Evaluating the impact of visual persuasion in a persuasive game about quantum computing

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March 15, 2024

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Abstract

Advancements in quantum computing continue to progress, bringing us closer to a future where these machines can be widely integrated. Recognising the potential transformative impact these computers will have, it becomes crucial for companies to anticipate and prepare for future changes. One approach to this preparation involves digital persuasive games, which have emerged as valuable tools for providing interactive and enjoyable educational experiences aimed at behavioural and attitudinal changes surrounding complex topics. Previous research has established theoretical models outlining optimal strategies for developing persuasive games. This thesis adopts the model presented by De la Hera, which emphasises the role of visual persuasion in influencing players. However, the validity of this model has not been conclusively confirmed or rejected. To assess the effectiveness of visual persuasion in enhancing player persuasion, I have developed two versions of a game, maintaining identical gameplay but incorporating additional visual elements in one version. Through a comparative analysis of these two versions, the primary objective of this study was to establish whether the version with visual elements had a higher persuasion level. Results indicate a perceived increase in persuasion in the version featuring visual elements. However, this effect lacks statistical significance. Consequently, a definitive determination regarding the effectiveness of visual persuasion within De la Hera's model remains inconclusive based on the findings of this study.

Contents

Acknowledgements

I extend my gratitude to Remco Veltkamp for his role as my supervisor, providing guidance, valuable feedback, and insightful advice. I also want to express my appreciation to Deb Panja for taking the time to serve as my second examiner.
Special thanks to Capgemini for granting me the opportunity to intern at their company. I thank Yvonne Kolen for her contributions as a process supervisor, offering valuable insights into my research, and being consistently approachable for any questions during the process.
I reserve a special acknowledgement for Camille de Valk, who not only shared profound insights into quantum computing but also provided me with the internship opportunity at Capgemini in the first place. Your genuine care for my project and the extra effort you put in exceeded expectations, and I am truly grateful for your support.
Without the support and contributions of these individuals, this thesis would not have been possible.

1 Introduction

One of the most notable domains of modern physics is quantum physics, dedicated to studying phenomena at the atomic and subatomic scale [1]. Particles at this scale show peculiar features not commonly observed in larger-scale particles. One example is 'wave-particle duality', where quantum objects display characteristics of both particles and waves depending on the specific context [2].

Understanding and explaining quantum phenomena requires a combination of mathematical models and physical interpretations. While these complex descriptions make the topic difficult to understand for many, researchers find these phenomena interesting. Since the first observations of quantum phenomena, scientists have been conducting continuous research to observe and explain the occurrences. This has resulted in explanations for previously unexplained occurrences, and the development of technological advancements, for example, the creation of lasers and MRI machines [3].

Recent developments in quantum physics focus on using its principles to enhance our digital performances and security [1]. Within this context, quantum computing has emerged, representing a distinct category of computing technology that takes advantage of quantum principles such as wave-particle duality. This approach potentially enables solutions to certain complex problems with reduced time complexity compared to classical computing. Developers are creating computers capable of hosting these quantum technologies to address challenges beyond the reach of classical computers. This new type of computer is called a 'quantum computer' [4]. An example of a quantum computer is IBM Quantum System One, shown in Figure 1. It was developed by the technology company International Business Machines Corporation (IBM), which specialises in computer hardware and software.

Contrary to a common misconception, quantum computers are not superior to classical computers for all purposes. Classical computers can handle the majority of computational problems, including complex ones. Nevertheless, when it comes to large or complex problems, classical computers take an extensive amount of time, making it practically equivalent to stating that they are incapable of computing these problems. On the other hand, quantum computers have the potential to outperform classical computers in solving specific large or complex computations with reduced time complexity and accuracy. Solving and accelerating these computations will both positively and negatively impact crucial domains [5].

Several institutions are actively promoting awareness and encouraging companies and organisations to ready themselves for the approaching impact of quantum computers. One notable example is Capgemini, a multinational IT consultancy firm with a dedicated Quantum Lab. In addition to developing applications, this department takes a proactive approach by organising and participating in informational events, such as presentations and interviews. These events delve into the workings and challenging concepts of quantum computing and their potential future impact. Capgemini's objective is to educate its clients about the potential of quantum computing, assist them in preparing for this future, and pursue collaborations.

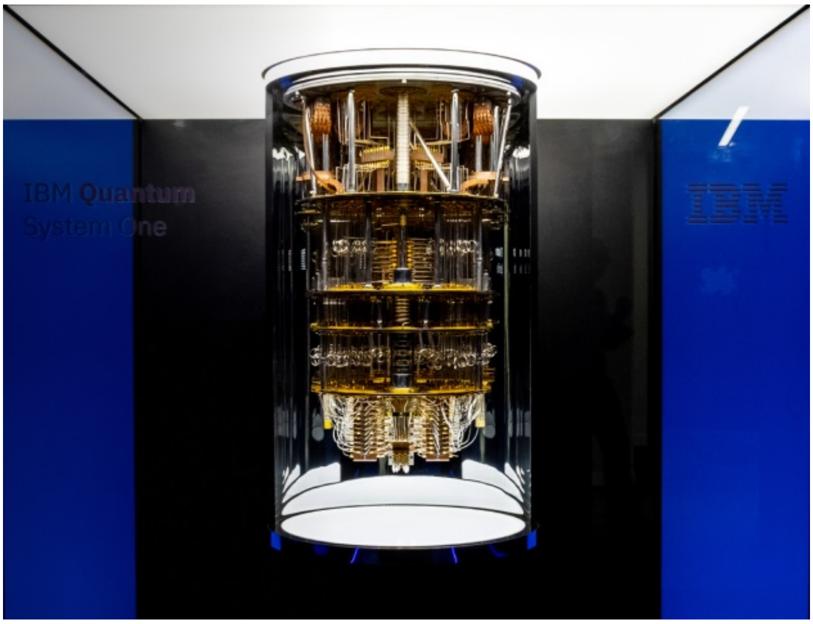


Figure 1: IBM Quantum System One [9]

In 2022, Capgemini created a game titled *Quantum Puzzle* [6] to advance its objectives. The game educates players by allowing them to engage with the workings of a quantum computer. Capgemini created this game to captivate visitors and offer an enjoyable exploration of quantum computing. This type of game falls under the category of serious games, which are games created without having a main goal of entertainment [7]. Their objectives are usually spreading knowledge, facilitating learning, allowing skill development, or persuading behavioural change using gameplay. Serious games find applications across multiple domains, including education, healthcare, and training scenarios [8].

Games have proven to be useful tools for educating people about various subjects [10]. They are not only enjoyable and engaging, but they also have the potential to enhance learning, surpassing traditional learning methods, such as presentations or plain written text [11]. This makes serious games interesting for the education of subjects perceived as mysterious and complex, such as quantum physics.

Ongoing education on quantum physics and computing is important, especially considering the potential impact of quantum computing in the future. Unfortunately, the term 'quantum' is frequently misused, often incorporated into product names by companies to convey the technological advancements of their products. Similarly, in movies and television shows, 'quantum' is often used to explain strange, unexplained events. This misuse can lead to confusion regarding the definition of quantum physics and its implications.

Despite the existence of serious games explaining the fundamental concepts of quantum physics and computing, there is a noticeable gap when it comes to games showing the potential future impact of quantum computers. Developing such games can help persuade players about the changes these computers could bring. To achieve this, the genre of persuasive games, specifically designed to alter players' attitudes or behaviours, plays an important role [12].

Previous researchers have formulated theoretical models explaining the best strategies for developing successful persuasive games. One model, presented by De la Hera in 2013 [13], defines multiple dimensions in the model aimed at enhancing persuasion in digital games. However, to my knowledge, this model has not been confirmed or refuted. Therefore, the study in this thesis aims to examine the effectiveness of one of the domains in this model by studying the influence on player persuasion. The selected dimension is visual persuasion, defined by De la Hera as "a process in which the visual representations function as cues that evoke intended meanings, premises and lines of reasoning" [13].

A digital game is developed that aims to persuade players that quantum computers will potentially have a significant influence in the future. Two versions of this game, featuring identical gameplay, are created. Version 1 does not focus on visual persuasion, while version 2 contains visuals specifically incorporated to increase persuasion. The persuasive impact of both versions is examined and compared through a user study. From these results, the effectiveness of visual persuasion in De la Hera's model may be confirmed or rejected.

The game is created in collaboration with Capgemini Nederland, which plans to present this quantum game at conferences. Capgemini is interested in such a game because, similar to *Quantum Puzzle*, it will capture attention, starting conversations about quantum computing and Capgemini's Quantum Lab. This engagement could lead to collaborations between Capgemini and other companies and organisations.

The contribution of the research in this thesis is to empirically test whether the element of visual persuasion is a meaningful component in De la Hera's model [13]. Based on the findings, I will formulate a design recommendation.

The thesis is structured as follows: Section 2 delves into the inner workings and current status of quantum computers. Following this, Section 3 explores the impact of quantum computing on four domains: cryptography, optimisation, machine learning, and simulations. Section 4 reviews related research and outlines the research questions this study intends to answer. Afterwards, Section 5 outlines the methods used to answer the research questions, including a description of the game design and experimental procedure. The experiment's results are presented in Section 6, followed by a discussion of these results, answering the research questions, and defining the limitations and possible future work in Section 7. Finally, the research findings are summarised and concluded in Section 8.

2 Quantum computers

The concept of a quantum computer began to emerge in the 1980s, with Paul Benioff being the first to propose the possibility of computers utilising quantum mechanical models [14]. This exploration was further encouraged by Yuri Main [15] and Richard Feynman [16]. In the mid-1980s, researchers began developing algorithms exclusively for quantum computers, enabling faster and more efficient computations compared to classical counterparts. The first working quantum computer was eventually created in 1998 [1].

In the upcoming sections, I will delve into the fundamentals of quantum computers, their key principles, and the current state of quantum computing research.

2.1 Quantum information

The first quantum computer from 1998 contained two quantum bits, or ‘qubits’. Qubits are the basic units of information in a quantum computer, similar to bits in classical computers. Unlike classical bits, which can be either 0 or 1, qubits can exist in a state that is a combination of 0 and 1, known as ‘superposition’ [17].

The state of a qubit can be expressed as the normalised linear combination of the two-dimensional basis vectors $|0\rangle$ and $|1\rangle$, as described by quantum wave function $|\psi\rangle$ [18]

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

with $\alpha, \beta \in \mathbb{C}$, $|0\rangle = (1, 0)$, $|1\rangle = (0, 1)$, and $|\alpha|^2 + |\beta|^2 = 1$. In this equation, $|\alpha|^2$ and $|\beta|^2$ represent the probabilities of measuring 0 or 1, respectively. If α and β are both nonzero, the qubit is in superposition.

The state, $|0\rangle$ or $|1\rangle$, will only be known after measuring the qubit in superposition. At the moment of measurement, the qubit transitions from a blend of possibilities to a specific state, a process known as ‘wave function collapse’.

In general, for n qubits, the quantum computer can be in 2^n different states at the same time. This means that with each additional qubit in a quantum computer, the number of possibilities the computer can simultaneously be in doubles. For instance, if you have one qubit, it can be either state $|0\rangle$ or $|1\rangle$. Compare this to the first quantum computer, which had two qubits, and now there are four possible states: $|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$. The equation of both qubits becomes

$$|\psi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$$

where $\alpha, \beta, \gamma, \delta \in \mathbb{C}$ and $|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$.

Computers use circuits to process information. These circuits consist of wires that carry information and undergo various operations executed by gates. Classical circuits incorporate operations like AND, OR, and NOT gates, which determine the output depending on input values. In quantum computing, the circuits are known as quantum circuits. These circuits employ qubits to represent and process information, undergoing quantum operations in the process. Quantum circuits typically start with all qubits set to $|0\rangle$. Quantum gates in these circuits perform logical operations on qubits, serving as the mechanisms for inputting data. Notable examples of quantum gates include the H-gate, which places a qubit in superposition, and the X-gate, which flips the state of a qubit from $|0\rangle$ to $|1\rangle$ and from $|1\rangle$ to $|0\rangle$.

2.2 Key principles

Superposition in quantum computers allows for quantum parallelism, enabling the simultaneous processing of multiple input values [19]. This process involves bringing a quantum system in a superposition of various input states and applying a specific transformation representing the to-be-evaluated function. The resulting state contains all output values for the input values in the superposition, enabling the computation of multiple outputs at once. This feature can be incorporated into quantum algorithms to perform computations, making them sometimes faster than classical algorithms.

Besides superposition, two other principles called 'entanglement' and 'interference' also play a crucial role in quantum computing.

When qubits are entangled, the outcome of their measurements is correlated, meaning that a measurement of one qubit in superposition gives information about the state of the other qubit. The simplest example of this phenomenon is the Bell state for two qubits [19]:

$$|\psi\rangle = \frac{1}{\sqrt{2}}|00\rangle \pm \frac{1}{\sqrt{2}}|11\rangle$$

In this scenario, there is a probability of 1/2 that the first qubit is 0. Without needing to measure the second qubit, this leaves state $|00\rangle$. Conversely, there is a probability of 1/2 that the first qubit is 1, leaving the state $|11\rangle$ without needing a measurement of the second qubit. Entanglement holds even if the qubits are separated by a distance [20].

Interference occurs when the wave functions of two qubits interact, resulting in constructive interference (increased amplitudes) and destructive interference (decreased amplitudes), as illustrated in Figure 2. This phenomenon can be used to control and manipulate qubit states. By controlling the phase of the qubit, constructive or destructive interference can be used to amplify or diminish the likelihood of specific outcomes. Quantum algorithms use interference to manipulate the probabilities associated with different states, enhancing the probability of the correct solution while discouraging incorrect ones.

Quantum computers employ superposition, entanglement, and interference to execute quantum algorithms. Shor's algorithm, developed for finding prime factors, illustrates the application of these quantum phenomena in the following ways [21]. The algorithm starts by placing each qubit in superposition, allowing for simultaneous exploration of multiple factorisation possibilities. Qubit entanglement aids in the identification of relationships between factors, while interference amplifies the probabilities of correct factorisation options and suppresses incorrect ones.

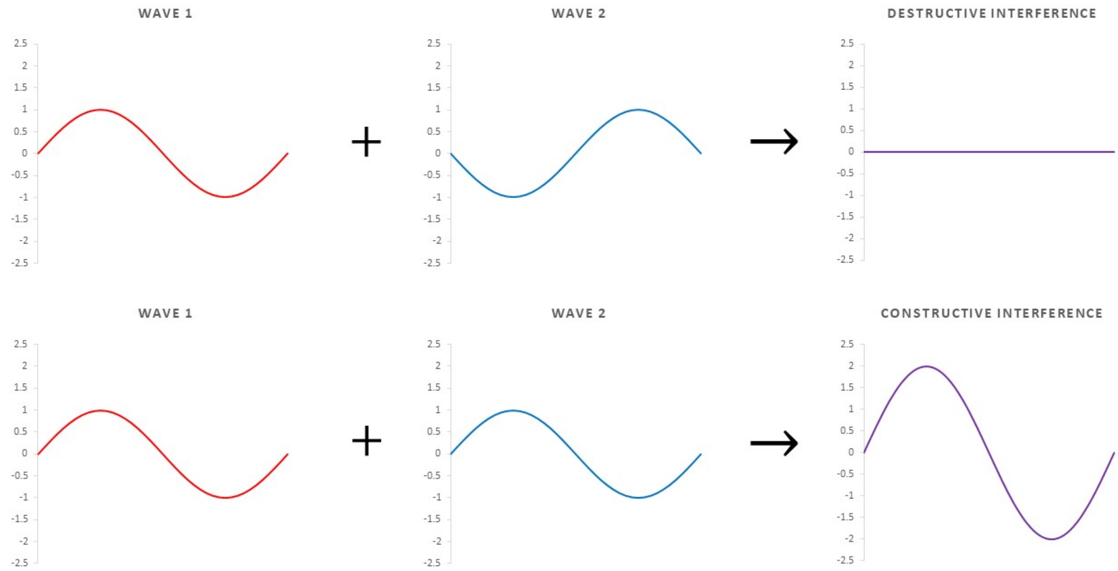


Figure 2: Destructive and constructive interference

2.3 Status of quantum computing

Currently, there exist more than 100 quantum computers worldwide, with the largest containing 1121 qubits. Ongoing advancements are made in the construction of these quantum computers. However, the current progression of quantum computers has difficulties, including insufficient qubit numbers and difficulties in creating high-quality qubits due to environmental noise [22]. This noise occurs when a quantum computer lacks proper isolation, leading to high error rates during operations. Maintaining proper isolation is crucial to prevent information leaks that can negatively impact delicate quantum effects. These leaks cause 'decoherence', a destructive process for quantum properties like superposition. As a result, classical algorithms remain preferable until quantum computers with a sufficient number of high-quality qubits are available.

The timeline for when quantum computers will outperform classical computers remains uncertain because of the various thresholds for the qubit quantity and quality per quantum algorithms. Companies developing quantum computers have outlined roadmaps to demonstrate their planned progress in the coming years. With these roadmaps, companies plan to create error-corrected quantum computers with increased scale, quality, and speed [23].

In line with these advancements, IBM introduced the IBM Quantum Platform in 2016, an online service providing public access to IBM's cloud-based quantum computing services. This platform allows users to interact with quantum processors, access tutorials on quantum computation, and explore quantum computing through experiments and simulations. The platform includes devices located at IBM Research headquarters, which users can access.

One method for interaction is Quantum Composer, a graphical programming tool enabling users to build and run quantum circuits on real hardware or simulators via a drag-and-drop interface. Another approach involves using Jupyter Notebooks with Qiskit, a software development kit for working with circuits, pulses, and algorithms on quantum systems [24].

Researchers have employed the platform for various experiments, including the development of a quantum variant of artificial life [25] and solving complex problems using quantum algorithms [26].

Despite optimistic expectations for quantum computers, scepticism exists due to the current lack of practical quantum advantage over classical computers. Some researchers express doubt about achieving scalable quantum computers, highlighting challenges such as avoiding decoherence at larger scales [22]. Additionally, while there are ongoing advancements in quantum computing, classical computers are also improving simultaneously. Furthermore, quantum algorithms demonstrate speedup only for specific complex problems [27], and promising quantum algorithms often have non-quantum alternatives with comparable complexity [28].

3 The impact of quantum computing

Quantum computers have the potential to become valuable devices, because of their ability to execute quantum algorithms. These algorithms have the potential to greatly impact the realm of computation by significantly accelerating computations that are currently executed by classical counterparts. The key domains that will be most influenced by quantum computers are cryptography, optimisation, machine learning, and simulations. I decided on these four domains following consultations with a quantum expert from Capgemini and an examination of previous research [1][5][29].

The following sections will explore the influence of each domain in detail.

