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Strings—Sounds from Human Collective Intelligence

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Abstract: *Strings* is a musical installation that explores, through an evaluation of the cooperative functions of collective intelligence, human interaction and transforms it into a multisensory experience. Equipped with biometric sensors, *Strings* captures in real time the physiological variations within a group of people, translating psycho-emotional shifts into a distinctive sound and visual design. During the performance, the audience actively contributes to generating sounds. Some members of the audience are invited to wear specific biometric sensors. A performer guides them so they can actively take part in the experience. This interaction generates a data flow that translates participants' emotional state changes into real-time sound textures. A musician handles live electronics, processing and modulating the generated sounds. The performance is enriched by an improvising solo musician, such as a guitarist or saxophonist, interacting with the evolving sound design. This dialogue between the audience, live electronics, and soloists forms an ever-evolving, self-regenerating sound cycle that responds to the collective emotions. Emotional engagement is amplified by real-time coloured projections that respond to psycho-emotional variations, enhancing the collective sense of connection. This research contributes to collective intelligence by providing an unexplored framework for integrating biometric data into artistic expression. Our investigation aims to demonstrate biofeedback's potential in fostering collaborative, emotion-driven interaction, bridging psychology, music technology, and human-computer interaction. By engaging both the scientific community and artists, this work opens new avenues for interdisciplinary research and application in interactive media, emotion-aware technologies, and collective creativity.

Keywords: Collective Intelligence; Emotions; Biometric Data; Biofeedback; Electronic Music; Real-Time Sound Generation; Sound Design; Human-Computer Interaction

1. Introduction

The concept of intelligence has long shaped fields of both art and science. Intelligence is the attribute of the most brilliant insights, artistic works, compositions, and scientific inventions that have marked the progress of different cultures and humanity. However, beyond the discoveries and innovations that highlight individuals capable of expressing formidable flashes of genius, it is essential to consider the context that serves as a fertile environment in which such insights take shape, materialise, and become progress for the entire society.

In his seminal work, *The Idea of Progress: An Inquiry into Its Origin and Growth* [1], Bury provides a comprehensive historical analysis of the concept of progress, tracing its development from the Enlightenment to the modern era. Bury argues that the idea of progress is not an inherent or self-evident truth but a constructed notion that emerged from specific cultural, scientific, and intellectual contexts. He examines how advancements in knowledge and societal changes fostered a belief in the possibility of continuous improvement in human conditions. By analysing various dimensions of progress—technological, moral, and social—Bury critically assesses the optimism associated with the belief in progress, highlighting both its inspirational power and its limitations. His work underscores the importance of understanding the historical and philosophical underpinnings of progress to appreciate its impact on contemporary thought and policy.

This idea of progress emphasises that society provides the foundation for individuals to develop their identities and fully express themselves. At the same time, society is the context in which those ideas find concreteness and realisation. Society is configured as a multidimensional space of sharing, where individuals, connected by various social, cultural, and political bonds, collaborate in processes enabled by the synergy of complementary skills. These cooperative processes, fueled by the integration of diverse knowledge and skills, enable increasingly complex activities that drive community evolution. Building on Bury's analysis of progress, this study examines how societal advancements emerge not solely from individual ingenuity but also from collective intelligence, a phenomenon rooted in the interplay of shared knowledge and collaborative effort.

This study explores how collective intelligence can be observed, measured, and conveyed through an interactive artistic installation. Specifically, it investigates the relationship between group psycho-emotional states and real-time generative sound design. The central research question asks how biometric data from a group of individuals can be transformed into a meaningful and evolving multisensory artistic experience that reflects the dynamics of collective intelligence. The hypothesis is that biometric signals, such as heart rate and galvanic skin response, contain measurable patterns that correlate with group interactions and can be translated into an engaging audiovisual performance. By leveraging real-time processing of physiological data, we anticipate that *Strings* will create an immersive experience that dynamically adapts to collective emotional fluctuations. The expected outcomes include demonstrating that biometric data can serve as a meaningful medium for collective artistic expression, establishing a methodological framework for integrating physiological data with real-time generative soundscapes and providing insights into how collective intelligence manifests in artistic and technological domains.

Understanding the meaning and strength of collective intelligence requires an exploration of the psychological mechanisms that shape individual interactions within groups. By examining key psychological and social theories, we can uncover the fundamental processes that drive collaboration and collective creativity.

2. Scientific Foundations of the Project

2.1. The Psychological and Social Context of Collective Intelligence

In order to understand the potential of collective intelligence, it is helpful to explore some fundamental psychological concepts. In this case, we focused our research on individuals' relationships within groups and social networks, drawing inspiration from key scientific ideas that informed both the technological and artistic development of Strings. We delved into Freud's concept of the uncanny [2] and Hoffman's theory of empathy [3]. They both analyse the interaction between individual psychology and collective dynamics. Freud's concept of the uncanny was a key starting point for our research, serving as the initial theoretical spark that set the course for exploring collective intelligence. Its fundamental exploration of psychological tension inspired a chain of inquiries, leading to the examination of empathy and broader social dynamics. This progression mirrors the way scientific and artistic development often unfolds, one idea igniting another, creating a network of interconnected perspectives. Freud's idea of the uncanny highlights the unsettling tension between familiarity and its sudden disruption, leading to feelings of both acceptance and rejection. This dissonance is particularly relevant in collective settings, where cohesion can be destabilized by uncertainty. Hoffman's theory of empathy offers a counterpoint by demonstrating [4, 5] how shared emotional responses reduce psychological distance, fostering collective engagement. In the context of *Strings*, this interplay is essential. While the uncanny could introduce moments of cognitive dissonance within the group, empathy acts as a binding force, enabling performers to re-establish synchronization and coherence within the musical and social framework. The tension between unfamiliarity (the uncanny) and familiarity (empathy) mirrors the dynamic of individual navigation within a collective. By exploring these concepts, we gain valuable insights into the construction of collaborative and supportive networks within groups. This approach contributes to a deeper understanding of effective collective intelligence.

