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Research Article ♪ **Araştırma Makalesi**

The application of quantum computing in music composition

Kuantum hesaplamanın müzik kompozisyonunda uygulaması

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ABSTRACT

Quantum computing and artificial intelligence, two prominent topics in science and technology, are rapidly advancing and extending their influence into numerous fields, including music. Quantum computer music, which merges the strengths of quantum computing and deep learning, heralds a new era in the integration of music creation with cutting-edge technology. The interactive quantum music composition "*Spinnings—Q1 Synth Trio*", created by Brazilian composer Miranda during the QuTune project at the Interdisciplinary Centre for Computer Music Research (ICCMR), in collaboration with the University of Oxford, stands as a notable example of quantum computer music. This study adopts a case study approach to thoroughly investigate the technical creative process behind this work, covering elements such as quantum computing, quantum properties, qubits, quantum gates, and quantum circuits, gradually unveiling the mathematical logic behind quantum algorithmic composition. The results of this study indicate that quantum algorithmic composition, as an emerging approach to music creation, not only generates unique music through the characteristics of quantum computing but also offers new possibilities for the integration of music, art, and technology. By applying quantum bits, quantum gates, and quantum circuits, this research demonstrates how quantum computing can provide new theoretical foundations and practical methods for music composition. Furthermore, the study discusses how to optimize the interactive creative experience in quantum music works and how to enhance the understanding and appreciation of quantum music among a broader audience of musicians and listeners. With the continuous advancement of quantum computing technology, quantum music is poised to contribute a distinctive dimension to the global flourishing of musical culture. This research offers fresh perspectives and ideas for the development of this field.

Keywords: quantum computing, algorithmic composition, music performance, artificial intelligence, system

ÖZ

Kuantum hesaplama ve yapay zeka, bilim ve teknoloji alanındaki öne çıkan iki konu olarak hızla gelişmekte ve müzik dahil birçok alanda etki alanlarını genişletmektedir. Kuantum bilgisayar müziği, kuantum hesaplama ile derin öğrenmenin avantajlarını birleştirerek, müzik yaratımında keskin teknoloji ile entegrasyonun yeni bir dönemini müjdelemektedir. Brezilyalı besteci Miranda tarafından, Oxford Üniversitesi ile işbirliği içinde Disiplinlerarası Bilgisayar Müzik Araştırmaları Merkezi'nde (ICCMR) yürütülen QuTune projesi kapsamında yaratılan etkileşimli kuantum müzik eseri "*Spinnings—Q1 Synth Trio*", kuantum bilgisayar müziğinin dikkat çekici bir örneğini sunmaktadır. Bu çalışma, eserin arkasındaki teknik yaratım sürecini kapsamlı bir şekilde incelemek amacıyla vaka çalışması yaklaşımını benimsemekte; kuantum hesaplama, kuantum özellikleri, kuantum bitleri, kuantum kapıları ve kuantum devreleri gibi unsurları ele alarak kuantum algoritmasıyla bestelemenin matematiksel mantığını adım adım ortaya koymaktadır. Bu çalışmanın sonuçları, kuantum algoritmik kompozisyonunun, müzik yaratımında yükselen bir yaklaşım olarak, sadece kuantum bilgisayarlarının özellikleriyle benzersiz müzikler üretmekle kalmayıp, aynı zamanda müzik, sanat ve teknolojinin birleşimi için yeni olasılıklar sunduğunu göstermektedir. Kuantum bitleri, kuantum kapıları ve kuantum devrelerinin uygulanmasıyla, bu araştırma, kuantum

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hesaplamanın müzik kompozisyonu için nasıl yeni teorik temeller ve pratik yöntemler sunduğunu ortaya koymaktadır. Ayrıca, çalışma, kuantum müzik eserlerinin etkileşimli yaratıcı deneyimini nasıl optimize edebileceğimizi ve daha geniş bir müzisyen ve dinleyici kitlesinin kuantum müziğini nasıl anlayıp takdir edebileceğini tartışmaktadır. Kuantum hesaplama teknolojisinin sürekli ilerlemesiyle birlikte, kuantum müziği, küresel müzik kültürünün zenginleşmesine özgün bir boyut katmaya adaydır. Bu araştırma, bu alanın gelişimi için yeni perspektifler ve fikirler sunmaktadır.

Anahtar kelimeler: kuantum hesaplama, algoritmik besteleme, müzik performansı, yapay zeka, sistem

1. INTRODUCTION

In recent years, the combination of quantum computing and artificial intelligence has catalyzed revolutionary changes across various interdisciplinary fields (Yang, Huang, et al., 2024), with music creation among them (Dunjko & Briegel, 2018). Since its inception in the late 1970s, quantum computing has primarily facilitated breakthroughs in scientific research, such as molecular simulation and algorithm optimization (Nimbe et al., 2021). However, with the emergence of the field of quantum computer music, quantum technology has begun to transcend the boundaries of science and engineering (Yang, Shen, et al., 2024), entering the realm of the arts, particularly in music composition, and revealing its unique artistic potential (Yang & Lee, 2024).

At the core of quantum computer music is the application of principles from quantum mechanics, including wave-particle duality, quantum superposition, and quantum entanglement (Miranda, 2024). These phenomena provide unprecedented opportunities for music creation. For example, the principle of quantum superposition allows quantum bits (qubits) to exist in multiple states simultaneously, enabling the generation of complex musical patterns and sound effects. Researchers around the globe are actively advancing the field of quantum music computation, employing quantum algorithms to tackle challenges in music sequencing, sound synthesis, and live performance (Dalla Chiara et al., 2015). These explorations not only drive technological innovation in music composition but also offer fresh perspectives on musical expression.

The first International Symposium on Quantum Computing and Musical Creativity (ISQCMC) marks a turning point in the development of quantum music. Although the world’s first quantum computer was officially announced in 2017, scholars had already begun exploring this field during the development of quantum simulation libraries. As early as 2010, Professor Hendrik Weimer (1966–) from the Department of Physics at Leibniz University Hannover showcased musical examples[1] created using the libquantum quantum simulation library[2] on his quantum blog[3]. In 2021, the first ISQCMC[4] was held, officially marking the acceleration of research in the field of quantum computing music (Miranda & Miller-Bakewell, 2022). The conference was initiated by Professor Eduardo Reck Miranda (1963–) from the University of Plymouth, based on the QuTune project[5]. It was co-organized by the University of Plymouth’s Interdisciplinary Centre for Computer Music Research (ICCMR), the Center for Computer Research in Music and Acoustics (CCRMA) at Stanford University, and the Quantum Computing Laboratory (CQC) at the University of Cambridge, among other institutions. The conference featured several high-quality research papers (Miranda, 2022) and performances of quantum computer music works, including “Zeno” (2019), composed by Professor Miranda for bass clarinet and electronic sound, and “Second Cornerstone” (2020), composed by Omar Costa Hamido (1990–) for kamâncheh (an Iranian bowed string instrument) and sheet music.

