

Exhibiting Advanced Mathematics with Casual Games in Science Centres

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Abstract: Mathematics is fundamental for civic participation and decision-making in an increasingly data-driven society and should therefore be approached as a lifelong learning pursuit. However, despite their role as informal learning environments, science centres rarely exhibit advanced mathematics. This can be attributed to the challenges of informal learning settings, where participation is voluntary and socially oriented, numerous exhibits compete for visitors' attention, and interactions are typically brief. These conditions make sustained engagement with abstract mathematical concepts difficult. This paper investigates how casual game-based exhibits can support engagement with advanced mathematics in science centre environments. The design of three interactive exhibits from a mathematics exhibition at Sweden's national science centre were studied through visitor observations and embodied interaction analysis of gameplay. Results show that visitors engaged in meaningful exploration, strategic reasoning, and collaborative discussion related to the mathematical content. Across the exhibits, five design principles were identified: (1) intrinsic integration of learning content and game mechanics, (2) hybrid physical-digital interaction, (3) clear and simple goals, (4) obvious game actions but challenging game mastery, and (5) multi-sensory and experiential learning content. The findings demonstrate the potential of casual game-based exhibits to make advanced mathematics accessible in informal learning environments and provide empirically grounded design principles for science centres and similar contexts.

Keywords: Game-based learning, Informal learning environments, Science centres, Mathematics, Casual games

1. Introduction

Science centres are informal learning environments designed to engage visitors of all ages with scientific and technological content through hands-on experiences. Unlike traditional museums, science centres prioritise active participation through interactive exhibits that encourage exploration and collaboration (Allen, 2004; Callanan et al., 2011; Rogoff et al., 2016). Designing for informal learning environments is challenging (Allen, 2004) because they serve diverse audiences, participation is voluntary and driven by personal interest, visits are primarily recreational and social, and learning must coexist with entertainment. Science centres typically offer a wide range of exhibits that compete for visitors' attention. Hence exhibit design must attract visitors' attention, invite interaction, and stimulate engagement with the exhibit content to achieve learning. Still, empirical knowledge of exhibit design is limited (Bobbe & Fisher, 2022). We suggest casual games as a suitable format for exhibit designs.

Mathematics is fundamental for everyday decision-making, civic participation, and critical engagement in a digitalized society. Science centre exhibitions rarely address advanced mathematics, instead they typically focus on basic concepts or links between mathematics and art. A mathematics exhibition was designed and opened in 2023 in Sweden's national science centre, targeting teenagers age 13-18 years. For such population, the exhibition must go beyond basic mathematics. This study examines the potential of using casual game-based exhibits to foster engagement with advanced mathematics, by investigating the design of three game-based exhibits and studying visitor engagement during gameplay. The exhibits address Voronoi diagrams, Nash equilibrium in game theory, and the tangent of a function's graph. Video data were analysed using embodied interaction analysis to identify productive learning interactions. Casual games were selected as design format due to their suitability for voluntary, social, and time-limited interactions. The paper proposes and empirically grounds five design principles for casual game-based exhibits for informal learning of advanced mathematics or similar domains.

2. Background and Related Work

2.1 Informal Learning in Science Centres

Informal science learning, often described as free-choice learning (Falk, Storksdieck, & Dierking, 2007), is self-directed, intrinsically motivated, socially situated, and shaped by visitors' interests, prior experiences, and physical surroundings. In a socio-cultural perspective (Vygotsky, 1978), science centre exhibits become tools mediating mathematics through interaction and game representations, in a social setting where visitors construct meaning together through gameplay. In these settings, personal relevance and meaningful activities

become critical since visitors navigate their own learning and decide freely what to engage with, for how long, and together with whom (Callanan et al., 2011).

Today, interactive exhibit design plays a central role in informal learning environments (Bobbe & Fisher, 2022), as interactivity often stimulate hands-on, active participation and engagement with the learning content (Barriault & Pearson, 2010). Visitors are however primarily motivated by enjoyable, exploratory, and socially meaningful experiences rather than explicit educational goals, and therefore the learning content should be embedded in an activity that attract the target population. Therefore, effective exhibit design must create interactive and intrinsically motivating experiences that encourage intellectual, physical, emotional, and social engagement, in our case mathematical concepts for the often difficult-to-engage teenage audience. Designing exhibits that attract and sustain visitor engagement is however essential for supporting meaningful learning experiences in science centre contexts.

