Happy Cycling

A bicycle-based collaborative interface for music making

Master Thesis

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Abstract:

Happy Cycling stands as a pioneering collaborative musical interface born from an innovative design concept. It transcends the realm of trained musicians to embrace a diverse audience and deliver an enjoyable, engaging, and meaningful musical experience in public spaces and museums. This achievement is realized through an accessible interface, utilizing repurposed bicycle wheels for interaction, and placing a strong emphasis on collaboration among participants. The user-friendly interface of the project encourages exploration and self-expression. A custom-made sensor system featuring IMUs and hall effect magnetic switches controls audio playback and effects.
The evaluation produced positive outcomes, underscoring the project's success in providing a significant collaborative musical experience. Nonetheless, it's worth noting that the interface proved more challenging for novice musicians, while experienced players found it more accessible and rewarding. Potential biases in the evaluation, including underrepresentation of certain aspects and musical categories, should be acknowledged in the assessment of these results.

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Rapportens indhold er frit tilgængeligt, men offentliggørelse (med kildeangivelse) må kun ske efter aftale med forfatterne.

Contents

Preface

This master thesis report has been written in fall 2023 under the supervision of Dan Overholt. I extend my gratitude to him for his invaluable assistance throughout the months of diligent research and creation. I also want to thank Jesper Greve and Peter Williams of AAU Manufakturet and Andreas Moltesen for their support during the design and construction stages.

The essence of this project lies in the creation of a collaborative interface tailored for spontaneous music creation within the context of interactive sound installations. This innovative system repurposes recycled bicycle components, readily available throughout the city of Copenhagen, to offer an engaging and instinctive platform for music improvisation.

The technical implementation was carried on using the programming software Max-MSP, various M5 ATOM Matrix sensor devices and hall effect switches and an ESP32 development board. The system takes advantage of the WiFi technology built-in the ESP32 to transmit data wirelessly within the networked system of sensors and microcontrollers.

Designed to be readily accessible for spontaneous interaction, this system is intended for deployment in art galleries, venues, and festivals, thereby aiming to deliver an engaging and fun auditory and interactive experience to the audience.

Aalborg University, October 16, 2023

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Chapter 1

Introduction

The landscape of musical instruments is undergoing a transformation, marked by the emergence of a novel category – collaborative instruments. With its origins dating back to the pioneering work of John Cage and Stockhausen [29], this trend has come a long way. Over the years, these collaborative instruments have evolved, driven by cutting-edge technologies and electronic systems. Their primary objective is to provide immersive and gratifying musical experiences, transcending the traditional confines of musical expertise and making the enchanting world of music accessible even to individuals with limited formal training. While it is true that certain collaborative instruments cater to trained and expert musicians [14], the instruments under current discussion stand apart by their unwavering commitment to the enhancement of the player's experience [27]. Their core mission is to cultivate the subtle interpersonal dynamics that naturally unfold when players engage in collaborative music-making, focusing not just on the musical outcome but also on the rich tapestry of interactions between players.

In the realm of collaborative interactive art and music-making, "Happy Cycling" stands as a pioneering exploration of unconventional design concepts. It employs repurposed everyday objects to craft an intuitive and approachable interface, ultimately striving to provide an engaging, enjoyable, and profoundly meaningful musical journey for every participant in the experience. This journey through the transformative landscape of collaborative instruments offers an intriguing exploration of how technology and design are harmoniously converging to democratize the joys of musical engagement. The following pages delve deeper into the many facets of these collaborative instruments, dissecting their historical roots, design philosophies, and their impact on the music-making experience.

1.1 Motivation and Goals

The motivation behind this project is driven by a strong desire to explore unconventional and innovative designs, employing repurposed objects to facilitate music-making in public spaces. The system's core philosophy revolves around inclusivity, extending its accessibility beyond trained musicians to encompass a diverse audience. Strong emphasis is placed on fostering collaboration among audience members, with the belief that collaborative work can help individuals with limited musical backgrounds understand the musical process and interaction, rendering their music-making experience more enjoyable. The interface is therefore designed to be user-friendly and inherently intriguing, leveraging its traits of approachability and amusement while offering ample opportunities for exploration and expression.