Building on past achievements and looking to the future, quantum music continues to explore specialized subfields related to music composition. As the global influence of the community grows, the second ISQCMC[6] International Symposium was held in Berlin in October 2023, with the appearance of Asian experts among the peer reviewers. The papers presented at the conference showed that while cutting-edge topics such as quantum algorithmic composition, quantum-assisted composition, quantum instrument design, and quantum computing live performance remain central, there is now an emerging focus on more artistic and qualitative

[1] Weimer’s Quantum Computer Music Examples:www.quantenblog.net/physics/quantum-computer-music4o mini

[2] libquantum Quantum Simulation Library: www.libquantum.de/

[3] Weimer’s Quantenblog: www.quantenblog.net/hendrik

[4] The First International Symposium on Quantum Computing and Musical Creativity (ISQCMC): iccmr-quantum. github. io/1st_isqcmc/

[5] The QuTune project is a quantum computing music programming toolbox developed in collaboration between the University of Plymouth and the University of Oxford, aimed at driving technological innovation in the field of music.

[6] The Second International Symposium on Quantum Computing and Musical Creativity: indico.desy.de/event/ 38609/ page/4475-information

discussions, such as quantum aesthetics, quantum computational musicology, and the intersection of quantum computing and music theory.

Quantum computer-assisted music composition, particularly quantum algorithmic composition (QAC), has emerged as a pivotal subfield of computer music (Hamido, 2022). QAC harnesses the distinctive characteristics of quantum computing to generate music, providing musicians with novel tools for creative exploration. A notable example of this is *"Spinnings—Q1 Synth Trio"*, an interactive quantum music piece created by Brazilian composer Eduardo Reck Miranda during the QuTune project at the Interdisciplinary Centre for Computer Music Research (ICCMR), in collaboration with the University of Oxford. This study aims to uncover the principles of quantum algorithmic composition and its application in music creation by examining the work's algorithmic design, interactive system, and live performance evaluation. This analysis not only offers a framework for understanding and evaluating quantum music works but also presents new approaches for future quantum music composition.

2. METHOD

This study employs a case study approach to analyze the creative technical pathway of *Spinnings*. This section focuses on the fundamental principles of quantum computer algorithmic composition, gradually presenting the mathematical logic behind this process, from quantum computing and quantum properties to qubits, quantum gates, and quantum circuits. The emphasis is placed on how quantum computing provides both a theoretical foundation and practical methods for music creation.

2.1. Quantum Computing and Quantum Characteristics

Quantum computing, an emerging domain within computer science, is based on the unique properties of quantum mechanics, bringing new perspectives and possibilities to music research and practice. Richard Feynman introduced the concept of quantum computers to directly manipulate data using quantum phenomena, thus ushering in a new era of quantum computing. Modern quantum computing not only integrates cutting-edge technologies such as machine learning and cloud computing but also demonstrates significant application potential in fields like chemistry, mathematics, biology, and finance. In music technology, quantum computing has the potential to advance computational musicology, including research on interdisciplinary subjects such as algorithmic composition. Key characteristics of quantum mechanics—specifically wave-particle duality, quantum entanglement, and multi-state superposition—provide both a theoretical basis and operational mechanism for quantum computing (Polychronakos, 2024).

1- Wave-Particle Duality. This fundamental concept of quantum mechanics indicates that microscopic particles, such as electrons, exhibit both particle-like and wave-like properties (Yoon & Cho, 2021). It can be likened to the multiple attributes of musical elements, where pitch and timbre coexist.

2- Quantum Entanglement. Another essential characteristic of quantum mechanics describes the interaction and connection between particles. When two or more particles become entangled, measuring one particle will instantaneously affect the state of the other particles, regardless of the distance between them (Hrmo et al., 2023). This characteristic can explore complex non-local relationships between musical elements, such as the interplay between harmony and melody.

3- Quantum Superposition. This fundamental property of quantum bits (qubits) distinguishes them from classical bits. Unlike classical bits, which can only represent a state of 0 or 1, qubits can exist in a superposition of states simultaneously. This uncertainty provides quantum computing with parallel processing capabilities (Kounalakis et al., 2019). The thought experiment of Schrödinger's cat[7] serves as a vivid illustration of quantum superposition (Wang et al., 2022), offering new solutions to complex issues such as harmonic connections and pitch set arrangements.

Quantum computing utilizes the superposition state and quantum entanglement of qubits to achieve exponential information processing capabilities during computation. Compared to classical computing, quantum computing demonstrates significantly higher efficiency in tackling specific problems, such as large

[7] Schrödinger's cat, proposed by Austrian physicist Erwin Schrödinger (1887–1961) in 1935, illustrates quantum superposition with a cat that is both alive and dead simultaneously. The thought experiment has since fueled debates in physics and philosophy, including discussions on parallel universes.

number factorization (Shor's algorithm) and random database searches (Grover's algorithm). Many problems in the field of musicology research exhibit high computational complexity, such as identifying music dataset tags in music information retrieval and analyzing timbre spectra in voice synthesis. As the complexity of these problems increases, classical computing struggles to address them effectively, necessitating the use of quantum computing (Miranda, 2022). It is important to note that the superposition state of quantum computing primarily reflects an advantage in computational power. To address complex computational challenges such as algorithmic composition, it is essential to design an overarching quantum algorithm based on the characteristics of quantum computing, progressing from "quantum bits" and "quantum gates" to "quantum circuits."

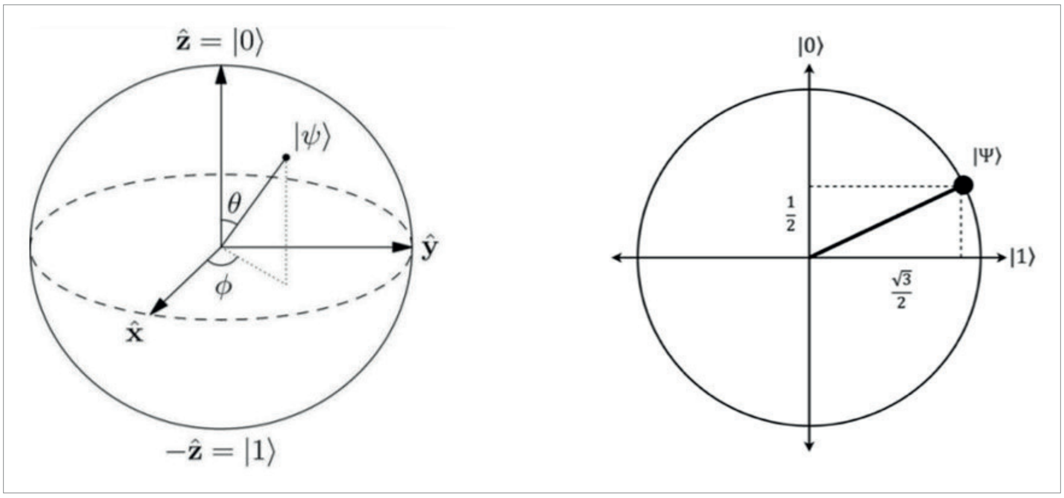
2.2. Quantum Bits - Quantum "Notes"

In musicology, notes serve as the fundamental elements that constitute melody and harmony, while in the realm of quantum computing, quantum bits (qubits) play a similar role, effectively acting as the "notes" of the quantum domain. The state of a quantum bit can be visually depicted using the Bloch sphere[8], a geometric model.