3.1 Cryptography

Cryptography focuses on securing messages using encoding methods to keep out unauthorised individuals [30]. The senders of a message encode the information with a key (encryption), and the intended recipients use a key to reverse the encryption (decryption). Cryptographic algorithms, known as ciphers, are used to carry out this encryption and decryption to ensure confidential communication. An example of a cipher involves shifting each letter in the alphabet a certain number of spaces, with the key representing the number of spaces. For instance, if each letter is shifted two spaces to the right, 'A' becomes 'C', 'B' becomes 'D', and so on.

Two types of cryptographic systems exist: symmetric and asymmetric. When the sender and receiver share the same key, the cryptographic system is called symmetric. A method is asymmetric when different keys are used for encryption and decryption. The encryption key is made public, while a related secret key is used for the decryption. In asymmetric cryptography, anyone can encrypt a message, but only those with the private key can decrypt the message.

An example of asymmetrical cryptography is the RSA cryptosystem, a widely used method for securing online information, notably for financial transactions [31]. RSA uses asymmetric cryptography to create a public key using the multiplication of two large prime numbers, which are kept secret to avoid unwanted decryption of the information. The RSA's security is based on the idea that factoring the product of two large prime numbers is a computationally intensive task for classical computers [32].

Classical computers can decode these asymmetric cryptographic systems, but this requires excessive time. This essentially makes classical computers incapable of breaking asymmetric systems, ensuring them relatively secure for practical use. Nevertheless, continuous development of new systems is crucial, motivated by advancements in computational abilities.

Quantum computers can pose a threat to current secure asymmetrical systems such as RSA. In 1994, mathematician Peter Shor developed a quantum algorithm called Shor's algorithm [21], that utilises the abilities of quantum computing to find prime factors in polynomial time. This allows the decoding of messages secured with the RSA cryptosystem with a significantly faster time complexity compared to the exponential time complexity of the most efficiently known classical factoring algorithm [33]. When quantum computers can run algorithms like Shor's algorithm, the currently used methods for secure transmissions become unsafe.

To prevent this from happening, researchers are actively developing encryption systems resistant to decryption by quantum algorithms. This research area is known as post-quantum cryptography [34]. The National Institute of Standards and Technology (NIST) initiated a post-quantum cryptography standardisation program in 2016. The program aims to establish new security standards, evaluate new encryption methods and security measures, and ultimately select proposals that will become official standards [35]. NIST intends to publish these new standards by 2024 [36].

Another method besides post-quantum cryptography is quantum cryptography. Quantum cryptography enhances the security of data transmissions by using quantum key distribution (QKD) [37]. QKD generates a secret key known only to the sender and receiver, used for encrypting and decrypting messages. Using the principle that measuring a quantum object alters its state, QKD detects such alterations if a third party attempts eavesdropping. This mechanism ensures a higher level of security for current cryptosystems.

3.2 Optimisation

Optimisation deals with finding the best solution to a given problem from a set of possible solutions. In the future, it is expected that quantum computers can be used to speed up the process of solving complex problems compared to classical algorithms or find a better solution to the problem.

An example of quantum optimisation is the quantum approximate optimisation algorithm, which briefly presented an improved approximate solution to combinatorial optimisation problems [38]. Combinatorial optimisation problems involve finding an optimal solution from a finite set of solutions [39]. An example of such a problem is the travelling salesman problem, where the quantum approximate optimisation algorithm has demonstrated promising potential applications [40]. The objective of the problem is to determine the shortest possible route given a list of locations and the distances between them that visit each location exactly once, finishing at the starting location. This problem is NP-hard, meaning that it lacks a known polynomial-time algorithm. For small instances of the problem, a classical computer can find optimal solutions in a reasonable timeframe. As the size of the problem increases, the time required for a solution grows exponentially, making it difficult for classical algorithms.

Another noteworthy quantum optimisation approach is quantum annealing, which is an optimisation technique for identifying the global minimum of a function [41]. Quantum annealing was developed as a faster method for solving challenging problems compared to classical computers, particularly those featuring a finite set of objects with multiple local minima.

Quantum annealing starts with looking at all possible solutions for a problem at once. Then, it follows the rules of quantum mechanics to change the amplitudes of the different possibilities. The change in amplitudes allows quantum tunnelling between the states, meaning the system can tunnel across the amplitudes to search for the best solution [42]. If the amplitudes change slowly, the system stays close to the best solution at each step. However, if the amplitudes change quickly, the system might explore other options but with a higher chance of ending up with the best solution. When the process stops, the system is expected to have found the best solution to the problem.

A field that can benefit from quantum optimisation is the financial sector, especially in managing the uncertainties associated with asset performance, prices, and returns [43]. The goal of applying optimisation to these uncertainties is to minimise the risk, defined as the deviation of actual returns from expected returns. Risk reduction strategies involve creating optimal portfolios that balance risk and return, such as aiming to maximise return for a given risk or minimise risk for a desired return. The difficulty of creating these portfolios lies in constructing and adapting them based on market conditions, as incomplete knowledge of the market frequently leads to treating assets and portfolios as random. There is speculation about quantum computers enhancing success rates in risk computation compared to current approaches. However, there is scepticism due to the current challenges of quantum computers, such as low qubit count and noise issues, and a lack of evidence demonstrating efficiency improvements [44].

3.3 Machine learning

Machine learning is a field of artificial intelligence focused on creating and studying statistical algorithms that can learn from data, generalise to new data, and perform tasks without explicit instructions, instead of relying on human programming [45]. Machine learning can typically be divided into three learning categories: supervised, unsupervised, and reinforcement learning [46]. In supervised learning, computers learn general rules that can map inputs to outputs by being provided with example inputs along with their desired outputs. On the other hand, unsupervised learning requires the algorithm to identify patterns and structures in the input data without any labels or guidance. This can be utilised, for example, to discover hidden patterns in data. Reinforcement learning involves a computer program interacting with a dynamic environment while trying to achieve specific goals and receiving feedback.

Machine learning involves complex algorithms and large datasets for analysis. Quantum machine learning combines quantum algorithms with machine learning programs, using quantum computers to enhance the speed of classical machine learning algorithms. Researchers theorise that this can be achieved by employing qubits and quantum operations or outsourcing challenging subroutines to quantum devices [47].

There are two main types of quantum machine learning: quantum-enhanced machine learning and machine learning of quantum systems. Quantum-enhanced machine learning involves quantum algorithms that solve machine learning tasks more efficiently than classical methods. These theoretical algorithms require encoding classical data into a quantum computer, applying quantum operations, and measuring the results. One example of this involves triangle-finding algorithms to detect triangles in graphs. Research has demonstrated the existence of quantum algorithms for triangle finding, showing improvements in terms of the number of operations required compared to previously known methods [48]. This improvement is observed for both dense and sparse graph data.

During machine learning of quantum systems, classical machine learning methods are applied to data generated from quantum experiments. This technique is used to study, for example, the behaviour of quantum systems.

3.4 Simulations

Simulations are valuable tools for understanding and studying complex systems by modelling them on a computer [49]. Simulations are not always necessary for advancing research, but they are useful for research that is difficult to carry out or takes a long time in real life. Using simulations to conduct research more efficiently can also lead to reduced research costs. Unfortunately, classical computers cannot always accurately simulate large systems, especially systems involving quantum mechanics. The challenge in quantum systems comes from the considerable amount of computer memory required to store the quantum states because an n-particle quantum system requires storing 2^n probability values classically. Additionally, simulating the evolution of this system leads to an exponentially growing computation time scaling with the number of particles in the system [50]. Consequently, classical computers face limitations in simulating quantum systems with even a relatively small number of particles.

Quantum computers can potentially accelerate the simulation of quantum systems, a concept often attributed to Richard Feynman in 1982 [16]. Quantum computers can simulate quantum systems with several qubits comparable to the number of particles in the original system, reducing the computation time. This capability comes from their ability to exploit quantum properties, such as superposition and entanglement. Research by Kim et al. shows that noisy 127-qubit quantum computers can produce more accurate models than a brute force method by classical computers [51]. This research indicates that quantum computing is feasible in an era before achieving fault tolerant quantum computers.

Quantum simulations potentially enable the study of atoms and particles in unconventional conditions, such as within a particle collider. Moreover, these simulations are valuable in addressing unresolved physics problems, especially in areas like low-temperature and many-body physics, where the complex quantum mechanics of systems currently cannot be accurately simulated.

Quantum simulations also have the potential to advance research in fields like drug discovery. Typically, researchers conduct time-consuming tests on molecule structures one by one through physical experiments or simulations on classical computers, which vary in accuracy. Quantum computers, even with just a few tens of qubits, have the potential to surpass the limitations of classical computers in simulating the chemical properties of molecules [52]. The precision and speed offered by quantum-simulated structures could significantly improve this process, making it more cost-effective.

4 Related works and Research questions

In the following sections, I will provide an overview of previous research that is relevant to this study. The relevant literature encompasses research into serious games, models developed for the design of persuasive games, the role of visual persuasion in games, methods for measuring the effectiveness of persuasion, and a selective overview of existing quantum games. Each of these areas provides valuable insights, forming the foundation for my research question, as defined in the final section.

4.1 Serious games

Credited to Clark C. Abt in 1970, the term 'serious games' originally refers to analogue games with educational purposes, emphasising that they were not primarily for amusement but still could be entertaining [53]. Over time, the definition has evolved to encompass games with a primary goal other than entertainment [7].

With the advancements in digital technologies, serious games transitioned into the digital field, becoming more accessible and gaining popularity. A notable example includes *Oregon Trail* [54], a text-based game created in 1971 that educates players about the history of Oregon's migration trails. It is one of the earliest and most famous serious games and has remained popular after its creation. Simultaneously, the military sector recognised the value of serious games as cost-effective and safe training tools, resulting in the creation of games such as *The Bradley Trainer* [55] to instruct soldiers on how to operate Bradley tanks. Even the U.S. Army started developing games, such as *America's Army* [56] in 2002 to motivate players to join the army. The creation of these games marked the start of the current serious games trend [57].

Serious games have demonstrated a positive effect on players' motor skills, knowledge, psychological factors, and social skills [8]. This positive influence has driven the widespread development of serious games, particularly in education and training scenarios. For instance, within healthcare, serious games like *Captain Novolin* [58] educate children on diabetes management, while games like *Cardio Ex* [59] aid in medical training for accurate disease diagnosis. However, some experts have raised concerns about the standalone effectiveness of serious games in education [60]. They recommend integrating these games into a broader learning approach that combines traditional teaching methods with gaming elements, a strategy that has proven to be effective [61].

An important category within serious games for this research is persuasive games, which focus on attitude or behaviour change through education or awareness raising [12]. Multiple studies have found that comparing a persuasive game to a video or written text conveying the same information has demonstrated a higher persuasive impact for the game [62][63]. However, certain studies have reported no increase in impact for games compared to videos or text [64].

Notable examples of persuasive games include *Dumb Ways to Die* [65], created by Metro Trains Melbourne to promote rail safety, and *Riskio*, a tabletop game that enhances cyber-security awareness by revealing the mechanics of cyber attacks and prevention strategies, encouraging players to adopt these precautions in real-life situations [66]. Studies showing the positive impact of persuasive games include two instances focused on phishing scams: *Smells Phishy?* and *Phishy*. These games have demonstrated improvements in players' knowledge and awareness of phishing scams [67] and their ability to detect them [68].

A popular subcategory within persuasive games are games designed to integrate physical activity into an entertaining gameplay experience, often referred to as 'exergames' [69]. The evolution of digital exergames has undergone significant transformations, particularly in response to advancements in hardware technology. The first digital exergame was *Mogul Maniac* [70] by Atari, Inc., a slalom skiing game playable with a joystick or the Atari Joyboard, a dedicated balancing board for the game [71]. The introduction of balancing boards and floor mat controllers popularised the creation of exergames, leading to the creation of the first major and one of the most popular exergames *Dance Dance Revolution* [72], where players interact with a floor mat featuring arrows corresponding to the beat of songs.

The release of the Nintendo Wii in 2006, with its introduction of tracking players' hand motions, resulted in games like *Wii Sports* [73] and contributed to bringing exergaming to mainstream attention [74]. Subsequent technological advancements, demonstrated by the Microsoft Kinect in 2010, enabled full-body motion tracking through sensors, resulting in still popular games such as *Just Dance* [75]. While motion sensors for full-body tracking are available, the use of controllers persists, as seen in Nintendo's *Ring Fit Adventure* [76], which monitors players' leg and arm motions using a leg strap and handheld wheel.

Exergames are also created for virtual reality platforms, as demonstrated by *Beat Saber* [77]. In this game, players slash blocks in rhythm with accompanying music. Notably, the creation of exergames is not limited to specific gaming consoles, with mobile games like *Zombies, Run!* [78] offering an immersive zombie apocalypse scenario through sound and music, encouraging players to jog outdoors.

Another important category of persuasive games is advertisement games, or 'advergames'. Commercial brands develop these types of games to promote their products or services and boost sales [79]. An early example is the game *Tapper* [80], initially developed by brewery company AB InBev to advertise Budweiser beer. More recently, the restaurant chain KFC released the advergame *I Love You, Colonel Sanders!* [81], a dating simulator game aimed at promoting KFC food.

Despite their popularity with brands, the effectiveness of these types of games remains unclear. Many brands claim that advergames increase product sales [79]. One study found that people are more likely to have positive views towards the game and brand if the game is closely related to the product the brand is promoting [82]. On the contrary, a later study showed that while players of advergames tend to remember the brand better, their opinion about the brand has not significantly changed, and extended gameplay can even hurt their perception of the brand [79]. Additionally, an even later study suggests that the persuasive impact of advergames is comparable to a standard 30-second television commercial for the same brand [83].

4.2 Persuasive game design models

Numerous studies have explored effective approaches for the development of persuasive games. Khaled et al. studied how elements of shared persuasion, such as group opinion and team performance, impact the smoking habits of players in their game *Smoke?* [84]. Another example comes from research by Orji et al., who examined how persuasive strategies can be adapted based on the specific gamer type the player is part of [12]. Despite these contributions, there is a shortage of models to guide the design of persuasive games, with the existing ones being mostly theoretical. The rest of this section explains some examples of these models.

The Persuasive Systems Design (PSD) model, developed by Oinas-Kukkonen and Harjumaa, is a well-known framework for achieving behaviour and attitude change [85]. The framework involves three phases.

The first phase involves understanding key issues to keep in mind while designing a persuasive system.

Subsequently, an analysis of the persuasion context is performed in three steps. First, the intent of the persuasion is defined, which can either be behavioural or attitude change. Next, the event is defined using three aspects: (1) use context, which reflects people's attitude toward the persuasion context; (2) user context, relating to the individual differences among the users (e.g. their situations and goals); and (3) technology context, indicating the availability and features of technology. The last step is to establish the strategies to ensure persuasion.

The last phase is the design of the system features, consisting of four categories: primary task, dialogue, system credibility, and social support. Primary task supports users in the main task by, for example, simplifying complex tasks and providing personalisation. Dialogue support aims to motivate users through verbal cues such as praise, rewards, and reminders. System credibility support describes designing a credible persuasion system by incorporating principles such as trustworthiness, real-world feel, and expertise. Finally, the principles of social support implement social influence within persuasion systems through methods such as cooperation and competition.

Yusoff and Kamsin created a model that implements persuasive elements in games to enhance user interaction in persuasive games [86]. They defined three types of persuasive elements. The first type is visual elements used for emotional engagement in the players. Next are procedural elements, containing the rules in the game used to motivate the player to perform certain actions. Lastly are digital elements, which include abstractions, such as game warnings. Their goal is to enhance the learner's experience, authenticity and ownership.

The authors also proposed using three interaction media to increase attention in persuasive games: cognition (stimulating attitudes through the interaction between the game and players), emotion (capturing player interest and influencing their emotions), and social interaction (employing various tactics to sustain attention).

Siriaraya et al. [87] introduced a model for the development of persuasive games, presenting a cookbook as a metaphor for their model (the Meal). This model addresses the lack of a comprehensive framework for designing and developing persuasive games regardless of the context. The model consists of four main stages (the Dishes): defining the desired effects, investigating the user's world, designing the game, and evaluating the effects. Each stage consists of materials or components which need to be considered (the Ingredients) and the actions designers can take (the Utensils). An example given in the article is: using the utensil "literature study" to examine the ingredient "game world preferences" in the dish "user's world" [87].

The model that this research focuses on was created by De la Hera [13]. De la Hera designed the model to (1) enable an analysis of persuasiveness within digital games, (2) aid in identifying design issues in persuasive structures, (3) allow comparative studies to examine behaviours and differences in using games as a medium for persuasion, and (4) function as a guide for developing persuasive games [13]. The model, depicted in Figure 3, consists of three rings, each corresponding to distinct levels of persuasion.

The blue innermost ring (Signs) represents persuasive dimensions in the symbolical world. The dimensions are visual, linguistic, sound, and haptic persuasion, which respectively relate to how persuasive games can communicate meaning with visual representations, language, sound and music, and all forms of nonverbal communication involving touch.

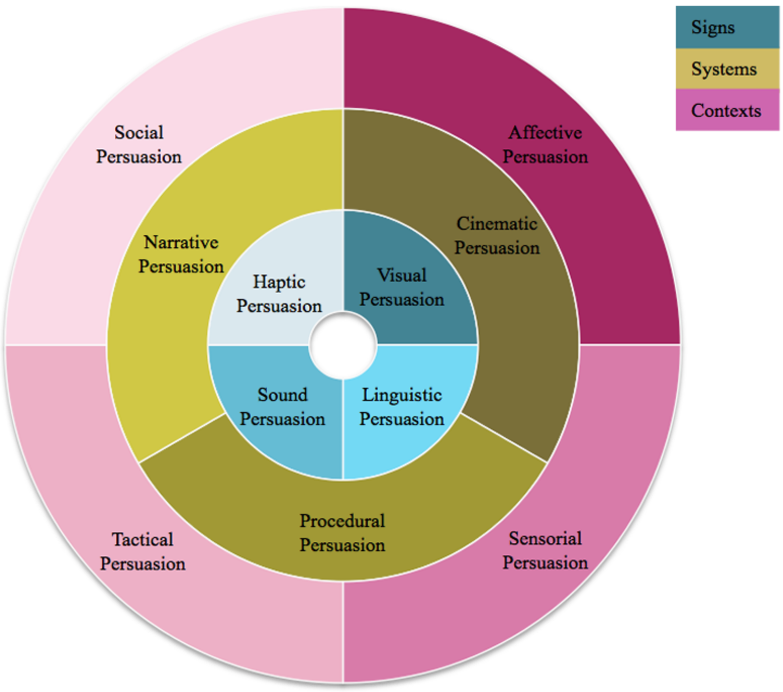


Figure 3: De la Hera's concept model for the analysis and development of persuasive elements in persuasive games [13].

The middle ring (Systems) establishes the connections between the dimensions from the innermost ring. It includes cinematic persuasion, which involves the connections crafted through the cinematography of the game, influencing the relationship between visual and sonic representations. Procedural persuasion refers to "the interpretations addressed by the rules of the persuasive game between visual, haptic, sonic and linguistic representations which guide players' interpretation" [13]. Narrative persuasion includes the story, space, time, characters, and interaction with the game's rules.