2.2 Casual Games as a Design Paradigm

Casual games have become a widespread phenomenon, through delivery by mobile technology. The term “casual” is ambiguous, it can refer to the game format, the player, the playing style, or the business model (Kuittinen, et al., 2007). Here, we refer to casual as the *game format*, meaning games that typically have broadly appealing content, intuitive controls, simple gameplay mechanics, immediate rewards, and are suitable for short play sessions. Here, we mimic the game format but apply the principles to learning content rather than to content without deeper meaning as common in casual games. Note that a casual game format neither implies a casual player nor casual gameplay (Kultima, 2009). A player can be fully engaged playing a casual game a key requirement for informal learning exhibits.

King (2021) suggests combining principles of casual and serious games into an activist-casual game design framework. He argues that “thinking casual” can benefit serious game design by increasing accessibility and reducing development costs. However, the framework has not yet been empirically evaluated. Our approach is to apply casual game features to advanced mathematics content to be used in informal learning settings. The key characteristics of casual games are: 1) easy-to-learn gameplay, 2) short sessions, i.e., designed for quick, spontaneous play sessions, 3) low barrier to entry, i.e., perceived as inviting and clear, 4) immediate engagement, i.e., instant fun and no preparation, and 5) broad audience, i.e., appeal to most people. Hence, casual game features suit informal learning environments well.

2.3 Game Design for Learning

The most important and challenging issue in game design for learning is how to integrate the domain-specific learning with the game mechanics and game design. Ke (2016) conducted a comprehensive and in-depth systematic literature review addressing the questions effective content-game integration. Her findings show that learning games are often designed to deepen, broaden, or perspective-change of knowledge, and that learning content integration was primarily achieved through game representation and simulation. Game-like elements from the learning domain were represented as game elements to achieve effective integration of conceptual learning. Such intrinsic integration embeds learning content within the core game mechanics, making learning and gameplay inseparable (Habgood & Ainsworth, 2011). The other key mechanism of game integration were visual simulations. Effective integration must align learning mechanics directly with the game mechanics to make learning an inherent and inevitable component of the gameplay experience. Finally, Ke's (2016) findings advocate games supporting meta-reflection and iterative learning, where repeated gameplay reach a state of flow (Csikszentmihalyi, 1991). Intrinsically motivating games supporting players' autonomy, competence and relatedness (Ryan & Deci, 2000), facilitate experiences of flow.

Design principles devoted to science centre learning (Bobbe & Fisher, 2022) function as complement to the above findings. The first principle, enabling social interaction around the exhibit, is a design requirement seldom fulfilled in casual games but essential to be experienced by a group and to stimulate discussion. The second principle, a low-pressure setting where visitors can watch others play and get interaction cues, likewise. The third principle, making the experience meaningful and relatable to real-world contexts becomes relevant when the casual game features learning content. All the above perspectives have informed the exhibit designs in this study.

3. Research Design and Methodology

3.1 Research Context

The research context is *Mathrix*, a mathematics exhibition at Sweden's national science centre, Universeum (Figure 1), designed to engage teenagers and adults in exploring and discovering the mathematics underlying everyday activities. The exhibition aims to stimulate interaction with exhibits and mathematical concepts while fostering more positive attitudes towards mathematics. This study focuses on three interactive exhibits in a casual game format, representing advanced mathematical ideas in the form of a theory (Nash equilibrium), a mathematical model (Voronoi diagrams), and a mathematical relation (the tangent of a curve).



Figure 1: The mathematics exhibition Mathrix, Universeum science centre, Sweden

3.2 Design-based Research Approach

The exhibits were developed through a user-centred, iterative design process based on rapid prototyping and continuous evaluation. An interdisciplinary team comprising a project manager, educators, researchers in mathematics, learning, user experience and game design, as well as architectural designers, contributed educational, technological, spatial, and experiential perspectives throughout the process. Evaluation was integral to the design work and included iterative testing during development and post-opening visitor studies examining engagement and learning at both exhibit and exhibition levels. This paper draws on three design-in-use studies: a visitor movement study covering the entire exhibition and two visitor studies of the casual game exhibits.