The representation of quantum bits as "polymorphic notes" is grounded in mathematical models. Just as the placement of notes on a staff determines their pitch and duration, the state of a quantum bit is defined by its position on the Bloch sphere, which represents various quantum states. As illustrated in Figure 1, the Bloch sphere, which symbolizes quantum bits, is a geometric model akin to a globe. It can occupy either of the two base states or exist in a superposition of these states, meaning it exhibits characteristics of both. This special superposition state comprises two complex amplitudes, where one represents the amplitude of the quantum bit in the state |0> and the other represents the amplitude of the quantum bit in the state |1>, while adhering to the normalization condition $|\alpha|^2 + |\beta|^2 = 1$.

Figure 1

Bloch sphere (left) and superposition state amplitude modulation (right)



Similar to a music "dice-throwing" game, during the final measurement, the quantum bit collapses into one of the base states. Although the quantum bit appears to have values of both |0> and |1> during the superposition, when measured, it collapses irreversibly to one of the base states. This process is analogous to the flipping of a coin; until the moment of observation, we cannot ascertain whether the heads or tails side is facing up. As depicted on the right side of Figure 1, if we assume $|\alpha|$ and $|\beta|$ correspond to 1/2 and √3/2, respectively, then the probability of measuring the quantum bit as |0> is 25%, while the probability of it being |1> is 75%. The power of quantum computing lies in leveraging this superposition state for efficient parallel computation.

The parallel computing capability of quantum computing stems from the characteristics of this superposition state, allowing quantum computers to significantly outperform classical computers in terms of computational efficiency. In quantum algorithmic composition, the principles of quantum computing can inspire the exploration

[8] The Bloch sphere, named after Swiss physicist Felix Bloch (1905–1983), is a classic geometric representation in quantum mechanics.

of new creative methodologies and theories, where the superposition state and collapse characteristics of quantum bits can be analogized to elements of music creation, such as duration, rests, and counterpoint, thereby leading to the creation of unique "quantum music" works.

2.3. Quantum Gates - Quantum "Harmonic Counterpoint"

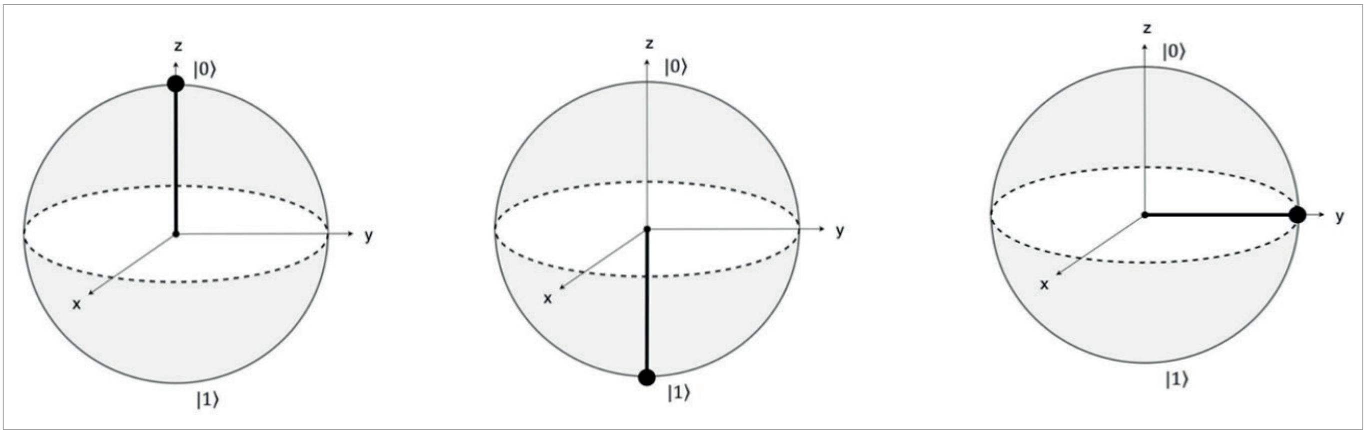
Harmonic counterpoint refers to the harmonious combination and precise arrangement of different musical notes. Similarly, in quantum computing, quantum gates can be viewed as the quantum analog of "harmonic counterpoint." Quantum computers perform calculations through quantum gates, much like classical computers use logical gates. Quantum gates operate on qubits, utilizing their unique superposition and entanglement characteristics to achieve complex computational processes.

1- Single Quantum Gates. These are akin to the processing of monophonic melodies in music. Single quantum gates act on individual qubits, such as Pauli gates (X, Y, Z), which achieve 180-degree rotations around the X, Y, and Z axes of the Bloch sphere. This operation is comparable to compositional techniques like melody reflection and retrograde. The Hadamard gate, on the other hand, places the qubit in a superposition state, similar to the transformation of a pitch sequence in composition (see Figure 2).

2- Multiple Quantum Gates. These correspond to harmonic progressions in music. Multiple quantum gates, such as the Controlled NOT gate (C-NOT gate), are based on the principle of quantum entanglement. They influence the target qubit by controlling the state of another qubit, thereby achieving the core functionality of quantum computing. This operation is analogous to the relationships found in harmonic counterpoint, where the movement of a leading note influences the root note's position or function.

Figure 2

The original vector is (left), the vector inverted by the Pauli-X gate is (middle), and the vector processed by the Hadamard gate is a superposition state (right)



The operation of quantum gates can be described by computational modeling. This modeling approach is based on linear algebra, where the positions and states of vectors in quantum Hilbert space are represented in matrix form (Elgendy, Younes, Abu-Donia, & Farouk, 2024). This process is similar to constructing themes or motifs in musical composition. For instance, the evolution of the C-NOT gate can be expressed as a 4×4 matrix (Equation 1.1), enabling the computational transformation of quantum bit states through multi-state superposition and entanglement (Equations 1.2-1.6). Complex harmonic structures and interwoven counterpoint voices can all be analyzed and developed through this modeling approach.