The outermost ring (Contexts) involves the persuasive dimensions cognitively influencing how players perceive the game. These dimensions include affective, sensorial, tactical, and social persuasion. Affective persuasion aims at creating cognitive frameworks that evoke emotions linked to the conveyed message. Sensorial persuasion evokes sensory experiences using the five senses. Tactical persuasion offers engaging experiences for players by presenting intellectual challenges. Social persuasion shapes the players' attitudes using experiences that encourage them to form connections with others.

4.3 Visual persuasion

Visual persuasion is a way of persuasive communication through visual elements such as images or text. De la Hera defined visual persuasion as "a process in which the visual representations function as cues that evoke intended meanings, premises and lines of reasoning" [13].

Researchers studying visual persuasion focus typically on one of three areas: nature, function, or evaluation [88]. Nature is related to the unique components of visual elements, function relates to their purpose, and evaluation determines if they fulfil their function.

Kjeldsen has defined three primary methods for conveying persuasive messages through visual elements: icons, indexes, and symbols [89]. Kjeldsen also suggests that visual persuasion can leverage four persuasive attributes of visuals: presence, realism, immediacy, and semantic condensation. Presence is the ability of visuals to support persuasive arguments, realism uses visuals to make the environment appear as realistic as possible, immediacy is the ability of visuals to be immediately understood, and semantic condensation is the ability of a visual to have multiple meanings at once.

The effectiveness of visual persuasion depends on factors such as the intended audience, the importance of the message, and the context behind the elements. De la Hera emphasises the importance of lighting, colour, and perspective in designing visual elements, particularly in digital games [13]. De la Hera also identified that for digital games, visual persuasion extends to (1) interface design, (2) character design, (3) object design, (4) spatial design, and (5) splash or menu screen design.

An example of interface design is visible in the exercise game *Ring Fit Adventure* [76], where the visual cues motivate the player. When the player puts increasing effort into an exercise, the in-game character's hair ignites, the fire gradually changing from orange to yellow the more effort is put in (see Figure 4).

Additionally, the character design in *Ring Fit Adventure* is designed to enhance persuasion. As illustrated in Figure 5, the enemies are modelled after fitness equipment, and

Figure 4: An example of interface design in *Ring Fit Adventure*.

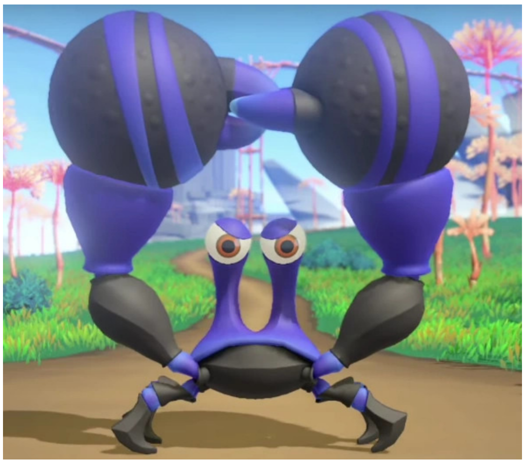


Figure 5: An example of character design in *Ring Fit Adventure*.

the final boss is presented as a well-trained dragon. This character design aligns with the game's fitness theme and visually motivates the player to engage in physical activity.

In the game *I Love You, Colonel Sanders!* [81], object design is used to show KFC food appealingly. While the overall visual style of the game follows a Japanese cartoon style, there is a deliberate shift when showing food. In these moments, the visuals are more realistic, emphasising the attractiveness of the presented food in real life. Stars are projected around the food, accompanied by in-game dialogue that highlights the appeal of the dish (see Figure 6).

When the main character tastes the food, the environment transforms, revealing a galaxy with a bright light situated in the middle, as can be seen in Figure 7. This demonstrates how spatial design is used to once again emphasise the appeal of KFC food through a visually

Figure 6: An example of object design in *I Love You, Colonel Sanders!*.

Figure 7: An example of space design in *I Love You, Colonel Sanders!*.

captivating setting.

Finally, an example of visual persuasion in menu screens is visible in *Dance Stage EuroMIX* [90]. In this game, the song options are presented as CDs that players can scroll through, as depicted in Figure 8. The presentation of song options is designed to draw a connection to real-life experiences, as CDs were commonly used when the game was developed.

Figure 8: An example of menu design in *Dance Stage EuroMIX*.

4.4 Measuring persuasion

Usually, the effectiveness of persuasive systems is evaluated through objective measures like player behaviour observation, and more subjective methods such as user self-reporting and self-reflection. Research on persuasion can benefit from creating standardised systems for studies reliant on these subjective results, especially when comparing the persuasive effects of different media formats. Implementing consistent evaluation frameworks improves the reliability of researchers' findings.

The Perceived Persuasiveness Questionnaire (PPQ) is a notable tool for assessing the perceived persuasion of technology [91][92]. The PPQ was created within the theoretical framework of the PSD model [85]. Originally, PPQ was used to evaluate the persuasiveness of a digital weight loss intervention and has since been used in other studies, such as examination of the persuasive impacts of virtual agents [93]. The PPQ evaluates perceived persuasiveness across four categories defined by the PSD: primary task support (TASK), dialogue support (DIAL), credibility support (CRED), and social support (SOCI). Additionally, PPQ measures persuasiveness according to four constructs associated with persuasion: overall perceived persuasiveness (PERS), unobtrusiveness (UNOB), effort (EFFO), effectiveness (EFFE), and use continuance (CONT). Table 1 shows an overview of the PPQ constructs and their explanation. The table is an adapted version of Table 2 presented by an evaluation study from Beerlage et al. [94]. The PPQ is presented in Appendix A.

PPQ construct	**Description**
Primary task support (TASK)	Whether the technology helps to achieve the goal
Perceived dialogue support (DIAL)	Whether the technology provides feedback and guidance to the user
Perceived credibility (CRED)	The perceived reliability and trustworthiness of the technology
Perceived social support (SOCI)	Whether the technology allows the user to share with and learn from their peers
Perceived persuasiveness (PERS)	Whether users think that the technology is valuable and has an influence on them
Perceived unobtrusiveness (UNOB)	How disturbing the technology is to daily life
Perceived effort (EFFO)	The endeavour that the technology entails
Perceived effectiveness (EFFE)	The efficacy of the technology
Use continuance (CONT)	Willingness of users to adopt the technology in the future

Table 1: An overview of the PPQ constructs, adapted from Table 2 presented in the study by Beerlage, et al. [94].

4.5 Quantum games

Games implementing the theories surrounding quantum physics have been created since the early 1980s. One of the earliest examples is *Quantum* [95], a commercial game with gameplay featuring particles on the quantum scale. Recent titles such as *Quantum Break* [96] and *Mass Effect* [97] integrate quantum physics in their storylines without extending their applications into the gameplay mechanics. *Quantum Break* uses quantum physics to explain time travel, while *Mass Effect* features devices known as 'quantum entanglement communicators' to enable instant communication at the speed of light between spaceships.

What distinguishes these commercial games from the majority of games related to quantum physics is their emphasis on entertainment. In contrast, a significant part of games about quantum are designed for educational purposes.

In this research, 'quantum games' refer to serious games designed to interactively explain principles of quantum mechanics, offering users educational experiences to understand complex quantum concepts. For instance, the online platform *Virtual Lab* simulates an optical table, allowing players to interact with and gain an understanding of quantum phenomena [98].

Rather than developing entirely new games, developers have also incorporated quantum mechanics into established games. This strategy can help players better comprehend complex theories by allowing them to compare the quantum version with the original versions. Examples of such games include *Quantum Minesweeper*, introducing elements of superposition and entanglement into *Minesweeper* [99]. Additionally, multiple versions of quantum *Tic-Tac-Toe* exist where every move is in superposition [100][101][102]. Similarly, *Quantum Chess* explores superposition in its gameplay by allowing the chess pieces to occupy more than one space on the board [103].

In addition to games explaining quantum physics theories, some specifically focus on quantum computing principles. *Quantum Odyssey*, for instance, visualises quantum gates and circuits, allowing the player to experiment with these concepts and increase interest in quantum computing [104]. Tech companies like IBM have also developed quantum computing games such as the board game *Entanglion* [105] and the mobile game *Hello Quantum* [106]. *Entanglion* introduces players to quantum computing concepts such as qubits, quantum gates, superposition, and entanglement, while *Hello Quantum* educates players about the inner workings of quantum gates. Google has also created games such as *The Qubit Game* [107], where players build a quantum computer one qubit at a time, gaining insights into its components. Additionally, both Fujitsu, a multinational ICT equipment and services corporation, and Capgemini have created arcade games aimed at explaining qubit interactions manipulated by quantum gates, respectively *Quantum Arcade Game* [108] and *Quantum Puzzle*.

Notably sparse are games related to the potential impact of quantum computers. Some examples I found were *QuaSim*, a digital game developed to explain quantum cryptography [109], and *Encrypt me!*, a physical game for explaining advanced quantum concepts, such as qubit entanglement and quantum cryptography [110].

The popularity of developing quantum games increased after the launch of the IBM Quantum Platform, enabling the development of games designed to run on quantum computers using quantum programs and executing them on quantum processors. *Quantum Battleship* [111], which incorporates qubits into *Battleship*, emerged as the first game designed to be playable on a quantum computer in 2017. Additionally, *Quantum Cat-sweeper* [112] presents another quantum variation of the game *Minesweeper*, using qubits to determine the likelihood of bombs on the tiles.

The rise of quantum games has been encouraged by the organisation of events like game jams and hackathons, such as the Quantum Game Jam. This event invites both quantum experts and game developers to collaboratively develop quantum games within a limited time frame to contribute to scientific work [113]. After the first edition in 2014, it continues to be held remotely every year [114]. The collaboration between quantum experts and game developers during these events continues to drive innovation between quantum physics and gaming, leading to games such as $Q|Cards\rangle$ [115], where players use cards as quantum gates to interact with qubits and determine the winner by inputting their scores on the Quantum Platform.

4.6 Research questions

In summary, persuasive games, a subset of serious games, aim to produce attitude or behaviour change through engaging gameplay. Effective approaches for their development have been explored in numerous studies, with the focus of this research being on De la Hera's model, which offers a guide for integrating persuasive elements in games [13]. Visual persuasion, a form of communication through images or text, is emphasised within De la Hera's framework, highlighting factors such as lighting, colour, and perspective. Examples of interface, character, object, spatial, and menu design illustrate how visual elements across various design aspects enhance persuasive communication, thereby motivating player engagement. The persuasive systems are evaluated by a combination of objective measures and subjective methods, with standardised systems like the PPQ enhancing research reliability across various studies.

Within the realm of quantum physics and gaming, numerous commercial and educational quantum games are available. Nevertheless, there exist a limited number of games focused on illustrating the potential impact of quantum computing.

This research aims to assess the effectiveness of visual persuasion, as outlined in De la Hera's model, in enhancing the persuasive impact of a digital game designed to communicate the potential impact of quantum computers. Two game versions are developed, with one having additional visual persuasion elements. A user study is conducted to measure the persuasive impact on two groups of participants who engage with one of the game versions.

The research question defined to achieve the goal is:

Does the implementation of visual persuasion design improve the level of persuasion among players?

5 Methods

In this section, I elaborate on the materials used in creating the game, delve into the overarching game design in both versions, and explain the additional visual elements incorporated into version 2. Subsequently, the process for conducting the experiment comparing the two versions is outlined, along with details on the questionnaire and participant information.

5.1 Materials

The two versions of the persuasive game developed for this research were created as 2D games using the Unity engine. Interaction with the game is made possible through mouse and keyboard inputs. This game is compatible with all Windows, MacOS, and Linux devices. Game objects in the game were found on the internet, developed by an external party, or created by myself.

5.2 Game design

There exist two versions of the game — version 1 and 2 — each featuring four levels corresponding to a distinct impact category. Version 1 lacks any incorporated visual persuasion elements, while version 2 includes additional visuals to try and enhance the persuasive message. Aside from these additions, the design and gameplay remain consistent.

The game adopts a 2D format with a simplified design for clarity and comprehension and is presented in English. The primary colour scheme draws inspiration from the Capgemini palette, incorporating shades of blue, green, and purple.

The levels are designed to present players with challenges that effectively showcase the capabilities of a quantum computer. They aim to offer an enjoyable and immersive experience, finding a balance between being sufficiently challenging to captivate players and yet accessible enough for those with limited gaming experience. The level design emphasises a user-friendly and swift gaming experience, ensuring that each level can be completed within a 5-minute timeframe, including reading, resulting in a total gameplay duration of approximately 20 minutes.

All levels share a common structure. At the beginning of each level, text informs the players about the gameplay. For levels requiring additional clarification, a video explanation of the gameplay is incorporated. Afterwards, players engage in the game segment of the level. Upon completion, players receive a score based on their performance, sometimes presented as a ranking among other players and at other times as an indication of how well the player solved the problem. This scoring mechanism serves two purposes: to motivate players to improve their performance and to highlight the capabilities of quantum computers. Simultaneously displayed with the score, an explanation detailing the quantum computer's capabilities for that specific level is provided. In certain levels, an advanced or realistic version of the problem is presented to underscore its difficulty for both the player and a classical computer, emphasising the unique capabilities of a quantum computer.

The subsequent four sections provide detailed explanations of each of the four levels.

5.2.1 Cryptography

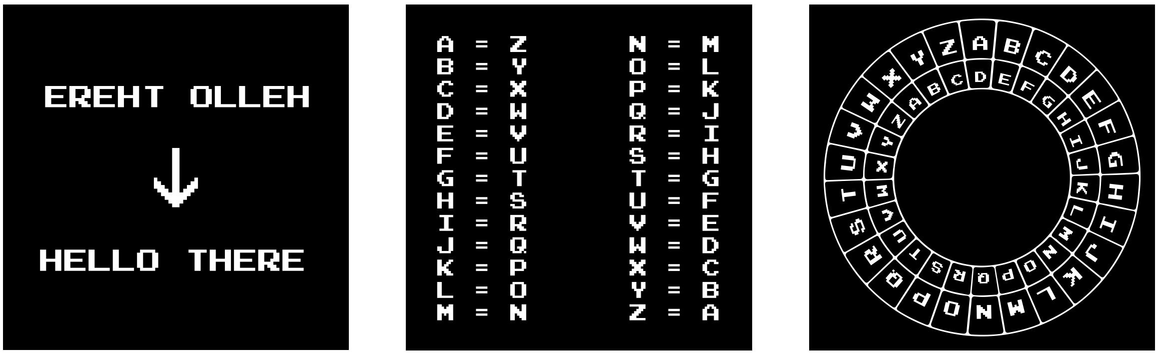
The cryptography level aims to demonstrate the future capability of quantum computers to decipher existing encryption methods. While I take some inspiration from QKD for the level, the goal is not to explain this concept.

In this level, players are educated about cryptography and the potential of quantum computers to compromise our existing encryption and decryption techniques. They are informed that the gameplay serves as an illustration of this vulnerability. Players are tasked with decoding words using three ciphers while a quantum computer actively seeks to intercept the data. The player's task is to decode as many words as possible before the quantum computer cracks the decoding cipher. When this happens, the cipher changes. The player's score is determined by the number of words successfully decoded.

The three ciphers featured in the level are shown in the following order: backward transposition, Atbash, and Caesar (refer to Figure 9). Each cipher allows the decoding of five distinct words, starting with a three-letter word and progressively increasing in length up to a seven-letter word.

The game begins with an encoded message and a displayed cipher for decoding, as can be seen in Figure 10. Players use the keyboard to input the decoded word. If the player successfully decodes a word, the new word appears with "CORRECT!" above it in green. On the other hand, if the decoding is incorrect, "Try again" in red appears above the current word. This process is displayed in Figure 11.

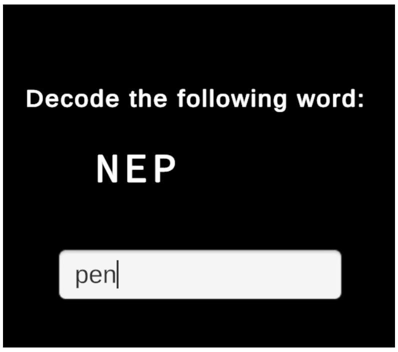
After 30 seconds or when all words for the current cipher are decoded, the warning screen appears, indicating that the quantum computer has intercepted the decoding method, and the cipher will change. The detection of an eavesdropper is based on the QKD abilities, but not directly linked to it. The warning screen is displayed for seven seconds. Afterwards, the player can continue decoding messages, using a different cipher and five new words. The game concludes either when the time for the last cipher expires or if the player successfully decodes all words associated with the cipher. Subsequently, a scoreboard reveals the player's



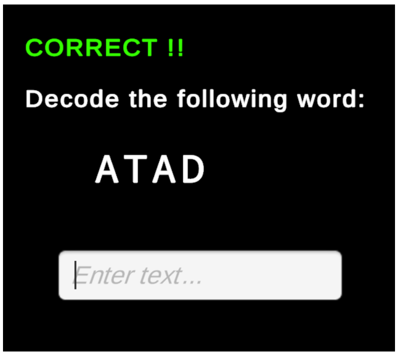
(a) Backwards transposition (b) Atbash (c) Caesar cipher

Figure 9: The three ciphers used for the gameplay in the cryptography level.

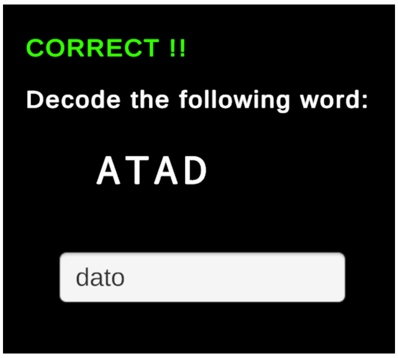
Figure 10: The gameplay in the cryptography level.



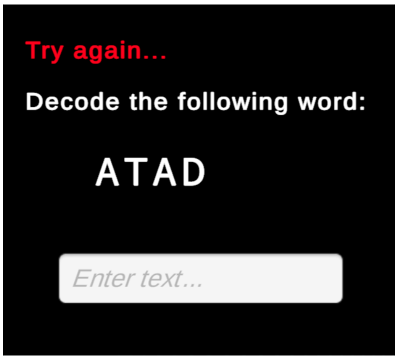
(a) Putting in the correct answer.



(b) A correct-message is displayed and the next word appears.



(c) Putting in the incorrect answer.



(d) An incorrect-message is displayed.

Figure 11: Inputting correct and incorrect messages during the cryptography level.

score, comparing it to previous scores in a top 5 ranking achieved by other players. If the player has secured a position in the top 5, the message “Congratulations! You set a new high score!” is displayed, and their score is highlighted in green within the ranking.

The full design of the gameplay is presented in Appendix C.1.

5.2.2 Optimisation

To illustrate the influence of quantum computing on optimisation problems, the level centres around a specific optimisation problem: the travelling salesman problem.