These psychological frameworks are particularly relevant to the *Strings* project because they illustrate the core tension in collective intelligence: the balance between individual autonomy and group cohesion. The uncanny describes moments of disruption within a collective, potentially destabilizing the emergent intelligence, whereas empathy fosters the synchronization necessary for effective group collaboration. By understanding these dynamics, we can explore how participants respond emotionally and cognitively to the system's real-time feedback, influencing the musical and social outcome of each performance. Additionally, alternative psychological models provide further insight into the emergence of collective intelligence. Integrating these perspectives strengthens our understanding of how psychological mechanisms underpin the evolution of collective intelligence in an artistic context.

The dynamics of *Strings* find an interesting parallel in the concept of connective intelligence theorized by Derrick de Kerckhove [6]. Just as the system's sensors collect and connect real-time data, facilitating a collective response, connective intelligence describes how connections between individuals, mediated by technologies or interactive systems, create emergent intelligence. De Kerckhove argues that this form of intelligence is not simply the sum of its parts but a dynamic and interconnected entity, capable of evolving through sharing and interaction. In *Strings*, the sensor network acts as a collective nervous system, translating individual interactions into a shared experience. Like De Kerckhove's *datacracy*, in which data shapes the collective experience, this translation allows participants to perceive and respond to the group *thought*, demonstrating how connectivity can indeed generate a form of collective intelligence.

While individual psychological experiences such as empathy and the uncanny influence interpersonal interactions, collective intelligence also emerges from broader group dynamics. The technological mediation of *Strings* demonstrates how real-time connectivity can shape group behaviour, reinforcing the idea that intelligence arises not only from psychological mechanisms but also from the structural dynamics of interaction. Social psychology provides valuable insights into how individuals function within groups, shaping collaborative efforts and decision-making.

2.2. Group Dynamics and Psychological Theories

Lewin's field theory [7], a cornerstone of social psychology, emphasises the dynamic interplay between individuals and their immediate environments. According to Lewin [8], behaviour is not determined exclusively by internal drives but also emerges from the "life space". The life space is a unique psychological field encompassing an individual's subjective representation of their world, shaped by past experiences, current desires, and future expectations. Within this life space, "valence" plays a crucial role. Objects, situations or relations within the environment carry either positive or negative valences, attracting or repelling the individual. Maintaining equilibrium within this dynamic field is essential. Any disruption to this balance creates tension, motivating the individual to restore harmony.

The "boundary zone" represents the interface between the individual's internal world and the external environment. This dynamic interplay is encapsulated in Lewin's equation:

$$B = f(P, E) \tag{1}$$

Where behaviour (B) is a function of the interaction between the person (P) and the environment (E). Lewin extended his theory to group dynamics [9], emphasising that groups are more than the sum of their parts. He coined the term "group dynamics" to describe the ever-changing relationships within a group, influenced by individual interactions and the group's overall dynamic.

Research supports the significance of group cohesion: positive, cohesive groups tend to be more productive and effective than those riddled with conflict. Leadership style plays a crucial role in shaping group dynamics. Lewin's research highlighted the contrasting impacts of authoritarian and democratic leadership styles on group productivity and member relationships.

Henri Tajfel's social identity theory [10] posits that individuals derive a sense of self-worth from their group memberships. This "social identity" fosters a sense of belonging and distinction through comparisons with other groups. Group success enhances individual self-esteem (BIRGing), while failure can lead to distancing oneself from the group (CORFing). Understanding these dynamics is crucial for fostering mutual support and maintaining group cohesion, even during challenges.

Cognitive biases, as explored by Tversky and Kahneman [11], also significantly influence group behaviour. These biases arise from "heuristics," mental shortcuts used to make quick judgments in complex situations. While helpful for efficient decision-making, heuristics can lead to systematic errors in perception and judgment.

The "motivated tactician" model, introduced by Fiske and Taylor [12], highlights the flexibility of human cognition. When motivated and possessing sufficient cognitive resources, individuals tend to engage in more careful and analytical processing, reducing the impact of cognitive biases. However, when under pressure or lacking resources, individuals rely more heavily on mental shortcuts, increasing the likelihood of errors. By understanding the interplay of social identity, cognitive biases, and individual motivation, we can gain valuable insights into the factors that influence group dynamics.

Culture significantly influences social behaviour. Geert Hofstede's work [13] highlights the distinction between individualistic and collectivist cultures. In individualistic cultures, autonomy and personal responsibility are emphasised, while collectivist cultures prioritise interdependence and shared responsibility. These cultural values shape self-concept and social behaviour. While Paul Ekman demonstrated [14] the universality of certain facial expressions, cultural norms significantly influence how emotions are displayed. Some cultures encourage open emotional expression, while others regulate it more strictly. Triandis further emphasises [15] the profound impact of culture on cognition and behaviour, influencing aspects like sensitivity to group dynamics and the degree of individual autonomy. Nonverbal communication (NVC) plays a critical role in social interactions. Facial expressions, gestures, eye contact, and interpersonal distance all convey crucial information about relationships. Edward T. Hall's concept of "proxemics" [16] identifies distinct zones of interpersonal space, from intimate to public, reflecting the varying levels of intimacy and formality in social interactions.

The interplay of group dynamics, social identity, and cognitive biases highlights the complexity of human collaboration. Building upon these psychological foundations, the concept of collective intelligence offers a broader framework for understanding how knowledge, skills, and creativity are shared across groups to solve complex problems.

2.3. Collective Intelligence

Pierre Lévy's concept of collective intelligence [17] posits a decentralised network where knowledge is shared and distributed among individuals to address complex societal challenges. This dynamic system, evolving through the interplay of human interaction and technology, transcends hierarchical structures, fostering intelligent and collaborative groups. Lévy envisions a future where humanity develops the capacity for "thinking together", a flexible and dynamic process that enables individuals to contribute their unique perspectives while harmonising within the collective. A key element, in Lévy's view, is the anthropological "knowledge space," a new realm where shared knowledge becomes the foundation of social organisation. Digital technologies facilitate the inclusive distribution of expertise, enabling collective interaction and learning on an unprecedented scale. However, the potential for social exclusion remains a critical concern. Ensuring equitable access to technology and promoting digital literacy is crucial for harnessing the benefits of collective intelligence while mitigating potential downsides. Lévy's vision extends to the realm of democratic governance, where collective intelligence empowers citizens to actively participate in shaping their communities. This participatory model emphasises continuous dialogue and shared decision-making, moving beyond traditional centralised power structures. In the artistic sphere, collective intelligence is transforming creative processes, inviting active audience participation. Interactive art forms blur the lines between creator and consumer, fostering a dynamic and collaborative exploration of meaning.