$$C-NOT=\begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix} \tag{1.1}$$

$$|00\rangle = \begin{bmatrix}1\\0\\0\\0\end{bmatrix},\ |01\rangle = \begin{bmatrix}0\\1\\0\\0\end{bmatrix},\ |10\rangle = \begin{bmatrix}0\\0\\1\\0\end{bmatrix},\ |11\rangle = \begin{bmatrix}0\\0\\0\\1\end{bmatrix} \tag{1.2}$$

$$|\Psi'\rangle = C-NOT|00\rangle = \begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}1\\0\\0\\0\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\end{bmatrix} = |00\rangle \tag{1.3}$$

$$|\Psi'\rangle = C-NOT|01\rangle = \begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}0\\1\\0\\0\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\end{bmatrix} = |11\rangle \tag{1.4}$$

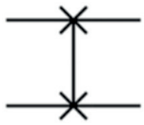
$$|\Psi'\rangle = C-NOT|10\rangle = \begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}0\\0\\1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\1\\0\end{bmatrix} = |10\rangle \tag{1.5}$$

$$|\Psi'\rangle = C-NOT|11\rangle = \begin{bmatrix}1&0&0&0\\0&0&0&1\\0&0&1&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}0\\0\\0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\end{bmatrix} = |01\rangle \tag{1.6}$$

Designing quantum algorithms necessitates the use of various common single and multiple quantum gate components. As outlined in Table 1, this study presents a compilation of frequently used single and multiple quantum gate components. While other quantum gates, such as rotation gates and phase gates, will not be discussed in detail here, they can be referenced in the existing literature (Miranda, 2022). By beginning with quantum bits and progressing through a series of quantum gate components, one can construct a large, complex quantum circuit capable of performing intricate computations. The design of a specific quantum circuit for a given computation constitutes the essence of the quantum algorithm, which ultimately determines the structure and form of the musical work.

Table 1

Common qubit gates

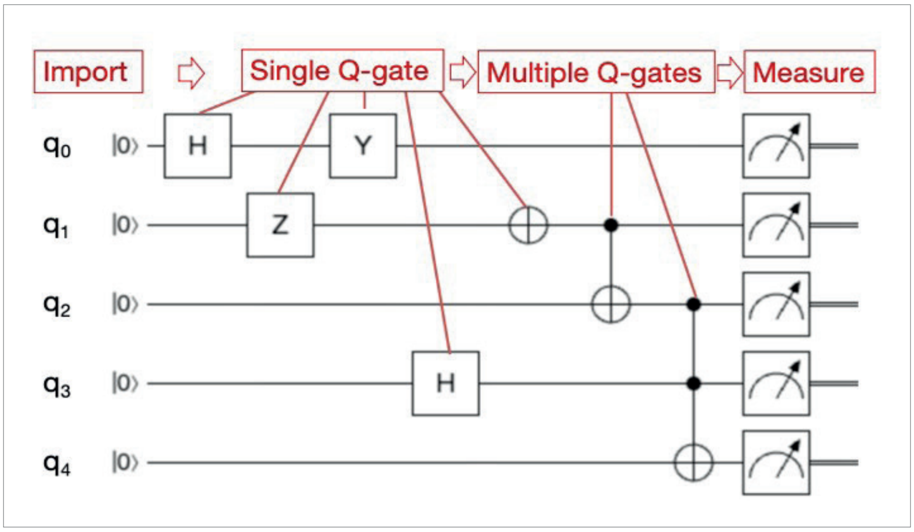
Number	Name	Matrix representation	Diagram
1	Pauli-X Gate	$\sigma_x = \begin{bmatrix}0&1\\1&0\end{bmatrix}$	
	Pauli-Y Gate	$\sigma_y = \begin{bmatrix}0&-i\\i&0\end{bmatrix}$	
	Pauli-Z Gate	$\sigma_z = \begin{bmatrix}1&0\\0&-1\end{bmatrix}$	
	Hadamard Gate	$H = \begin{bmatrix}1&1\\1&-1\end{bmatrix}$	
2	C-NOT Gate	$C-NOT(x) = \begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{bmatrix}(x)$	
	SWAP Gate	$SWAP(x) = \begin{bmatrix}1&0&0&0\\0&0&1&0\\0&1&0&0\\0&0&0&1\end{bmatrix}(x)$	
...	...	...	...

2.4. Quantum Circuits - Quantum "Staff"

Quantum circuits serve as the structural framework for quantum algorithms, creating complex computational pathways by connecting fundamental quantum gates. This design bears a striking resemblance to the staff in music notation, where the arrangement and combination of notes constitute melodies and harmonies. In a similar manner, quantum circuits combine quantum gates in a sequential manner along a timeline to construct the "Music Movement" of quantum computing. Quantum circuit diagrams typically consist of qubits and quantum gates, as illustrated in Figure 3. For instance, a circuit comprising five qubits can complete a specific computational task through the combination of single and multiple quantum gates, with each quantum gate functioning analogously to compositional techniques such as cadence, Neapolitan harmony processing, and more.

Figure 3

A quantum circuit diagram consisting of 5 qubits



Multi-qubit quantum systems can also be described using tensor product function models. Quantum computers operate in tandem with classical computers, storing computational results in quantum bit registers, which can subsequently be retrieved and processed by classical computers. This process is analogous to the role of sound cards in music production, facilitating analog-to-digital conversion. Classical computers serve as an interactive interface between users and quantum computers, allowing real-time access to quantum measurement results, such as the computational outcomes of a four-qubit system demonstrated in Equation 2. These results can be transformed into elements of music creation, such as notes, pitches, and frequencies. Thus, this process combines the mathematical logic of quantum computing with the melody and rhythm inherent in music creation, providing a novel perspective and new tools for algorithmic composition.

$$|\Psi\rangle = C_0|0000\rangle + C_1|0001\rangle + C_2|0010\rangle + \cdots + C_{14}|1110\rangle + C_{15}|1111\rangle \quad (2)$$

The essence of quantum algorithms lies in the customization of quantum circuits to resolve specific problems. By employing precisely calibrated sequences of quantum gates, quantum computers can manipulate qubits to achieve efficient computations, thereby overcoming the limitations of traditional computers when faced with complex problems. Within the artistic domain of algorithmic composition, the design principles of quantum circuits take on a new significance, empowering musicians and composers to explore new frontiers of music creation and discover innovative forms of musical expression and structure.

2.5. Quantum Gates

The research is structured around a five-step approach. First, it provides an overview of the revolutionary changes brought by quantum computing and artificial intelligence in music composition. Next, the article elaborates on the basic concepts and principles of quantum computing, including quantum bits, quantum gates, and quantum circuits. It then introduces the specific technical approach of *Spinnings* as a case study.

Finally, the research discusses various works, addressing algorithmic tools, work types, and constraints, and draws conclusions.

Regarding existing quantum computing technologies and musical works, this study demonstrates the feasibility of analyzing the principles of algorithmic composition and its practical applications. This research aims to spark further exploration in the field. After understanding the technological background, it is hoped that composers in fields such as electronic music composition, music technology, and digital music production will gain an understanding of quantum computing through this article, thereby using it to enhance their own compositions and performances.

