Game-Based Generation of Binary Data for Use in Bell Inequality Experiments

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***Abstract*— The game industry is wide and diverse, and the same can be said about the focus of games, as not all of them have entertainment in their core design. Many focus on pragmatic matters like education or science; such games are called serious games. One specific implementation of a serious game involves generating pseudo-random binary sequences (0 or 1) by observing the behavior of human players during gameplay for quantum research. Notably, the data collection process is often embedded subtly within the gameplay mechanics, potentially without the user's explicit awareness. In our case, these human-sourced bits are intended for use in quantum experiments testing Bell inequality, where unpredictable input plays a key role in addressing the freedom-of-choice loophole. The game serves as a covert interface between intuitive human decision-making and the controlled conditions of a quantum experiment. It is specifically designed to preserve the randomness and independence required for such foundational tests. This paper presents three serious game prototypes and explores how their core mechanics enable the extraction of behaviorally grounded binary sequences suitable for Bell experimental use as well as practicality of their deployment.**

I. INTRODUCTION

Serious games are interactive digital applications designed not primarily for entertainment, but to achieve specific functional objectives such as education, training, behavior modeling, or in this case structured data collection through player behavior [1]. Piispanen et al. (2025) categorize quantum games into three distinct dimensions:

- **t**he perceivable dimension,
- **i**nvolving visual, narrative,
- **m**echanical integration of quantum physics into gameplay; the dimension of quantum technologies, which encompasses the use of actual quantum hardware or quantum-based software simulations; and the dimension of scientific purposes, where games serve educational, citizen science, or benchmarking roles.

This category is exemplified by games such as Quantum Moves 2, in which players contribute experimental data by solving tasks related to quantum state control, without being explicitly informed about the underlying data collection process [2].

Bell experiments serve as crucial tests in quantum physics, aiming to confirm the predictions of quantum mechanics and rule out local hidden variable theories. These experiments typically involve pairs of entangled particles measured at separate locations in different settings to get an estimation of the statistical correlations between the results. If the observed correlations violate a mathematical constraint known as the Bell inequality, it implies that no theory based on local realism can fully explain the results. A critical assumption in these experiments is the freedom of measurement setting choice: the selection of which measurement to perform on each particle must be statistically independent of any hidden variables that could influence the outcomes. Violating this assumption would leave open the so-called freedom-of-choice loophole, which could allow a classical explanation of quantum correlations. To close this loophole, many recent experiments have explored the use of external randomness sources, including cosmic photons and human-generated decisions, to ensure that measurement settings are selected in a manner that is causally disconnected from the entangled system [3]–[5]. One example is the use of high-redshift quasars as random sources, where photons emitted billions of years ago were used to determine measurement settings in real time [4].

An illustrative case of a large-scale application of human-generated randomness is the BIG Bell Test experiment, conducted by The BIG Bell Test Collaboration described in Nature. Approximately 100,000 participants contributed nearly 100 million binary choices via an online game. Binary choices in this context refer to decisions with two possible outcomes,such as selecting between two options, where each outcome is recorded as 0 or 1. These human-generated bits were streamed in real time to research teams on several continents, where they were used to select measurement settings in a series of thirteen synchronized quantum experiments designed to test local realism. The results of the BIG Bell Test were unequivocal: All participating laboratories observed statistically significant violations of Bell inequalities. In the most precise tests, the statistical significance reached up to 143 standard deviations, an exceptionally high value made possible by the large number of measurement trials and the strength of the observed quantum correlations. More than 90 million binary choices were collected from approximately 100,000 participants, providing the statistical power necessary to achieve such robust results. Such strong violations confirmed the impossibility of local hidden variable theories and effectively closed the freedom-of-choice loophole, demonstrating that human-generated randomness constitutes a valuable source of experimental decisions entirely causally

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disconnected from the quantum systems under measurement. In the BIG Bell test, offline bitstreams displayed small but measurable deviations - on the order of a standard deviation - from live human data and synthetic randomness. The current system is designed to replicate and investigate this effect, enabling statistical comparison of human input in real time. The approach outlined in the current prototypes is aligned with this methodology, with the aim of confirm and extend the findings of the BIG Bell test using sophisticated game mechanics to further improve the quality and diversity of human-generated randomness [3].