Collaboration and competition are intertwined forces within collective intelligence. While collaboration fosters shared goals and resource-sharing, competition drives innovation and ensures efficiency. The concept of "coopetition", a blend of cooperation and competition, exemplifies this dynamic, where organisations collaborate on strategic initiatives while simultaneously competing in the marketplace. The design and development of *Strings* hinge on understanding the principles of collective intelligence, including collaboration, competition, and the role of technology.

As collective intelligence evolves over time, it is deeply influenced by the prevailing cultural and intellectual climate—what is often referred to as the *Zeitgeist*. Examining the role of *Zeitgeist* allows us to understand how historical and technological shifts shape the way people collaborate and innovate.

2.4. *Zeitgeist*: The Spirit of Time

Zeitgeist [18], a German term meaning "spirit of the time", encapsulates the prevailing cultural, intellectual, and political climate of an era. Originating with Johann Gottfried Herder [19, 20], this concept, popularised by Hegel

[21], emphasises how each historical period possesses a unique spirit that drives societal development and shapes human consciousness. Philosophers like Hegel and sociologists like Durkheim and Weber explored how Zeitgeist manifests in societal trends. Hegel's dialectical method, for example, posits that history progresses through the clash and synthesis of conflicting ideas. Durkheim's concept of "collective conscience" highlights the shared beliefs and values that define a particular era.

Zeitgeist is evident in the evolution of music and technology. The digital era, characterised by rapid technological advancement and increased connectivity, has profoundly influenced collective intelligence. Platforms like SoundCloud, Bandcamp, and GitHub have democratised access to music creation and dissemination, fostering participatory culture and enabling new forms of collective creativity. Music genres themselves evolve in response to Zeitgeist, reflecting the social and political currents of their time. The counterculture of the 1960s, for instance, gave rise to distinct musical movements, while the increase in technology in the 1980s fueled the emergence of electronic music genres. Hip-hop, conventionally credited to the Bronx in the 1970s, exemplifies how Zeitgeist shapes artistic expression. This genre emerged as a reflection of urban culture and socio-political activism, with collective intelligence fuelling its evolution and dissemination.

The concept of Zeitgeist, which emphasises the influence of prevailing cultural and historical forces on collective consciousness, provides a valuable model for understanding *Strings*. By recognising the significance of Zeitgeist, *Strings* can effectively leverage the power of collective intelligence to explore new ideas in musical expression.

Having established the theoretical foundations of collective intelligence and its cultural manifestations, we now turn to its practical application. The Strings project embodies these principles, translating group interactions into real-time artistic and sonic experiences.

3. Strings: Sounds from Human Collective Intelligence

Strings: Sounds from Human Collective Intelligence emerged from a research group focused on computational sonology and sound topology. This project aims to explore the practical implications of collective intelligence by merging artistic expression with advanced technology. Building upon the theoretical framework discussed previously, *Strings* investigates how collective intelligence manifests in real-world scenarios. Through the integration of biometric sensors, live electronics, and solo musicians, the project translates physical and emotional dynamics into immersive sound and visual experiences. This approach mirrors the collaborative nature of collective intelligence, where diverse elements converge to create a unique and emergent outcome. *Strings* emphasise interactivity and audience participation, reflecting the contemporary Zeitgeist. The *Strings project* leverages the use of software platforms such as Max/MSP, Ableton Live, and other software. These platforms facilitate real-time data processing and sound manipulation, enabling musicians and participants to co-create different sound textures. The integration of technology into artistic practice enhances audience engagement and expands the possibilities for musical expression. *Strings* aim to apply theoretical insights into collective intelligence to a real-world artistic endeavour. By exploring the dynamic interplay between collaboration, competition, and cultural evolution within the context of a musical performance, the project sought to understand how these concepts manifest in artistic practice.

In our methodology, we focused on optimizing real-time biometric data processing using various algorithms. One approach similar to our work is the application of optimization techniques in *Skin Color Segmentation Based on Artificial Neural Network Improved by a Modified Grasshopper Optimization Algorithm* (2020) [22], which demonstrates how advanced optimization algorithms can improve the accuracy and efficiency of complex data analysis systems. Future iterations of our work may explore similar strategies to optimize the flow of real-time data and improve system responsiveness.

The *Strings project* utilises a system (Figure 1) equipped with biometric sensors to capture the nuances of human interaction. Key sensors include Galvanic Skin Response (GSR) sensors and pulse sensors connected to an ESP32 microcontroller. GSR sensors measure changes in skin conductance, providing insights into emotional arousal levels. Pulse sensors monitor heart rate, reflecting various physiological and emotional states. The use of GSR as an indicator of psycho-emotional arousal is well-established in both scientific research and medical applications. Studies [23] have demonstrated its effectiveness in assessing emotional responses in various contexts, including cognitive research, psychiatric evaluations, and human-computer interaction (iMotions, 2024; Tobii Connect, 2024) [24]. In clinical settings, GSR has been explored as a tool for understanding psychiatric and mental disorders, providing insights into autonomic nervous system activity and emotional regulation (Vetrugno, D'Elia,

& Montagna). In this project, GSR data was calibrated to determine participant activation levels reliably, filtering out signal noise to enhance measurement accuracy. Similarly, BPM data was processed within a defined range (60–180 bpm) to distinguish low from high activation states, ensuring consistency across different participants. These calibrations were crucial in maintaining the integrity of biometric measurements and their correlation to collective musical expression. The ESP32 board, programmed using the Arduino Integrated Development Environment (IDE), is integrated into a wearable fanny pack for participant comfort. The Arduino IDE is a versatile, cross-platform application that facilitates the writing, compiling, and uploading of code to Arduino-compatible microcontrollers, including the ESP32. IDE supports programming languages such as C and C++ and provides an environment for creating and testing interactive projects. Biometric data is collected from participants via sensors attached to their fingers and transmitted wirelessly to a computer running Max/MSP software for subsequent processing and interpretation.