3. RESULTS

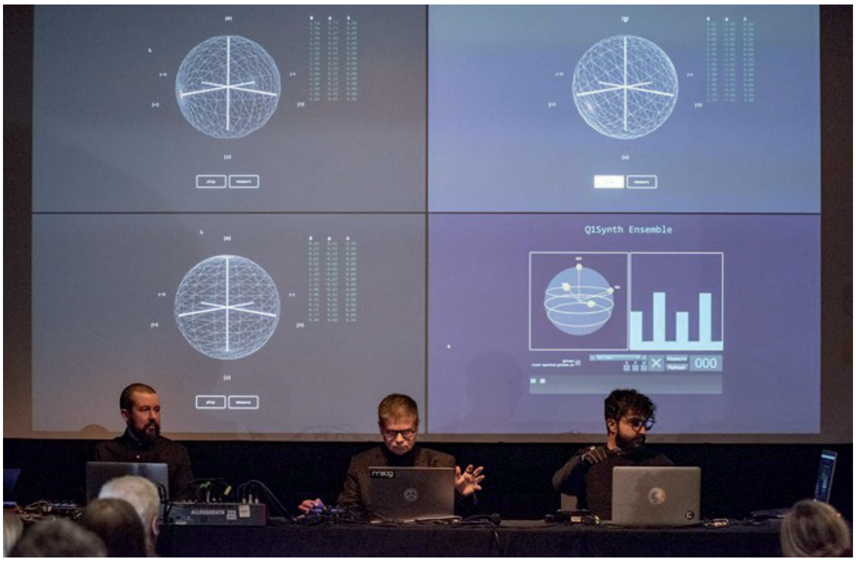
Quantum algorithm composition, as an emerging method of music creation, is illustrated through representative quantum music works. *Spinnings* is a live performance facilitated by human-computer interaction, utilizing three Q1 synthesizer systems.

3.1. Live Performance

Miranda, a Brazilian composer specializing in chamber and electronic music, serves as the director of ICCMR at the University of Plymouth and is a leading researcher in computer music science. His research interests include electronic music, AI-based music, and quantum computer music. Spinnings was created during the QuTune project, a collaboration between ICCMR and the University of Oxford, and represents a significant advancement in quantum algorithmic composition for timbre design. The piece, featuring a trio of Q1 synthesizers, premiered on December 8, 2022, at the Goethe-Institut in London. Figure 4 captures the press conference and live recording, with composer Eduardo Reck Miranda (center), Pete Thomas (left), and Paulo Taborai (right).

Figure 4

"Spinnings" premiere press conference[9]



[9] The Goethe-Institut Quantum Studio: https://www.goethe.de/prj/lqs/en/eve/sou.html

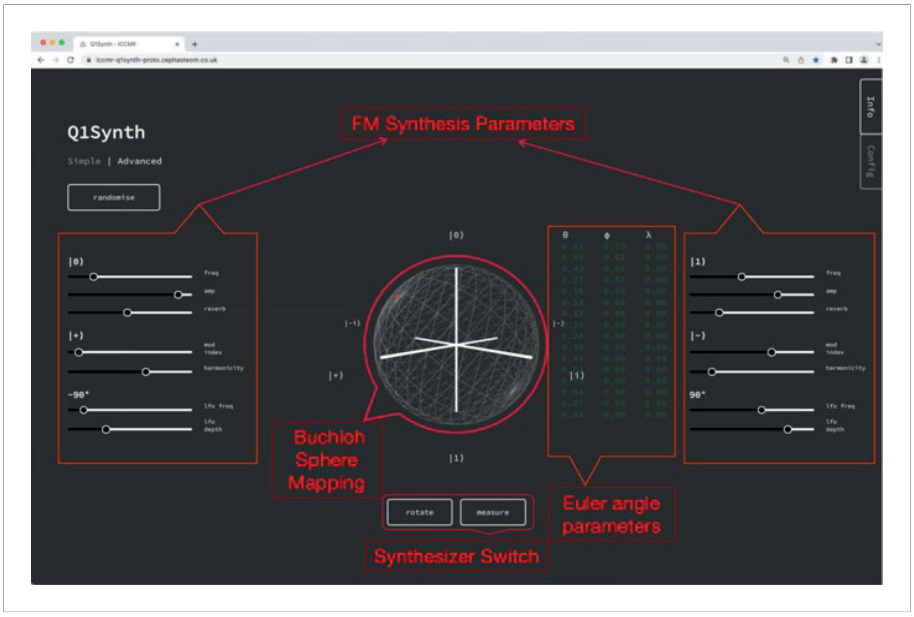
3.2. Construction of the Quantum Synthesizer System

Spinnings is performed through the interaction of three Q1 synthesizers, which capture the Euler angles [10]of hand movements using MIDI[11] gesture controllers to drive the performance (Miranda et al., 2023). The central computer station maps the state vector to the quantum circuit and sends the information to a quantum computer for measurement. The measurement results are then fed back to the synthesizers, which use frequency modulation (FM) synthesis to generate sound. The output from the three synthesizers is integrated and rendered into a standard audio format.

The Q1 synthesizer system combines the physical properties of quantum bits with the geometric model representation of the Bloch sphere (Figure 5). Miranda designed a geometric model of the quantum bits on the Bloch sphere, allowing dynamic manipulation of the state vectors through MIDI controllers and gesture mapping. In this setup, the position of the state vector is represented by a red dot, and rotating the sphere (either by dragging the mouse or via gyroscope mapping) adjusts the state vector. This dynamic process is built around three types of Euler angles (θ, φ, λ). The "rotate" and "measure" buttons serve as the synthesizer's switches. During performance, the system takes over control from the user, moving the measurement vector towards the pole based on measurement results, creating a unique random performance through the Q1 synthesizer's mechanism. The rotation button allows users to adjust the Euler angles of the Bloch sphere in real time, modifying the sound parameters accordingly, while the measure button triggers a quantum circuit measurement that generates a sound effect based on a specific probability distribution.

Figure 5

The Q1 synthesizer[12]



The Q1 synthesizer's sound control, which is achieved by mapping the three Euler angles to FM synthesis parameters. The synthesizer's interface includes multiple FM synthesis parameter sliders that are displayed on both sides of the Bloch sphere. The default parameter settings are as follows:

$$\theta = \{\text{Frequency}, \text{Amplitude}, \text{Reverb}\} \quad (3.1)$$

$$\varphi = \{\text{Modulation Index}, \text{Harmonicity}\} \quad (3.2)$$

$$\lambda = \{\text{LFO Speed}, \text{LFO Depth}\} \quad (3.3)$$

[10] Euler angles are used to describe the orientation in three-dimensional Euclidean space. Named after Leonhard Euler (1707–1783), they are typically represented as α, β, γ, or ψ, θ, φ.

[11] Musical Instrument Digital Interface (MIDI), introduced in the early 1980s, enables communication between electronic instruments.