This article is motivated by the need to design serious games that people can play for people's entertainment while unknowingly generating binary choices that will be fed into quantum experiments. The games presented in this work are deliberately designed to contain hidden decision points, each corresponding to a binary value (bit). By introducing three game prototypes and detailing how they facilitate the generation of randomness, this article lays the groundwork for future experiments that aim to collect such data in real time and apply them to testing one of the most fundamental questions in physics. It also serves as an extension of previous human-in-the-loop Bell experiments, by embedding decision-making in richer, more interactive, and engaging gameplay environments.

II. Materials and methods

This study represents the first stage in a broader research agenda: the design and implementation of serious game prototypes capable of generating binary inputs for use in Bell quantum experiments. At this stage, the focus has been on developing games that enforce binary decision-making. In future phases of the project, the games will be deployed remotely, allowing participants to interact with them remotely. Binary decisions will be logged in real time and stored in a centralized database, enabling the collection of human-generated bitstreams. The binary sequences will be streamed in real time directly to the quantum control system. The system will register, transmit, and receive the stream of bits in real time. To maintain causal separation between the source of randomness and the quantum measurement devices, the bitstream will be continuously broadcast without prior selection or tagging of which bits will be used. This ensures that the measurement apparatus cannot predict or infer any part of the random input in advance.Only those bits that temporally coincide with a laser pulse triggering a quantum measurement will be selected and applied as measurement-setting inputs. In parallel, all generated bitstreams will be recorded in a secure database, enabling retrospective analysis and offline use during periods of low player activity. This dual-path architecture allows for comparison between live human-sourced randomness and pre-generated sequences.

In the experimental stage involving human participants, individuals will be recruited from the adult population (aged 18 and over), with equal gender representation, in accordance with ethical standards and documented informed consent. A central goal of this phase is to evaluate whether the participant's awareness of the experiment's purpose—defined as the sense of purpose has any influence on the resulting data, particularly on the observed violations of Bell inequalities. Participants will be assigned to one of four experimental conditions:

1) no knowledge—they simply play the game,
2) minimal knowledge,
3) full knowledge while still playing,
4) full knowledge but without gameplay, participants instead steer the system from a lab-based interface.

This experimental structure is motivated by the philosophical question of observer awareness in the Copenhagen interpretation of quantum mechanics. Rather than replicating the Big Bell Test, this experiment aims to test whether varying degrees of human cognitive engagement affect non-local correlations in a Bell setup. Participants will include students and academic staff from , as well as additional age-diverse volunteers to ensure a broader behavioral spectrum.

The experiment will employ a double-blind protocol, in which the control condition consists of a non-human trial conducted immediately after the human-involved session to preserve identical physical conditions. All groups (1–4) will be mutually isolated and blinded from the knowledge of other group assignments until the experiment concludes. Likewise, support staff will be assigned to individual groups without awareness of the broader structure. Upon unblinding, the collected data will be analyzed statistically to assess intergroup differences, with a focus on significance levels expressed in units of standard deviation.

A. Serious Games as Data Resource

The use of serious games in this project provides a naturalistic environment for human binary decision-making, these systems enable the extraction of human-sourced pseudo-random sequences for use in Bell experiments [1]. In the experimental context, each validated bit from the human-generated sequence is directly mapped to a measurement setting in a Bell experiment involving pairs of entangled quantum particles. Specifically, one bit determines which measurement basis is applied on one side of the experiment, while another independent bit determines the basis on the opposite side. These settings are selected at the moment of measurement, immediately before each entangled photon pair is detected, ensuring that the choice is not causally influenced by any hidden parameters in the quantum system. Each detector then registers a binary outcome (, +1 or −1) [3], [6]. These bits must be generated under strict independence from the quantum system itself, ensuring that the selection of measurement settings cannot be causally or informationally linked to any hidden variables influencing the particle outcomes. However, even under such conditions, the interpretation of experimental violations of Bell inequalities is not free from conceptual challenges. In particular, the quantum measurement problem raises the question of whether the act of measurement itself and the assumptions underlying it might influence the observed correlations. Although this issue is beyond the scope of this study, it represents a fundamental open problem that could impact the interpretation of such experiments [3], [7].