The choice to incorporate familiar objects into the design is motivated by the belief that the audience's familiarity with the utilized objects will serve as a bridge to establish an immediate and profound connection with the musical system. It is argued that these commonplace items help establish an immediate cognitive link between the observed object and its conventional utility, thus becoming suggestive a specific type of interaction. This project uses bicycle wheels, because they are "the most ubiquitous objects" within the urban landscape of Copenhagen. Here, bicycles serve as an emblematic symbol of daily life, fostering a profound sense of familiarity among the city's inhabitants. The revelatory moment occurs when participants discover that these objects possess the unexpected ability to produce sound, triggered by the most natural of actions associated with them, such as spinning the wheel.

1.2 Research question and problem statement

How to design an engaging and meaningful interface for music making in public spaces, that fosters collaboration between audience members, using repurposed everyday objects?

Chapter 2

Analysis

2.1 Collaborative music-making in public spaces: design strategies

Designing interactions for public spaces, such as galleries and museums, poses unique challenges due to the diverse range of individuals comprising the audience. Visitors to such events posses varying levels of musical expertise, ranging from musical novices [4] to those with more advanced backgrounds. Providing meaningful musical experiences to such a diverse audience is a complex undertaking, and it typically entails the development of interfaces that ensure an inclusive and engaging experience for all [2]. While novices may seek a rewarding musical result without engaging in elaborate and sustained interaction, as highlighted by the principles of "instant music" [10] and "low entry fee" [30], more expert visitors might desire access to more advanced creative efforts over time. To accommodate these needs, the focus of the interaction often shifts towards promoting collaboration among audience members, thus rendering the musical process a fun group activity [2] rather than a daunting attempt to play music.

Previous research in the field has contributed a range of design strategies aimed at creating meaningful musical experiences for broad audiences. While collaborative interfaces are instrumental in establishing such connections [2], this literature review also highlights principles that extend beyond collaboration.

2.1.1 Simple and intuitive interfaces

A fundamental and universally accepted design principle that encourages novices to engage with the musical system, is designing interfaces that are simple, intuitive, and easy to learn [5]. This principle is particularly relevant in contexts such as museums or galleries with a substantial number of visitors, where individuals

often have limited time to become familiar with the interface. The amount of "play time" can be influenced by several other contextual factors, such as the capacity of the space, the presence of other waiting audience members, and the possibility that the player's companions may move on, as demonstrated during Bengler's and Bryan-Kinns' public exhibition of *Polymetros* [2].
A common strategy to address this principle suggests limiting the range of musical possibilities [5], for example, by allowing players to modify some parameters inherent to the music rather than creating music from scratch. This is often achieved through the use of pre-recorded musical phrases to guide players towards a predetermined musical output. The main argument against this approach is that these restricted possibilities for affecting the music leave players with very limited control and influence over the music [19] [29], and give rise to the question whether they are sufficient to convey a 'sense of musical agency and the genuine experience of making music' [2].

Another common strategy to address the simplicity of the interaction is that of designing interfaces that serve a single or a limited set of functions. Perry Cook's principles "programmability is a curse" and "smart instruments are often not smart" underscore the idea that while providing players with the ability to configure, redefine, and remap an instrument's parameters may seem empowering, it can, in fact, lead to confusion and a state of "interactive paralysis" [10].

Perry Cook's PhISEM instrument collection serves as compelling evidence in support of these principles. PhISEM comprises instruments crafted from everyday objects such as the Fillup Glass, the Java Mug, and the Frog Maraca, among others. Cook conducted tests with these instruments involving children and noted that their success stemmed from the fact that each instrument served a single function and consistently performed that function when activated [10]. This observation underscores the expectation among users that an instrument should behave predictably and reliably. Having an instrument with a fixed set of functions that cannot be reprogrammed contributes to a sense of security and consistency in interaction. Cook also highlights the significance of using everyday objects in the instrument's design. He notes that people derived great enjoyment from creating fairly complex music with these seemingly simple and whimsical devices [10]. This approach is rooted in the idea that the interface should not resemble traditional musical instruments, which tend to convey a sense of complexity and expertise. This perception can be intimidating, particularly for novices, and may deter them from engaging in musical activities. By using familiar objects in the design, the aim is to create a sense of comfort and ease, encouraging a diverse audience to explore and enjoy the musical experience without feeling overwhelmed by the prospect of needing prior expertise.