[12] Q1 Synthesizer official website: https://iccmr-q1synth-proto.cephasteom.co.uk/

- Frequency: Pitch;
- Amplitude: Loudness;
- Reverb: Room size and wet/dry mix;
- Modulation Index: The number of overtones in the spectrum;
- Harmonicity: Defines the richness of the sound when combined with the modulation index;
- LFO Speed: The rate at which the Low-Frequency Oscillator (LFO) creates vibrato or tremolo effects;
- LFO Depth: The intensity of the vibrato effect.

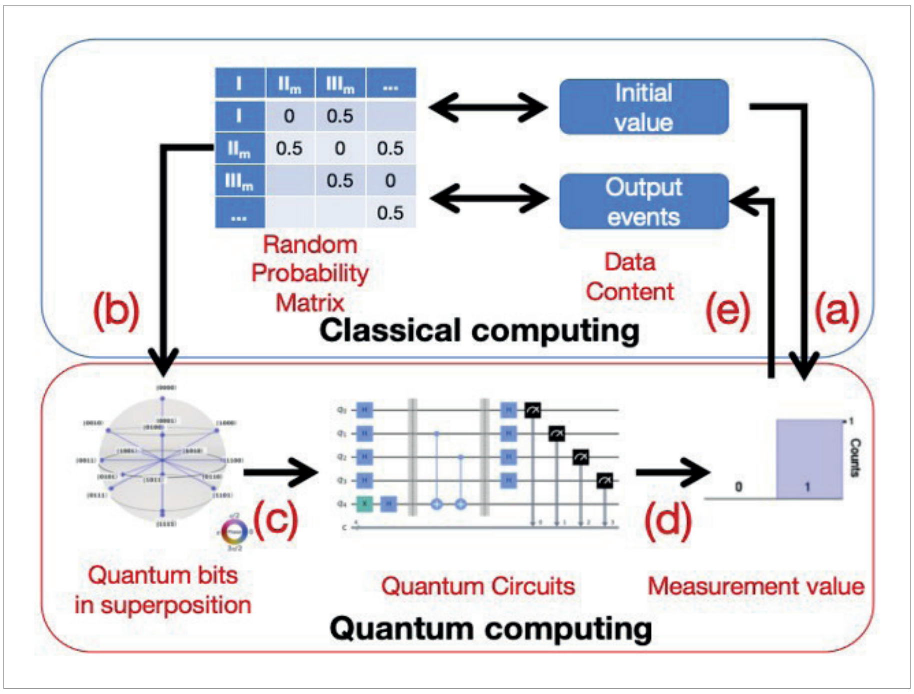
When a measurement command is detected, the system constructs a simple quantum circuit to calculate the angle of the coordinate axis. This is sent to a cloud-based quantum computer, which returns the measurement result. The Q1 synthesizer is currently connected to an IBM quantum processor located in the United States.

3.3. Quantum Interactive Computing Process

The algorithm design of *Spinnings* employs the Hadamard gate to entangle the three Q1 synthesizers, and the measurement process is programmed as a probability matrix to create the compositional rules based on probability distribution weights. The interactive quantum circuit process in the Q1 audio processing system incorporates both quantum and classical computing methods (Figure 6). Given the initial degree of the harmony sequence (a), the quantum system first outputs the measurement event and then calls the quantum bit (b), enters the designed quantum circuit (c), runs the quantum computation (d), and outputs the measurement result as a measurement event (e). This result is used by the classical computer to continue the loop, selecting the next probability degree. If the measurement result is 0, the sequence corresponding to the left column is selected; otherwise, the opposite occurs. The process of selecting these values determines the sound synthesis and performance of the Q1 synthesizer.

Figure 6

Overall quantum circuit computation flowchart

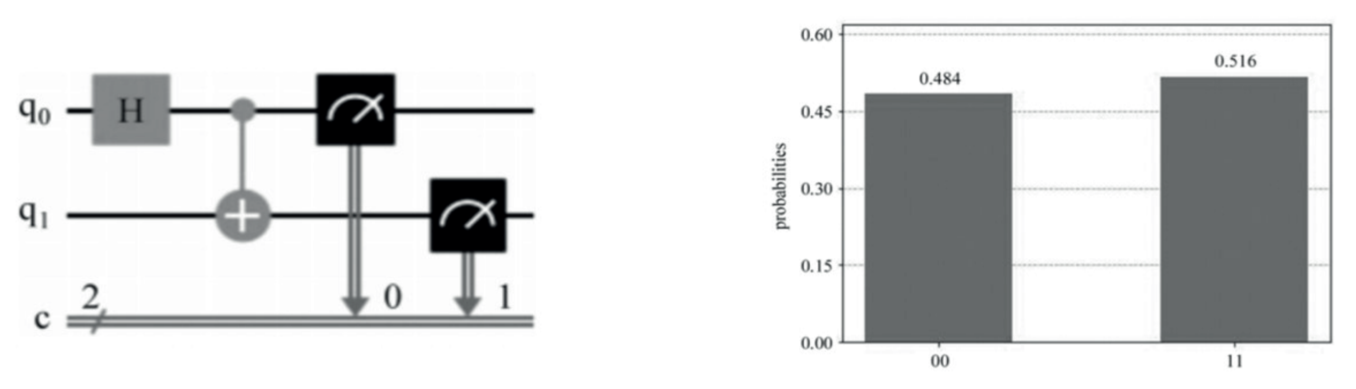


The quantum entanglement circuit used in *Spinnings* introduces a novel "dialogue mechanism" that achieves unprecedented harmony and synchronization during improvisational performances and creative collaboration between musicians. The corresponding quantum circuit design requires only a single qubit and a Hadamard gate (Figure 7). The Hadamard gate places the qubit's state vector into an equal-weighted superposition, meaning that when the qubit is measured, there is an equal chance of returning 0 or 1. This assumption of equal probability forms the basis of the probability matrix (Childs et al., 2013). As one musician plays the

Q1 synthesizer, their movements influence the other musician's instrument through quantum entanglement, generating sound modulations based on whether the measurement returns 0 or 1.