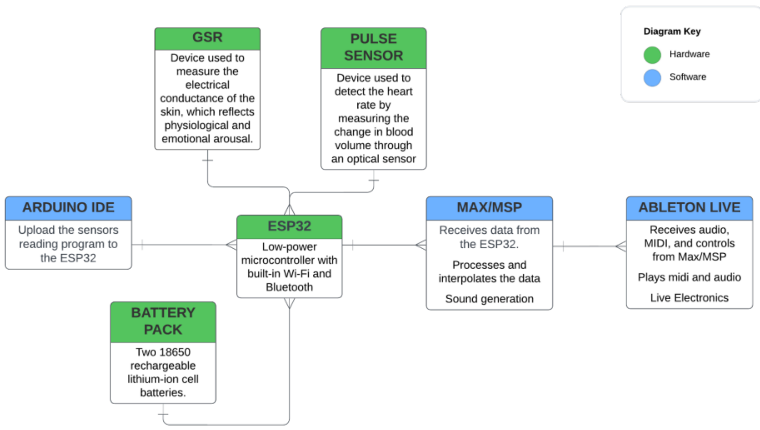

Figure 1. Strings software and hardware diagram.

This diagram illustrates the entire setup of the Strings project, encompassing both hardware and software components. It showcases the flow of biometric data from the participants to the Max/MSP software through the embedded sensors, with the data being processed and transformed into musical outputs. The figure outlines the integration of various devices, including Galvanic Skin Response (GSR) sensors, pulse sensors, the ESP32 microcontroller, and the Max/MSP platform used for real-time data processing.

Given the known challenges of biometric signal acquisition—such as motion artefacts, environmental noise, and individual variability—the system incorporates a multi-layered calibration process to enhance data reliability. The first filtering stage occurs at the hardware level, where biometric signals are pre-processed to remove extreme outliers. The second stage takes place within Max/MSP, where real-time interpolation filters further refine the incoming data. Real-time interpolation filters ensure that only meaningful fluctuations in physiological responses contribute to sound generation. The system is designed to detect consistent patterns rather than isolated spikes, reducing the influence of random fluctuations.

Within the Max/MSP environment, the collected biometric data undergoes a calibration process to account for individual physiological variations. *Strings* informatic systems acquire biometric data through sensors connected to Arduino boards. As previously discussed, the system employs sensors to measure galvanic skin response (GSR) and heart rate. Data collected from each sensor is transmitted in real-time to a computer running Max/MSP. Within Max/MSP, data from individual participants is categorised (GSR or heart rate). For each category, data from different participants is aggregated using various mathematical operations:

- Sum: The total of all values within the category.
- Mean: The arithmetic average of values within the category.
- Range: The difference between the minimum and maximum values.
- Standard Deviation: The arithmetic deviation from the mean.

The range of possible outcomes for each operation is divided into discrete subgroups representing "activation levels" of the group for that specific data category. For instance, a high average GSR value might correspond to a high level of emotional activation. The interplay between the number of participants, sensors, and data interpolation operations generates a vast array of potential combinations. These combinations can be ordered and indexed based on the group's psycho-emotional activation level in real-time. While qualitative descriptions provide valuable insights, this study also integrates quantitative measures to assess the relationship between biometric signals and collective intelligence. Specifically, the correlation analyses were conducted between GSR/BPM fluctuations and sound parameters, identifying statistically significant patterns. For example, a Pearson correlation coefficient (r) exceeding 0.75 was observed in multiple sessions, suggesting a strong relationship between group emotional arousal and sonic variations.

Additionally, variability assessments (standard deviation) were applied to monitor the range of physiological responses across participants, ensuring that individual differences did not disproportionately skew collective data interpretation. This combination of statistical methods strengthens the claims regarding biometric indicators as reflections of collective emotional states. The succession of measurements thus creates a dynamic update of the group's psycho-emotional state, forming a kind of "map" of the collective experience.

Each data category is associated with various musical outputs. Biometric inputs were mapped to specific musical parameters based on empirical testing to ensure coherence between physiological activation and audio output. The mapping process followed a structured framework:

- GSR (arousal level): Controls oscillator pitch shifts and modulation rates—higher GSR values increase pitch vibrancy and tremolo intensity.
- Heart Rate Variability (HRV): Influences rhythmic density and modulation effects—more significant fluctuations in BPM correspond to increased percussive complexity.
- Group Emotional Activation Index: A dynamic composite of average GSR and BPM used to determine reverb depth and harmonic layering.

This structured mapping was refined through iterative testing, ensuring that musical changes accurately reflected participants' collective psycho-emotional states. The calibration process also ensured musical coherence, preventing excessive sonic shifts caused by isolated outlier data.

Each data category is associated with various musical outputs:

- Digital Oscillators: Activation levels can control the frequency, amplitude, and waveform of oscillators.
- MIDI Tracks: Data can be translated into MIDI notes, controlling pitch, duration, and velocity.
- Effects and Modulator Parameters: Data can modulate parameters of audio effects like LFOs, reverb, delay, filters, etc.
- Other MIDI Parameters: Parameters such as pitching and BPM can be dynamically controlled.

During a performance, each combination of input data and categories triggers a specific sound, set of sounds, effects, or musical processes. This system generates musical experiences by dynamically combining a wide range of possible states that arise from the interactions and emotions of different people during a performance. The goal is to explore the relationship between collective emotional experience and its sonic expression, offering a performative experience that reflects the group's dynamics.

The development process of *Strings* involved an iterative testing and calibration phase with real groups in various situations. This phase was crucial for calibrating the ranges of values sent from the sensors to Max/MSP and for defining sound design computational and electronic choices. The tests allowed for collecting data on the system's actual response to variations in the group's psycho-emotional state, enabling the refinement of the mapping between biometric data and musical parameters. Diverse contexts were considered to ensure the system's robustness and reliability under various conditions.

The participant selection process was designed to ensure broad applicability rather than being restricted by predefined criteria. The initial focus was on validating the system's ability to process biometric data in real-time and generate meaningful sonic interactions. This open-ended approach allows for future exploration of how specific participant characteristics might influence emergent patterns in collective musical expression. The testing phase was conducted in two stages. The first set of sessions focused on the technical validation of the system, ensuring proper sensor functionality, data acquisition, and sound generation. Once the system's reliability was confirmed, subsequent sessions shifted towards assessing the music generation process itself, examining whether the transformations in sound accurately reflected biometric variations.