The introductory text at the beginning of the level establishes the player as an employee of a package delivery company. The objective is to determine the shortest route while visiting every designated location on a map, starting and finishing at the dispatch centre. The player's selected route length and the time taken to find the route are tracked.

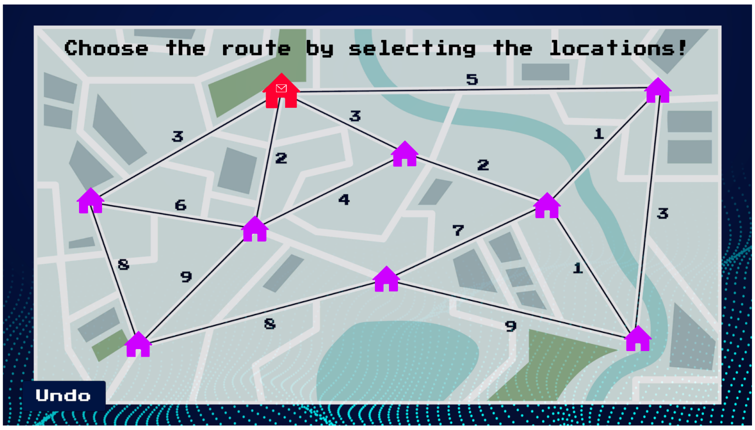
Upon starting the game, a map is presented featuring eight purple locations is presented, and one additional location is designated as the dispatch centre. The dispatch centre is distinguished by its red colour, slightly larger size, and envelope icon. The dispatch centre is both the starting and ending location, while the remaining eight locations must be visited once. Some locations are connected by black roads to indicate possible connections, while others cannot be connected, and therefore lack a black road. Each black road is labelled with a number denoting the time it takes to travel between the locations.

Once the player clicks on the starting location, a thick dark blue line follows the player's mouse. Clicking on another location connects them with the dark blue line, adding the travel time to the total. The player can undo location selections using the ‘Undo’ button, subtracting the road length from the total route. Undoing is allowed for every location except the dispatch centre because this is the starting location anyway. After visiting every location and clicking on the dispatch centre, the thick line disappears. A button in the bottom right appears, allowing the player to finish the game. This progression in the gameplay is displayed in Figure 12.

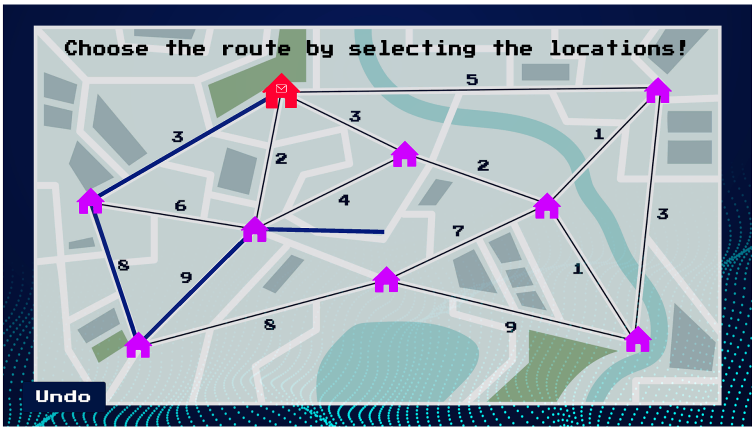
After finishing the game, a screen appears, showing the player's travel distance and the time taken to find the route. Alongside, a screenshot of the shortest route is shown, as well as text comparing the performances of classical and quantum computers in this scenario. Both will find the shortest route, but for smaller problems like these, the classical computer will find it faster compared to a quantum computer. To see a bigger scenario with 30 locations, the player can click the ‘Next’ button.

Pressing the button presents the player with a screenshot of a more complex scenario featuring 30 locations, which is not interactive. The text beneath the image explains that classical and quantum computers can both calculate the fastest route, but the classical computer would take days, whereas the quantum computer can achieve this in a matter of minutes.

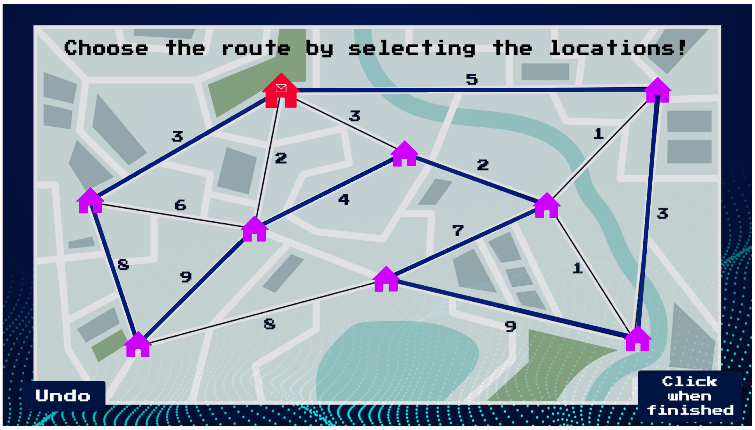
For a comprehensive overview of the level design, refer to Appendix C.2.



(a) Start of the gameplay. No locations are connected yet.



(b) The gameplay involves selecting the route between locations, represented by a prominent blue line.



(c) Once the player has visited all locations and finishes the route at the starting location, a 'Finish' button appears.

Figure 12: The progression of the gameplay in the optimisation level.

5.2.3 Machine learning

Quantum machine learning can be used on graphs to make predictions and provide recommendations. In this level this is shown with the example of triangle finding, which is associated with the financial sector by using this algorithm to identify circular transactions. The connections between nodes symbolise transactions within a financial system, involving individual people, stores, and banks.

The players are informed that circular transactions, where money flows in a circle, are considered suspicious and should be investigated for potential fraud. The player's objective is to detect all circular transactions by selecting the parties involved. Transactions are represented by moving lines between parties, gradually fading after a few seconds. Over two minutes, players can identify three circular transactions by clicking on individuals, stores, or banks engaged in the suspected transactions. A video demonstrates how the player can select these circular transactions within the game.

Throughout the game, transactions will occur in a seemingly random pattern. To improve gameplay, individuals are coloured white, stores are yellow, and banks are red. The start of each transaction line carries the colour where the transaction goes, while the end reflects the colour that the transaction originates from. Clicking on a party causes its colour to desaturate, indicating its selection. When the player has selected the parties involved in a circular transaction, they can confirm their choice by pressing a button in the bottom left corner. This will show the confirmation text "Selection confirmed". After the confirmation, the selected parties cannot be interacted with anymore. After two minutes, the game concludes. The gameplay is illustrated in Figure 13.

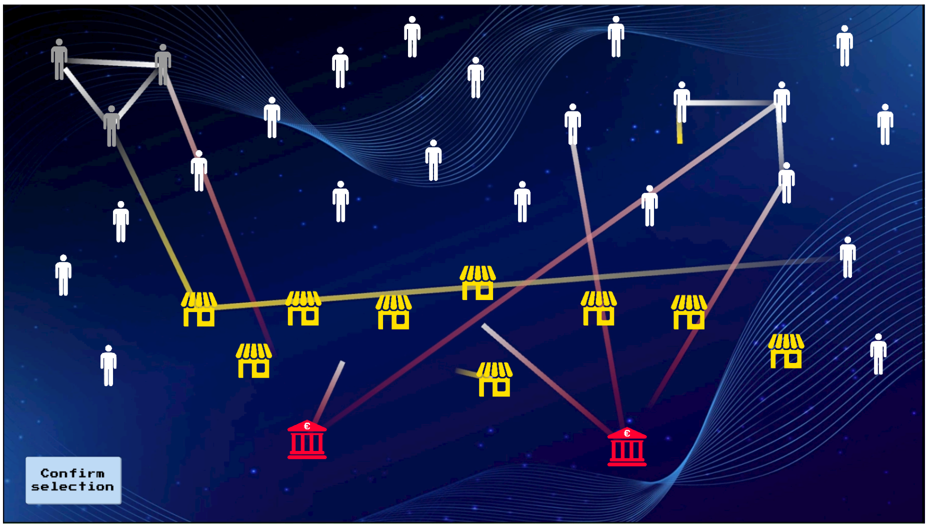


Figure 13: The gameplay of the machine learning level. The three individuals in the top left engage in a circular transaction. They were initially white, but after being selected by the player they are grey.

The ending screen reveals the number of circular transactions spotted by the player and how many of these are correct. The explanatory text highlights the efficiency of quantum computers in detecting circular transactions, particularly valuable in realistic scenarios with a higher number of transactions. Clicking the 'Next' button introduces a scenario with significantly more transactions, resembling real-life situations where quantum computers potentially excel in detecting circular transactions despite the increased complexity.

An overview of the level is presented in Appendix C.3.

5.2.4 Simulations

This level is designed to show the advanced simulations by quantum computers using a medical field-related example. The focus is on creating molecules, where the atomic bonds between atoms determine properties such as colour, smell, toxicity, and stability.

In the introduction, players are informed that their goal is to create atomic bonds between the atoms of three molecules: water (H_2O), formaldehyde (CH_2O), and ethanol (C_2H_6O).

To illustrate the gameplay, an example of formaldehyde is presented in Figure 14.

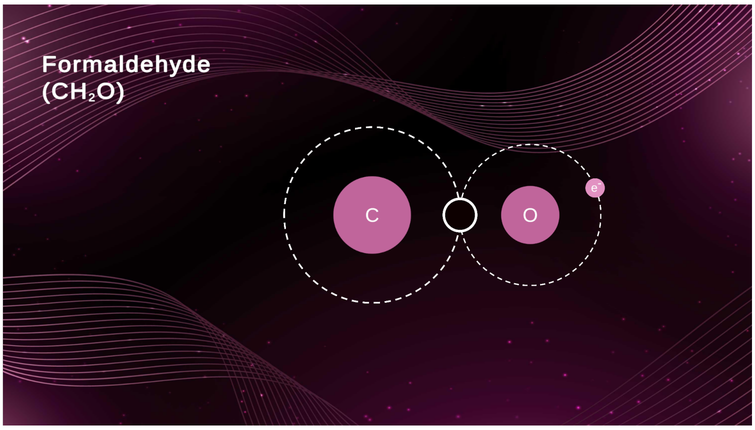
These molecules consist of atoms, each surrounded with a dashed white circle on which electrons rotate (see Figure 14a). The circles overlap at specific points, identified as connection points. When the electron occupies this circle, it lights up in green, and players can press the spacebar to create atomic bonds. This process is displayed to the players in an instructional video. A percentage is displayed based on the electron's position in the connection point (see Figure 14b). A score of 100% indicates a perfect placement, while the outermost connection point results in a score of 15%. The player's overall score is determined by averaging all individual scores throughout the game.

At any moment, the game displays one, two, or three atoms with electrons rotating around them. If multiple atoms are displayed, all electrons must be in their designated connection points simultaneously to turn green. However, the size of formaldehyde and ethanol presents a challenge, making it too difficult and overwhelming to connect all atomic bonds simultaneously. As a solution, formaldehyde is split into two phases, while ethanol is divided into four phases to ensure a more manageable and accessible gameplay experience.

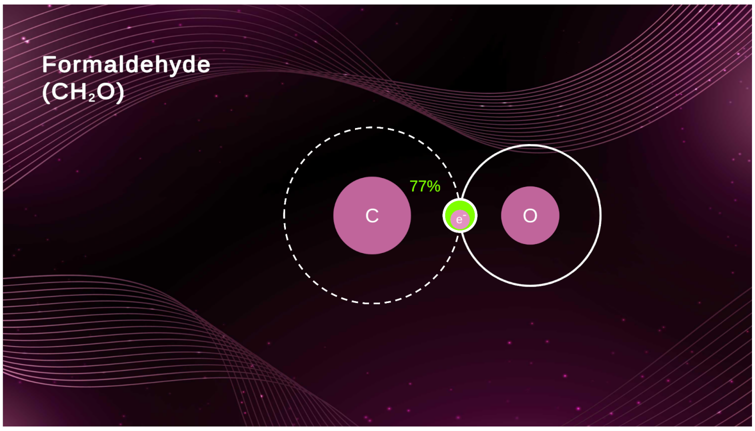
Upon connecting electrons, the screen briefly pauses. The dashed white circles around the connected atoms transform into a complete circle, and individual scores for each connection are displayed in green. When the molecule transitions to the next phase, the electrons and connection points vanish, but the complete white circle remains (see Figure 14c).

After 15 seconds into a phase, a 'Skip' button appears, allowing players to skip a phase if it proves challenging (see Figure 14d). Clicking this button sets the score for each electron at 15%.

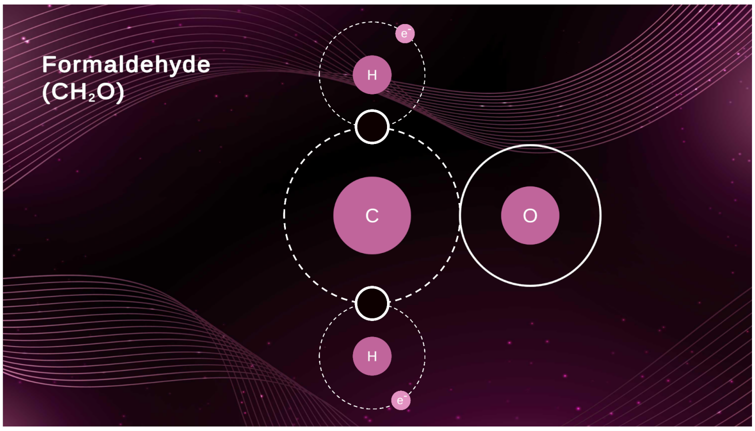
Upon connecting the last electrons, the screen displays the player's score, comparing it to previous scores in a top 5 ranking achieved by other players. If the player's score surpasses any in the ranking, the text "Congratulations! You set a new high score!" appears, and the score is highlighted in green within the ranking.



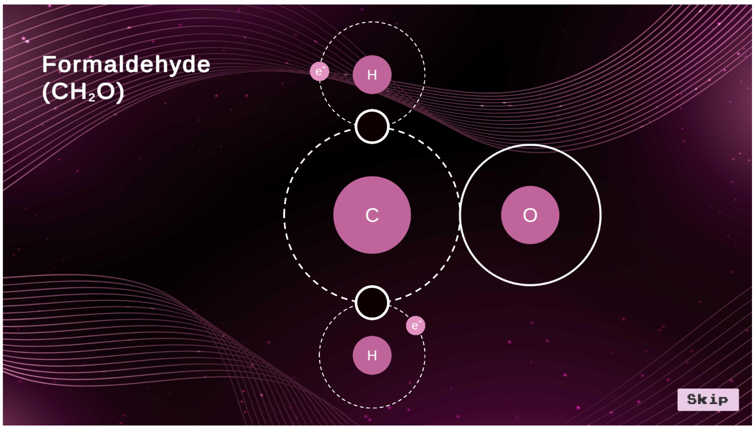
(a) The first phase of the molecule features only the C- and O-atoms, with an electron rotating around the O-atom.



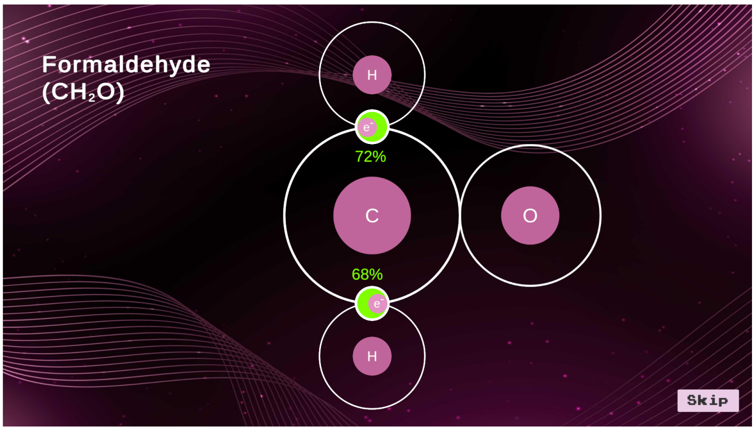
(b) The conclusion of the first phase happens once the player successfully captures the electron in the connection point.



(c) The second and final phase of the molecule. Both H-atoms must be connected to the C-atom, requiring both electrons to be in the connection point.



(d) After 15 seconds, the 'Skip' button appears in the bottom-right corner.



(e) The conclusion of the second phase.

Figure 14: The gameplay in the simulations level during the formaldehyde molecule.

Clicking the 'Next' button presents a screen explaining that quantum computers can efficiently determine the optimal positions of electrons, enabling a more accurate understanding of molecule properties. A ranking displays scores that three quantum computers from different years (2020, 2025, and 2030) would achieve in the game, showing how they perform compared to the players and emphasising the potential future advantage of quantum computers.

The full design of the level is presented in Appendix C.4.

5.3 Visual persuasion elements

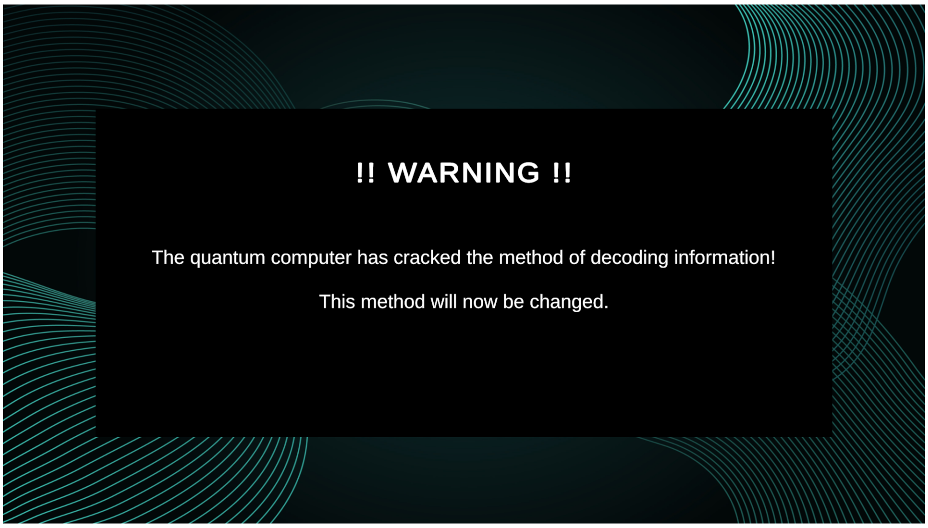
The primary goal behind the integration of visual persuasion elements in version 2 is to enhance the overarching message regarding the potential impact that quantum computers have on the future. To achieve this, a visual representation of the quantum computer is incorporated as a recurring character. This choice ensures that the computer becomes a central and consistent presence, featured prominently in every level, thereby reinforcing the narrative of its significance throughout the entire experience. Additional elements are customised for each level to convey information about the impact of the quantum computer in each domain.

Within the cryptography level, the focal point revolves around illustrating the potential threat that quantum computers pose to cryptographic systems. In version 2, this message is intensified through the incorporation of visual elements within the pop-up screen designed to alert users when an eavesdropper is detected. In this reconstructed interface, the quantum computer is visually depicted as an eavesdropper, accompanied by warning signs on both sides and a red background, accentuating the danger of the computer. The visual difference between version 1 and version 2 can be seen in Figure 15.