To preserve this condition, the bit generation process must meet three methodological criteria:

1) the decision must be forced and binary,
2) it must arise from a context that is unpredictable and cognitively driven,
3) the player must be unaware of the role their input plays in the broader experimental system.

By embedding decision triggers into dynamic and narratively coherent game environments, the designed serious games function as covert randomness interfaces capable of producing statistically usable data for quantum non-locality tests. This ensures that the core assumption of free and independent choice—central to the validity of Bell experiments is addressed at the behavioral level through gameplay [3].

B. *Application in Bell Experiments*

Bell tests are designed to evaluate whether the correlations between measurement outcomes can be explained by any local hidden variable theory. A common formulation involves two observers, Alice and Bob, each of whom receives one particle from an entangled pair. Alice chooses between two measurement settings, typically labeled A and A', while Bob chooses independently between B and B'. The selection of these settings must occur at the moment of measurement and must be statistically independent of any variable that could influence the outcomes.

In the present framework, binary sequences generated by human players through serious games are used to supply these measurement settings. A single bit from the player is mapped to either A or A' for Alice (e.g., 0 = A, 1 = A'), and a second, independently sourced bit determines Bob's setting (0 = B, 1 = B'). Once settings are selected, each party performs a measurement and records a binary outcome (e.g., +1 or –1). This process is repeated in many trials, covering all combinations of settings.

The collected data are analyzed by comparing the outcomes of measurements performed by two observers, each of whom independently chooses between two alternative settings. For every combination of these settings, the experimenters calculate the average correlation between the results,that is, how often the outcomes tend to agree or disagree. These average correlations are then combined into a single value known as the CHSH expression, named after Clauser, Horne, Shimony, and Holt, who introduced this formulation to test local hidden variable theories. The CHSH value summarizes the strength of the observed correlations in different measurement settings. According to classical theories based on local realism, this value cannot exceed a fixed limit. A result exceeding this limit indicates that no explanation based on local hidden variables can account for the observed correlations, implying that the measurement outcomes are influenced by non-local quantum effects, even when the two observers are spatially separated. These correlations are then used to calculate the CHSH expression (1):

$$S = [E(A, B) + E(A, B') + E(A', B) - E(A', B')] \quad (1)$$

If the value of S exceeds 2, the upper bound set by any local hidden variable model, the experiment demonstrates a violation of the CHSH inequality. Such a result is thus interpreted as a signature of non-classical behavior, consistent with the predictions of quantum mechanics. The entangled particles display correlations that cannot be explained by any model obeying both locality and realism. In contrast, if $S \leq 2$, the observed correlations remain within the classical regime, and no definitive conclusion about quantum non-locality can be drawn. According to quantum theory, the maximum possible value of the CHSH parameter for entangled systems $S = 2\sqrt{2}$ [3], [8].