Figure 7

Quantum circuit diagram of the qubits entanglement experiment (left) and visualization of experimental measurement results (right)



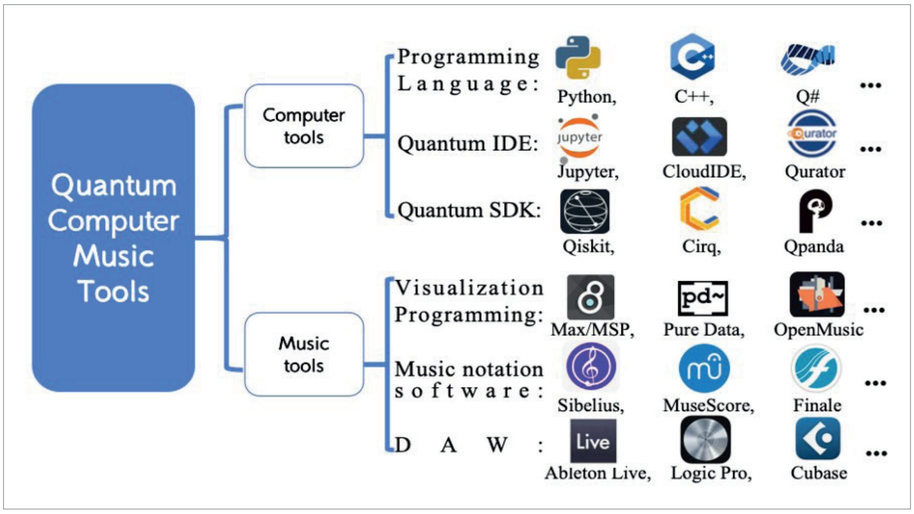
4. DISSCUSSION

4.1. Findings

Leading composers are using innovative tools to integrate quantum computing into their compositional practices. Similar to the development of the interdisciplinary field of computer science and music, composers who focus on algorithmic composition typically come from backgrounds in either computer science or music. This distinction highlights the difference between computer musicology and music informatics (Amoroso, 2017). Not only *Spinnings*, but also works such as *Second Cornerstone* (2020), composed by Omar Costa Hamido (1990–) for kamâncheh (an Iranian bowed string instrument) and sheet music, utilize computer music tools and quantum computing tools, which are applied in the practices and applications of both fields. Based on the composers' disciplinary backgrounds, interactive tools can be categorized into two types of quantum computing algorithmic composition tools—computer-based and music-based. Contemporary composers focused on quantum algorithmic composition combine programming and composition tools from both fields. *Spinnings*, for example, is an interactive performance achieved through music-based tools, while its core Q1 synthesizer relies on computer-based tools for its design and development.

Figure 8

Quantum computing-based algorithmic composition tools (Duarte, 2020)



As seen in figure 8, Duarte’s research proposes a series of programming tools as the basis for algorithmic composition (Duarte, 2020). Quantum algorithmic composition not only focuses on the design and construction of algorithms but also requires consideration of the overall system design. Whether it is the quantum circuit synthesizer used for FM discrete modulation synthesis in *Alice·Apple* (2022) (with six quantum bits entangled), or the encoding/decoding method used to generate sound materials through quantum representation of audio in *Rasgar·Saber* (2023), both examples demonstrate how quantum computers are gradually moving beyond their role as tools for auxiliary composition. They are increasingly being utilized as primary generators for interactive control, timbre synthesis, and music generation.

There are several dedicated applications, such as Strangeworks, IBM Quantum Experience, and QPS, that allow the online design of quantum circuits. The initial stages of algorithmic composition in quantum computing typically revolve around quantum computing tools. Musicians who specialize in this area often come from computer science backgrounds and naturally use familiar programming tools to create music. However, for musicians with a primarily music background, practicing quantum algorithmic composition requires overcoming significant programming language barriers. Quantum programming experts are also working to develop integrated software environments that combine both computer tools and music tools, which is becoming the inevitable path for musicians in this field.

4.2. Recommendations

Quantum music is a further extension of the electronic music genre. The development of electronic music reflects the evolution from analog technologies to digital technologies, and now to the current era of AI technology. Throughout this process, the classification standards of electronic music have become diversified due to differences in technology, geography, and historical context. From specific musical forms to computer music, and then to AI-generated music, each phase mirrors the characteristics of the technological era it belongs to.

The classification of quantum music can draw upon these existing frameworks for electronic music (Sofer, 2020), with a particular focus on the “algorithmic object” as the primary basis for categorization. Similar to the division between “human” and “computer” in algorithmic composition, human-computer interaction is a defining feature of quantum computer music. Composers need to consider three interactive entities during creation: the computer, human-computer collaboration, and the creator. Based on these interactive subjects, quantum music can be classified into three categories:

1- Quantum Instrument Works. In this category, quantum computers serve as interactive subjects. They can be used in conjunction with traditional instruments to develop new timbres or operate independently as instruments. Works in this category can take the form of solos, concertos, or chamber music.

2- Quantum Computer Interactive Works. These works emphasize human-computer collaboration, exploring different modes of interaction such as interactive quantum music, quantum improvisation, and quantum computer ensembles. This category showcases the potential of quantum computers in real-time music creation.

3- Acoustic Works. Centered around the creator’s musical expression, quantum multimedia music includes multi-channel quantum electroacoustic music (such as stereo, surround sound, and panoramic sound) as well as works that combine visual elements, like quantum audio visualization and quantum soundscapes.

Grasping the essence of quantum computer music composition does not require rigid adherence to specific labels or terminology. Labels are merely “symbols”; the key lies in whether the musical content and formal characteristics correspond precisely. Different organizations and events, such as the Beijing International Electronic Music Festival[13] and the Shanghai IEMC[14], have established their own classification systems (for details on categories, see the official website links in the notes).

As quantum algorithmic composition continues to evolve, its development and classification will inevitably change. However, analyzing current musical examples corresponding to different types of quantum music creation provides a foundation for understanding the classification. In this study, classification is based on

13 Beijing International Electronic Music Festival Link: http://musicacoustica.zjcm.edu.cn/

14 International Electronic Music Competition (IEMC) Link: https://www.iemcchina.com/

interactive techniques, which not only satisfy the logical requirements of analyzing works but also highlight the importance of interaction tools as the technical core of quantum computer music.

4.3. Limitations

Currently, quantum algorithmic composition is still in its infancy, and the accessibility and stability of quantum hardware limit broader experimentation. Additionally, public awareness of quantum algorithmic composition need further development. The road to maturity for quantum computing is still fraught with challenges. One significant issue is Quantum Decoherence[15], which affects the stability of quantum bits in superposition states, limiting their ability to maintain coherence during parallel processing. As a result, algorithm optimization has become a key focus of ongoing research.

As of this writing, to ensure optimal quantum coherence, the design of quantum circuits must be constrained to shallow depths (approximately 10 layers) and narrow widths (around 5 qubits). Quantum algorithms serve merely as foundational building blocks of quantum systems, and their practical applications must address interaction challenges between quantum systems and interactive platforms. Additionally, robust quantum systems rely heavily on effective quantum programming and computational tools.

Looking ahead, the potential of quantum computing in music composition and performance holds immense promise. As quantum hardware becomes more accessible and stable, it is expected to open new avenues for experimentation and creativity in the music industry. Future developments in quantum algorithmic composition may lead to the expansion of interactive methods, moving beyond single MIDI gesture controllers to a more diverse array of interactive tools and techniques. This evolution could significantly enrich the expressive and creative possibilities of quantum music, enabling composers to explore new dimensions of sound, harmony, and texture that were previously unimaginable. Ultimately, the fusion of quantum computing and music is anticipated to contribute substantially to the evolution of music as an art form, offering new frameworks for creativity and innovation. As quantum technology advances, its impact on music may help shape a unique and vibrant cultural movement, further enriching the global music landscape with novel artistic expressions.