Each session began with the establishment of a neutral emotional baseline among participants to maintain consistency in experimental conditions. This procedure ensured that any variations in the sonic output were primarily driven by the system's response to real-time biometric inputs rather than external environmental factors. Given that the biometric sensors are embedded in textile materials that closely adhere to the skin, external environmental factors such as ambient temperature or humidity had minimal influence on the data. Furthermore, individual physiological differences were accounted for through a data calibration process in Max/MSP, ensuring the accuracy and consistency of the readings across participants. While movement is part of the immersive experience and interaction, it is treated as an integral element of the collective dynamics rather than a factor to be mitigated. As a result, each group contributed uniquely to shaping the evolving sonic atmosphere, reinforcing the concept of emergent collective intelligence through music.

The Figure 2 presents a visual representation of the entire system, emphasizing the devices surrounding the computer and their connections via Wi-Fi. It illustrates how the hardware has been specifically designed and assembled to meet the unique requirements of the Strings project. All components are connected and functioning, providing a clear depiction of how the biometric sensors, the microcontroller, and the central computer communicate seamlessly. The figure demonstrates the ad-hoc nature of the system's construction, customized to facilitate real-time data transmission and processing, which is pivotal to the performance's interactive dynamics and its real-time response to participant inputs.

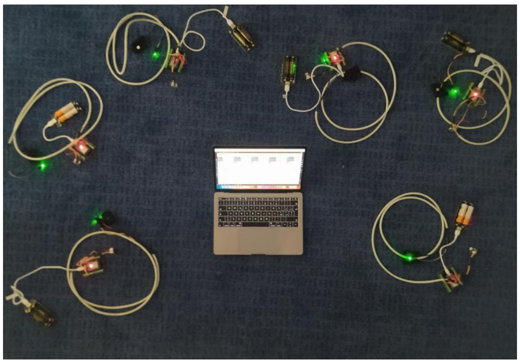

Figure 2. Strings devices on and connected via Wi-Fi.

Strings: Sounds from Human Collective Intelligence explores the intersection of art, technology, and human interaction. Utilising state-of-the-art biometric sensors and live electronics, it translates the subtle dynamics of collective human behaviour into a multisensory artistic experience. This project provides valuable insights into the potential of technology to enhance artistic expression and foster new forms of audience engagement. The live performance component of the project emphasises audience participation. Participants are invited to wear biometric sensors and engage in guided movements and interactions. These interactions, facilitated through physical contact and visual cues, generate real-time sounds that reflect the group's dynamic behaviour.

The Figure 3 provides a detailed view of the sensor-wearing setup, with the fanny pack serving as the wearable housing for the biometric sensors. The textile component on the fingers is designed to securely hold the sensors in place, ensuring accurate data collection while preventing contamination or interference from external factors. This feature is an essential element of the setup, as it addresses concerns regarding data integrity and user comfort. The figure emphasizes the careful design choices made to ensure the biometric data collected is reliable, which is key to achieving meaningful interactions between the audience and the sound design.

Figure 3. Strings fanny pack and sensors.

The live performance incorporates live electronics and a solo instrument, such as a guitar or saxophone. The musician interacts with the real-time biometric data, influencing the evolving sound textures. This interplay creates a dynamic dialogue between the musician, participants, and the generated sounds. This multi-layered process involves biometric data, live electronics, and solo performance. This process generates a continuous feedback loop between participants and the evolving soundscape. This feedback loop intensifies the collective experience, making each performance an exploration of human interaction and artistic expression.

4. Biometric Data to Sound

Understanding audience reactions in the Strings project requires a framework for categorizing physiological and emotional states. One crucial concept in this categorization is arousal, which refers to the level of activation within an organism. This activation manifests both physiologically, through changes in heart rate, respiration, and neural activity, and psychologically, through subjective experiences of alertness and emotional intensity. Arousal operates on a continuum, ranging from deep relaxation to heightened excitement or stress. This concept is particularly relevant in performance settings, where variations in arousal influence audience engagement and the dynamic evolution of collective experience. As observed by Yerkes and Dodson [25], performance increases with arousal up to a certain point, beyond which further arousal leads to a decline. Furthermore, Eysenck [26] utilized the concept of arousal to explain individual differences in personality, highlighting its role in shaping behavioural responses and engagement levels.

The Yerkes-Dodson Law illustrates the relationship between arousal and performance (Figure 4). Performance increases with arousal to an optimal point, beyond which further arousal leads to a decline.

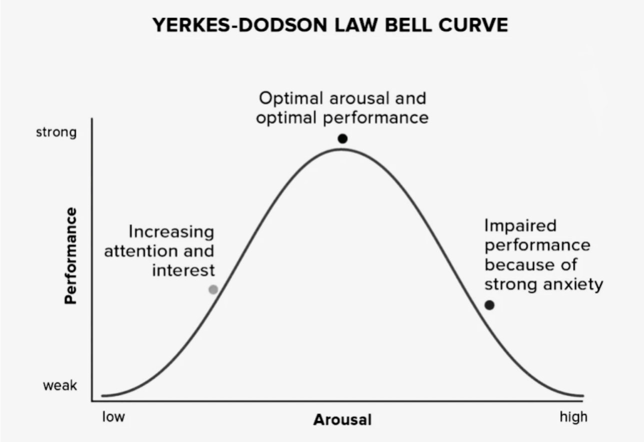

Figure 4. Yerkes-Dodson law curve.

To further refine our classification of audience responses, we incorporate the Arousal-Valence Model, as developed by James A. Russell [27]. This model describes emotional experiences along two core dimensions: arousal (intensity of the emotion) and valence (pleasantness of the emotion). High-arousal, positive-valence emotions include excitement and joy, whereas high-arousal, negative-valence emotions encompass stress and anxiety. Conversely, low-arousal, positive-valence states reflect calmness, while low-arousal, negative-valence states relate to sadness. By applying this framework, the Strings project organizes biometric data into distinct emotional categories, improving the precision of real-time emotional mapping within the performance environment.