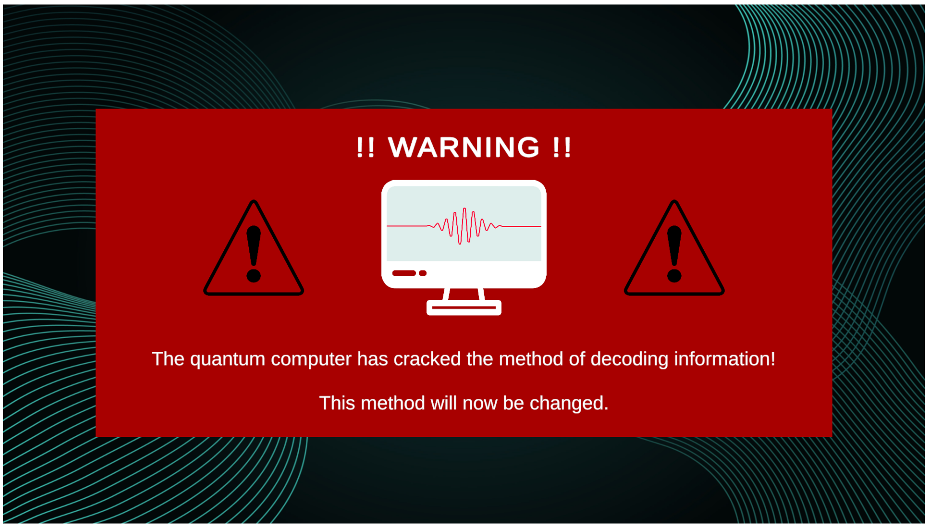
For the optimisation level, the visual components are created to highlight the superior speed of the quantum computer in tackling the travelling salesman problem, particularly when faced with larger problem sizes, in comparison to both the player and classical computers. The visual representation is introduced at two key moments in the level: after the player completes the game for nine locations, and when presented with a scenario involving 30 locations. In both instances, visual representations of the classical and quantum computers are featured alongside loading bars indicating their progress. In the initial scenario with nine locations, the loading bar of the classical computer slightly outpaces that of the quantum computer. In contrast, during the scenario with 30 locations, the quantum computer's loading bar speeds ahead at a much faster pace. This contrast serves to illustrate that for smaller problem sizes, the classical computer exhibits greater speed, while for larger problems, the quantum computer achieves a faster performance. Both loading screens presented in version 2 are displayed in Figure 16. In version 1, these two loading screens are absent.

In the machine learning level, the visual elements are designed to highlight the quantum computer's capability to quickly identify circular transactions in comparison to the player. This is visually shown through a dedicated screen presented after the two minutes of gameplay. The screen features an image of the quantum computer, accompanied by a rapidly progressing loading bar, as illustrated in Figure 17. This loading screen is only implemented in version 2, not in version 1.

In the simulations level, the visual elements are created to depict the remarkable speed of the quantum computer. Following a similar approach to the machine learning level, a screen shows the quantum computer's image placed above a rapidly moving loading bar, as can be seen in Figure 18. The screen is presented after the player's score is displayed. In version 1, the loading screen is absent and the score of the player is immediately presented after the gameplay is finished.

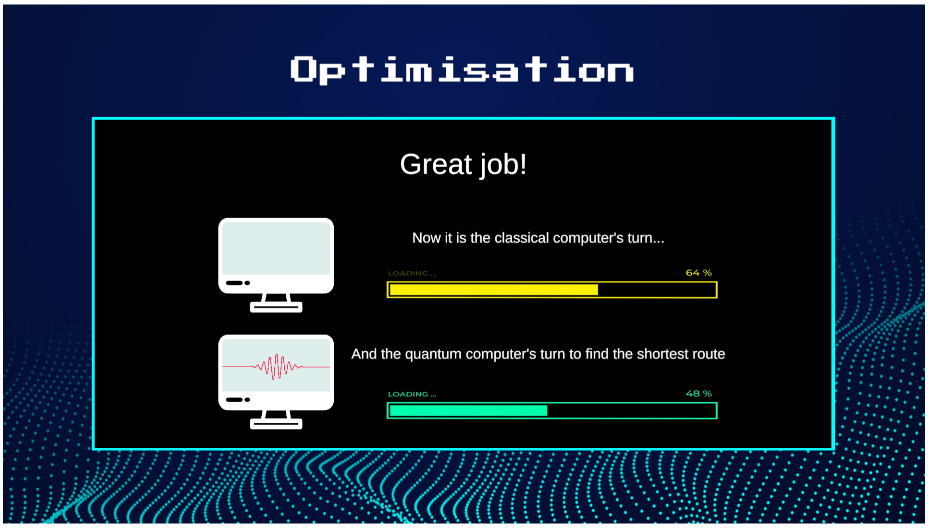


(a) Warning screen in version 1

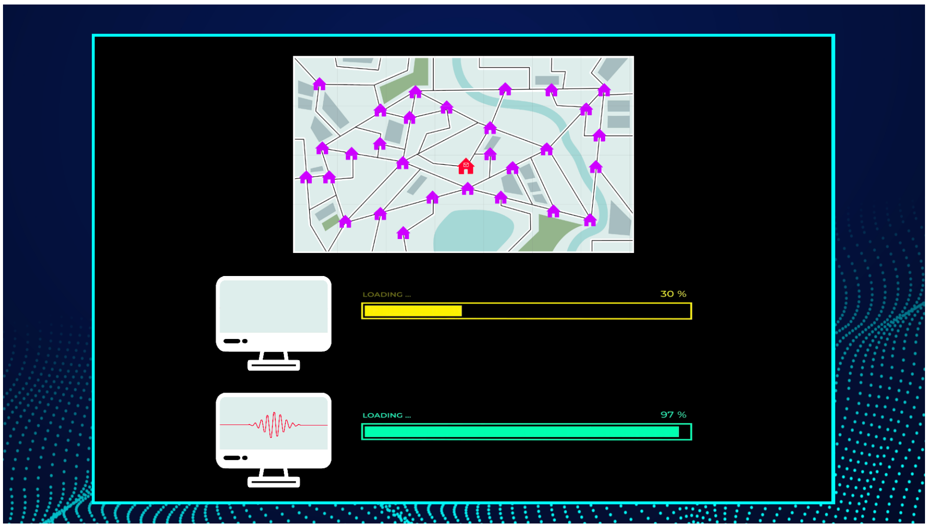


(b) Warning screen in version 2

Figure 15: The warning screens displayed in the cryptography level.



(a) Loading screen after nine locations



(b) Loading screen after 30 locations

Figure 16: The two loading screens depicting the travelling salesman scenarios in the optimisation level of version 2.

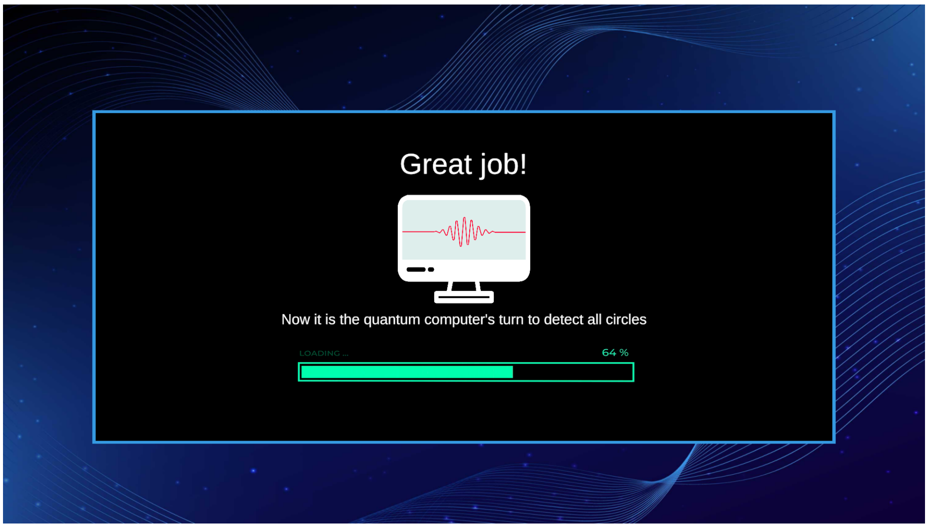


Figure 17: Loading screen for the machine learning level in version 2.

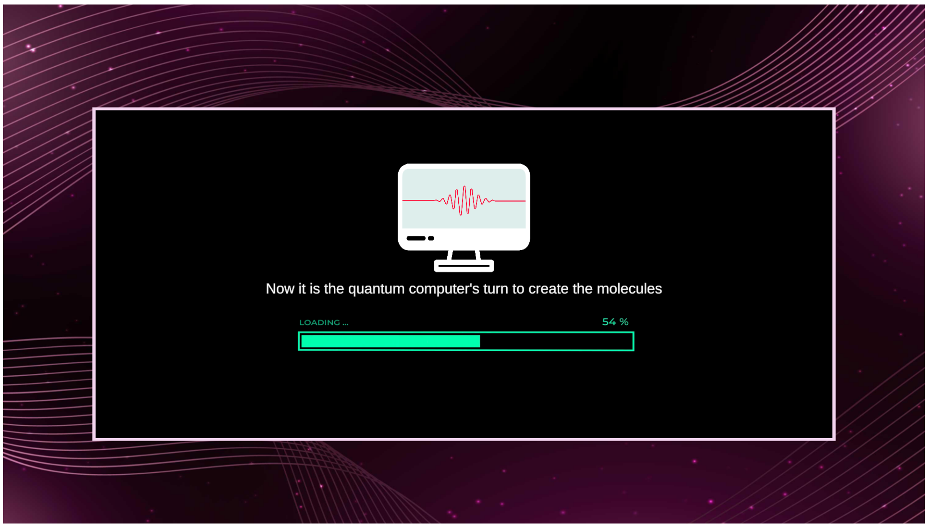


Figure 18: Loading screen for the simulations level in version 2.

5.4 Experiment procedure

Participants in the study are directed to a laptop, where each is presented with an information sheet detailing the experiment's objectives and procedures. This digital document explicitly outlines participants' right to withdraw from the experiment at any juncture. Following this, participants are asked to provide digital consent by signing the document, permitting the use of their personal information (such as gender and age) during the data processing phase.

Subsequently, participants proceed to an online questionnaire that explores their knowledge of quantum computing, potential opinions on the subject, and attitudes toward learning about complex scientific topics.

After completing the questionnaire, participants are asked to play with the game downloaded onto their laptop, which could be either version 1 or version 2, depending on the device. A list will be kept of which version the participants play. The distribution of versions is evenly divided among the laptops, ensuring that both groups playing each version are of equal size. All participants receive instructions to navigate through all four levels of the game.

After completing the game, participants are directed to fill out a final online questionnaire designed to gather insights into their opinions about the game and the information provided. Additionally, the questionnaire aims to identify any shifts or changes in their initial opinions.

The Ethics and Privacy Quick Scan of the Utrecht University Research Institute of Information and Computing Sciences was conducted to ensure ethical research. It classified this research as low-risk with no fuller ethics review or privacy assessment required.

5.4.1 Questionnaire

In the research process, questionnaires serve as important tools for capturing players' subjective experiences with the game. A consent form and pre- and post-game questionnaires have been designed to gather valuable insights at different stages of the study. All documents are presented to the participants using the online survey software Qualtrics, which is linked to my personal Utrecht University account.

The consent form is essential for securing the player's permission to utilise non-identifiable personal information for the analysis of results. It provides information about the purpose of the study, the steps taken, time estimation, confidentiality of the study, and the participant's rights. The consent form can be viewed in Appendix B.1.

The pre-game questionnaire plays an important role in understanding the participants' background information, including previous knowledge of quantum mechanics and computing, and their opinions about the topic before engaging with the game (see Appendix B.2). This assessment enables an understanding of the starting point of participants and the potential impact of the game on their opinions.

The final questionnaire, given after completing the game, aims to capture the players' reflections on the persuasiveness of the game and to test if their opinion on the topic has changed. For this questionnaire, an adapted version of the PPQ [94] is used, with statements presented on a 7-point Likert scale. As there is no continuous use of the game from the participants after playing the game once, the constructs UNOB and CONT and their associated items are removed. The construct SOCI is also removed because there are no peers present. From the other constructs, only the statements relevant to the research are used.

In creating this questionnaire, several additions have been made to enhance the depth of understanding. Firstly, I included a follow-up question to allow participants to explain their answer to the statement “The game makes me reconsider my opinion about quantum”, providing additional insights into their responses. Additionally, an extra statement, presented on a 7-point Likert scale, has been incorporated to gain an understanding of the players’ changed opinions on quantum computing and the impact of visual elements. The statement is: “The visual elements in the game strengthen the persuasive message”, and it has been linked to a new construct, called Visual persuasiveness (VISU). Participants are also asked to elaborate on their answers to this statement. Lastly, a follow-up question in the form of a yes-no question is presented to participants regarding their motivation to learn more about quantum topics after playing the game.

The final visualisation of the statements of the PPQ linked to the constructs is presented in Table 2. The full post-questionnaire as presented to the participants, including the follow-up questions and the additional question at the end, can be found in Appendix B.3.

Both the pre- and post-game questionnaire results are analysed to study the effectiveness of the learning and persuasion processes in the game. Furthermore, a comparative analysis is conducted to identify any significant differences in results between the two versions of the game. To achieve this, an independent t-test is used, allowing for a statistical examination of the data and the exploration of the impact of visual persuasion elements on player experiences. Additionally, a Pearson correlation is calculated for the pre- and post-questionnaire to find correlations between the answers to the questions and statements.

Construct	**Statements**
Primary task support (TASK)	S1. The game helps me understand the impact of quantum computing. S2. The game encourages me to learn about the impact of quantum computing.
Perceived credibility (CRED)	S3. The information given in the game is trustworthy. S4. The game shows expertise.
Perceived persuasiveness (PERS)	S5. The game has an influence on me. S6. The game is personally relevant for me. S7. The game makes me reconsider my opinion about quantum computing.
Perceived effort (EFFO)	S8. Playing the game does not require a lot of effort from me. S9. Playing the game is straightforward for me. S10. Playing the game is not laborious.
Visual persuasiveness (VISU)	S11. The visual elements in the game strengthen the persuasive message.

Table 2: Eleven statements from the post-game questionnaire, aligned with respective constructs. The first ten statements and constructs draw inspiration from the PPQ [94]. The final statement is created to address the specific research questions in this project.

5.4.2 Participants

The required sample size for the experiment is determined by the formula outlined by Sauro and Lewis in their book [116]. The equation for the sample size in a between-subject comparison study is given by

$$n = \frac{2z^2s^2}{d^2} \tag{1}$$

Here, n represents the sample size, z is the two-sided z-score based on the chosen confidence level, s is the standard deviation from a previous study or evaluation, and d refers to the critical difference.

The confidence level indicates the level of reliability that the interval contains the true proportion of a population [116]. A target confidence level of 95% is chosen as it is a frequently used value, resulting in $z = 1.96$. Due to a lack of previous research, s cannot be determined. Fortunately, d can be defined as a fraction of s, making a definition of s unnecessary [117]. When d is defined as a fraction of s, it essentially becomes the product of the effect size and the standard deviation. The effect size is the magnitude of a statistically significant difference between the two methods. This results in Equation 1 becoming

$$n = \frac{2z^2s^2}{e^2s^2} = \frac{2z^2}{e^2} \tag{2}$$

with e representing the effect size.

In 1988, Cohen established threshold values of 0.2, 0.5, and 0.8 for small, medium, and large effect sizes, respectively, which can be used to determine the target sample size [118]. I chose to target the medium threshold, setting $d = 0.5s$. Consequently, the calculation for the target sample size becomes

$$n = \frac{2 \cdot 1.96^2}{0.5^2} = \frac{7.6832}{0.25} \approx 31 \tag{3}$$

Therefore, the goal is to gather 31 participants for the study.

Participants are recruited from inside and outside Capgemini, with the goal of finding individuals possessing limited knowledge of quantum computing. They are informed that a digital game about quantum computing was created to research whether it can persuade players of the significant influence these computers will have in the future. Additionally, they are notified that participation requires a good level of English, an interest in quantum computing and a time commitment of 20 to 30 minutes. To prevent potential bias in their responses, participants are kept unaware of the existence of two versions of the game and the objective of comparing them.

6 Results

This section presents the results from the experiment's questionnaires. Firstly, information about the participants obtained through the pre-game questionnaire is outlined. The second subsection explores the quantitative outcomes derived from the post-game questionnaire. Finally, the qualitative findings from the same questionnaire are described.

6.1 Demographics

Over a span of two weeks, a total of 27 participants were recruited, consisting of 18 males and nine females. The age scale among participants varies from 21 to 57, with an average age of 29.

With a sample size of 27, the intended size of 31 participants was not realised. To account for the reduced size, the level of confidence can be adjusted, as suggested by Sauro and Lewis [116]. Since Equation 2 was initially used to calculate the target sample size based on the chosen confidence level and effect size, it can be modified to determine the confidence level based on the effect size and sample size. The calculation of the confidence level using the modified Equation 2 is expressed as follows:

$$z = \sqrt{\frac{1}{2}e^2 n} = \sqrt{\frac{1}{2} \cdot 0.5^2 \cdot 27} \approx 1.84 \tag{4}$$

With a z-score of approximately 1.84, a confidence level of 90% is maintained.

The pre-game questionnaire revealed that two participants held a neutral stance on engaging with complex scientific topics, while the remaining 25 displayed openness to them.

In terms of awareness of quantum concepts, 24 participants were familiar with both quantum mechanics and computing. One participant had no prior knowledge of both quantum mechanics and computing, another had heard about quantum computing but not quantum mechanics, and a third was familiar with quantum mechanics but not quantum computing. Among the 25 participants familiar with quantum computing, 19 considered their knowledge minimal to none, four claimed to be knowledgeable, and two described themselves as very knowledgeable.

Interestingly, only 15 participants were aware of the practical applications of quantum computing. Regarding the four impact domains, 10 participants mentioned the applications of quantum computing in cryptography, six answers highlighted its role in optimisation, four in machine learning, and four in the simulations domain. Outside of the four impact domains, responses about the applications included the power of quantum computers, their complexity, the difficulty in development, and the awareness of existing quantum computers.

Notably, 18 participants expressed a positive outlook on quantum computing. In contrast, the remaining nine participants had a neutral viewpoint on quantum computing, with seven attributing this to a lack of knowledge to form an opinion. The remaining two participants explained their view by acknowledging both positive and negative aspects of the development of quantum computing.

6.2 Quantitative results

6.2.1 Independent t-test

The quantitative findings of the experiment are the result of participant responses to the statements presented in Table 2. The table displays the mean and standard deviation values for each version. Additionally, their means are subtracted to show the differences between them.