Most of the strategies exposed above are tailored to facilitating the music-making process for novices, and they most likely will not appeal to more expert players. This consideration underscores the importance of striking a balance between simplicity and virtuosity [30], by not letting the initial ease of use hinder the development of musical expressivity over time.

2.1.2 A metaphorical approach to mapping

The use of metaphors in the design of intuitive mappings is a powerful strategy to enhance the approachability and transparency of interactive music systems. Metaphors are powerful figures of speech in which one object or concept is described through the qualities of another, offering a unique way of looking at things from different perspectives. Furthermore, they draw their meaning from a shared repository of "common knowledge" derived from various aspects of human experience and culture. This is the reason why, in the context of electronic musical system design, they play a crucial role in facilitating a rapid and intuitive comprehension of the device's functionality [11] and the interaction associated with them. Metaphors can therefore be used to present a complex and intricate musical process in a simplified manner, grounded in commonly understood concepts. By aligning the system's interactions with familiar and easily understood metaphors, users can more naturally relate to the actions they perform and the outcomes they produce. The use of metaphors is particularly effective in enhancing *transparency* of control, a principle that refers to the extent to which the relationship between the player's gestural input and the resulting sound output is readily apparent and comprehensible to both performer and audience [13]. Increased transparency contributes to heightened *expressivity* in performances, allowing for the effective conveyance of emotions and meanings through music [13].

A notable example of metaphorical mappings is Luke Dahl's and Ge Wang's *SoundBounce* [11], an iPod-based collaborative instrument. The authors drew inspiration from the metaphor of "sound as a ball" after observing that holding the iPod with the screen facing up and performing a wrist-tilting gesture, resembled the act of bouncing a ball on a pad. Shortly after they realised that they could pass the ball among a co-located network of iPods, effectively creating a collaborative ball-playing game. In SoundBounce, a physical model of a bouncing ball is implemented and sonified using FM synthesis. The height of the virtual ball controls both the frequency of the carrier oscillator and the amplitude of the modulating oscillator. As the ball rises, the sound rises in pitch and becomes spectrally brighter, aligning with the metaphorical association between spatial height and melodic pitch height. Impact sounds are generated whenever a performer bounces the virtual ball, and if a player fails to hit the ball before it falls below a certain height, a crashing sound is triggered. The sound-producing gestures are also consistent with the ball game metaphor, a factor that further contributes to the coherency and realism of the user experience. Players take aim by holding the iPod horizontally and pointing it at another player, then pass their sound by making an over-handed throwing gesture.

2.2 Collaboration in music-making activities

Other principles for designing meaningful musical experiences for broad audiences emphasize the collaborative aspects of the interface in establishing creative connections between players. It is evident in previous literature that establishing meaningful connections among participants can enhance the overall enjoyment of the experience and lead to unexpected musical results that would be otherwise unachievable [29]. This is particularly achievable when the interface is designed with simplicity in mind, as it directs the participants' energies toward mutual interaction rather than grappling with complex musical intricacies.

2.2.1 Traditional Ensembles

Collaboration stands as a cornerstone of traditional music ensemble performance, wherein the combined efforts of individual musicians yield a collective musical outcome. From a strictly technical viewpoint, the significance of collaboration lies in its direct correlation with the quality and cohesion of the music produced. The rich and varied pool of cognitive resources within a group opens up possibilities for the development of novel musical ideas and diverse modes of interaction, enhancing creativity and expressiveness [3]. Therefore, musicians actively pursue collaborations to broaden their creative horizons, seeking partnerships that spark new creativity, and lead to the generation of innovative musical concepts. They aspire to explore unfamiliar territories in the research of richer and more diverse sounds, while nurturing their personal development and musical growth. The social aspect of collaborative music-making is equally important, and it should not be overlooked, as collaboration enables musicians to establish meaningful connections with like-minded individuals who share their interests and passions [3]. Moreover, the social dimension of collaboration adds an element of enjoyment and engagement to the musical journey. Collaborative music-making often becomes a shared adventure, where the process of creating music is not just a technical exercise but a collective experience filled with joy, interaction, and shared creativity.