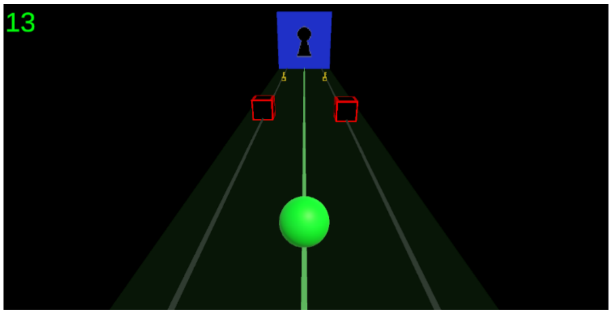
III. Results and discussion

A. *Digital Run*

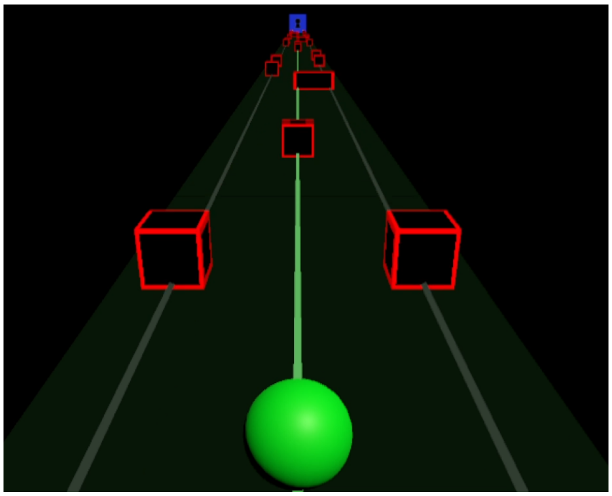
Game Digital Run (Fig.1) is designed as an endless runner with a retro-futuristic visual style in minimalist environments. The player continuously navigates through a stream of approaching obstacles by choosing whether to move left or right. This dynamic flow, combined with the increasing difficulty, creates an engaging gameplay loop that encourages sustained participation. The game motivates the participation of the player by offering immediate feedback on success or failure, as well as a natural progression of the challenge without explicit instruction. The game takes advantage of the timing of the natural reaction of the player and spatial judgment, strengthening immersion while generating a steady stream of binary decisions.

he game is accessible to players of all ages and suitable for both children and adults. Its intuitive control scheme—based entirely on lateral movement—requires no prior gaming experience or complex input, making it approachable for younger audiences.The absence of violent, graphic, or abstract content makes the game appropriate for educational settings and suitable even for children, ensuring a safe and accessible experience for players across all age groups.

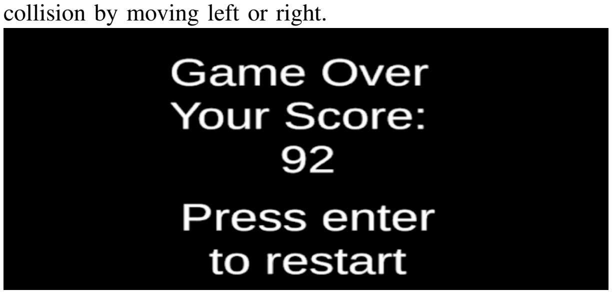
The core mechanic, which is binary lateral movement, supports the generation of a pseudo-random bitstream, but not every movement is recorded. Key to this mechanism is the appearance of a "decision obstacle", which is a special object positioned in the center lane, which can only be avoided by shifting either to the left or right lane. The direction chosen by the player is mapped to a binary value (left = 0, right = 1). To ensure that the decision is both forced and behaviorally meaningful, each of such obstacles is preceded by another obstacle that can only be avoided via the middle lane. This guarantees that the player is already centered and must consciously choose a side to continue. The bit generation speed varies between every decision obstacle, averaging around 1 bit every 8 seconds.



(a) The player navigates forward through a tunnel-like environment.



(b) A mid-game moment requiring a binary decision to avoid collision by moving left or right.



(c) End-of-game screen showing the final score and prompt to restart.

Fig. 1: Screenshots from the *Digital Run* prototype illustrating the core game mechanics.

From the perspective of Bell experiments, Digital Run implements a structured bit-generation mechanism that satisfies key conditions for producing behaviorally independent measurement settings. A bit is generated only when the player encounters a specific obstacle configuration ensuring that inaction is not possible and that each binary outcome results from an explicit, forced choice. Importantly, players are never informed which interactions produce bits, which guarantees that their choices remain independent from the quantum system. Although the current implementation was not integrated into a live Bell experiment, the output can be validated for uniformity and then used to control the measurement settings in Bell test. The controlled logic of obstacle sequencing, combined with covert bit extraction, makes Digital Run a practical prototype for generating high-quality human-derived randomness suitable for experimental tests of quantum non-locality.

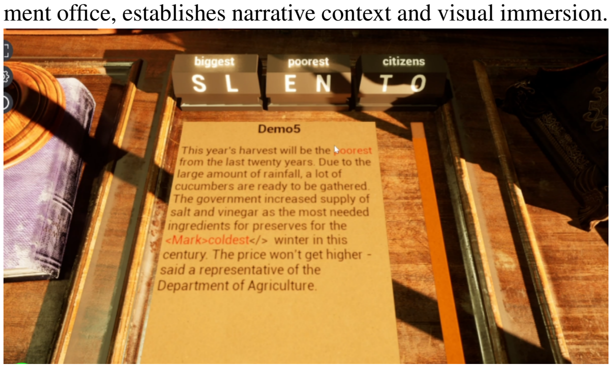
B. *Censor Office*

Game Censor Office (Fig.2) adopts the structure of a satirical document review simulator set in a dystopian state bureaucracy. The player takes on the role of a low-level censor responsible for reviewing incoming documents. Rich environmental storytelling, structured progression mechanics, and well-defined character roles contribute to a compelling narrative background and enhance narrative immersion. Player engagement is driven by escalating task complexity, pseudo-moral choices, and system feedback, which is supporting the generation of larger and more behaviorally diverse datasets.