A visual representation of the Arousal-Valence Model (Figure 5). The image shows a two-dimensional space with arousal on the vertical axis and valence on the horizontal axis, with examples of emotions placed within the quadrants.

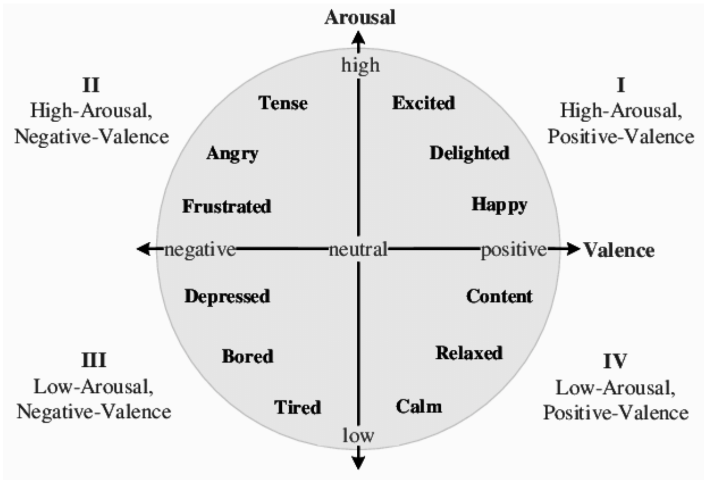

Figure 5. Arousal-Valence Model.

Building upon these theoretical foundations, each received biometric parameter, such as heart rate variability and galvanic skin response, is analyzed within a specific range of activation and non-activation. Rather than treating data as continuous, the system categorizes them into discrete sub-ranges, each representing a distinct level of psycho-emotional engagement. These defined ranges allow for a structured approach to mapping physiological inputs to sound parameters, ensuring that shifts in the collective emotional state are accurately reflected in the sonic output. The categorization process follows a structured framework, balancing empirical testing with theoretical models to create a responsive and meaningful interactive experience.

The *Strings* system classifies biometric data into varying levels of activation, following the principles of the Arousal-Valence Model. As shown in Figure 6, all incoming data undergo an intricate process of interpolation, ensuring that each combination of parameters can trigger specific musical elements, including pitch, oscillators, note sequences, or chains of audio effects.

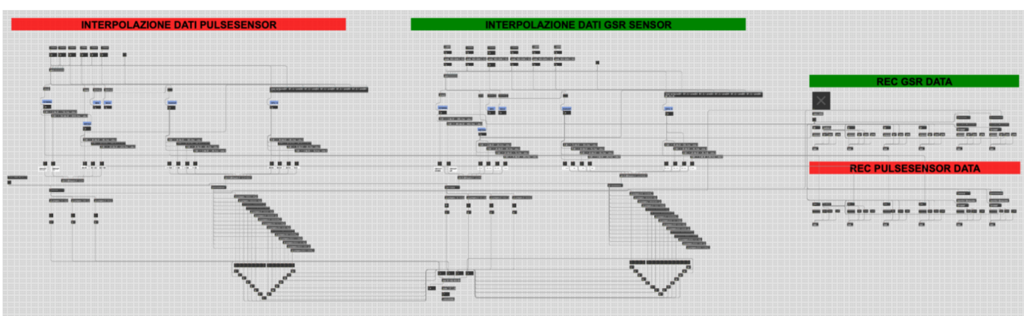

Figure 6. Max/MSP subpatch; data interpolation system.

This interpolation system accounts for all connected devices and the specific sensors within each device, refining its responsiveness through iterative testing. Given that heartbeat is an objectively measurable parameter, it serves as a key example of the data interpolation process (Figure 7). In Max/MSP, six heartbeat sensors contribute to real-time data analysis, categorized using different statistical measures:

- Sum: Establishes an activation/non-activation threshold at 720, determining whether the system engages or remains inactive.
- Mean: Defines three activation levels: low (60–90 BPM), moderate (90–120 BPM), and high (120–180 BPM).
- Range: Expands into four activation levels: 0–30 BPM (lowest), 30–60 BPM, 60–90 BPM, and 90–120 BPM (highest).
- Standard Deviation: Further refines activation intensity with four levels: 0–15 BPM, 15–30 BPM, 30–40 BPM, and 40–50 BPM.

Through this structured approach, the system dynamically categorizes audience engagement, allowing for real-time modulation of sound parameters.

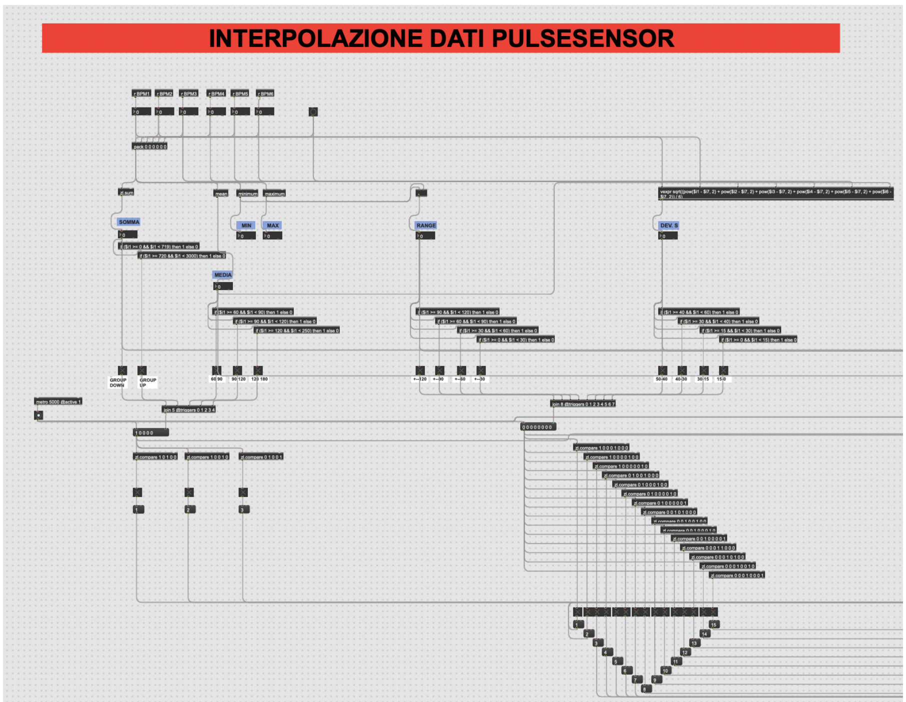

Figure 7. Data interpolation; example on BPM data.