Communication serves as the lifeblood of this collaborative process, encompassing both verbal and non-verbal cues. Effective communication ensures that musicians share their musical insights, align their creative visions, and respond adeptly to changes within a performance. These dynamics, when harmoniously navigated, enhance musical synergy, resulting in a performance that transcends the sum of its parts. Non-verbal communication cues are integral to this process. They encompass a rich tapestry of signals and interactions, including habits and behaviours learnt through personal contact with other practitioners and by observing and interpreting their actions [18]. Eye contact, facial expressions, body language, subtle physical gestures and expressive postures become a language of its own, enabling musicians to remain acutely attuned to one another and to adjust their own performance in real-time to create a harmonious whole [3].

2.2.2 Networked musical systems

In recent decades, the advent of cutting-edge technologies has inspired fresh perspectives on collaborative music-making. These perspectives transcend the traditional paradigm music ensembles, leveraging upon electronically-facilitated musical systems that underscore interdependency among players. As exemplified by Weinberg [29], interdependency refers to the ability of the players to influence each other's contributions to the final musical outcome, through electronic or mechanical connections between their instruments. This feature has been demonstrated to cultivate nuanced interpersonal dynamics [20] and enhance the overall player experience [20] [29] of making music.

Previous literature [1][20][29] offers valuable insights into the evolution of networked musical systems. These sources collectively acknowledge John Cage as a pioneering figure in this field. In his composition *Imaginary Landscapes No. 4* (1951), designed for 12 transistor radios and 24 performers, each radio is assigned to a pair of performers. One performer controls the frequency while the other controls the volume. This composition exemplifies a rudimentary form of inter-player dependency, where performers are intimately connected in their tasks and intentions, wielding the power to profoundly shape the musical outcome. However, it is noteworthy that direct electronic or mechanical links between performers or their instruments are still missing. Similarly, Stockhausen's *Mikrophonie II*, created in 1964, engages 6 performers divided between 2 tam-tams, 2 microphones, and 2 filters. This composition shares characteristics with Cage's work, emphasizing a fundamental form of interdependence among performers. A significant milestone in the history of electronically interconnected musical networks occurred in 1978 with the formation of *The League of Automatic Composers*. This group of three performers introduced a setup featuring early computers and a basic communication protocol that allowed them to exchange musical instructions in real-time, enabling them to influence each other's work directly. This development marked the first instance of an electronically interconnected musical network in history.

Weinberg's seminal work [29] offers a comprehensive taxonomy of networked musical systems, classifying them based on their social organisation and on the nature of their connections [20], on the level and nature of the inter-player-dependency, on their location and other parameters. Such distinctions are vital for situating the proposed sound sculpture within the spectrum of interactive musical systems.

Weinberg's taxonomy distinguishes between:

- Local vs. Remote Networks: In small-scale local networks, performers share a physical space, enabling real-time communication and nuanced interpersonal interaction among 3 to 10 closely situated players. In contrast, large-scale local networks accommodate 10+ participants, but may prioritize broader group dynamics over individual contributions. Remote networks, on the other hand, connect dispersed performers, often via the internet, hindering the transmission of clear gestural performance cues [1].

- Process-centered vs. Structure-centered Networks: Process-centered networks prioritize the player's experience (social, creative or educational), often fostering exploratory interactions devoid of a defined direction or goal. In contrast, structure-centered networks guide players toward specific objectives, potentially offering rewards. Interaction dynamics may adopt a collaborative or competitive approach.

- Centralized vs. Decentralized Networks: Centralized networks are typically controlled by a computerized hub that generates music based on player input. In these networks, power dynamics can range from monarchic, with a designated leader guiding interactions, to democratic. Decentralized networks instead, lack a central hub, allowing direct communication among players. Weinberg classifies these as anarchic, when they offer maximum player freedom.