3.3 Data Production

The studies were conducted during school holidays, when the science centre attracts large numbers of school-age visitors. Data collection comprised structured observations of visitor movement and behaviour throughout the exhibition and video-recorded observations of embodied interaction during gameplay at two exhibits. Observation is a suitable method for studying game-based learning as it captures participants' play patterns and interactions (Jabbar & Felicia, 2015). Participants were recruited among voluntary visitors. For the exhibit studies, written informed consent was obtained from participants and, where applicable, from legal guardians of participants under 15 years of age. To protect privacy, video recordings captured only hands and exhibit displays, while audio was recorded separately. In the movement study, the exhibition was divided into observation zones that were monitored in sequence. Visitors approaching exhibits were categorised as *ignore*, *attend*, or *interact*, depending on the visitor's (dis)engagement with the exhibit. Field notes documented movement patterns. In the exhibit studies, visitors who voluntarily approached an exhibit were invited to participate. Gameplay was unguided and of self-determined duration to maximise ecological validity, and post-game reflections were collected following play.

3.4 Analysis Methods

Visitor movement data were analysed by calculating engagement measures for each exhibit based on observed behaviours. For example, interaction rate was defined as the proportion of passing visitors who actively interacted with an exhibit, with higher rates indicating greater attractability. Video-recordings were transcribed and analysed using interaction analysis (Jordan and Henderson, 1995) supported by data analysis software. Visitors' embodied conversations (verbal interactions annotated with relevant gameplay actions) were coded as *Learning talk*, *System talk* or *Affective talk* (Liu & Heer, 2014). The strength of video-recorded data is the ability to repeatedly examine detailed sequences of interaction (Heath & Hindmarsh, 2010), enabling fine-grained analysis of gameplay behaviour and learning processes.

4. The Casual Game Exhibits

Below, we describe three mathematics exhibits in casual-game format from the exhibition Mathrix. The first exhibit introduces the game-theoretical concept of Nash equilibrium, the second explores the mathematical model of Voronoi diagrams, and the third illustrates a fundamental relationship in differential calculus.

Figure 2: The Nash-theory exhibit (left), the Voronoi-model exhibit (middle), the graph-relation exhibit (right)

The Nash-theory exhibit (Figure 2, left), *Me or We*, is a two-player game based on the Nobel Prize-winning concept of Nash equilibrium, a theory with applications ranging from pricing strategies and Cold War deterrence to cooperation, trust, and collective action. Players repeatedly choose between competing (*me*, red button) and collaborating (*we*, green button) without knowing the other player's choice. The scoring system creates strategic tension: mutual collaboration yields two points each, mutual competition yields none, while a competing player gains three points and the collaborating player loses one point. This simple mechanic introduces dilemmas of trust and opportunism, allowing players to explore strategic behaviour and discover that while competition is a non-losing strategy in a single round, optimal play becomes less obvious across the ten-round game.

The exhibit “*Voronoi – Natural Phenomena and Mathematical Model*” (Figure 2, middle) introduces visitors to Voronoi diagrams, patterns found both in nature (e.g., giraffe coat markings) and in applications such as urban planning, robotics, and logistics. Mathematically, a Voronoi diagram partitions an area into regions around points (seeds), where each region contains all locations closest to its seed. The exhibit consists of a large horizontal display and four coloured buttons, allowing up to four players to compete to capture the largest area. Players take turns placing three seeds each, after which the system generates and animates the Voronoi diagram as regions expand from the seeds until constrained by neighbouring regions or the display boundary. This visual simulation both demonstrates the underlying model and builds anticipation around the outcome. The player whose seeds generate the largest combined area wins. Minimal interface instructions encourage exploration and discovery, while a nearby information board provides a deeper explanation of the mathematical concept.

