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Designing Quantum Games and Quantum Art for Exploring Quantum Physics

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***Abstract*—In this paper, the design processes of five games, simulations, and interactive art installations involving quantum physics is reported and reflected. These projects were developed between 2019 and 2022 and include smaller game jam projects and longer-term collaborations with a professional game company. The design reflections explore the issues that can influence the success of serious and applied games, as well as art pieces used in science communication, research, or educational roles. Based on these experiences, it is evident that design constraints, design values, effective communication, and the valuation of each other's expertise are at the center of successful quantum game development.**

***Index Terms*—Game Design, Serious Games, Applied Games, Quantum Physics**

I. Introduction

Quantum games are defined as "... *games that reference the theory of quantum physics, quantum technologies, or quantum computing through perceivable means, connect to quantum physics through a scientific purpose or use quantum technologies.* " [1]. Quantum games have been developed for various purposes (education, research, and entertainment), but also out of the mere curiosity on the topic [2], [3]. Whatever the means, gaining interest towards quantum physics and quantum technologies is important under the societal impacts of the *second quantum revolution* [4], [5].

The need for a basic understanding of quantum physics in engineering sciences has grown. However, traditional approaches to studying quantum phenomena rely heavily on mathematical formalism, limiting accessibility to those with the time and background who can grasp the underlying concepts [6], [7]. Visualisations and interactive methods on computers have long been used to bridge this gap and provide students with a connection to quantum phenomena [8]–[11]. Including games in educational materials has also inspired quantum physics educators [12]–[17]. Quantum games, in particular, have shown potential as tools for citizen science and teaching intuition through playfulness [4], [18]–[22]. Citizen science involves engaging citizen scientists in academic research. Furthermore, developing games on quantum computers serves both as a means to learn quantum computing and to explore the capabilities of quantum computers [23], [24].

To gain further insight into the unique design space of quantum games and art, this study examines five quantum projects developed between 2019 and 2022. By analysing these projects, valuable contributions can be made to the field of quantum game development, especially for serious purposes. These projects vary in duration, ranging from several months to just a couple of days.

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Several of the presented projects are influenced by the development of the Quantum Black Box (QBB), a Python-based interface aimed at systematic research on complex numerical quantum physics problems (See Table I). The QBB project was initiated by the researchers in the Turku Quantum Technology (TQT) group in 2017 and it focuses on optimisation control problems related to Bose-Einstein condensates [25]. The simulation takes two input parameters that represent the positions of the first and last wells in a triple-well potential. It generates a dynamic plot showing the probability distribution of the system based on the variation of these parameters. The study of Bose-Einstein condensates is related to the engineering of memory-control units for a quantum computer.

Subsequent projects involve the simulation of quantum walkers, which are the quantum counterparts of classical random walkers [26]. While classical random walkers select their walking direction randomly at each step, quantum walkers can simultaneously explore all possible paths due to the principles of quantum physics. Quantum random walkers can be used as a valuable tool for illustrating key aspects of the quantum world and are actively studied in the domains of quantum computing, quantum communication, and quantum biology.

The author's main involvement in the presented projects has been as a quantum physics expert, assuming different roles ranging from a consulting expert to a solo developer. Based on these diverse experiences, the author provides observations and reflective insights from the perspective of a quantum physicist with a background in the study of quantum foundations and interaction design. The aim is to shed light on the requirements of a quantum game development process. These findings are offered as valuable resources for anyone interested in undertaking similar projects.

II. Method

For the research methodology, the author utilises an adoption of the Research through Design approach. This involves employing a social-scientific autoethnographic analysis of the development process, which includes keeping design diaries, self-observational memos, and meeting notes with the development team [27], [28]. To go beyond a mere autobiography of personal experiences [29], the author also revisits conversations exchanged through email or messaging platforms like Slack and Discord to gain additional insights into design choices and development processes. Additionally, visual materials such as pictures, videos, and older versions of project files are utilised for reflective purposes. During report writing, these materials undergo an iterative process of examination and reflection on the impacts of design choices and restriction on the end product. Furthermore, the author's perspective is informed by years of participation, supervision, and mentoring of other quantum game development processes and quantum art installations.