- Synchronous vs. Sequential (Real-time vs. Non-real-time) Networks: Synchronous networks enable players to manipulate peers' outcomes in real-time, fostering constantly evolving, immersive musical experiences. In contrast, sequential networks involve players generating musical material that others can transform "off-line" before "resubmitting" it to the group.

Weinberg illustrates these relationships in a series of meticulous sketches, showing the connections between players, and introduces the fascinating concept of *weighted gates* [29], which determine each player's influence level on the final outcome. He uses the term "flower" to address a centralised synchronous network, where all players are constantly connected to a central hub in real-time; "wheelbarrow" to address a centralised sequential network, where each input stage builds upon the previous one; "star" and "stairs" to address a decentralised synchronous and sequential networks, respectively.

Jordà builds upon this foundation, introducing additional criteria for the classification of musical networks, including:

- User-Number and User-Number Flexibility: Addressing the number of individuals required to play the instrument and whether this number can flexibly change.
- User-Role Flexibility: Examining role assignments and the potential for roles to change, as well as whether a player can cover multiple roles simultaneously.
- Interdependencies and Hierarchies: Assessing the level of influence each player exerts on the musical output of their peers.

An emerging research branch in the realm of networked musical systems, led by British researcher and PhD student Steve Symons, represents a significant evolution in the field. Symons has introduced the concept of "entangled" instruments, a novel form of deeply interdependent musical instruments that places a strong emphasis on the player experience [27]. Symons argues that the inherent design of entangled instruments plays a major role in affecting the players' perception of each other and of the instrument they engage with.

2.2.3 Promoting collaboration: design strategies

The importance of collaboration in traditional music practice, with communication playing a pivotal role in facilitating this collaborative dynamic, is well established; and the profound impact of effective collaboration on the quality of the produced music and the emotional resonance of a performance is widely recognized. However, translating these principles into the design of networked systems and interactive installations poses intriguing challenges, which include making sure that players understand their role as part of the group, providing a structure that can guide the players' interactions and providing channels for the players to efficiently communicate their musical intentions.

To effectively communicate their musical intentions, players need a clear understanding of their own contributions as well as those of their peers. This aspect can be particularly challenging for novices approaching interactive musical systems, where the direct link between the sound-producing gesture and the sound-producing mechanism is often missing [30]. To address this, Bryan-Kinns underscores the importance of *shared* and *consistent representations* as a means to establish a common ground for communication and interaction [9]. These shared representations can take various forms, such as visual, auditory, or haptic feedback, and serve to inform players about each other's actions and contributions. A practical example provided by Bryan-Kinns suggests that each player's interventions must lead to distinct alterations in the musical output. For instance, allowing players to shift the octave of a specific melodic line or change the rhythm of a particular sequence has proven effective in helping them identify their own contributions [2].

Once the players understand their contribution and their role in the music-making process, they must be able to communicate their intentions effectively. This underscores the importance of designing interfaces that enable clear and efficient communication between players. Design principles derived from the literature offer valuable guidance on creating interfaces that optimize this essential aspect of collaborative interaction.
Jensen and Marchetti, for instance, underscore the significance of eye contact and reciprocal visibility [18] as a mean of communication between players. This dynamic allows musicians to maintain awareness of one another, facilitating the coordination of their movements and the communication of their musical intentions. However, it's essential to consider whether the affordances of the instrument enable nuanced and complex musical interactions. If the design process overly simplifies and restricts the musical experience, the potential for communication among players may become limited and result in sterile interactions that lack the capacity for creative exploration.
Symons [27] on the other hand, emphasises the role of physical interaction as a communication channel for establishing a deep connection between players. This dynamic channel of communication enables musicians to transcend the boundaries of verbal language and convey their intentions and emotions through bodily gestures and movements. When musicians engage physically with their instruments and fellow performers, they create a shared language of movement and expression, allowing for nuanced musical dialogues and emotional connections that enrich the collaborative experience. The establishment of a physical connection between players can be signaled by the player's synchronization and mirroring of movements, physical touch, responsive movements and physical proximity [9].