The *Tangent* exhibit (Figure 2, right) explores the relationship between a curve and its slope. Designed as a racing-style game, players aim to follow a moving target curve as closely as possible using a 20 cm rotatable red stick beneath the screen. The stick controls the slope of the player-generated curve, visualised as a red line, while the target curve is displayed in white. The area between the two curves is highlighted, and smaller deviations yield higher scores. As gameplay progresses, the target curve becomes increasingly difficult. Mathematically, the exhibit reverses the traditional problem: instead of finding a tangent from a curve, players generate a curve by controlling its tangent. Through this direct physical manipulation, players experience visually and haptically how changes in slope determine the shape of a curve.

The three exhibits represent central mathematical constructs: models, theories, and relations, but being common constructs in other domains, the design principles are applicable beyond mathematics.

5. Findings

5.1 Engagement and Attractiveness

The movement study recorded 2,383 visitor–exhibit interactions across 22 exhibits (Alfredsson, 2023). The most common visitor group was families comprising one or more adults and children under 13. Observation counts per exhibit ranged from 50 to 170, reflecting differences in visitor traffic between central and more secluded exhibition areas. The three game exhibits Nash, Voronoi, and Tangent accounted for 72, 64, and 56 observations,

respectively. Analysis identified three exhibit characteristics associated with high attractability: hybrid physical-digital game formats, enclosed spaces with familiar activities, and self-mirroring exhibits. The three games achieved interaction rates of 40%, 39%, and 36%, placing them among the six most engaging exhibits in the exhibition and far above the least engaging exhibits (6–10%). Overall, the findings indicate that the game exhibits were highly successful in attracting attention and stimulating interaction, with hybrid physical-digital games emerging as the most popular exhibit format.

1.1 Learning Interactions: the Nash Game

In the visitor interaction study of the Nash game exhibit (Pareto et al., 2023), five visitor groups comprising 11 participants (5 males, 6 females) were recorded and analysed. Seven participants belonged to the primary target group (upper secondary school students) and four were young adults. The groups, consisting of two or three players, played between one and eight game sessions each, yielding 21 analysed games. Gameplay sessions lasted 4–12 minutes, somewhat longer than typical visitor interactions due to study participation, but still illustrating the limited attention span available to science centre exhibits.

Across all groups, at least one player discovered and adopted a distrustful winning strategy, a finding also confirmed in post-game interviews. This strategy proved highly successful and often led to victory. Two groups displayed uneven strategic performance, with one player demonstrating strategic play while the other did not, whereas the remaining three groups performed more equally, resulting in greater experimentation, more strategic reasoning, and more games played. For example, one participant explained: “I pretended I wanted to collaborate in the beginning ... but then, in the end, I tried to win anyway,” a strategy that succeeded in three of four games. Similarly, a group of upper secondary students reflected: “To win, you only needed to beat the opponent one round, then play red the rest. If the goal is to maximize the points, we could have collaborated more. But it was fun!” These observations suggest that players developed an experiential understanding of Nash theorem’s strategic implications through gameplay.

5.2 Learning Interactions: the Voronoi Game

In the visitor interaction study of the Voronoi exhibit, 20 visitor groups comprising 57 participants were recorded and analysed (Thilén, 2024). Groups consisted of two or three players and included 27 children under 13, 9 teenagers or young adults, and 21 adults over 25, with an even gender distribution. The groups played 86 games in total, ranging from 1 to 12 rounds per group. Gameplay duration averaged 5:53 minutes per group (range 1:31–16:12), totalling 118 minutes, and 15 of the 20 groups played three or more rounds, indicating sustained engagement and interest.

Analysis of action-annotated gameplay conversations showed that 73.0% of visitor talk related to learning, comprising 34.4% mathematical learning talk and 38.6% game-mechanics learning talk. Mathematical learning talk involved observing, predicting, and interpreting patterns, identifying relationships, and applying strategies, as illustrated by statements such as “*I placed them where no one else was because then I get a bigger area*” and “*There will be very little of this colour, I’m completely sure*”. Learning talk related to game mechanics concerned rules, gameplay decisions, previous outcomes, and turn-taking. Affective talk accounted for 15.2% of utterances, including expressions of enjoyment, surprise, and curiosity (e.g., “It’s quite fun when you understand how it works”), while the remaining 11.8% concerned interface-related issues.