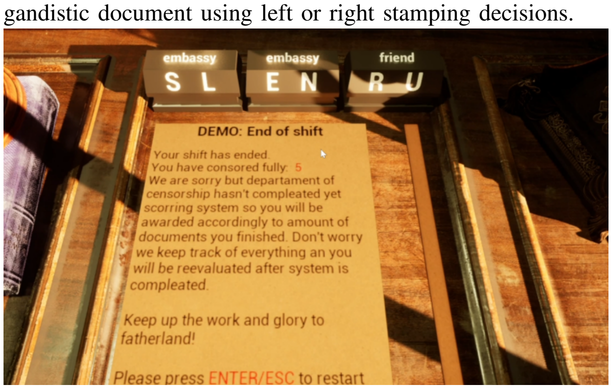
Due to its satirical tone and dystopian setting, Censor Office is primarily intended for adults and adolescents who possess sufficient reading comprehension skills (language settings are configurable). However, its modular structure enables easy modification of in-game content, making it possible to adapt the experience for different target groups,including school-aged children,by adjusting both language and narrative complexity. This flexibility opens the potential for use in educational or outreach contexts with age-appropriate content substitutions.

Binary data in Censor Office are generated through a stamping interface in which the player evaluates incoming documents using decision stamps. Each choice is mapped to two keys with hidden binary values (0 or 1) assigned to them, those keys changing after each action. This dynamic setup prevents fixed associations between keys and bit values, supporting randomness in user input, as well as user spamming one key constantly. However, not every interaction results in data capture. Bit generation is conditionally triggered only during interactions with documents that match an internally predefined pattern remaining invisible to the player. These triggers are embedded within the document handling logic and are automatically activated during gameplay when the appropriate criteria are met. As a result, the player's choice looks natural and unremarkable, occurring in a flow consistent with the narrative and the demands of the task. Thanks to all of this data, generation can achieve speeds of 1 bit every 3 seconds for new users, 1 bit per second for users with basic knowledge of the game, and more than 3 bits per second for experienced users.

(a) The player's workspace, styled as a retro-futuristic government office, establishes narrative context and visual immersion.



(b) A mid-shift task requiring the player to evaluate a propagandistic document using left or right stamping decisions.



(c) End-of-shift summary with a final document presented, closing the session.

Fig. 2: Screenshots from the *Censor Office* prototype illustrating the interactive decision interface.

From the perspective of Bell experiments, the Censor Office meets the necessary criteria for generating binary input that is grounded and independent in behavior. The decision points are forced and contextually embedded, ensuring that players cannot avoid making a choice, nor predict which interactions are relevant for data collection. Because the triggering conditions for bit extraction are fully hidden within the document classification system, player actions remain decoupled from their experimental role. This supports the assumption of free and causally unconnected measurement-setting choices. The narrative-driven environment and the varied task structure help reduce repetition and pattern formation, increasing the likelihood that successive bits are statistically independent. Moreover, by embedding randomness generation within an engaging gameplay loop and coherent story, Censor Office encourages users to return and continue playing over time. This sustained participation significantly improves the volume and consistency of the collected data, making the Censor Office a valid and scalable source of human-generated randomness for future Bell test implementations.