5. CONCLUSION

Spinnings represents a milestone at the intersection of quantum computing and music creation. It not only demonstrates cutting-edge technology in interactive system design and quantum synthesizer development but also opens a new frontier in computer music by integrating advanced quantum algorithms with traditional music theory. Although the piece primarily utilizes basic quantum gate algorithms for timbre synthesis, it offers a glimpse into the innovative possibilities that concepts like quantum walks could bring to musical elements such as counterpoint and texture.

Looking to the future, expanding the range of interactive techniques beyond a single MIDI gesture controller or delving deeper into quantum algorithm and circuit design could significantly enhance the creative space and expressive potential of quantum music. Through the technical analysis of quantum instruments and interactive systems in *Spinnings*, this study reveals that there is still considerable room for improvement in quantum music algorithm design. At the same time, the deeper integration of quantum computing technology with music creation and performance remains a field ripe for further exploration.

The construction of quantum algorithms has emerged as a core paradigm in quantum computer music, driving innovation at the technical level while introducing new possibilities for performing arts. In this context, composers are not only creators of music but also experts in technology, controlling quantum instruments through real-time interactions that provide audiences with a novel and unprecedented musical experience. This innovative performance model, based on quantum programming, is shaping a new paradigm for quantum computer music and paving the way for fresh possibilities in the evolution of music as an art form.

[15] Quantum Decoherence refers to the process in quantum mechanics where the coherence of an open quantum system gradually diminishes over time due to quantum entanglement with its external environment.

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Ethical approval

No data collection process requiring Ethics Committee approval was carried out in this study.

Author contribution

Study conception and design: WY, JL; data collection: WY, JL; analysis and interpretation of results: WY, JL; draft manuscript preparation: WY, JL. All authors reviewed the results and approved the final version of the article.

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Conflict of interest

The authors declare that there is no conflict of interest.

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Yazarlık katkısı

Çalışmanın tasarımı ve konsepti: WY, JL; verilerin toplanması: WY, JL; sonuçların analizi ve yorumlanması: WY, JL; çalışmanın yazımı: WY, JL. Tüm yazarlar sonuçları gözden geçirmiş ve makalenin son halini onaylamıştır.

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REFERENCES

Amoroso, R. L. (2017). Introduction to Conscious-Quantum Computer Musicology: New Genres, Technology and Ontology of Experience. In *Unified Field Mechanics II: Formulations and Empirical Tests* (pp. 575-583). World Scientific.

Childs, A. M., Gosset, D., & Webb, Z. (2013). Universal computation by multiparticle quantum walk. *Science, 339*(6121), 791-794.

Dalla Chiara, M. L., Giuntini, R., Leporini, R., Negri, E., & Sergioli, G. (2015). Quantum information, cognition, and music. *Frontiers in Psychology, 6*. https://doi.org/10.3389/fpsyg.2015.01583

Duarte, A. E. L. (2020). Algorithmic interactive music generation in videogames: A modular design for adaptive automatic music scoring. *SoundEffects-An Interdisciplinary Journal of Sound and Sound Experience, 9*(1), 38-59.

Dunjko, V., & Briegel, H. J. (2018). Machine learning & artificial intelligence in the quantum domain: A review of recent progress. *Reports on Progress in Physics, 81*(7), 074001.

Elgendy, R., Younes, A., Abu-Donia, H. M., & Farouk, R. M. (2024). Efficient quantum algorithms for set operations. *Scientific Reports, 14*(1), 1-24.

Hamido, O. C. (2022). QAC: Quantum-Computing Aided Composition. In E. R. Miranda (Ed.), *Quantum Computer Music: Foundations, Methods and Advanced Concepts* (pp. 159-195). Springer International Publishing.

Hrmo, P., Wilhelm, B., Gerster, L., van Mourik, M. W., Huber, M., Blatt, R., Schindler, P., Monz, T., & Ringbauer, M. (2023). Native qudit entanglement in a trapped ion quantum processor. *Nature Communications, 14*(1), 1-6.

Kounalakis, M., Blanter, Y. M., & Steele, G. A. (2019). Synthesizing multi-phonon quantum superposition states using flux-mediated three-body interactions with superconducting qubits. *Npj Quantum Information, 5*(1), 1-7.

Miranda, E. R. (Ed.). (2022). *Quantum computer music: Foundations, methods and advanced concepts*. Springer International Publishing.

Miranda, E. R. (2024). The advent of quantum computer music: Mapping the field. *Reports on Progress in Physics, 87*(8), 086001.

Miranda, E. R., & Miller-Bakewell, H. (2022). Cellular automata music composition: From classical to quantum. In *Quantum computer music* (pp. 105-130). Springer.

Miranda, E. R., Thomas, P., & Itaboraí, P. V. (2023). Q1Synth: A quantum computer musical instrument. *Applied Sciences, 13*(4), 2386.

Nimbe, P., Weyori, B. A., & Adekoya, A. F. (2021). Models in quantum computing: A systematic review. *Quantum Information Processing, 20*(2), 80.

Polychronakos, A. P. (2024). Quantum mechanical rules for observed observers and the consistency of quantum theory. *Nature Communications, 15*(1), 1-7.

Sofer, D. (2020). Categorising electronic music. *Contemporary Music Review, 39*(2), 231-251.

Wang, Z., Bao, Z., Wu, Y., Li, Y., Cai, W., Wang, W., Ma, Y., Cai, T., Han, X., Wang, J., Song, Y., Sun, L., Zhang, H., & Duan, L. (2022). A flying Schrödinger's cat in multipartite entangled states. *Science Advances, 8*(10), eabn1778.

Yang, W., & Lee, I. (2024). Research on the construction of AI composition system based on HMM. *Yegah Musicology Journal, 7*(3), 216-240. https://doi.org/10.51576/ymd.1536267

Yang, W., Huang, C.-F., Huang, H.-Y., Zhang, Z., Li, W., & Wang, C. (2024). Research on the improvement of children's attention through binaural beats music therapy in the context of ai music generation. In X. Li, X. Guan, Y. Tie, X. Zhang, & Q. Zhou (Eds.), *Music Intelligence* (pp. 19-31). Springer Nature. https://doi.org/10.1007/978-981-97-0576-4_2

Yang, W., Shen, L., Huang, C.-F., Lee, J., & Zhao, X. (2024). Development status, frontier hotspots, and technical evaluations in the field of ai music composition since the 21st century: A systematic review. *IEEE Access*, 12, 89452–89466. https://doi.org/10.1109/ACCESS.2024.3419050

Yoon, T. H., & Cho, M. (2021). Quantitative complementarity of wave-particle duality. *Science Advances, 7*(34), eabi9268.