtonian understanding of space to a relativistic conception of spacetime. This allows us to challenge and extend design conventions embedded in current tools. Second, this departure from conventional design assumptions serves to reveal the fundamental and invariant components of VNX that would otherwise remain obscured. Third, a spatiotemporal approach to the design of dynamic interaction integrates the temporal dimension into a single conceptualization, bridging spatial and dynamic aspects of virtual navigation that the literature tends to treat in isolation. Fourth, because our implementation concerns curved yet locally Euclidean geometries, findings are not confined to non-Euclidean applications but are generalizable to conventional spatial constructions as well. Finally, this case study serves to explore the frontier of VNX, probing the limits of what current tools can produce and what the human sensorium can experience.

4.3.3 Research through Exploratory Gamemaking. We pursue iterative prototyping using the Unity game engine. The main challenge of this project is the implementation of non-Euclidean navigation, which necessitates departing from the Euclidean-Newtonian framework of the engine.

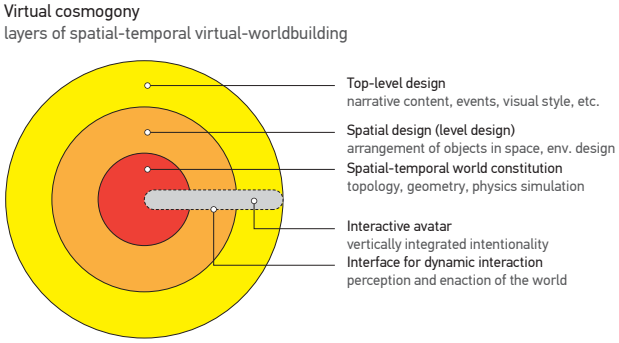

Figure 2: Diagram of the virtual cosmogony concept.

To approach this challenge, we analyze the first principles of VNX design and conceptualize a preliminary model of "virtual cosmogony" (figure 2), consisting of two interrelated components:

- an interactive avatar (or "player controller" in gamemaking terms), which provides modalities for sensing and acting to a user via an interface, and is embedded within
- a synthetic environment, comprising three consecutive layers: a core layer concerning the spatiotemporal construction of the environment (its topology, geometry, and physics simulation); a middle layer where scenography and level design take place; and a top layer encompassing events, goals, and narrative content.

For this project, and in accordance with the scoping heuristics outlined above, we focus on the dynamic interactions between the avatar and the core layer of the synthetic environment, abstracting from the upper layers pertaining to scenography, visual style, and narrative.

We translate this framing into a set of design decisions to guide prototyping. First, we pursue modularity and configurability over a fixed artifact, inspired by the configurable platformer prototype developed by Brown [12], aiming to explore how different configurations of fundamental components give rise to qualitatively different forms of VNX. Second, we implement non-Euclidean navigation through 2D curved surfaces embedded in 3D space. In line with the principle of modularity, spatial constructions are generated procedurally rather than through static geometry, enabling real-time variation and control. Third, we follow a relativistic paradigm, replacing the engine's default physics with procedurally calculated gravity. Fourth, all relevant parameters—concerning spatial constructions, physics simulation, and avatar mechanics—are exposed to users through an in-game interface, enabling systematic exploration of the design space. Fifth, we adapt the prototype to accommodate different user interfaces (mouse and keyboard, game controller, and VR headset) to investigate the role of sensorimotor coupling in shaping VNX.

5 Design Outcomes

5.1 Implementation

Following multiple design iterations, we develop a minimal, modular, and configurable prototype in Unity capable of producing a range of qualitatively different navigable environments (figure 1).

We approach the production of spatial constructions through procedural mesh generation. We develop an engine to generate free-form ground surfaces by extruding 2D sections along linear or curved paths in real-time. This approach produces a set of non-standard yet locally Euclidean geometries in 3D space (figure 3), including tubular, rectilinear, contorted, toroidal, and Möbius surfaces, in addition to conventional flat surfaces.

To make these surfaces navigable, we develop a procedural and relativistic gravity engine. Each ground surface is assigned a gravitational behavior according to its cross-section (figure 3), and gravity is computed individually for each rigid body in real-time relative to its adjacent ground surface. This replaces the engine's built-in absolute gravity with a relativistic model in which gravitational orientation is determined locally rather than globally.