III. Projects

To structure this paper, the five projects and their development processes are described in chronological order (See Table I). It is important to note that these projects have not only progressed concurrently but have also influenced and even initiated other projects in the process.

TABLE I
QUANTUM GAME AND QUANTUM ART PROJECTS PRESENTED IN THIS ARTICLE. THE "QBB" STANDS FOR THE SIMULATION QUANTUM BLACK BOX PRESENTED AND "QW" STANDS FOR A NUMERICAL SIMULATION OF A QUANTUM WALKER EITHER ON A STRING (1D) OR ON A 2-DIMENSIONAL NETWORK (2D) (SEE SECTION I). "CS" IS SHORT FOR CITIZEN SCIENCE, "OR" STANDS FOR OUTREACH AND "EDU" FOR EDUCATIONAL.

GAME	YEAR	SIMULATION	PURPOSE
Hamsterwave	2019	QBB	CS
QWiz	2019	QBB	CS
Lemminqs Condensate	2022	QBB	CS
Quantum Garden	2018	QBB, QW (2D)	CS, OR
Quantum Playground	2020	QW (2D)	OR, Edu

Many of the projects presented in this paper are related to a special tool called *the Quantum Black Box* (QBB). QBB was originally introduced at a quantum physics themed game jam, the *Quantum Game Jam* (QGJ) in 2017 and was part of this annual event until 2019 [2]. QGJs are events that usually last over a single weekend and through them teams consisting of quantum physicists, game developers, artists and other talents develop quantum physics related games according to an event specific theme [2]. Since 2020 these events have been organised online, but without the involvement of the QBB project [30].

The five projects reflected on in this paper are: *Hamsterwave, QWiz, Lemminqs Condensate, Quantum Garden*, and *Quantum Playground*. First the pieces and their development process is presented. Subsequently reflections on these processess are provided.

A. Hamsterwave

Hamsterwave is a puzzle game of a little hamster inside a hamsterball, floating on ocean waves and trying to escape from a shark [31]. The player controls the shape of the ocean wave, and aims to reshape it so that the hamster reaches an island on the right-hand-side of the screen (See Figure 1). The game was developed with Unity to run on PC.

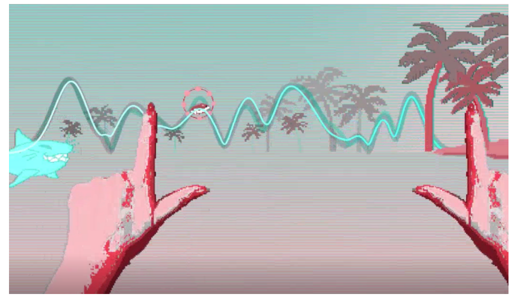


Fig. 1. Screenshots from the project *Hamsterwave*

Hamsterwave was initially developed as a citizen science game prototype during the QGJ 2019. Later, it was further developed and exhibited at a local library game exhibition in September 2019 before the pandemic [32]. The shape of the ocean wave directly corresponds to the shape of the plotted wave probability distribution simulated by the QBB. The objective of the game is to optimise the localisation of the wave from one side of the screen to the other. The player does this by moving two "Goddess hands", which represent the locations of the leftmost well and rightmost well. To add a sense of urgency, a time limit in the form of an approaching shark is introduced to motivate players to complete the procedure quickly. The game can be played in an iterative manner.

The original concept that brought the team together for *Hamsterwave* was proposed by an acclaimed indie game designer, which involved the movement of frames at different speeds in a captivating presentation illustrating relative movement between two individuals. This intriguing and complex idea inspired two experienced developers and two quantum physicists to join in the brainstorming process. Among the team members, only the author had prior familiarity with the QBB. The game jam's theme, 'Noise in the wheel,' and incorporation the QBB into the game provided considerable motivation to the team. However, it became evident during discussions that the original idea of the moving frames did not easily align with this design decision. As the initial brainstorming phase was coming to a close, the team decided to shift their focus towards the concept of a hamster and a hamster wheel. It was agreed that the QBB could be utilised to generate a wave pattern for the ocean waves on which the hamster could surf. Subsequently, an experienced game artist joined the team to create the exceptional artwork. The sound effects were sourced from the children of one of the developers, while an experienced game musician attending the event was enlisted to compose the music.