Providing opportunities for both structured and open-ended collaboration is an effective strategy to guide the players' interactions. Structured collaboration introduces specific tasks or challenges that players must tackle collectively [29]. These structured activities can take the form of musical games, synchronized performances, like IRCAM's visionary Urban Musical Game [24], or collaborative compositions or beat-making, like Bryan-Kinns' Daisyphone [8], where participants are given clear objectives to achieve together, promoting a sense of unity and accomplishment. The choice of collaborative activities or challenges within the interface can significantly impact the depth of interaction. For instance, activities that encourage players to share ideas, coordinate actions, or engage in joint problem-solving tend to foster more substantial dialogues. On the other hand, open-ended collaboration embraces spontaneity and exploration within the musical interaction [29]. It allows players to engage in unscripted musical dialogues, encouraging improvisation, experimentation, and free-form expression. In such scenarios, the interface serves as a flexible and dynamic playground for players to interact with one another creatively. These open-ended experiences, says Weinberg, can often lead to unexpected musical discoveries.

2.2.4 Assessing the quality of a collaboration

Assessing the quality of collaboration in musical interactions is a multifaceted endeavor that encompasses various critical factors, such as the players' level of engagement, creativity, expressiveness, emotional connections, and their overall satisfaction regarding the musical outcome. These factors are rooted in Bryan-Kinns' concept of *mutual engagement* [9], somewhat associated with Sawyer's concept of *group flow* [25]. Defined as "points at which people creatively spark together and enter a state of group flow", mutual engagement plays a fundamental role in assessing the quality of a collaboration. This concept describes a creative activity in which players engage in both self-expression and co-creation with others. Mutual engagement is characterized by several key elements, including a reduced sense of self-awareness, a heightened appreciation for each other's contributions, a commitment to individual and shared goals, engrossment in the group dynamic, and a continuous process of iterative interpretation and modification of peers' contributions [9]. Key cues for identifying mutual engagement often overlap with the concept of flow. These cues include *mutual awareness*, which denotes a shared understanding among all players about who occupies the collaborative space, their current contributions to the musical output, and with whom they are interacting; *proximal interaction*, which argues that players will work closer to each other when they are mutually engaged; *mutual modification*, which denotes the players' tendency to modify each other's contributions; *contribution to joint product*, which highlights the players' alignment with the musical intentions of the group; *attunement to other's contributions*, which manifests as players respond, mirror, or transform each other's musical input, reflecting their engagement and comprehension of their peers' creative expressions. Within the concept of attunement, three distinct levels emerge: *acknowledgement* signifies a basic awareness of another peer's contribution, *mirroring* denotes players replicating or reflecting each other's input, and *transformation* illustrates players actively adapting and reshaping each other's contributions. Bryan-Kinns proposes a few design strategies to promote mutual engagement. One key strategy is *co-location*, which entails that the players share the same auditory and physical space. This setup mirrors natural conversational settings and has can enhance the players' understanding of the collective musical output, enabling them to grasp the impact of their individual contributions, and it can facilitate real-time, barrier-free communication. Another noteworthy aspect highlighted in this research is *mutual modifiability*, which consists in allowing each player to directly modify their peers' contributions. This approach promotes an egalitarian approach to role assignment, fostering a positive attitude among players. However, it's essential to make sure that players cannot modify each other's content to the extent that it becomes unrecognizable, as this could undermine the sense of agency critical for a coherent musical experience.

Similar to mutual engagement is Sawyer's concept of *group flow*. Group flow is described as a collective state of heightened creativity and performance. Within this state, musicians achieve an extraordinary level of synchronization and synergy, they transcend individuality, becoming part of a unified whole, where the boundaries between performers blur. This shared mental state allows musicians to tap into creative potentials they might not access when playing alone. The sense of anticipation and the fluidity of interaction within the group enable musicians to explore new musical ideas and take risks they might not have considered in a solo context [25]. The most common cues that indicate the presence of a good group flow are a high level of coordination, a high level of creativity and expressivity, a strong bond and a unified direction in problem-solving and goal-achievement, a high level of emotional connection, the implementation of constructive feedback and a high level of enjoyment and satisfaction with regards to the musical outcome.