Further analysis revealed three levels of strategic reasoning: display-oriented reasoning (placement relative to the overall display), self-relational reasoning (relations between one’s own dots), and social-relational reasoning (relations to other players’ dots), with the richest strategic discussions involving all three. Analysis of five longer and mathematically rich sessions revealed a recurring four-stage learning trajectory: engaging, observing, interpreting, and testing, which aligns well with Kolb’s experiential learning cycle (Kolb, 1984), suggesting that meaningful learning emerged through collaborative gameplay.

In summary, the two gameplay studies indicate that visitors developed an experiential understanding of the mathematical constructs underlying the games (the Nash theory and the Voronoi model), and that the social setting of the exhibit and the game design played key roles in fostering engagement and meaning-making. The Tangent exhibit has not yet been evaluated with visitors.

6. Analysis and Discussion: Design Principles for Casual Math Games

Combining a cross-case analysis of the three exhibits with empirical findings on visitor engagement and learning yielded five design principles for casual game-based exhibits in science centres.

Principle 1: Intrinsic Integration of Learning and Mechanics

The first and most important principle is the intrinsic integration of learning content and game mechanics, identified as a core characteristic of successful educational games (Habgood & Ainsworth, 2011; Ke, 2016). Achieving this principle requires expertise in both the learning domain and game design. It involves designing gameplay around a fundamental property of the target concept, typically through domain-faithful representations, simulations of domain processes, and game mechanics that mirror meaningful actions within the domain.

In the Nash game, gameplay consists of ten repeated Nash-equilibrium situations in which players choose between collaboration (green button) and competition (red button). Since independent decision-making is a defining condition of the Nash theorem, the game is designed with separate screens and hidden choices to ensure a domain-faithful representation of the concept. The public display allows other visitors to follow the unfolding gameplay, consistent with Bobbe and Fisher's (2022) second exhibit design principle, while also enhancing the psychological intrigue of the game.

In the Voronoi game, players compete to capture the largest area by placing colour-coded seeds, while an animated simulation visualises how the resulting regions emerge. The game mechanics directly represents the defining property of Voronoi diagrams; that spatial partitioning is determined entirely by seed placement, also the players only game action. While maximizing area is not an inherent property of the model, it motivates players to explore and mentally visualize how different seed configurations affect the outcome, an effect reinforced by the post-decisions simulation of seed growth.

In the Tangent game, the target path, the steering mechanism, and the player-generated curve, correspond directly to a function, a tangent at each position determining the player-generated curve. That a tangent determines the change of a curve at each position is an inherent property of the mathematical relation, here used as an input device to "draw" the curve. The coloured area between target and player curves visualises the deviation, mathematically corresponding to the integral of the curve difference.

Principle 2: Hybrid Physical-Digital Interaction

Aligned with the casual game principle of a low barrier to entry, all three exhibits combine physical input devices with digital displays. Science-centre experience and visitor studies indicate that physical controls trigger interaction more readily than purely digital interfaces. Their resemblance to familiar everyday objects provides strong affordances and lowers participation thresholds (Norman, 2013). Digital displays complement these affordances by presenting game content, visualisations, gameplay overviews, and immediate feedback, thereby supporting engagement and learning-content representation. In the Nash game, coloured buttons are used for decision-making, while the display presents outcomes and strategic prompts. Similarly, Voronoi combines buttons and touch interaction for seed placement with a display visualising the evolving diagram. In Tangent, a rotatable stick controls gameplay, while the display visualises both the target and player-generated curves.

Principle 3: Simple Game Goals

The game goal should be simple and immediately understandable, in line with casual game design principles. In the Nash game, players aim to maximise points over ten rounds, either individually or collectively. The dual objective is intentional, encouraging reflection on the consequences of Nash equilibrium while increasing the game's strategic depth and enjoyment. Although frustrating to some players, this ambiguity was designed to stimulate reasoning and learning. In the Voronoi game, the goal is to capture the largest area, while in the Tangent game players aim to mimic a target curve through tangent-controlled drawing.