During the game jam, an initial proof of concept for *Hamsterwave*'s mechanics was developed. However, due to the mechanics of the game where the hamster's rigidbody was tied to bounce on top of the simulated wave, players naturally gravitated towards building a slope-like structure. As a result, the winning condition of maximising the population of the right well in the simulated Bose-Einstein condensate was not effectively emphasised. Despite this deviation, the game gained attention, attracted players, and received positive feedback during the showcase exhibition

After the QGJ, *Hamsterwave* was further developed for exhibition purposes. To accomplish this, one of the original developers was hired to implement the necessary changes still maintaining the core mechanics and concept of the game. As a secondary goal was to collaborate with the author in orders to modify the gameplay in a way that would direct the player's main objective towards optimising solutions for the underlying QBB-related problem. Although *Hamsterwave* already had a polished appearance and was fully functional by the end of the jam, it was deemed not yet exhibition-ready. It is common for game jam prototypes to require additional work before becoming fully developed games, although this post-jam development may not be readily apparent to end users

The allocation of resources prioritised improvements to graphics and additional game menus. The aim of this project was to create a self-contained game that could be easily downloaded, installed, and played on any computer without the need for additional Python libraries required by QBB. However, due to limited resources, it was not feasible to secure dedicated involvement of a physics consultant.

1) Project reflections: Overall, *Hamsterwave* proved to be a captivating and engaging installation, successfully appealing to players and maintaining their interest. However, it fell short of fulfilling its intended purpose as a citizen science game.

The author of this paper not only served as part of the *Hamsterwave* design team but also played a role as one of the organisers of the QGJ in 2019. While not fully present throughout the entire development process, the author provided separate consultation on the game concept and the incorporation of the QBB. Active participation during the brainstorming and early game design phases proved crucial in introducing the QBB-based wave shape to the game, but the lack of dedicated expertise of QBB for the later phases may be considered constituting to the compromises made in the game development with respect to the citizen science aspect.

The further development of *Hamsterwave* was partially managed under the project overseeing the QBB. However, the game failed to inspire all of the QBB research team members, making the author the sole advocate for its potential as a citizen science game. Consequently, the limited resources of the QBB project were focused on another game, leaving *Hamsterwave* with limited support.

The lack of sufficient interaction between the developer and the physicists following the QGJ resulted in restricted communication, mainly limited to online messaging and a few face-to-face meetings. While it is common for game jam projects to stagnate in terms of further development and team communication, this serves as an example highlighting the need for full involvement of an expert researcher in the field to transform an appealing game into a functional citizen science game. The question of whether *Hamsterwave* could have been sufficiently transformed and tweaked to serve crowdsourcing remains unresolved.

B. QWiz

QWiz is a citizen science game that challenges players to comprehend the behaviour of a fascinating liquid controlled through the manipulation of two levers. The liquid is contained within a system consisting of two conical flasks interconnected by a complex network of glass tubes. The objective is to transfer the liquid from the left flask to the right flask using the red and blue levers (see Figure 2). To indicate the success of the player's actions, a pointer indicator is provided on the table. Developed using Unity, *QWiz* is available on multiple platforms, including virtual reality (VR), PC, and touch screens.

Fig. 2. A screenshot from the project *QWiz*. Player uses the red an blue levers to control the locations of the blue flames underneath the flask system, which then affects the shape of the electric current on the back as well as the levels of liquid in the flasks, or "bottles". In the middle of the table is an arrow indicator for the quality of the player's actions.

The game development for *QWiz* was a collaborative effort between the TQT research group and the game development company MiTale, spanning from 2019 to 2020. The project involved a diverse range of skills from the gaming company, including game designers, artists, and programmers responsible for the mechanics, interface development, and the creation of a server system for remote QBB operation. The project also engaged five quantum physics researchers, including the author, who actively contributed throughout the development process.