When testing various user groups, differences exist between the results. A t-test is conducted to examine whether a significant difference exists between the means of the two user groups. Given that each version of the game is tested with a distinct group, the independent t-test can be performed to examine a null hypothesis, typically defined as showing no difference between the groups. The null hypothesis of this study is defined as:

H_0: There is no difference in the level of persuasion between the two versions.

The result of the t-test is the test statistic, providing an estimate of the true difference between the two versions. The formula to calculate this t-score is [116]:

$$t = \frac{\hat{x}_1 - \hat{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{5}$$

where $\hat{x}$ represents the means per statement for versions 1 and 2, s is their standard deviation, and n is their sample size.

From the t-scores, the p-value can be calculated, determining how compatible the data is with the assumed null hypothesis. A lower p-value suggests that the observed results are less likely to occur under the null hypothesis, potentially leading to a rejection of the null hypothesis. Two types of tests exist: one-tailed, which examines the results in one specific direction; and two-tailed, which assesses whether there is a difference between the two versions without direction. The one-tailed p-value is chosen to determine if there is an increase in version 2 parameters.

Cohen's calculation is employed to calculate effect size d per statement by subtracting the two means and dividing them by a standard deviation [118]:

$$d = \frac{\hat{x}_1 - \hat{x}_2}{\sqrt{\frac{(n_1-1)s_1^2+(n2-1)s_2^2}{n_1+n_2-2}}} \tag{6}$$

where $\hat{x}$ represents the means per statement for versions 1 and 2, s is their standard deviation, and n is their sample size.

Table 3 shows minor mean differences between versions, lacking statistical significance. S3, S5, and S10 show a slight decrease in mean scores for version 2, while the other statements display slight increases. Interestingly, statement one is statistically significant for confidence level of 90% (p = 0.078), with a medium effect size according to Cohen's criteria (d = -0.562). Furthermore, S3, S4, S8, and S11 have small effect sizes, and the remaining statements show very small effect sizes.

Construct analysis reveals no statistical significance in differences between version 1 and 2 answers (see Table 4). Generally, the constructs score higher in version 2, except for CRED. Cohen's d indicates small effect sizes for TASK, EFFO, and VISU, while CRED and PERS have very small effect sizes.

Combining the scores for the original constructs in the PPQ (TASK, CRED, PERS, EFFO) yields a mean score of 5.06 for version 1 versus 5.17 for version 2. Including VISU, the scores become 5.08 and 5.22, respectively, with no significant differences found in both calculations (t = -0.552, p = 0.293; and t = -0.608, p = 0.274). Both effect sizes are small (d = -0.213, and d = -0.234).

The results for the last question ("After playing the game, are you more motivated to explore or learn more about quantum mechanics/computing?") show 11 of 14 version 1 participants and 9 of 13 version 2 participants answering yes. Transforming yes to 1 and no to -1, the mean of version 1 is 0.5714 (SD = 0.85163) and version 2 0.3836 (SD = 0.96077), with a difference of 0.18681. The t-score is 0.536, p-value is 0.299, and d = -0.206, indicating a small effect size.

	Version 1		**Version 2**					
	Mean	**SD**	**Mean**	**SD**	**Difference**	***t*-score**	***p*-value**	**Cohen's *d***
S1	5.36	0.929	5.85	0.801	-0.489	-1.460	0.078	-0.562
S2	5.50	0.941	5.54	0.877	-0.038	-0.110	0.457	-0.042
S3	5.43	1.222	5.08	1.115	0.352	0.779	0.222	0.300
S4	5.36	1.008	5.69	0.751	-0.335	-0.973	0.170	-0.375
S5	4.64	0.842	4.54	1.266	0.104	0.254	0.401	0.098
S6	4.07	1.269	4.23	1.536	-0.159	-0.295	0.385	-0.114
S7	3.64	1.550	3.69	1.750	-0.049	-0.078	0.469	-0.030
S8	5.14	1.703	5.77	0.599	-0.626	-1.293	0.107	-0.483
S9	5.79	0.893	6.00	1.414	-0.214	-0.475	0.320	-0.183
S10	5.43	1.505	5.31	1.377	0.121	0.217	0.415	0.084
S11	5.57	0.646	5.77	0.927	-0.198	-0.647	0.262	-0.249

Table 3: Group statistics and independent t-test for each statement presented on a 7-point Likert scale in the post-questionnaire.

	Version 1		**Version 2**					
	Mean	**SD**	**Mean**	**SD**	**Difference**	***t*-score**	***p*-value**	**Cohen's *d***
TASK	5.43	0.756	5.69	0.596	-0.264	-1.001	0.163	-0.386
CRED	5.39	1.022	5.38	0.870	0.008	0.022	0.491	0.009
PERS	4.12	0.893	4.15	1.152	-0.035	-0.088	0.465	-0.034
EFFO	5.45	1.217	5.69	0.907	-0.240	-0.577	0.285	-0.222
VISU	5.57	0.646	5.77	0.927	-0.198	-0.647	0.262	-0.249

Table 4: Group statistics and independent t-test for each construct.

6.2.2 Pearson correlations

Pearson correlation calculations were employed to identify significant correlations among responses to all questions in the pre- and post-questionnaires. A two-tailed p-value was used to assess differences between compared pairs, considering both positive and negative correlations. Only the results with a confidence level of 95% are displayed. The Pearson correlation coefficient r follows thresholds: weak = 0.1, moderate = 0.3, strong = 0.5 [118].

Eight distinct significant correlations can be observed between the participants' agreement scores on the statements (see Table 5). Additionally, there are two significant correlations between constructs (see Table 6). There are also four correlations regarding answers to the post-questionnaire question "Were you aware of any practical applications of quantum computing in real-world scenarios before this study?" (see Table 7). Finally, there are six with the pre-questionnaire question "After playing the game, are you more motivated to explore or learn more about quantum mechanics/computing?" (see Table 8).

Table 5 and 6 show positive correlations, meaning that participants who agree with one statement also agree with the correlated statements. Strong correlations are observed between S1 and S7, S3 and S4, S5 and S6, S8 and S10, and S9 and S10. On the other hand, S1 and S4, S4 and S5, and S5 and S10 exhibit moderate correlations.

Construct correlations in Table 6 also demonstrate positive associations. TASK and CRED exhibit a moderate correlation, while TASK and PERS display a strong positive

	Correlation with	**Pearson's r**	**p-value**
S1	S4	0.470	0.013
	S7	0.544	0.003
S2	-	-	-
S3	S4	0.643	< 0.001
S4	S1	0.470	0.013
	S3	0.643	< 0.001
	S5	0.399	0.039
S5	S4	0.399	0.039
	S6	0.656	< 0.001
	S10	0.416	0.031
S6	S5	0.656	< 0.001
S7	S1	0.544	0.003
S8	S10	0.612	< 0.001
S9	S10	0.543	0.003
S10	S5	0.416	0.031
	S8	0.612	< 0.001
	S9	0.543	0.003
S11	-	-	-

Table 5: Significant correlations among participants' agreement scores on statements.

	Correlation with	Pearson's r	p-value
TASK	CRED	0.462	0.015
	PERS	0.604	< 0.001

Table 6: Significant correlations among participants' agreement scores on constructs.

	Correlation with	Pearson's r	p-value
Were you aware of any practical applications of quantum computing in real-world scenarios before this study?	S1	-0.504	0.007
	S3	-0.385	0.048
	S4	-0.406	0.035
	CRED	-0.434	0.024

Table 7: Significant correlations in participants' awareness of quantum computing applications before the study. It is a yes/no question, coded as 1 for "yes"-responses and -1 for "no"-responses.

	Correlation with	Pearson's r	p-value
After playing the game, are you more motivated to explore or learn more about quantum mechanics/computing?	S2	0.543	0.003
	S4	0.446	0.020
	S5	0.506	0.007
	S6	0.502	0.008
	TASK	0.490	0.010
	PERS	0.538	0.004

Table 8: Significant correlations in participants' motivation to learn about quantum mechanics/computing after playing the game. It is a yes/no question, coded as 1 for "yes"-responses and -1 for "no"-responses.

correlation.

On the other hand, correlations with the yes/no question in Table 7 are negative. For these types of questions, a "yes"-answer is represented by 1, and a "no"-answer by -1. The table indicates that participants answering "no" rated correlated statements higher, while those answering "yes" rated the statements lower. The correlation between the question and S1 is strong, while the others are moderate.

Table 8 indicates positive correlations. Participants answering "yes" tend to agree more with the statements. There is a moderate correlation between S4 and TASK and strong correlations for the others.

6.3 Qualitative results

In addition to the quantitative results, qualitative results were gathered as follow-up questions after presenting the quantitative statements S7 and S11.

S7 received relatively low Likert scores for both versions, suggesting a limited impact of the games on altering participants' opinions about quantum computing. Respondents who disagreed often stated that the game did not influence their opinion as they already possessed the knowledge presented in the game. Some participants disagreed with S7 because the game did not change their opinion but reinforced it. One participant remarked "It has shown me a lot of additional areas where quantum computing might be relevant, but it hasn't changed my opinion". Another disagreed because "The game only showed positive sides of quantum computing", and another remarked "While I think we hear a lot about the positive side of quantum computing, this game made me more aware of the negatives sides". On the contrary, some participants who agreed found the topic easy to understand and more interesting than initially thought.

Regarding statement S11, most participants generally agreed, with only two being neutral. Respondents who agreed often highlighted that the visual elements in the game enhanced the persuasive message. Several participants appreciated the clarity and simplicity of the visuals, emphasising their role in making complex concepts more understandable and intuitive. Some participants were positive regarding the colour palette and found the visual representation interesting, enjoyable, and encouraging. Interestingly, diverse opinions emerged about the thematic relevance of visuals to quantum computing. Two version 1 participants described the visuals as "techy/quantumy" and having a "quantum feeling". In contrast, another version 1 participant commented: "The game looks good, but the design of the visual elements is not very related to quantum computing".

Participants who played version 2 appreciated the inclusion of problems on a larger scale. Others mentioned that the visual and interactive elements provided perspective on the speed and efficiency of quantum computing. For one neutral respondent, visuals were unimportant due to a general curiosity about scientific topics.

Overall, participants in both groups perceived the visuals as contributing positively to their understanding of the complex topic of quantum computing.

7 Discussion

7.1 Principal findings

The goal of the study in this paper is to compare the influence of two versions of a game about the impact of quantum computing on participants' levels of persuasion. The quantitative results, presented in Tables 3 and 4, offer insights into mean differences, statistical significance, and effect sizes between the versions.

Higher mean scores on the Likert scale indicate higher participant agreement with statements about the game's persuasive impact. In general, both versions received positive feedback, with participants expressing agreement levels ranging from slightly agree (5) to agree (6) for eight out of eleven statements. The scores on these eight statements indicate that the game achieves its goal, is reliable, trustworthy, requires low effort, and has visuals that strengthen its message. Notably, the three perceived persuasiveness statements gained lower scores. On average, participants gave scores between neither agree/disagree (4) and slightly agree (5) regarding the game's influence on them or its relevance. Additionally, participants did not change their opinions about quantum computing after playing the game, as this statement scored between slightly disagree (3) and neither agree/disagree (4).

Minor mean differences exist between version 1 and version 2. Slight decreases are displayed in scores for trustworthiness, influence on the player, and laboriousness in version 2. The remaining statements show slight increases in the agreement for version 2. The statement about the game aiding in understanding the impact of quantum computing (S1) is significant at the 0.10 level with a medium effect size, suggesting a potential impact of version 2 on this statement. The remaining differences are not statistically significant and exhibit small effect sizes, indicating a potentially insufficient sample size. Overall, the differences between versions appear to have a limited impact on participant responses.

The averaged constructs show a mean perceived persuasion between neither agree/disagree and slightly agree, while other constructs fall between slightly agree and agree. Analysing the constructs reveals no significant differences between versions. Despite generally higher scores in version 2, the only lower-scoring construct is the game's perceived credibility, with an insignificant difference. Combined construct scores per version exhibit no significant differences, indicating consistent response patterns across versions. However, the small effect sizes suggest the need for a larger sample size to enhance the credibility of the findings.

The qualitative results provide a deeper understanding of participants' perspectives. The low Likert scores on both versions for statement S7 indicate a limited impact on altering views about quantum computing. Participants noted that the game did not change their opinions, attributing it to their pre-existing knowledge. They remarked that the game either had no influence on their views or reinforced their existing opinions.

Overall, the participants agreed that the visuals in the game strengthen the persuasive message, emphasising that the clarity and simplicity of the visuals make the complex concepts more understandable. However, participants displayed varied opinions about the visual elements, with some strongly associating them with quantum computing and others finding them less relevant.

The quantitative and qualitative results indicate that variations between between the versions did not result in significant changes in the overall perceptions of the participants. From these results it can be concluded that the null-hypothesis H_0 cannot be rejected.

Pearson correlation calculations revealed significant findings at the 0.05 level between participants' answers on the statements (Table 5), constructs (Table 6), previous awareness and statements (Table 7), and motivation to learn more and statements (Table 8).

Strong correlations were observed among agreement scores between multiple statements. The correlations suggest that those who believed the game helped them understand quantum computing found the game showing expertise and were more likely to reconsider their opinions. Furthermore, participants who found the game showing expertise were more likely to perceive it as trustworthy and more influenced by the game. Additionally, participants who felt influenced by the game were also more likely to perceive it as personally relevant and not laborious. Participants who found the game not laborious also perceived playing as straightforward and requiring less effort.

Construct correlations indicated that participants finding the technology helpful were more likely to perceive it as credible and persuasive.

Participants lacking prior knowledge about quantum applications exhibited a strong positive correlation with the perceived game's ability to enhance understanding. Additionally, moderate correlations were found with perceived trustworthiness and expertise, suggesting that these aspects are more influential for those with limited awareness.

Table 8 reveals positive correlations between the motivation to explore quantum mechanics/computing and the game's perceived influence on various statements. These include encouragement to learn, perceived expertise, perceived influence, and personal relevance. Furthermore, correlations were observed with the perceived successful goal achievement and persuasiveness.

7.2 Research questions

Based on the results, the research question can be addressed. The combined responses from participants who played version 1 resulted in an average rating ranging between slightly agree and agree (5.08). In comparison, participants who experienced version 2 also provided an average rating falling within the slightly agree to agree range, leaning slightly closer to agree (5.22). These findings imply a potential improvement in players' levels of persuasion when a game incorporates visual persuasion design. However, the p-value indicates that differences between the two versions did not result in significant shifts in overall participant perceptions (p=0.274).

Further analysis of the participant responses for each statement reveals a noteworthy increase in agreement for version 2 in only one statement, specifically regarding the game aiding in understanding the impact of quantum computing (S1). Despite this significant change, the responses to the remaining statements did not exhibit statistically significant differences between the two versions.

These results suggest that the answer to the research question remains inconclusive.

7.3 Limitations & Future work

Several limitations emerged during the discussion of the results. Firstly, the study faced a constraint in the form of a small sample size of 27 participants. Cohen's d analysis indicates that a lower d value requires larger sample sizes. Only for S1 did the sample size reach the medium threshold, suggesting that a sample size of 27 is insufficient for the other statements and the final question. Future research could benefit from having a larger and more diverse participant pool to enhance the validity of the findings.

Another potential limitation revolves around the visual design choices made in version 2. Selecting the elements of visual persuasion is subjective, which gives the possibility that different design choices could result in a bigger perceived persuasion difference between the two versions. Consulting with a visual design expert during the creation of such games could be beneficial. It could also be valuable to develop more versions of the game, each featuring different visual elements, and compare the perceived persuasiveness against each other. This approach would help identify the most effective strategies for visual persuasion by exploring the impact of different visual designs.

Furthermore, the study relies on self-reported measures, which might introduce social desirability bias. Future research could consider expanding the PPQ to include a more objective questionnaire or observational elements.

Lastly, a suggested modification for future research involves ensuring that participants have limited knowledge about quantum computing before engaging with the game. This adjustment comes from the observation that some participants in the current study possessed significant prior knowledge, potentially influencing their responses. Focusing on participants with little to no knowledge, or even those with a negative view of quantum computers, may better align with the game's emphasis on highlighting positive aspects.

8 Conclusion

This research aimed to evaluate the effectiveness of visual persuasion in a digital game, aligning with the conceptual persuasion model proposed by De la Hera [13].

Two versions of a game about the potential influence of quantum computers were created, with one version having additional visual persuasion elements. The game contains four levels, each showing a distinct potential impact domain of quantum computing: cryptography, optimisation, machine learning, and simulations.

A user study compared the persuasive impact on two groups of participants engaging with either version. The results are gathered using a questionnaire containing statements on a 7-point Likert scale to capture the perceived persuasion in the game.

Upon analysing the results, I found no significant difference in perceived persuasion between the two game versions. While incorporating visual persuasion design positively contributes to participants' perceptions, the effect lacks the magnitude required for a significant enhancement in persuasion levels. Consequently, no definitive conclusion can be drawn regarding the applicability of visual persuasion within De la Hera's model. Therefore, until further research, I recommend retaining visual persuasion as one of the dimensions in the model to create a successful persuasive game.

The study encountered limitations, including small sample size, subjective visual design choices, reliance on self-reported measures, and potential bias from participants with prior knowledge. Future research could address these limitations.

In summary, this research contributes to the understanding of the role of visual persuasion in digital games focused on complex scientific topics. While the results suggest positive perceptions of both game versions, further exploration with larger sample size, objective measures, and refined visual design choices would enhance the reliability and applicability of the findings.

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Appendix

A Perceived Persuasiveness Questionnaire

The original PPQ as presented in Multimedia Appendix 3 of the evaluation study by Beerlage et al. [94]

Construct	**Original item**
Primary task support (TASK)	1. XYZ[1] provides me with means to [action][2]. 2. XYZ helps me [action]. 3. XYZ helps me change [action].
Dialogue support (DIAL)	1. XYZ provides me with appropriate feedback. 2. XYZ provides me with appropriate counselling. 3. XYZ encourages me.
Perceived credibility (CRED)	1. XYZ is trustworthy. 2. XYZ is reliable. 3. XYZ shows expertise. 4. XYZ instills confidence. 5. XYZ is clearly made by professionals.
Social support (SOCI)	1. I get support from my peers through XYZ when I need it. 2. Through XYZ, I can share my experiences with my peers. 3. Learning from my peers' actions is beneficial for me.
Perceived persuasiveness (PERS)	1. XYZ has an influence on me. 2. XYZ is personally relevant for me. 3. XYZ makes me reconsider [action].
Unobtrusiveness (UNOB)	1. Using XYZ fits into my daily life. 2. Using XYZ disrupts my daily routines. 3. Using XYZ is practical / convenient for me. 4. Finding the time to use XYZ is not a problem for me.
Perceived effort (EFFO)	1. Using XYZ does not require a lot of effort from me. 2. Using XYZ is straightforward for me. 3. Using XYZ is laborious. (Reversed item)
Perceived effectiveness (EFFE)	1. My chances of [action] improve by using XYZ. 2. In my opinion, using XYZ has an effect on [action]. 3. In my opinion, XYZ has no effect on [action].
Use continuance (CONT)	1. I am going to continue using XYZ. 2. I will be using XYZ in the future. 3. I am considering discontinuing using XYZ. 4. I am not going to use XYZ from now on.