To render these environmental constructions experienceable, we develop a first-person player controller that resides on a relativistic frame of reference, allowing it to adapt dynamically to arbitrary surface orientations rather than being locked to a fixed vertical axis (figure 4). A spring system keeps the controller hovering at a fixed distance from the ground surface, avoiding potential errors of conventional collision-based movement mechanics. Movement mechanics are adapted from fast-paced FPS games, including jumping, double jumping, and dashing.

All dynamic properties and mechanics of the player controller are exposed through a "Player Intentionality Editor" (figure 5), allowing

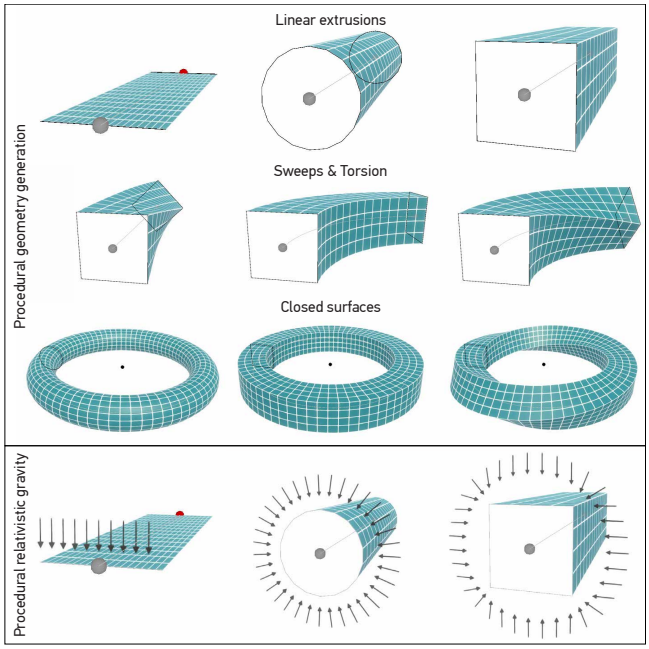

Figure 3: Ground surfaces produced through procedural mesh generation (top), and their corresponding relativistic gravitational patterns (bottom), demonstrating the range of locally Euclidean geometries achievable through this approach.

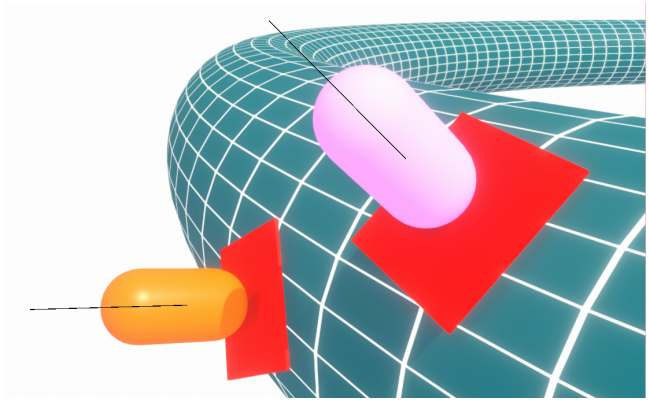

Figure 4: Two player controllers on independent relativistic frames of reference navigating a torus surface, demonstrating orientation adaptation on non-standard geometries.

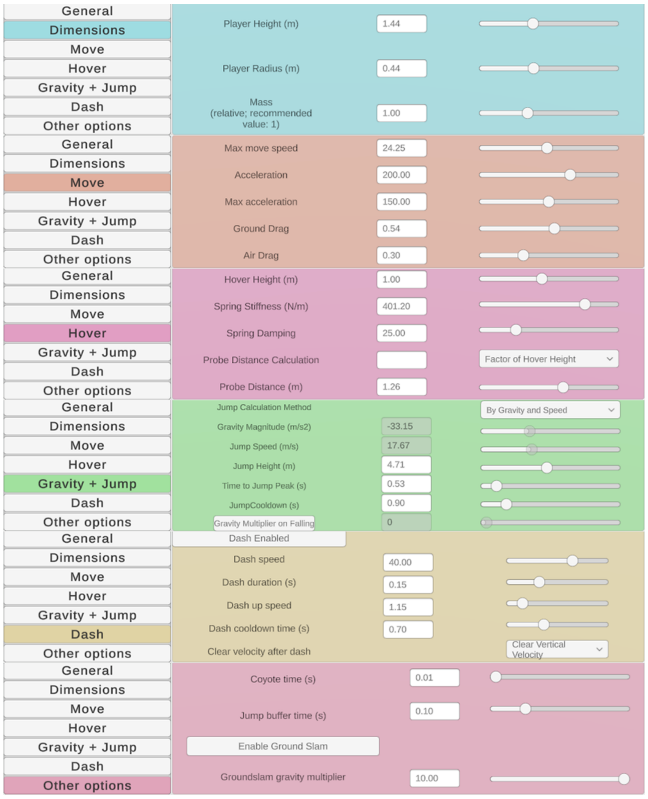

Figure 5: The prototype's Player Intentionality Editor, an in-game interface which exposes all relevant parameters to the user, allowing their configuration and fine-tuning in real-time.

users to configure these parameters and explore their experiential effects in real-time.