The game development process can be divided into two distinct phases. The game company took charge of designing the game interface, mechanics, artwork, and audio, while closely collaborating with the physicists in bi-weekly meetings and continuous discussions on the Slack platform.

The initial design concept for the game focused on utilising hand movements in virtual reality (VR). However, this approach proved challenging to connect with the underlying problem in an unambiguous manner, leading to the introduction of a workbench concept featuring two levers controlling a liquid system with two bottles and a complex tube arrangement representing the well structure of the QBB. This revised version represented the well population numbers by liquid levels on the bottles and provided also a separate representation for the positions of the potential wells through blue flames moving underneath the bottle strucure. The challenge remained in effectively representing the system's dynamics in a way that could be easily understood and provide meaningful feedback.

To enhance the visual cues in the interface, the physicists requested the inclusion of a plot of the simulation within the game. This was implemented as an electric-resembling wave at the back of the examination table, with the y-axis reversed. In addition, a small arrow indicator for the success of the moves was added to the virtual table as suggested by the game developers.

Initially developed for virtual reality, *QWiz* is now available for browser and mobile platforms [33]. The author actively participated in the project from its initial brainstorming and prototyping stages until the end of 2020, when the project was transitioned from the game development company. Furthermore, the author had the opportunity to exhibit the game at various locations, observing and gathering feedback from players of diverse ages and backgrounds.

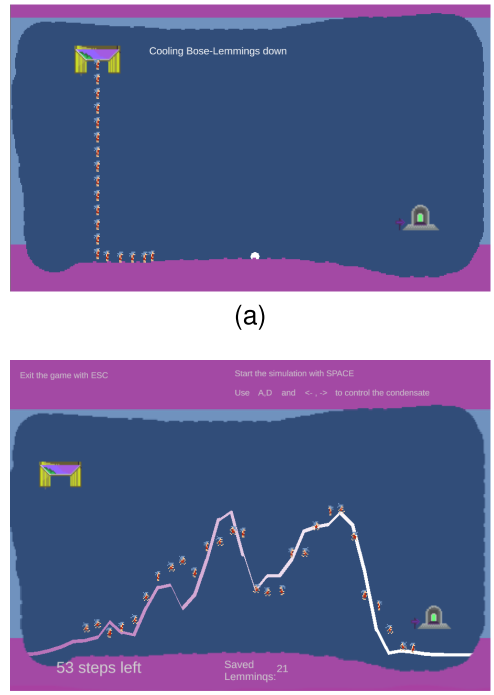
1) Project reflections: The development of *QWiz* has highlighted the challenges associated with integrating a complex quantum physics problem into a game concept. It became evident that creating an engaging and entertaining game is inherently difficult, let alone designing it to serve as a tool for solving a specific mathematical problem that requires expertise in another field. The inclusion of the quantum physics aspect must be considered from the very early stages of brainstorming and game idea generation.

The author observed communication gaps between developers and quantum physicists during the initial stages of game brainstorming, which may explain any lack of intuitive feedback for the user. Efforts were made during later stages of development to address this issue, such as the inclusion of signalling elements on the game table. It is worth noting that one of the design objectives was to create a game that could be adaptable to other types of optimization problems, highlighting the importance of avoiding overly restrictive design choices.

As there are several versions of *QWiz* made for different devices, it is clear that updating all of them takes a considerable amount of time. It should be stated clearly though that time should also be reserved for complete testing of all these versions, as different deployments may work with varying efficiency and have different types of user experiences depending on the device used. Emphasis was made towards the webGL version as it is able to reach the largest audience and hence has the most potential as a possible citizen science game. The game is still available at an online learning environment [15]. The correlation of the underlying simulation and funtions of the citizen science game should be carefully user-tested before employment.