The system maps biometric data onto a set of musical parameters in Ableton Live, where different activation levels correspond to specific sound texture configurations. The selection of pitches, note combinations, and effects is determined by the detected activation range, influencing the generated sound. Audio effects such as reverb, delay, and modulation are applied based on the system's categorization of biometric inputs, while spatialization adjusts the positioning of sounds within the virtual soundscape.

Through iterative testing, all biometric combinations have been collected and systematically scaled, allowing the system to refine its response over time. Each test introduced new possible combinations, which were incorporated into the system, while feedback from these trials enabled progressively more precise categorization. Figure 8 illustrates how different biometric inputs contribute to the activation of pitches, note sequences, and audio effects, which are then sent to Ableton Live for further sound processing. The system integrates all detected activation levels, ensuring that the generated sound reflects the overall physiological engagement rather than isolated signals. This structured combination logic enhances the coherence of the sonic output, making the system increasingly responsive and adaptive to biometric variations.

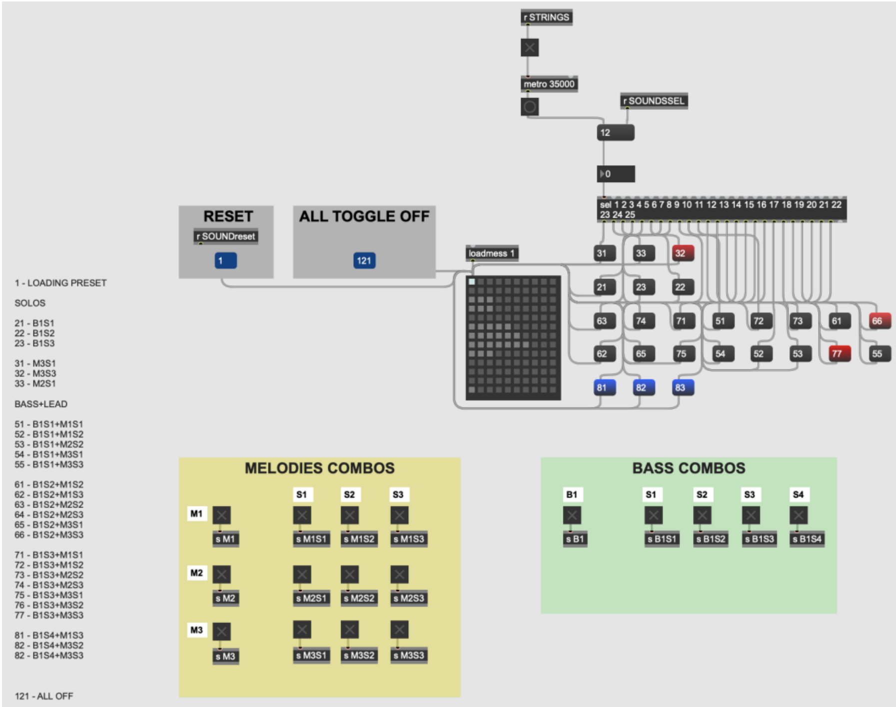

Figure 8. Sound generation combos.

To develop a cohesive and adaptive sound environment, the system employs a structured combination logic that integrates multiple biometric inputs into a unified musical response. Rather than triggering isolated sounds, this logic allows for the blending, layering, and modulation of sonic elements based on the evolving physiological data. By layering different sound components, the system generates multiple textures and timbres, with varying intensities determined by the combined activation levels of multiple biometric signals. This ensures that the sonic output remains rich and dynamic. Blending techniques are applied to ensure a smooth transition between different activation levels, preventing abrupt shifts in the auditory experience and maintaining a coherent sound flow. Rather than creating sharp changes, this logic allows the system to modulate musical parameters progressively, aligning with the continuous nature of biometric fluctuations. The adaptive nature of the system extends beyond fixed mappings, allowing musical structures to evolve dynamically in response to real-time variations in biometric data. Instead of rigidly following predefined sequences, the system continuously refines the relationship between biometric inputs and sound parameters, ensuring a responsive and immersive experience. To achieve a more accurate representation of collective engagement, data interpolation is guided by a weighted approach, ensuring that multiple biometric inputs are effectively integrated. This process does not prioritize any single data point but rather balances all received inputs to generate a comprehensive and representative dataset, allowing the system to modulate sound output in a way that reflects the overall physiological state. This comprehensive approach to combination logic ensures that the system does not simply react to isolated biometric triggers but instead continuously adapts to a complex and fluctuating set of inputs. The result is a responsive and immersive auditory environment that reflects the collective engagement levels in real time, maintaining coherence and musical integrity throughout the performance.

The system operates wirelessly in real-time, utilizing ESP32 boards that communicate via UDP with Max/MSP. This low-latency connection ensures that biometric data is continuously transmitted and processed without delay, allowing immediate sonic adaptation based on audience engagement levels. As activation data is received, it is interpolated and mapped to specific musical parameters in Ableton Live, ensuring a seamless transformation of physiological input into sound. This real-time responsiveness creates a dynamic feedback loop, where shifts in collective activation levels directly influence the evolving sonic landscape. The system's continuous adaptation enhances the immersive quality of the performance, ensuring that the generated sound is not only reactive but also fluidly aligned with the ongoing physiological and emotional state of the audience. Through this approach, the musical composition remains organically shaped by real-time biometric fluctuations, reinforcing the interactive and performative nature of the experience.

5. Results

The analysis of the collected data revealed intriguing patterns, as illustrated by the heart rate examples below (Figures 9 and 10). Early phases of the performances often showed relatively low heart rate variability, indicating a calmer state. However, subsequent interactions within the group and with the environment led to significant fluctuations in heart rate across different groups. These variations suggest that each performance generated a unique emotional and physiological landscape shaped by the specific dynamics and interactions of that group. Furthermore, the data consistently demonstrated a trend towards a gradual return to a more balanced state after periods of heightened activation. As shown in Lewin's field theory, this indicates the process of adaptation and self-regulation within the group.