Figure 6: The VR implementation using a custom balance board interface, where users navigate by leaning toward their desired direction.

The prototype is designed to accommodate different user interfaces, including mouse and keyboard, game controller, and VR headset. The VR implementation uses a custom balance board fitted with a tracker as movement interface, allowing users to navigate by leaning toward their desired direction (figure 6). Each interface configuration produces a qualitatively different form of embodied engagement, demonstrating the significant role of sensorimotor coupling in shaping VNX.

The deliberately minimal architecture of the prototype proved instrumental in isolating three fundamental components underpinning VNX: spatial construction, environmental simulation, and interactive avatar. We elaborate this tripartite ontology in the following section through the lens of DeLanda's environmental assemblage.

5.2 SpaceTimeCraft: A Tripartite Ontology for VNX

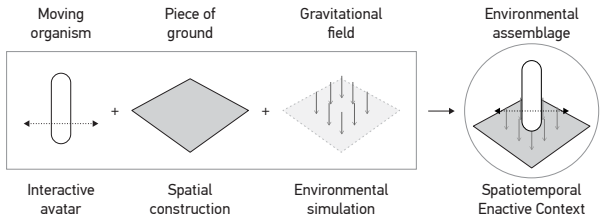

Figure 7: The SpaceTimeCraft tripartite model adapted from DeLanda's environmental assemblage.

Building on the concept of enactive cognition, we formalize the three components identified through prototyping into a tripartite ontology inspired by DeLanda's notion of the "environmental assemblage" [26, 66-67]. DeLanda defines this as the dynamic configuration between heterogeneous entities—an organism, a piece of ground, and a gravitational field—"joined together as such without the need for any homogenization," giving rise to emergent intensive relationships.

This concept proves particularly suited to the study of VNX, providing a minimal yet flexible and extensible ontology that captures the fundamental components necessary for generating an enactive context. We apply this model both as a design ontology and as a software architecture (figure 7), translating DeLanda's three entities—organism, ground, gravitational field—into three generic components of VNX:

- *Interactive avatar* (player controller): a virtual phenomenological intentionality [31, 52] that describes the modality of being-in-the-world for an autonomous agent, defining its modes of sensing and acting (input and output interfaces, sensorimotor contingencies such as visual perspective, mode of hearing, mass, capacities for movement and action).
- *Spatial construction*: the spatial context in which the avatar is embedded, described at a fundamental level through geometry and topology, and at a higher level through spatial and visual design.
- *Environmental simulation*: a set of laws and relationships that govern the materiality and temporal-dynamic behavior of the environment (gravity, friction, simulation frequency, and so on).

Together, these three components constitute what we term *SpaceTimeCraft*: a strong concept that conceptualizes VNX as a spatiotemporal enactive process emerging from their dynamic synthesis. The

model treats each component as a generic placeholder that can take different forms, allowing for the exploration of qualitatively different enactive contexts through their individual and combined configuration.

We demonstrate this capacity through the prototype, which can be configured to produce the conventional environmental constructions found in most videogames (absolute gravity in flat space), as well as more complex constructions such as navigation in relativistic non-Euclidean environments. The framework thus facilitates the exploration of partial aspects of VNX within a holistic dynamic gestalt—including the effects of different spatial configurations, physics parameters, movement mechanics, and user interfaces—demonstrating SpaceTimeCraft as a generalizable framework that provides both analytical purchase on existing instances and generative capacity for novel applications.

6 Discussion

Approaching VNX from the perspective of design practice (RQ1), we propose a conceptual shift in understanding virtual navigation as a spatiotemporal enactive process. SpaceTimeCraft integrates the elemental components of virtual navigation—spatial, temporal-dynamic, and phenomenological—into a holistic interaction gestalt, suggesting that VNX emerges in the dynamic synthesis of a spatial construction, an environmental simulation, and an avatar (a vicarious phenomenological intentionality) coupled to a user interface. By allowing both elemental and integrative perspectives, this model provides a unified framework that bridges virtual navigation as designed, analyzed, and experienced.