C. *Lemminqs condensate*

The *Lemminqs condensate* is a citizen science puzzle game prototype developed using Unity. In this game, the player is tasked with guiding little characters from one door to another, known as the exit. This is done by manipulating a wave of Lemminqs-characters by controlling the horizontal positions of the two doors. The shape and height of the wave play a crucial role, as the exit door is only reachable when the wave meets specific criteria (See Figure 3, row (a)). The game was published through itch.io as a downloadable executable file for PC. *Lemminqs condensate* was developed as a solo project



(a)

(b)

Fig. 3. Screenshot from the project *Lemminqs Condensate*. a) The initialisation stage of the QBB simulation. b) The Lemminqs-characters floting according to the plot of QBB.

during a quantum physics themed game jam. The game jam took place in 2021 as part of the Games Now! game design lecture series [34]. The concept for *Lemminqs condensate* had been conceived by the author prior to the event, but had not been brought to life until this event.

The development of *Lemminqs condensate* drew inspiration from previous quantum citizen science games such as *Bring home water*, *Quantum Moves*, and the core mechanics of *Quantum Composer*. These games effectively visualised the liquid-like behaviour of probability density plots of wave functions over time, providing an intuitive way for players to comprehend the game's objectives [22]. This served as a driving design guide for *Lemminqs condensate*. Additionally, the developer had a strong desire to incorporate *Lemmings*[1] inspired characters into a quantum game.

The two doors represent the relative locations of the leftmost well and the rightmost well in QBB. The shape of the wave of Lemminqs-characters stems directly from the probability distribution plotted by the QBB. The vertical position of

[1] *Lemmings* was a strategy game originally developed by DMA Design and published by Psygnosis for the Amiga in 1991.

the exit door is designed to be sufficiently high, requiring a significant and sustained population number in the right well to reach it.

The process of developing *Lemminqs condensate* was spanned over a single weekend at the end of the week-long game jam. The goal was to reach a functional representation of the design idea closely enough to communicate the the basics mechanics behind it.

1) Project reflections: Lemminqs condensate represents a prototype successful in achieving its intended purpose, with minor notes. Ideally, the Lemmiqs characters would have interacted with and populated the wave-shaped plot. In the current version the rigidbodies of the characters are tied to the line plotted by the simulation. This limitation can be attributed to the author's limited experience with Unity development at the time a well has the limited time at hands. Other constraints related to the challenge of the QBB integrating and the project being delivered as a solo project.

The key design objectives for *Lemminqs condensate* were to capture the essence of the original Lemmings characters and provide a clear visual representation of the wave plot generated by the QBB. Noteworthy strengths of this project include the author's comprehensive understanding of the QBB's primary goals, expertise in quantum physics theory, and ability to create the entire game from scratch. However, it is important to acknowledge that game development is a secondary area of expertise for the author.

The aesthetics of *Lemminqs condensate* may not be on par with the games discussed in previous sections. However, this deliberate design decision prioritised functionality over aesthetics due to the constraints of the limited development time. The primary value of *Lemminqs condensate* lies in its role as a functional prototype that effectively communicates both the concept of a citizen science game and its underlying mechanics and functionalities.

D. Quantum Garden

Quantum Garden is a captivating light installation featuring a board of LED lights connected to over 100 springs. The LED lights are controlled by a computer that remains hidden from the player's view (See Figure 4). When the player touches the springs, it triggers a visual response on the springboard. The player can then touch one of the springs to indicate their chosen outcome. *Quantum Garden* effectively showcases

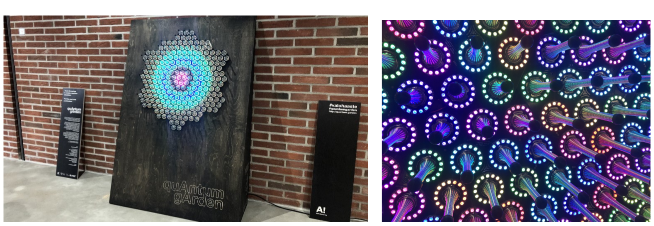


Fig. 4. Pictures of the installation *Quantum Garden*.

fundamental concepts of quantum physics, including quantum superposition, interference, and the inherit random nature of quantum measurements. The installation was designed as an interactive artwork with game-like elements, aligning with the artist's previous works. The development of *Quantum Garden* involved the collaboration of game artist Robin Baumgarten, a team of seven quantum physicists from the TQT research team, and a game scholar from Aalto University.