[1] The name of the system should go here
[2] The intent should go here

B User study documents

B.1 Consent form

RESEARCH INFORMATION SHEET

Evaluating the impact of visual persuasion in a persuasive game about quantum computing

by Sanna Heesakkers

UTRECHT UNIVERSITY

Version date January 10, 2024

What is the purpose of this study?
This study is part of my master's thesis project within the Game & Media Technology curriculum at Utrecht University. In this research, I developed a game centred around quantum computing, which is based on the principles of quantum mechanics. Quantum mechanics, a branch of physics, explores the behaviours of very small particles at the micro level. These particles show characteristic that are absent in larger objects. These particles can be used for the creation of a new type of computer: a quantum computer. A quantum computer uses quantum principles which, if they are stable and large enough, gives them the ability to perform very complex calculations with a higher precision and speed than a classical computer. Currently, quantum computers exist, but they lack the computational power required for performing complex tasks. However, as quantum computers advance, they will impact four domains: cryptography, optimisation, machine learning, and simulations of complex systems. The game I developed for this study contains four levels that illustrate how these domains will change in the future. Through engaging gameplay, the intention is to persuade players of the significant influence quantum computers will have in the future.

What will I do if I choose to participate in this study?
First, you will be asked to complete a questionnaire covering background information such as age, gender, and your highest level of education. It also delves into your knowledge about quantum mechanics/computing, along with your opinions on the subject. Next, I will ask you to play the game. After you have finished the game, I will once again ask you to fill in a questionnaire. This questionnaire focuses on the persuasive elements of the game and whether your perspective on quantum computing has changed.

How long will I be in the study?
The pre-game questionnaire will take around 5 minutes. The game itself will take around 20 minutes. The post-game questionnaire will take around 5 minutes. In total, you will spend approximately 30 minutes participating in the experiment.

Will information about me and my participation be kept confidential?
No personally identifiable information will be requested from you. Your replies will be treated with the utmost confidentiality and securely stored using the OneDrive version protected by Utrecht University's cloud service.

What are my rights if I take part in this study?
Participation in this study is entirely voluntary, and there is no compensation offered for your involvement. You have the option to decline participation. If you choose to take part, you retain the right to withdraw at any time without facing any penalties. In the event of your decision to withdraw after the experiment, the data collected from your experiment will immediately be deleted. Already aggregated data, such as averages, and encompasses your responses, will not undergo any modifications.

By digitally signing this form, you confirm your understanding of the nature of participation and consent to the use of your questionnaire responses for research purposes, unless you explicitly request termination.

B.2 Pre-game questionnaire

BACKGROUND INFORMATION

1. **What is your age? _______________**
2. **What is your gender?**
   - ☐ Male
   - ☐ Female
   - ☐ Non-binary / third gender
   - ☐ Other (please specify): _______________
3. **What is the highest education level you have achieved?**
   - ☐ No formal education
   - ☐ Practical education
   - ☐ High school (VMBO, HAVO, VWO)
   - ☐ MBO (Secondary Vocational Education)
   - ☐ HBO (Higher Professional Education)
   - ☐ WO Bachelor (University Bachelor's Degree)
   - ☐ WO Master (University Master's Degree)
   - ☐ PhD (Doctorate)
   - ☐ Other (please specify): _______________
4. **How open are you to learning about complex scientific topics?**
   - ☐ Very open
   - ☐ Somewhat open
   - ☐ Neutral
   - ☐ Somewhat resistant
   - ☐ Very resistant

QUANTUM KNOWLEDGE AND OPINION

5. **Have you heard about quantum mechanics before this study?**
   ☐ Yes ☐ No

6. **If yes, on what level would you describe your knowledge of the topic?**

   ☐ Expert

   ☐ Very knowledgeable

   ☐ Knowledgeable

   ☐ Slightly knowledgeable

   ☐ Almost no knowledge

7. **Have you heard about quantum computing / computers before this study?**
   ☐ Yes ☐ No

8. **If yes, on what level would you describe your knowledge of the topic?**

   ☐ Expert

   ☐ Very knowledgeable

   ☐ Knowledgeable

   ☐ Slightly knowledgeable

   ☐ Almost no knowledge

9. **Were you aware of any practical applications of quantum computing in real-world scenarios before this study?**
   ☐ Yes ☐ No

10. **If yes, please specify the areas you were aware of:** _______________

11. **What is your view on quantum computers?**

    ☐ Entirely positive

    ☐ Mostly positive

    ☐ Neutral / no opinion

    ☐ Mostly negative

    ☐ Entirely negative

12. **Please elaborate:** _______________

B.3 Post-game questionnaire

PERSUASION OF THE GAME

Please provide your feedback by responding to the following statements. Indicate your level of agreement or disagreement with each statement, ranging from *Strongly disagree* to *Strongly agree*.

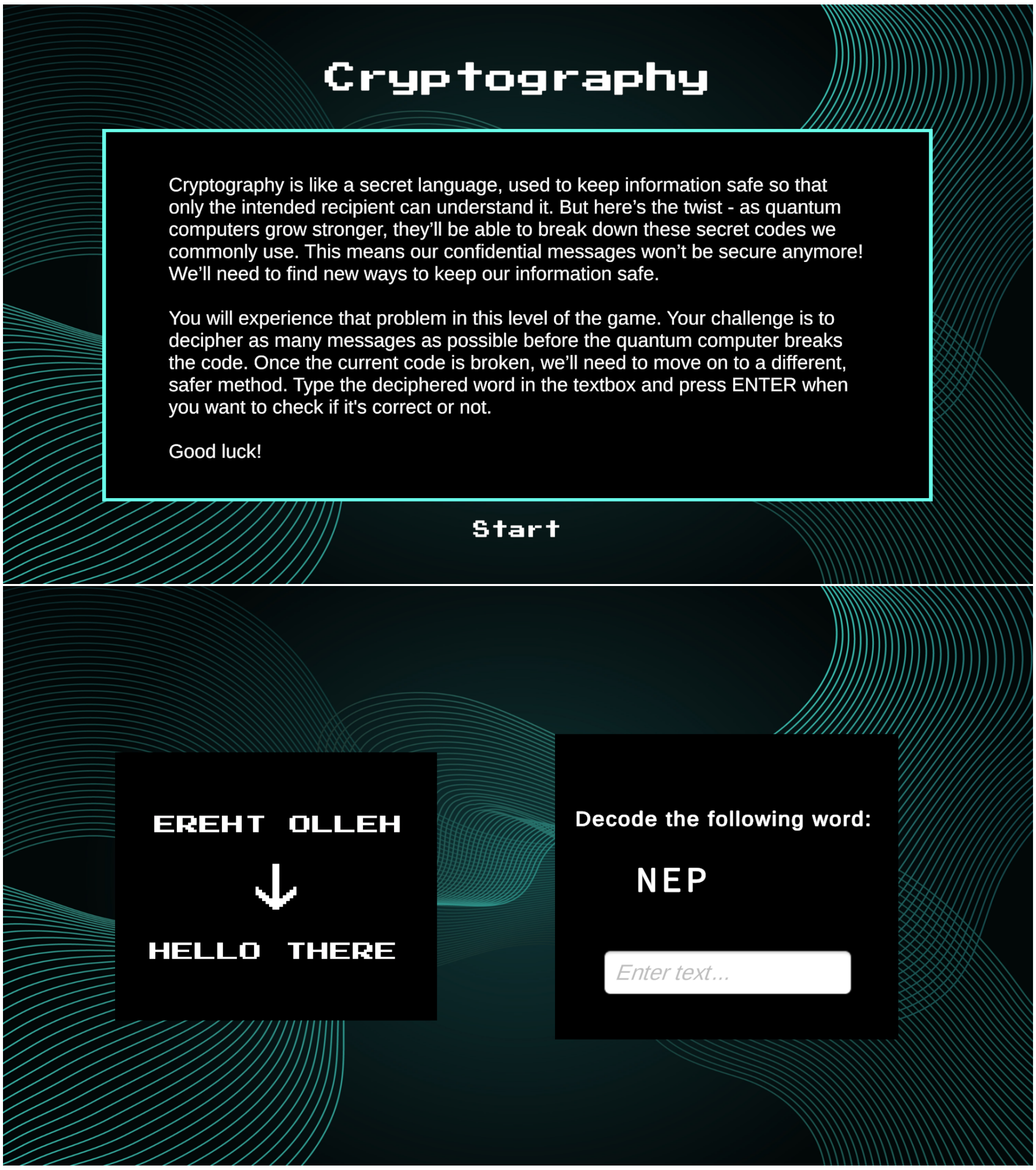
1. **The game helps me understand the impact of quantum computing.**
   Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree
2. **The game encourages me to learn about the impact of quantum computing.**
   Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree
3. **The information given in the game is trustworthy.**
   Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree
4. **The game shows expertise.**
   Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree
5. **The game has an influence on me.**
   Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree
6. **The game is personally relevant for me.**
   Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree
7. **The game makes me reconsider my opinion about quantum computing.**
   Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree

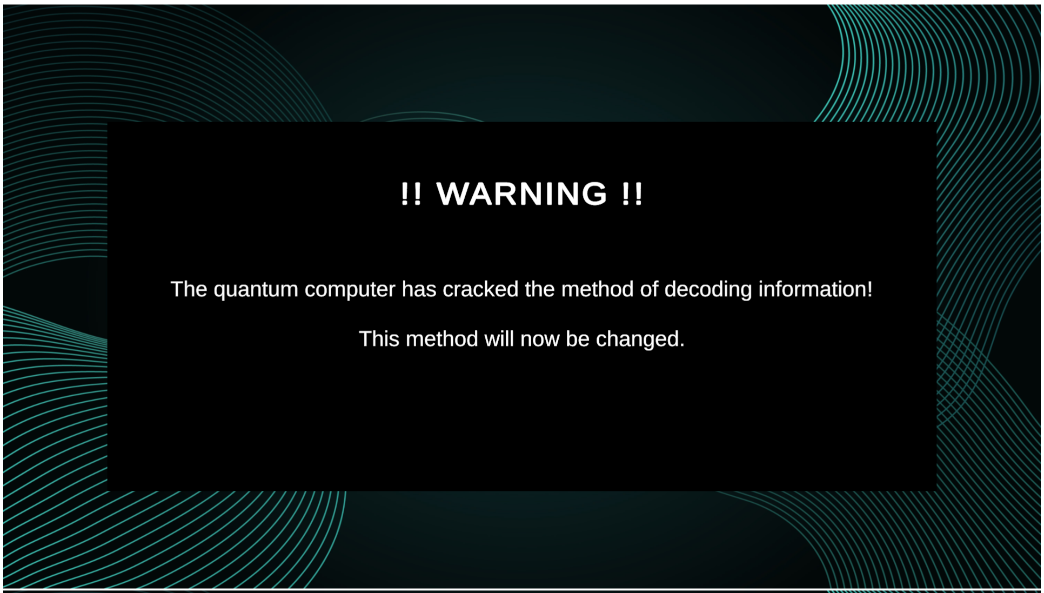
   Please elaborate: _______________
8. **Playing the game does not require a lot of effort from me.**
   Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree
9. **Playing the game is straightforward for me.**
   Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree
10. **Playing the game is not laborious.**
    Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree
11. **The visual elements in the game strengthen the persuasive message.**
    Strongly disagree ◯ ◯ ◯ ◯ ◯ ◯ ◯ Strongly agree

    Please elaborate: _______________
12. **After playing the game, are you more motivated to explore or learn more about quantum mechanics / computing?**
    ☐ Yes ☐ No

C Game design

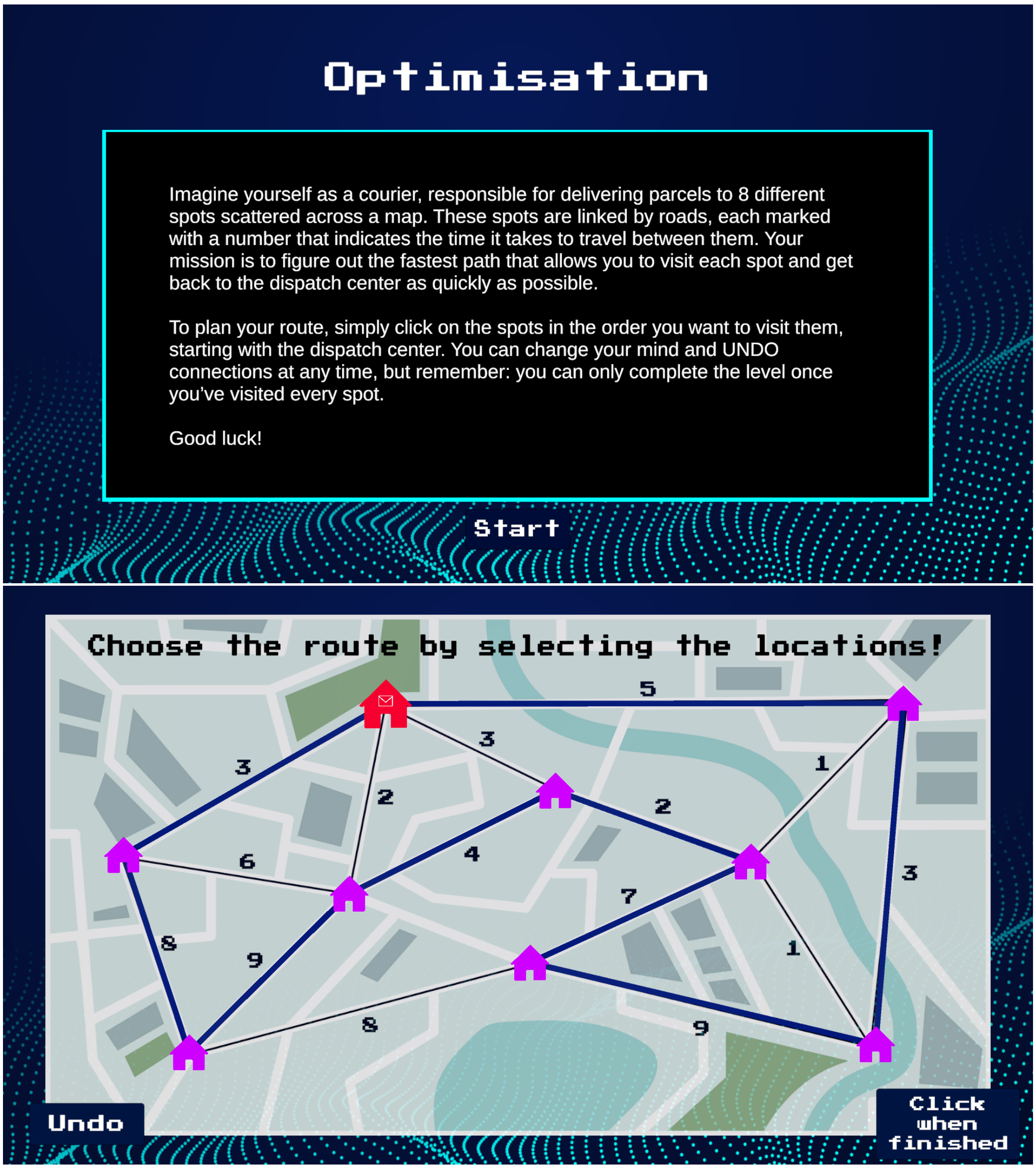
C.1 Cryptography

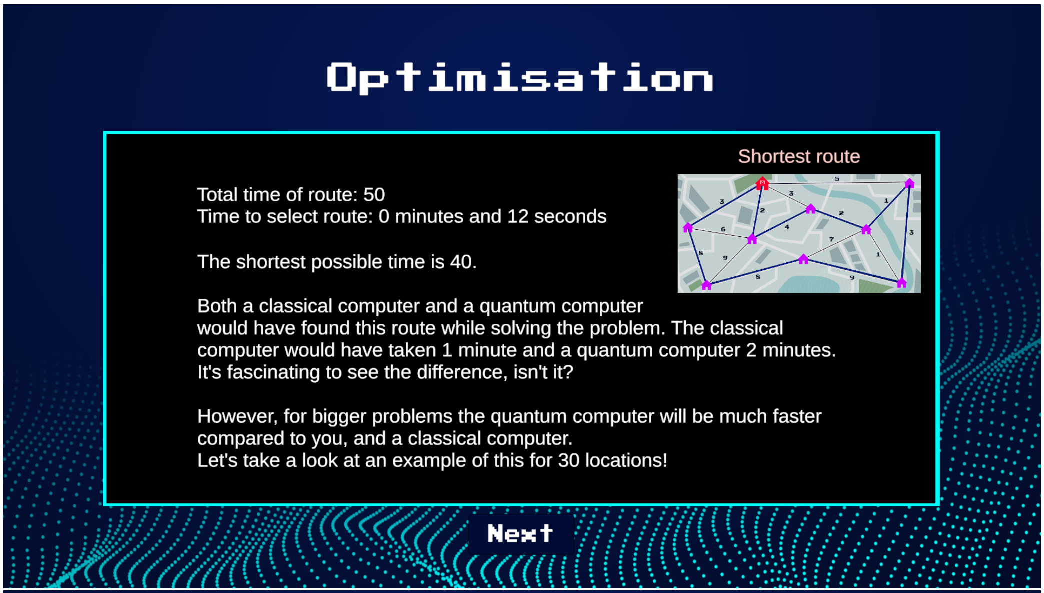


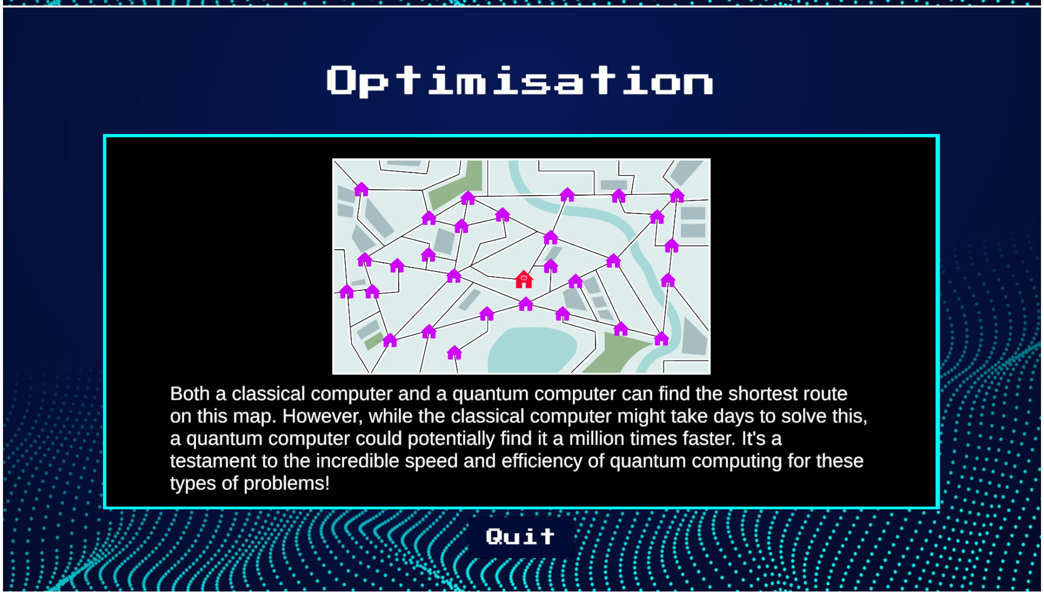

!! WARNING !!
The quantum computer has cracked the method of decoding information!
This method will now be changed.