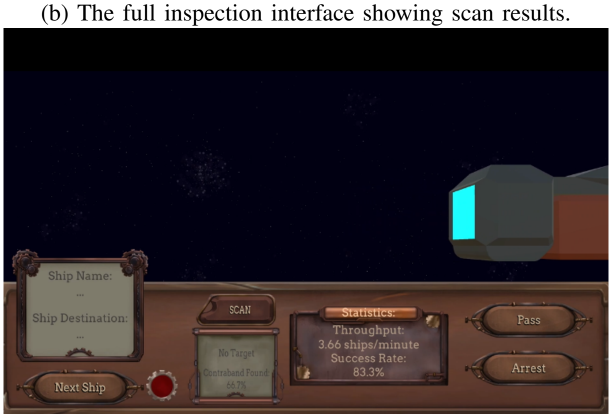
C. Stellar Gate

Game Stellar Gate (Fig 3) is a futuristic checkpoint control simulation set in a sci-fi universe. The player takes the role of a gate officer stationed at an interplanetary outpost, tasked with scanning and evaluating incoming transport units for contraband, violations, or anomalies. The game features a visually appealing sci-fi interface with holographic UI elements and atmospheric audio design, which enhances immersion. Gameplay unfolds through a series of inspection events in which the player must first decide whether to perform an additional scan and then choose either to allow passage or to order an arrest based on the scan result. As the game progresses, the complexity of information increases, involving subtle cues. These layered mechanics encourage attentive play and personalized decision strategies, motivating players to remain immersed for longer sessions while producing a sustained stream of behavioral data. The game employs simple mechanics combined into a set of micro-challenges, which requires the player to possess a basic understanding of decision logic and data correlation. This design encourages analytical reasoning while maintaining accessibility, striking a balance between low entry threshold and cognitive engagement.

Binary data in Stellar Gate are generated through a two-step decision process embedded in the inspection mechanic. The player first chooses whether to initiate a scan on an incoming unit. If a scan is performed, a second decision must be made: to allow passage or to order an arrest based on the scan result. Only this specific sequence scan, followed by allow or arrest, is considered a valid binary-generating event. The system after that logs the outcome as a bit: allow corresponds to 0, while arrest corresponds to 1. This decision path is monitored internally and marked by a trigger invisible to the player. All other combinations of actions, including skipping the scan or prematurely making a decision, are excluded from the data stream. This approach makes bit generation speed very varied and dependent on player behavior. The player is encouraged to make decisions at least once every 15 seconds, by the score that is regularly updated, informing them about missed scans. The bit generation speed averages around 20 seconds, but with a high deviation.

(a) The main control panel at the space checkpoint.

(b) The full inspection interface showing scan results.



(c) End-of-shift summary and transition screen.

Fig. 3: Screenshots from the *Stellar Gate* prototype illustrating the structure decision-making interface.

From the perspective of Bell experiments, Stellar Gate offers a structured method for generating human-sourced binary inputs through contextually meaningful, high-salience decision points. Bit generation is triggered only when the player voluntarily initiates a document scan and an action not required by the game progression and not signaled as relevant to data collection. This optionality functions as a behavioral filter and ensures separation between the player's decision-making process and its experimental purpose. Because scan-triggered interactions lead to binary decisions, they form a two-channel input stream that can be interpreted as measurement-setting choices in Bell tests. Once validated for independence, the resulting bitstream can serve as a reliable source of randomness. The system and its modular architecture allow for real-time deployment in distributed experimental setups, fully compatible with experiment protocols.

IV. Conclusions

The serious game prototypes presented in this article effectively fulfill key methodological criteria necessary to generate binary data for use in Bell quantum experiments. Each game introduces distinct decision-making mechanics that produce diverse and naturally unpredictable binary sequences. Digital Run leverages dynamic, reflex-driven choices, Censor Office centers around morally complex decisions within a realistic narrative context, and Stellar Gate features multi-step interactions requiring high attentiveness and voluntary decision-making by players.

These varied mechanics will probably significantly improve the state of the art in Bell experiments by introducing genuine human behavioral diversity, thus improving the statistical quality and reliability of the generated data. Employing serious games represents an innovative approach in quantum research, enabling more comprehensive and realistic exploration of non-local phenomena and establishing new benchmarks for the experimental use of human-generated randomness. Although the actual data collection phase has yet to begin, prototypes are promising tools for future experimental implementations. By capturing a broader spectrum of human-driven randomness, these games hold potential to provide more nuanced insights into the statistical characteristics of human-generated randomness compared to automated processes, contributing significantly to ongoing discussions about the foundational assumptions underpinning quantum non-locality tests.

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