1) Project reflections: The author joined the development of *Quantum Garden* in 2019, when the original version, running the QBB (see Section I), was updated to a version that simulates a continuous time quantum walk on a quantum network. While the author's reflections primarily relate to the later version of *Quantum Garden*, it is important to note their exposure to the earlier stages of development.

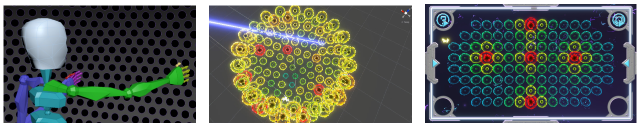
Quantum Garden provides a highly captivating and tangible means of visualising quantum phenomena. However, the installation, while visually appealing, does not inherently serve educational purposes without additional materials and the guidance of an educator, nor was it intended to do so. Typically, information regarding its functionalities is either displayed nearby or a knowledgeable individual is present to explain its meaning and purpose. Throughout various exhibitions and events, the author observed the immense joy, awe, and approachability experienced by visitors when interacting with the installation. On the most successful days, the installation attracted over 3,000 daily visitors, highlighting the challenges of showcasing and maintaining such a piece. Nonetheless, *Quantum Garden* stands as a remarkable outreach project for quantum physics.

The project owes its success to the exceptional expertise of the entire team and the utilisation of existing, captivating installations as a foundation. The artist's technical background facilitated seamless communication with the physicists. Additionally, the discussion surrounding the main functionalities and technical aspects primarily involved a core group of four individuals, while other team members were responsible for supplementary materials and organising exhibition logistics

E. QuantumPlayground

Quantum Playground is a VR environment featuring captivating simulations and a story-driven introduction. The player observes multiple small spheres arranged in a spherical formation surrounding them (See Figure 5a). The player selects one or multiple small spheres to initiate a simulation. A wave-like effect traverses through the spheres, causing changes in colour and size (See Figure 5b). The player is prompted to choose one of the spheres, aiming to correctly guess the sphere designated by the simulation. The installation incorporates a tutorial and was developed using Unity. The visual effects in *Quantum Playground* are generated through a numerical simulation of a quantum walker. The user selects a starting node represented by the spheres, and the simulation showcases the evolution of the probability density representation. The size and colour of the spheres correspond to the probability density of the quantum walker's wave function.

Quantum Playground is a collaboration between the research group of TQT, MiTale game developing company, and



(a) (b) (c)

Fig. 5. Screenshots from the project *Quantum Playground*. a) A visualisation used in communicating the idea of the application (*Boris Sokolov*). b) A screenshot from the Unity project of *Quantum Playground* used in communicating the current state of the simulation *(Aapo Pihkala)*. c) A screenshot of the WebGL version of the *Quantum Playground*

the author. The design objectives included visualising quantum effects without compromising the underlying mathematics and creating an engaging concept for users with varying levels of interest in quantum physics.

Responsibilities were divided between the game developers and quantum physicists, with the physics script written in C# by the physicists. The game developers focused on game design, UI/UX, and implementation, while maintaining close communication with the physicists. The virtual environment design and functionalities were developed alongside the physics script, with adjustments made to ensure clear and faithful visual representation. The simulation speed and performance were optimised, and the interactive storytelling elements were polished by the game developers.

A WebGL version of *Quantum Playground* was created to reach a broader audience, especially during COVID-19 restrictions. The WebGL version featured a reduced network of 108 nodes in 2D. The interface design and additional buttons were tailored to the application's storyline. The screenshot of the WebGL interface is shown in Figure 5c.

1) Project reflections: All team members, including game developers and physicists, possessed some background in developing games related to quantum physics. While not experts in both fields, they effectively communicated and identified crucial aspects to ensure the final product aligned with the physics principles. The physicists familiarized themselves with Unity, an uncommon platform in quantum research, and C# libraries for mathematical functionality.