You have decoded 15 messages!
Congratulations! You set a new highscore!
Ranking
1. 15
2. 15
3. 10
4. 7
5. 6
Quit

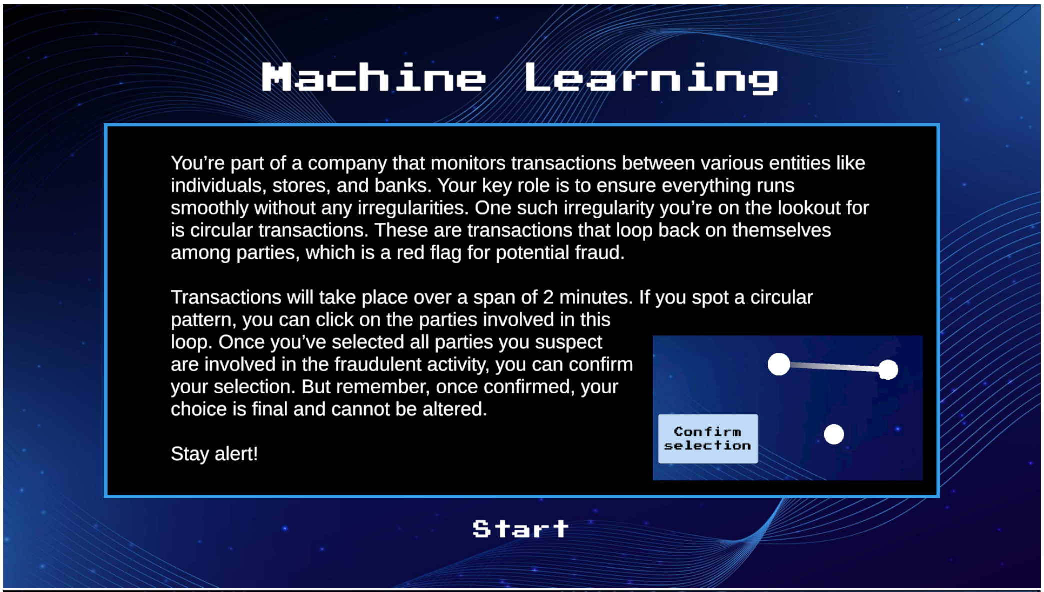
C.2 Optimisation

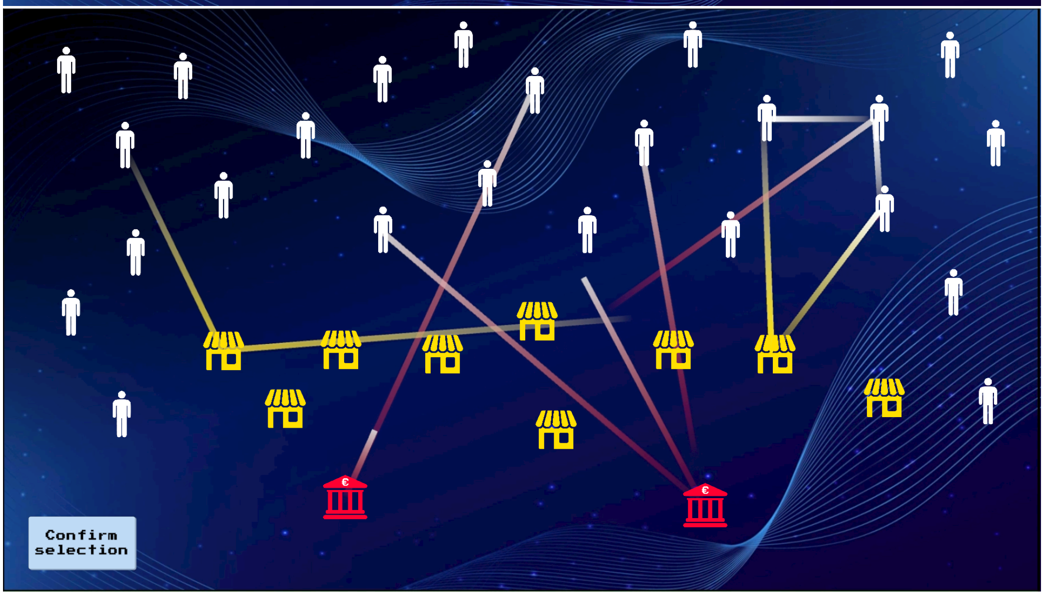


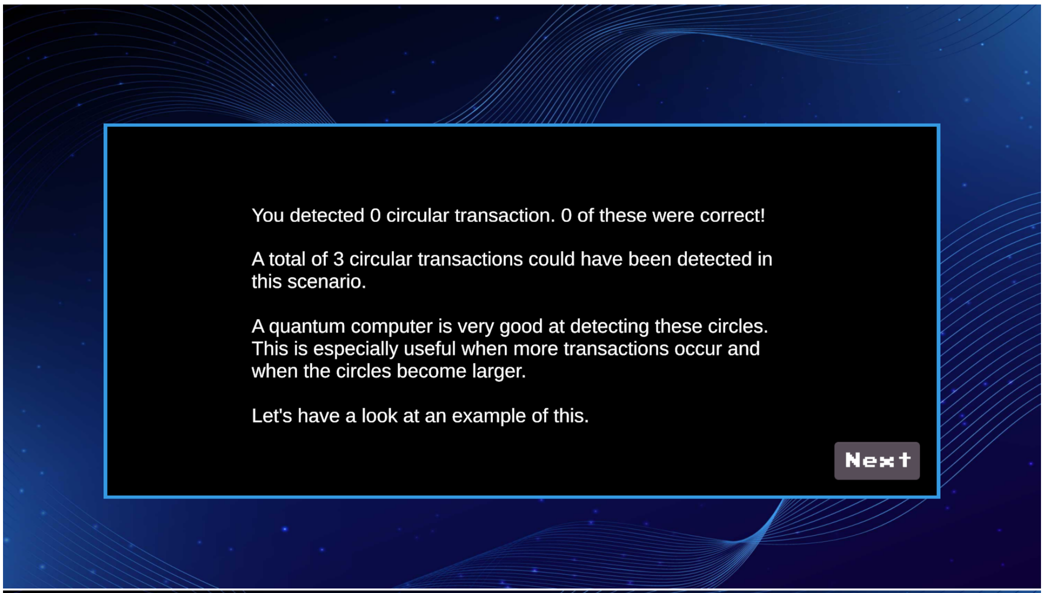

Optimisation
Shortest route
Total time of route: 50
Time to select route: 0 minutes and 12 seconds
The shortest possible time is 40.
Both a classical computer and a quantum computer would have found this route while solving the problem. The classical computer would have taken 1 minute and a quantum computer 2 minutes. It's fascinating to see the difference, isn't it?
However, for bigger problems the quantum computer will be much faster compared to you, and a classical computer.
Let's take a look at an example of this for 30 locations!
Next

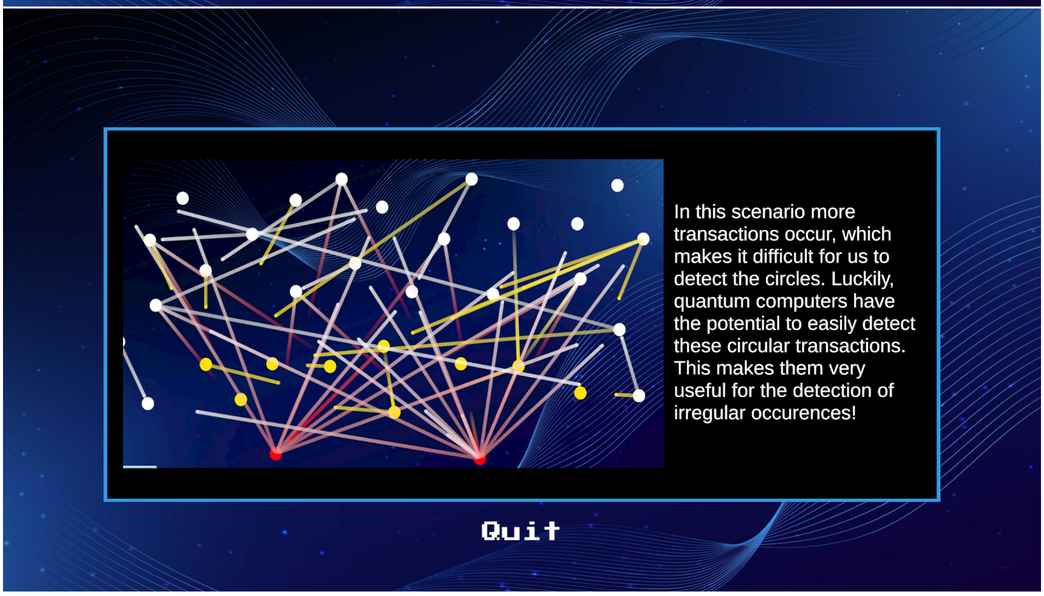

Optimisation
Both a classical computer and a quantum computer can find the shortest route on this map. However, while the classical computer might take days to solve this, a quantum computer could potentially find it a million times faster. It's a testament to the incredible speed and efficiency of quantum computing for these types of problems!
Quit

C.3 Machine Learning

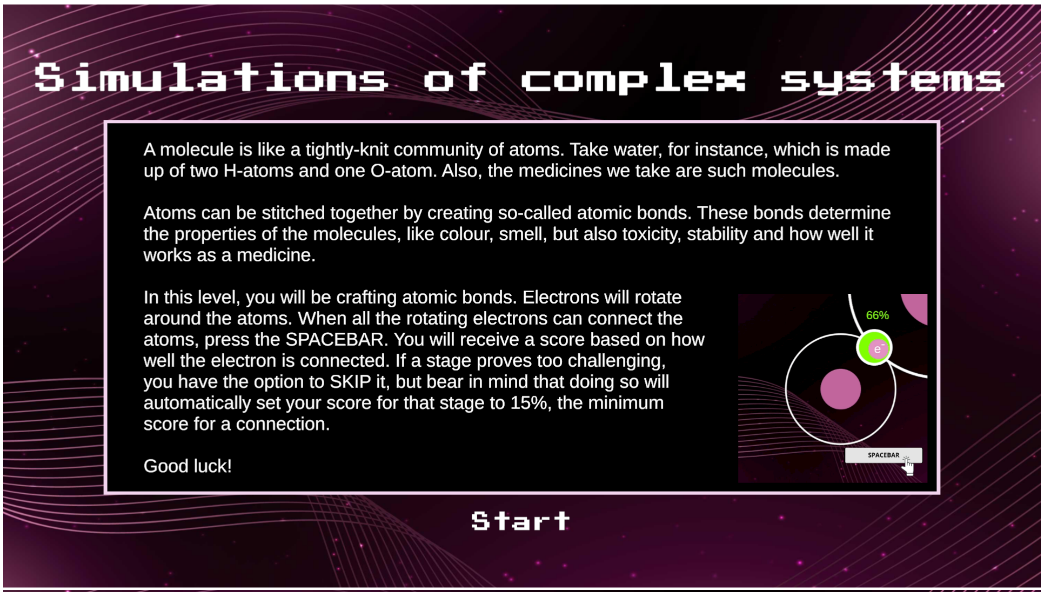


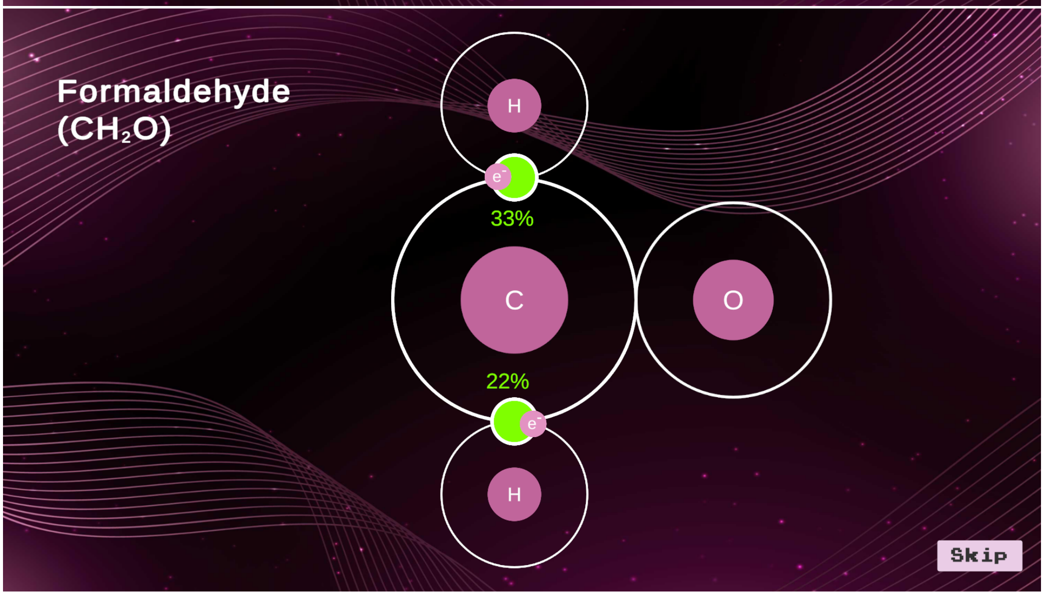


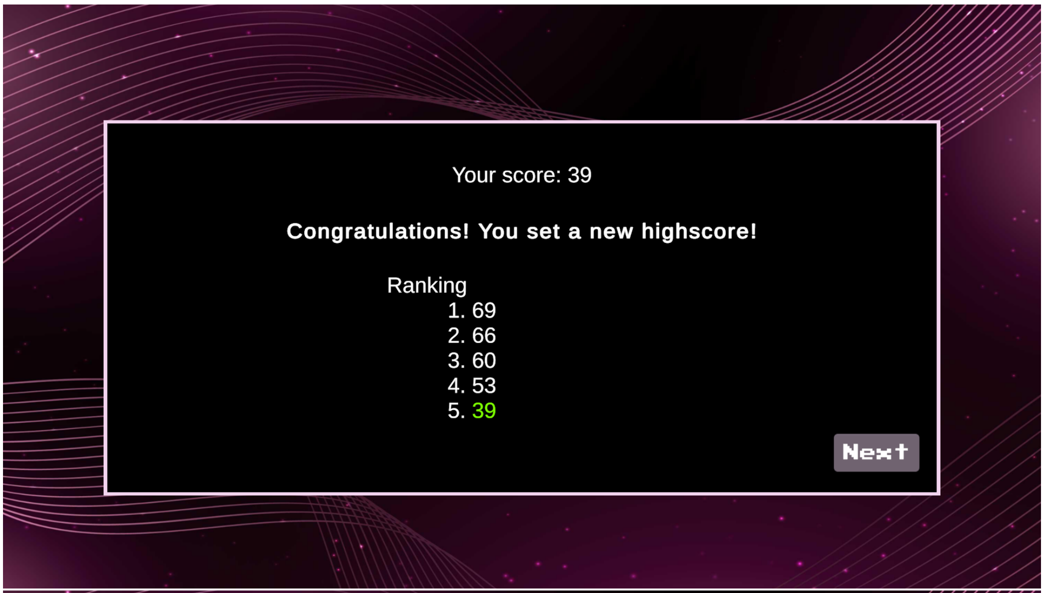

You detected 0 circular transaction. 0 of these were correct!
A total of 3 circular transactions could have been detected in this scenario.
A quantum computer is very good at detecting these circles. This is especially useful when more transactions occur and when the circles become larger.
Let's have a look at an example of this.
Next

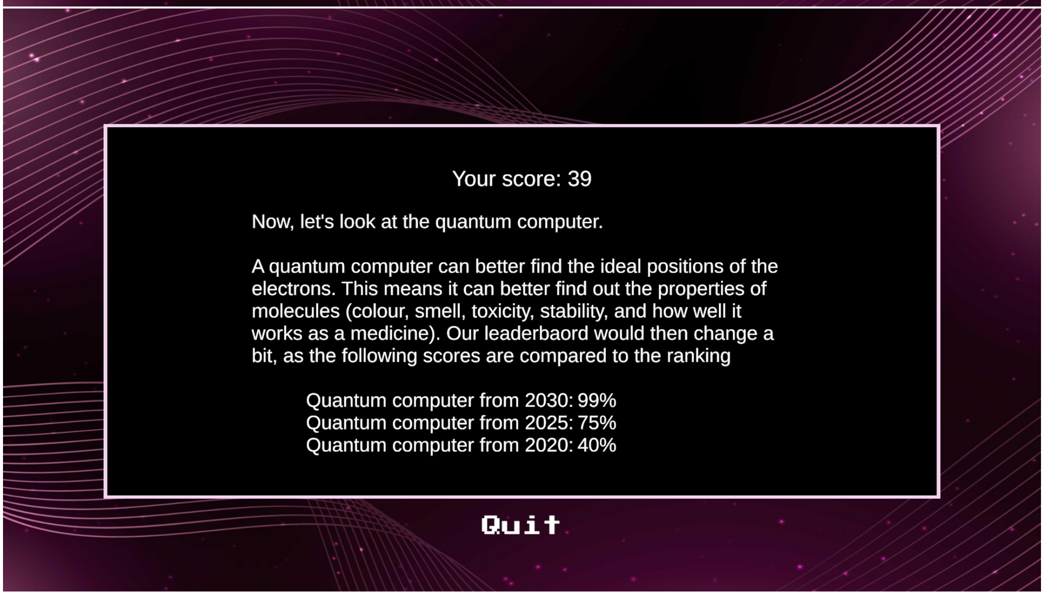

In this scenario more transactions occur, which makes it difficult for us to detect the circles. Luckily, quantum computers have the potential to easily detect these circular transactions. This makes them very useful for the detection of irregular occurences!
Quit

C.4 Simulations






Your score: 39
Congratulations! You set a new highscore!
Ranking
1. 69
2. 66
3. 60
4. 53
5. 39
Next


Your score: 39
Now, let's look at the quantum computer.
A quantum computer can better find the ideal positions of the electrons. This means it can better find out the properties of molecules (colour, smell, toxicity, stability, and how well it works as a medicine). Our leaderbaord would then change a bit, as the following scores are compared to the ranking
Quantum computer from 2030: 99%
Quantum computer from 2025: 75%
Quantum computer from 2020: 40%
Quit