2.3 State of the Art

The paper proceeds with a description of a few past and current instruments and installation works that have played significant roles in shaping and evolving the proposed project. These works collectively belong to the category of "networked instruments, performances, or interactive installations," and they share a common emphasis on interdependency [29] and player experience. Each of these works explores these aspects in its own distinctive manner. While some of them necessitate collaboration and integrate it as a fundamental element of their design, others take a more subtle approach, offering collaboration as an option, and eventually rewarding the audience for their collaborative engagement.

Stickatron and Elastiphone

Symons' research [27] found practical application in the creation of two entangled instruments known as *Elastiphone* and *Stickatron* [1]. These instruments use a gametrack device originally designed for virtual golf games, which provides a set of detailed and accurate x, y, z position coordinates by the means of two retractable wires. These wires connect to the controller's main body on one end and to the interactive objects on the other — a wooden stick for the Stickatron and a pair of gloves for the Elastiphone. This setup enables the system to precisely track the performers' movements in three-dimensional space.

In the case of the Stickatron (fig. 2.1), two players hold a wooden stick from opposite ends. As they pull the stick away from the controller, the retractable wires

[1] https://entangled-instruments.xyz/

stretch, triggering the VCV Rack [2] software to generate sounds. The interconnected movements of the two players, who are physically linked by holding the same stick, lead to significant variations in the produced sounds. Remarkably, the sound generation responds to events occurring in the middle of the stick, rather than at its ends. This design minimizes individual control over the sounds, and encourages players to collaborate closely, thinking together and co-acting to shape the sonic outcome.

In contrast, the Elastiphone involves each player wearing a glove connected to one of the retractable wires. The sounds are generated using granular synthesis in VCV Rack. Here, players are encouraged to move and respond to each other's actions in close proximity, as no sound is produced if they are too far apart. Elastiphone's full potential unfolds when the two players bring their hands together. This parameter defines the size of the granular window; by moving their hands in unison while maintaining the same distance, they can navigate through the audio buffer. This design encourages players to remain in close proximity, coordinate their movements, heighten their mutual awareness [9], and strengthen their interpersonal connection.

Stickatron and Elastiphone serve as exemplary models of networked instruments characterized by profound interconnection between players. These instruments underscore the fundamental principle that meaningful sounds can only be produced through collaborative thinking and action, as the parameters of the music are in a constant state of modulation through their communal effort. In this unique musical context, players are not capable of directly influencing each other's musical output because there exists none outside of their collective work. Symons has demonstrated his prowess in designing genuinely entangled instruments that prioritize player interaction and collaborative thinking, while still allowing minimal individual control [27]. Interdependency is an inherent aspect of the design, leaving no room for escape from the collective creative process. These instruments represent a significant advancement in the field of collaborative music-making, offering a new frontier for exploring the boundaries of musical expression and shared creativity.

[2] https://vcvrack.com/

Figure 2.1: A picture portraying two players of Stickatron

Tooka

The *Tooka* is a unique two-player musical instrument originally designed by Sidney Fels and Florian Vogt [14]. Subsequently, Fels worked closely with a group of trained musicians to refine and enhance the instrument's expressive capabilities [15]. Designed with a strong emphasis on the interplay between musicians, the Tooka has proven to be exceptionally effective in exploring intimate, engaged experience between players, and between the player and the instrument.

The instrument comprises two hollow plastic tubes, connected in the middle to form a continuous tube. Attached to each end are the mouthpiece, four buttons (in the last update) and a pressure sensor, which are used to control some of the instrument's modes. Each musician places their mouth on opposite ends, sealing the tube, and then collectively modulates the tube's pressure to manipulate sound using their mouth, throat, and lungs. Changes in pressure are measured by an air pressure sensor located at the junction of the two tubes. In the most recent version, a bend sensor was introduced to further enhance the instrument's expressive capabilities.