Initially, face-to-face brainstorming sessions fostered non-verbal communication, laughter, and creative ideas. However, the pandemic shifted communication to Slack and video calls. This transition facilitated one-to-one discussions between main developers and physicists, resolving technical challenges and identifying hindrances. Both teams had experienced coders, enabling efficient problem-solving through precise textual communication.

Videos and annotated screenshots were instrumental in adjusting the color spectrum and scaling to enhance visibility of the probability distribution and maintain fidelity to quantum numerics. These visual aids played a crucial role in fine-tuning the simulation rate, ensuring the user could perceive the fast and delicate quantum effects accurately (See Figure 5b).

IV. Summarising Project Reflections

The five presented quantum game and quantum art projects encompass diverse design journeys. In team meetings, the presence of numerous participants posed challenges in tracking discussions and encouraged reserved input. Detailed meeting notes became essential for recapping the process and aligning understanding.

The QBB project aimed to recruit a single game developed to fulfill the project needs, but it was soon realised that more diverse expertise was needed for the extent of the project. Overall, team members with previous experience in developing serious games demonstrated greater ease in maintaining focus during brainstorming and design processes than more inexperienced team members. This was particularly evident in projects *QWiz* and *Quantum Playground*. Their expertise allowed for effective tracking of deliverables and a deeper understanding of the needs communicated by the quantum physics researchers.

Observations from annual QGJs and the extended development durations of *QWiz*, *Quantum Garden*, and *Quantum Playground* highlighted the distinct working styles of developers and quantum physicists. Their expertise could not be expected to be fully mastered by each other, which necessitated awareness and understanding of their respective roles. Notably, the presented projects benefited from the involvement of dedicated quantum physicists throughout the extended development period.

Hamsterwave and *Quantum Garden* effectively generated interest, lowering user barriers. Exhibition visitors praised the visual appeal of *Hamsterwave* and its straightforward gameplay. *Quantum Garden*, while admired for its novelty, interactive nature, and simulations, could have benefited from clearer visual cues explaining its aim and inner workings. Still, these projects demonstrate the importance of an attractive game desing in quantum games with serious purposes.

Although captivating many players into solving the problem presented in *QWiz*, the VR version of *QWiz* was observed to limit interest of players. Some users found wearing goggles uncomfortable, especially when shared with numerous visitors. Although *QWiz* was played by hundreds of users in various formats, the allure of the VR set sometimes overshadowed the game itself, diverting players to other applications. A large screen showcasing the actions of the person using the VR was found entertaining and attracted players. Where *Hamsterwave* was observed to motivate towards several iterations of the gameplay, many found the interface of *QWiz* confusing and either asked for further clarification or discontinued their engagement with the game.

Realistic, large-scale quantum game projects require adequate resources in terms of manpower, funding, and time. Insufficient resources can hinder the project's success, as seen in the discontinuation of *Hamsterwave* due to discouragement from research leaders.

The exploration of these five projects highlights the importance of effective communication and the active involvement of both quantum physicists and game developers. It underscores the value of interdisciplinary experience and the willingness to acknowledge and appreciate each other's expertise.

For longitudinal projects, it is crucial to document design decisions throughout the development process, starting from the initial brainstorming phase. This holds especially true for projects that involve various communication formats. These reports facilitate effective communication, identify and rectify possible misunderstandings, and enable the parties involved to track the progress and prevent redundant or conflicting design decisions. The author recommends assigning a dedicated team member with experience in both game development and the relevant scientific field to oversee the overall process.

Pictures, sketches and visual forms of communicating are essential for game development and especially for quantum physics related projects [35]. This was shown true also in the presented projects. Visual forms of communication, alongside repetition and text-based summaries within the team, play a vital role in quantum game development. Care should be taken when technical language specific to each discipline is used, as it may hinder understanding among members from different backgrounds. In larger projects involving multiple stakeholders, having a dedicated person or team responsible for financial management ensures project continuity.