By abstracting from visual and narrative design elements, we locate the ground zero for VNX in the construction of spatiotemporal enactive contexts for embodied interaction. This contributes a broader and more foundational conception of design in the context of gamemaking, one that integrates spatial, dynamic, and phenomenological dimensions of navigable experience. Conventional game design operates within a spatial context assumed as given—an assumption reinforced by game engines that provide a fixed Euclidean-Newtonian framework as the default ground for design. Yet game design need not accept space as a given: the spatial context itself is a designable parameter. This reframes design from "design in space" to involve the "design of space" itself, opening new possibilities such as non-Euclidean or non-standard spatial constructions. Beyond spatial design, this reframing foregrounds the dynamic and phenomenological dimensions of navigable experience as essential design parameters: the simulation that governs the environment's dynamic behavior, and the phenomenological intentionality that renders it perceivable and interactable—dimensions that are often taken for granted or overlooked entirely, owing in part to the tacit nature of the experiences they produce.

6.1 Situating SpaceTimeCraft

SpaceTimeCraft responds to longstanding calls by practitioners for shared conceptual tools and vocabularies to support knowledge exchange in gamemaking [2, 15, 17]. It also builds on efforts within HCI and embodied interaction research toward taxonomies [8, 79], design guidelines [45], and frameworks [64]. Within game studies, it contributes to discussions of navigable space as a malleable "media type" [1, 30, 38, 58, 104] capable of accommodating diverse spatial configurations. In doing so, it offers a comprehensive conceptualization that serves as an alternative to notions such as "worldbuilding," which center on static, visual, and narrative components of synthetic environments better suited to non-interactive media, by foregrounding the dynamic and phenomenological dimensions essential to the felt quality of navigable experience.

As a strong concept for the gestalt of virtual navigation, SpaceTimeCraft builds on and extends existing design frameworks such as MDA [43] and "game feel" [93]. Where MDA offers an elementary ontology for the general relationship between design and player experience in videogames, SpaceTimeCraft provides greater granularity for the design space of VNX. "Game feel" provides a design perspective on the phenomenological dimension of "real-time control of virtual objects in a simulated space, with interactions emphasized by polish" [93, 6]. SpaceTimeCraft takes a more abstract approach, extending this concern in two directions. First, it emphasizes spatial construction and environmental simulation as designable parameters in their own right—the spatial and dynamic contexts in which control is exercised. Second, it provides an explicit ontological model that decomposes the gestalt into its constituent components, making it applicable to both analysis and generative design. SpaceTimeCraft is thus more specific than these frameworks in its focus on the gestalt of virtual navigation, yet more abstract and broadly applicable to navigable media as a whole, while carrying both analytical and design-generative capacity.

6.2 Four Modalities for Research and Design

Addressing RQ3, SpaceTimeCraft facilitates four key modalities for research and design:

- *Component isolation.* As a modular ontology, it allows for the isolation of individual components (avatar mechanics and interface, space, simulation) to investigate and prescribe their intrinsic properties.
- *Emergent qualities.* As a dynamic constellation, it accounts for interactions between components and enables the exploration of how individual properties give rise to emergent qualities of the assemblage as a whole.
- *Qualitative modeling.* It offers a descriptive and adaptable template for analyzing instances of VNX by qualifying their properties along three categories, facilitating qualitative comparison and supporting empirical studies that investigate correlations between qualitative attributes and user behavior.
- *Design flexibility.* As a generative design pattern, it provides an approach to VNX prototyping unencumbered by the limitations and assumptions embedded in contemporary design software, enabling alternative models of spatiality and physics beyond current conventions.

6.3 Methodological Contributions

Through an integrative mode of RtD, this project contributes a concrete methodological exemplar for practice-based design research in gamemaking, where such precedents remain notably scarce. In

doing so, we demonstrate the capacity of design to synthesize insights from diverse bodies of knowledge, and affirm experimental prototyping as a valid knowledge-generating method, capable of addressing gaps not accessible through analytical or empirical approaches alone, and of inquiring into foundational aspects of the medium that require constructive engagement with design practice.