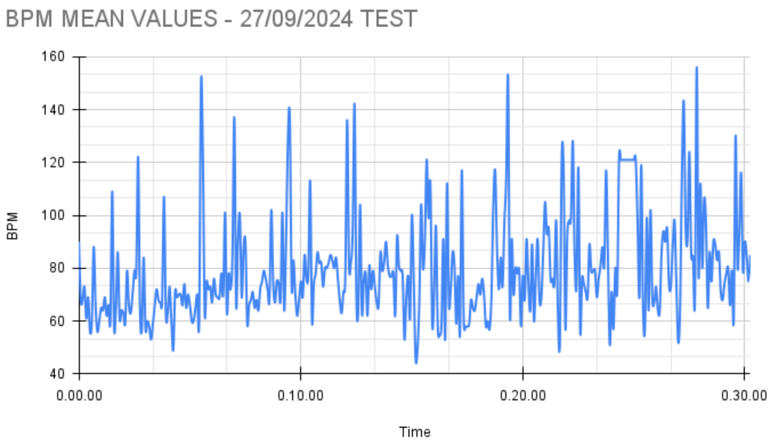

Figure 9. Strings test chart.

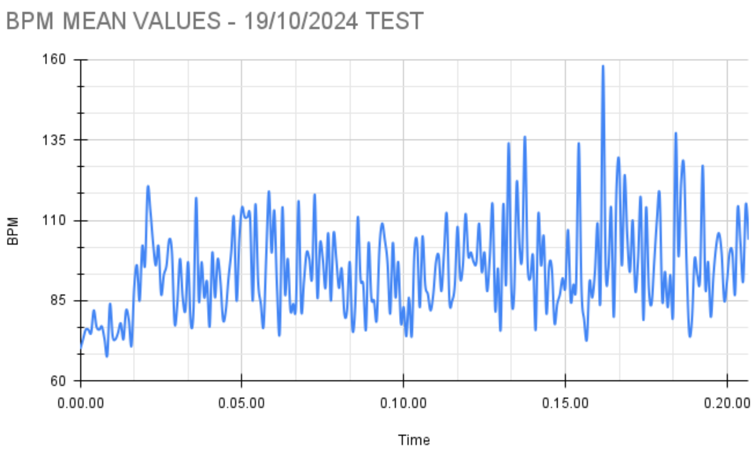

Figure 10. Strings test chart.

The study's methodology accounted for potential sources of signal contamination, such as motion artefacts and sensor misreadings. By integrating pre-processing filters and statistical variance checks, the system effectively discarded unreliable data, ensuring that observed patterns genuinely reflected collective dynamics rather than random noise. This methodological approach reinforces the validity of using physiological signals as indicators of group intelligence and emotional synchrony.

Furthermore, statistical significance tests were applied to compare biometric fluctuations between different performance phases. Results demonstrated that group emotional engagement, as reflected in GSR and BPM variations, is significantly correlated with sonic transformations. The quantitative validation further supports the hypothesis that physiological signals provide meaningful insights into the emergence of collective intelligence in a musical context.

All these elements, supported by all the collected data, emphasise the dynamic and emergent nature of collective intelligence observed in this research.

This figure shows a test chart of heart rate data (BPM) as an example of how the system collects and processes biometric inputs. The chart illustrates how fluctuations in heart rate are recorded and how these variations contribute to the system's real-time music generation process. By visually representing the heart rate data, this figure highlights the critical role of physiological signals in shaping sound parameters, such as rhythmic density and modulation. It is crucial to understand how the system translates emotional and physiological variations into musical outcomes, showing the link between biofeedback and sound design.

Similar to Figure 9, this chart provides another example of BPM data collection, further demonstrating the system's capability to gather and process heart rate variations. The comparison between different tests allows for a more robust understanding of how the system works across varied conditions and participant inputs. This figure underscores the consistency and reliability of the data collection process, illustrating its pivotal role in informing the dynamic soundscape and the evolving sonic textures during a performance.

6. Conclusions

Building on these insights, *Strings: Sounds from Human Collective Intelligence* explores the potential of human collaboration mediated by technologies. Drawing inspiration from psychological and sociological concepts, *Strings* translates these ideas into immersive audiovisual experiences that engage both artists and audiences as active co-creators. By integrating music technology, biometric sensors, and real-time data processing, *Strings* aims to render visible and audible the intricate network of interconnections within a group. This approach offers a perspective on the dynamics of collective intelligence and its potential for artistic expression.

The project's integration with artificial intelligence presents exciting avenues for future development. By analysing the collected data, the project can contribute to the development of AI models capable of recognising and reproducing specific group dynamics. Beyond technological advancements, *Strings* aspires to cultivate a deeper understanding of the value and potential of collective intelligence. The shared experience fostered through the project aims to inspire participants to reflect on their own role within a collective and recognise the power of collaboration in driving innovation and social progress.

Once the system has demonstrated its reliability and explored the full spectrum of artistic expression possibilities, there is significant potential for further development. One promising direction involves creating an integrated model in collaboration with technological industries to enhance its usability across various domains. Such advancements could extend the application of the system into different sectors, enriching its potential for real-world impact. Additionally, we would be glad if this research could contribute to medical fields, particularly within social sciences or psychological applications. The collective creativity aspects explored in this work will resonate across many disciplines, fostering growth in both artistic and practical spheres. Our research is positioned to provide meaningful insights and could be embraced widely in diverse settings, from creative industries to therapeutic contexts.

Author Contributions

Conceptualization, D.M.; methodology, F.F.; software, D.M.; validation, D.M. and F.F.; formal analysis, D.M. and F.F.; investigation, D.M.; resources, D.M. and F.F.; data curation, D.M.; writing—original draft preparation, D.M.; writing—review and editing, D.M. and F.F.; visualization, D.M. and F.F.; supervision, F.F.; project administration, D.M. and F.F. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data is unavailable due to privacy restrictions.

Conflicts of Interest

The authors declare no conflict of interest.

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