These lessons align with the common challenges faced in multidisciplinary projects and are supported by the observations and experiences of the author in various projects. It is worth noting that projects led by first-time quantum game developers encountered more difficulties compared to those involving experienced quantum game developers. Nonetheless, even experienced individuals can underestimate the associated challenges and the role of experienced game designers.

V. Discussion

Previous studies examining the design process of quantum physics-related games and art have primarily focused on the differences and miscommunication between physicists and other stakeholders [2], [35]. However, it is important to acknowledge that miscommunication can also occur among individuals with similar backgrounds. Particularly in situations where project members without prior knowledge of quantum physics or quantum games discuss between themselves the project's connection to quantum physics. Design decisions based on such discussions can have significant implications throughout the project cycle and may be challenging to rectify. This may have been the case with *Hamsterwave*, where attempts were made towards the end of the development process to align the mechanics with citizen science goals, requiring additional resources.

Shaeema Shaman presents her findings in her thesis "Quantum Games and Simulations" [22]. In *Quantum Moves 2*, players gained intuition through the clear visual representation of the probability distribution. This highlights the importance of proper visual representation. In *QWiz*, however, the emphasis was not on process visibility, as it aimed to develop into a game for optimization problems in general. This lead to the multiple clues hidden into the game play. Further research on the limitations of visual representation in complex interactive systems would be valuable.

Quantum Game Jams (QGJs) held between 2017 and 2019 yielded valuable insights for quantum game development, specifically demonstrated through the project *Hamsterwave*. The QGJs included introductory lectures on quantum physics concepts, but it was noted that these condensed explanations were not easily comprehensible [2]. Thus, there is a need to simplify the explanation of simulation tools and technologies for team members who are not yet familiar with them. In the case of the QBB, it was crucial to describe the simulation parameters, output values, and the specific value to be maximised. Visualisations and metaphors, such as drawings of the confining potential as glasses and probability density as liquids, were used to aid in communication between physicists and other team members. In the context of a game jam, teams without a physicist or with occasional assistance from a quantum expert tended to utilise the QBB as a random number generator or for visual effects rather than scientific gameplay [2].

This relationship is further observed in projects such as *Hamsterwave*, *QWiz*, *Quantum Garden*, and *Quantum Playground*, where the presence of a readily available and actively involved science expert was proved crucial for developing citizen science games. Additionally, in the longitudinal projects *QWiz* and *Quantum Playground*, it was evident that team communication improved and became more relaxed over time, significantly impacting the success of these projects.

The autoethnographic method, despite being subject to debate and critique [29], [36], was well-suited for analysing the projects presented in this study. While there is currently a limited number of scientific papers discussing the design process of quantum games and quantum art [2], [35], the abundance and diversity of such projects reflect a growing community of game developers and artists [1], [2]. Consequently, it is valuable to contextualise the findings within the established procedures and methods in the field of quantum games and quantum art. Although there were limitations, such as the absence of rigorous playtesting for the citizen science games, the design process still provides valuable insights for future projects, particularly in the realm of quantum physics.

In this study, achieving complete anonymity within the case study is challenging due to the limited number of individuals involved in the field of quantum games. However, the aim of this research is not to undermine individual viewpoints. Collaborating with other team members in a collaborative autoethnography [37] would have provided a more comprehensive perspective on quantum game development. Unfortunately, no participant, apart from the author, was consistently involved in all the presented projects.

VI. Conclusions

The paper examined five diverse interactive quantum physics projects developed between 2017 and 2020, with varying levels of author involvement. Two main findings emerged: projects that were not constrained by time or expertise achieved their intended goals, and active involvement of quantum physics experts and skilled game designers from the project's inception was crucial. Additionally, prior experience in quantum game development facilitated effective communication within multidisciplinary teams, with physical meetings playing a key role in the early stages and text-based communication being beneficial for addressing technical aspects. These insights highlight the significance of interdisciplinary collaboration, early expert involvement, and adequate project development time for successful quantum game design outcomes.

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