Principle 4: Obvious Game actions, challenging Game mastery

Game actions, the actions available to progress gameplay, should be extremely simple. A useful distinction is between how to play a game mechanically and how to play it well. While game actions should be immediately understandable, game mastery should provide sufficient challenge to encourage replay and exploration. Mastery may involve strategic reasoning, as in the Nash and Voronoi games, or motor skill, as in the Tangent game. The available actions are deliberately simple: choosing between a red or green button in Nash, placing three dots in Voronoi, and rotating a control stick in Tangent. By contrast, identifying effective strategies in Nash and Voronoi, or accurately tracing increasingly complex curves in Tangent, is considerably more demanding. This combination of simple actions, challenging mastery, and short play sessions is a defining characteristic of casual games and a key factor underlying their replayability.

Principle 5: Make learning content multi-sensory and experiential

The exhibits were designed to make abstract mathematical concepts directly experienceable through gameplay and physical interaction rather than symbolic representation. In Nash, players explore strategic decision-making, competition, trust, and collaboration through repeated choices and outcomes; in Voronoi, they investigate how regions emerge and constrain one another through spatial growth; and in Tangent, they physically experience how local changes in slope shape a curve. Together, the exhibits provide experiential, multi-sensory engagement with mathematics, a potential supported by the empirical studies presented above.

These design principles align with learning theories by supporting mediated action through tools and visualisations (Vygotsky, 1978), simulation-based learning (Ke, 2016), free-choice and self-directed learning (Ryan & Deci, 2000), and interactivity (Bobbe & Fisher, 2022). Despite the diversity of the audience, the games were accessible enough for virtually any visitor to understand the mechanics and goals, while engaging with the underlying mathematical concepts at varying levels of depth. The exhibits also align with pedagogical exhibit-design principles (Bobbe & Fisher, 2022) by fostering social interaction and collaboration, creating low-pressure learning environments, and establishing meaningful connections to the learning content, as reflected in the empirical findings.

7. Conclusion and Future Work

This paper investigated how casual game-based exhibits can support engagement with advanced mathematics in science centre environments. Through the design and empirical study of three interactive exhibits, the findings show that visitors engaged in meaningful exploration, discussion, and strategic reasoning related to concepts such as Nash equilibrium, Voronoi diagrams, and the relationship between a curve and its tangent. The studies further demonstrate that casual game formats can successfully attract visitors and sustain interaction in informal learning settings characterised by voluntary participation, short engagement times, and multiple competing activities.

Based on the exhibit designs and analyses of visitor interactions, five design principles for casual game-based exhibits were identified: (1) intrinsic integration of learning content and game mechanics, (2) hybrid physical-digital interaction, (3) simple game goals, (4) simple game actions combined with challenging game mastery, and (5) multi-sensory and experiential learning content. Together, these principles illustrate how abstract and advanced mathematical ideas can be made accessible, engaging, and socially meaningful through interactive gameplay.

The study contributes to both exhibit design and game-based learning research by providing empirically grounded design principles for casual game-based learning exhibits and demonstrating the potential of casual game design as a pedagogical approach for communicating complex mathematical concepts to broad public audiences. More broadly, the findings suggest that casual games can bridge engagement and learning in science centres, enabling visitors to encounter sophisticated ideas through playful exploration and social interaction.

Although based on three exhibits in a single science centre and detailed analyses of a limited number of visitor groups, the findings provide rich insights into visitor engagement and meaning-making, while pointing to the need for further validation of the proposed design principles.

Future research should evaluate learning opportunities in the Tangent exhibit, investigate longer-term engagement and collaborative meaning-making processes, and explore whether insights gained through gameplay transfer to formal mathematics learning. The proposed design principles should also be tested in other scientific domains and informal learning contexts.

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Ethics Declaration: This study was conducted in accordance with the ethical guidelines of the Swedish Research Council. No sensitive personal data were collected, and informed written consent was obtained from all participants and from legal guardians of participants under the age of 15.

AI Declaration: During the preparation of this work the author used ChatGPT Edu (GPT-5.5, OpenAI) to improve readability and language. After using this tool, the author reviewed and edited the content as needed and take full responsibility for the content of the publication.

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