Within this framework, we pursue exploratory and experimental gamemaking as a research method, elaborating on cursory discussions in the literature [62, 99]. Addressing RQ2, we document a structured design approach that operates against the grain of existing practices and is able to transcend the Euclidean-Newtonian conventions of contemporary game engines. By pursuing a spatiotemporal design paradigm akin to relativistic physics, we demonstrate the capacity of this approach to expand the design space, generating new experiential configurations and providing access to a largely unexplored region of navigable media. The result is a replicable design method for movement-based interaction that can be adapted to different design contexts.

7 Conclusion

With SpaceTimeCraft, we contribute a strong concept [44] for the gestalt of virtual navigation, applicable to videogames and navigable media more broadly, developed through an integrative mode of research through design applied to experimental and exploratory gamemaking. By abstracting from game-specific attributes such as narrative, characterization, and goals, SpaceTimeCraft offers a broader and more foundational conception of design in the context of gamemaking. It provides a minimally elegant tripartite ontology—spatial construction, environmental simulation, and interactive avatar—that serves both as a unifying analytical framework and as a generative design pattern for an experience that is synesthetic, corporeal, and resistant to conventional analysis. The model is designed to be abstract enough to allow for adaptation, extension, and transfer to different areas of application, while remaining comprehensive enough to accommodate different scopes and modalities of inquiry within a unified framework.

This framework reconfigures virtual navigation as a spatiotemporal enactive process subject to design, reconciling spatial, temporal-dynamic, and phenomenological perspectives into a holistic conceptualization. As an analytical framework, it enables the examination of existing instances of virtual navigation by qualifying their properties along these three fundamental categories, facilitating qualitative comparison and supporting empirical inquiry. As a generative design approach, it provides a structured yet flexible pattern for prototyping, enabling the systematic exploration of virtual navigation across its fundamental components—spatial constructions, environmental simulations, and avatar mechanics and interfaces. We demonstrate this capacity through the prototype which produces a range of different navigable environments by varying configurations across these components, including relativistic non-Euclidean constructions.

SpaceTimeCraft addresses the absence of shared frameworks bridging analytical, empirical, and design-oriented inquiry into virtual navigation, while advancing discussions of navigable space and the corporeal dimension of experience across videogames and movement-based interaction more broadly. This work also presents virtual navigation as a dynamically evolving phenomenon that cuts across technologies, design practices, cultural trends, and scholarly communities, warranting integrative approaches to its study.

Beyond its conceptual contributions, this work advances design research methodology. Our approach of integrative RtD offers a valuable methodological exemplar for practice-based design research in gamemaking where such precedents remain scarce. Within this approach we implement experimental gamemaking as a research method, demonstrating its capacity to generate intermediate-level knowledge, expand the design space, and inquire into foundational aspects of the medium that require constructive engagement with design practice. Through this process we also contribute a replicable design method for movement-based interaction capable of generating novel experiential configurations beyond the conventions embedded in current design tools.

As this work centers on experimental prototyping as a mode of inquiry, future work can test the framework in the contexts of design practice, videogame analysis, and empirical research. In design practice, workshops where practitioners apply this approach to prototyping can generate feedback and strengthen claims concerning its generative capacity for designing movement-based interaction. In analysis, the framework can serve as a template for identifying the distinguishing characteristics of instances of virtual navigation—for example, qualifying contemporary "boomer shooters" or comparing across diverse genres such as movement-intensive and slower-paced games. In empirical research, the framework's capacity for qualitative modeling can inform studies investigating correlations between specific attributes of VNX and user behavior. Further avenues include applications beyond videogames, such as VR training and embodied learning.

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A Scoping heuristics

The scoping heuristics developed for this study are defined as follows:

- **Embodied** refers to forms of navigation that involve a "vicarious kinesthetic" activity, where users interact through an avatar and its situated affordances for action within a virtual environment [31, 47, 52].

- **Relatable** describes enactive contexts that parallel real-world experiences by providing sensorimotor contingencies that users can intuitively engage with. Accordingly, we focus on forms of virtual navigation that enable embodied real-time interaction through a *first-person perspective* and allow for *continuous movement* in a three-dimensional (3D) space.
- **Movement-focused and intensive** describes interactive processes that require intuitive and skillful real-time engagement through movement. Such processes encourage movement as an expressive act of skillful know-how by providing 'deep' interaction mechanics that support skill development through practice and 'mastery'. Movement-focused refers to modes of interaction where spatial movement is the primary means of engagement, emphasizing immediate, dynamic motion over more deliberative navigational tasks such as wayfinding or orienteering. Meanwhile, intensive highlights real-time movement-driven interactions that demand intuitive spatiotemporal engagement, relying on pre-conscious moment-to-moment decision-making rather than analytical reasoning—often incentivized in videogames through movement-based challenges. In analyzing videogames, we focus on design patterns that position movement as a core interactive mechanic, and abstract from elements that are not directly tied to the experience of immediate movement, such as narrative structures, characterization, or scenographic aspects (e.g., visual design, architectural style).
- **Interface-transparent** concerns interaction interfaces that become perceptually transparent through practice, allowing users to incorporate them seamlessly into their skillset, thereby augmenting their capacity for intuitive and instinctive action [80, 95].
- **Medium-specific** describes enactive processes that are unique to interactive digital media. Combined with relatable, this heuristic highlights experiences that diverge from real-world activities due to, for example, their distinct sensorimotor contingencies and capacities for action, the intensity of interaction, or the structure of the environment (e.g. space and physics).

B Research Components

This work is part of a larger doctoral research project, supported by three research components: a hypertextual *Research Notebook*, an *Interactive Timeline Visualizer*, and a configurable videogame prototype. The prototype is documented in the main text. The other two components, which informed the research presented in this paper, are described below for context.

The Research Notebook presents an extensive collection of interconnected annotations on topics relevant to this study. Its construction was motivated by the need to make sense of a problematic research landscape where relevant literature is scarce and fragmented across distinct communities of practice, formal design research is largely absent, and critical inquiries into the evolving phenomenon of virtual navigation remain limited.

The notebook offers a concrete and comprehensive hypertextual elaboration of the concept of "annotated portfolios" [10, 33]. This is a tentative format proposed for communicating knowledge produced through RtD projects, also discussed in the context of game design research [18], with limited concrete precedents. Informed by the concept of "contemporary objects" [85] and the method of "integrative literature reviews" [20], the notebook was produced gradually to synthesize the wider body of related knowledge, and specifically scientifically informal yet substantive sources such as practitioner discourses, video essays, prototypes, videogames, and technologies. Through the creation of topical entries, the tracing of genealogies, and the mapping of connections between them, it accounts for the evolution of different dimensions of the phenomenon (e.g. videogames, technologies, discourses), while identifying recurring themes, extracting and examining shared attributes such as game mechanics and design patterns, and outlining directions for inquiry. This process was instrumental in generating the insights that inform this work. The notebook contains 380 entries organized in 14 thematic collections, with 102 entries reserved for annotations concerning individuals. It was produced as a web-based resource using the experimental publishing framework *Sandpoints* [59], which supports non-linear content organization and traversal via collections, keywords, links, and backlinks.

Complementing the notebook, an Interactive Timeline Visualizer (figure 8) was developed to offer perspective into the evolution of VNX through the visual mapping of events (videogame releases, technologies, exhibitions, publications) on the temporal domain. Built as a web application, it includes 278 entries that can be filtered by type, genealogy, or time period, allowing for inquiry across different layers of the phenomenon.

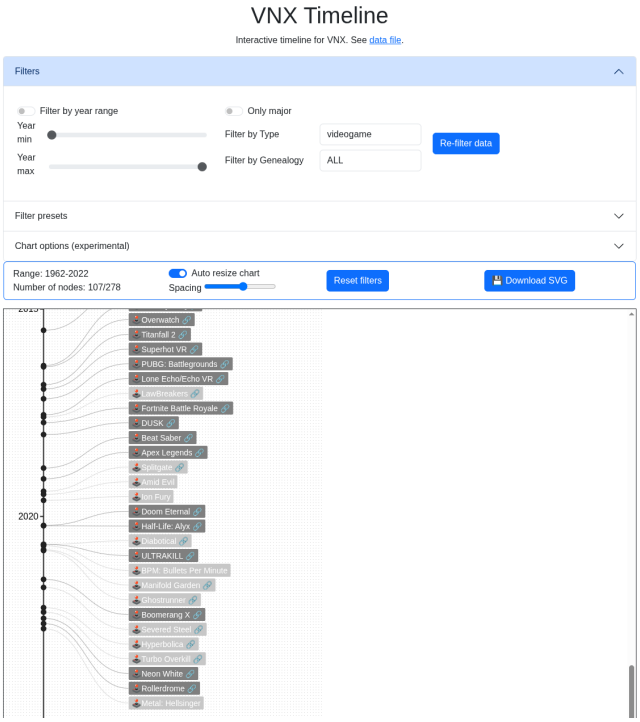

Figure 8: Screenshot of the VNX timeline visualizer, showing videogame releases between 2015 and 2025.