Several key aspects of the instrument encourage communication between the performers. One of the most significant aspects is the requirement for precise coordination of finger movements between the performers to play a specific scale or melody. This demands a constant awareness of each other's intentions, a concept underscored by Bryan-Kinns as *mutual awareness* [9]. This shared awareness not only harmonizes their musical output but also strengthens the interpersonal connection established during their performance. Another characteristic that fosters intimacy between players is the "capture/sustain" feature, which grants both musicians the ability to sustain or end a specific note while transitioning to the next one. Notably, both players wield influence over the ongoing sustained note and can bring it to an end at any moment. This aspect aligns with Weinberg's concept of interconnectedness, which hinges on each player's ability to affect their peer's contributions [29].

Figure 2.2: A picture portraying two players of Tooka

Explosion Village

Explosion Village [3] is an interactive installation created by Illutron [4], and it was featured at the 2008 edition of Roskilde Festival [5]. As Scandinavia's largest festival, Roskilde attracts a substantial crowd, primarily comprising teenagers and young adults who revel in a festive atmosphere. This dynamic setting provided the ideal backdrop for an engaging installation designed to encourage collaborative efforts among festivalgoers.

The focal point of the village was the Explosion Tower, which boasted a supersized gas cannon atop it. Additionally, there were eight empty water tanks, each equipped with contact microphones. Festival attendees were invited to engage with the installation by striking the water tanks. The intensity and frequency of these strikes were meticulously measured and accumulated over time. Upon reaching a predetermined threshold, the gas cannon would release an impressive burst of fire as a gratifying reward for the actively participating audience. The progression of accumulated energy was visually represented by ten sequential light bars, which illuminated individually as the tower approached its climactic moment. At the peak, participants would collectively raise their arms in jubilation, accompanied by a resounding cheer, as the spectacular burst of fire erupted from the gas cannon.

Explosion Village was conceived as an exploration into the potential for fostering extensive audience involvement, accommodating up to two hundred participants simultaneously. Remarkably, participants often found themselves falling into a rhythmic synchronization with one another, as this synchronization led to

[3] https://www.hobye.dk/works/2008-explosion-village
[4] https://www.illutron.dk/
[5] https://www.roskilde-festival.dk/da/

a more rapid accumulation of energy in the installation. Therefore, participants naturally observed and emulated each other's behaviors, striving to synchronize their actions and lock into a unified beat.

Figure 2.3: A picture portraying the massive fire outburst of the the gas cannon of Explosion Village (Roskilde Festival 2008)

ToneTable

John Bowers' *Tonetable* [6] is a table-top installation that melds sound and computer graphics to create an interactive and collaborative experience. Bowers' research focuses on exploring the deployment of interactive collaborative interfaces in public settings, with a keen interest in addressing the challenges of engaging the public in collaborative activities.

At its core, ToneTable features a table that serves as the primary focal point for interaction, accompanied by a multi-speaker audio setup. Projected onto the tabletop is the physical model of a fluid surface, upon which originally five, later reduced to four, virtual objects float in a natural and gentle meandering behavior. Using trackballs, players gain the ability to control the source position of virtual waves, which in turn exert influence on the movement of the floating objects. Notably, each of these objects is associated with a distinct musical tone. The spatial distribution of these tones across the multi-speaker setup corresponds to the positions of the virtual objects within the fluid surface. Bowers' design philosophy was driven by a desire to incorporate inherent incentives for exploring the table and to encourage collaboration among players. He ingeniously designed a concealed scenario within the interface: when two players align their waves, the combined force becomes powerful enough to set the object into orbit around the display, serving as a rewarding revelation of the collaborative aspects of the interface.

This project raises interesting considerations on design principles such as that of "layers of interaction and variety of behaviours", and the positive impact that sharing the same interactive medium has on.

Figure 2.4: A picture of the audience playing Tonetable

Chapter 3

Happy Cycling

3.1 A new collaborative musical instrument

Happy Cycling is an interactive sound sculpture designed for exhibition in public spaces, with a focus on creating an engaging and collaborative musical experience for a diverse audience. The sculpture seeks to offer a balance between simple, accessible interaction and the potential for more sophisticated musical outcomes through collaboration. A key feature of Happy Cycling is its use of everyday objects as the central components of interaction. These objects are thoughtfully chosen to establish a clear and intuitive connection between the object's physical behaviour and the resulting musical output. This approach enhances the accessibility of the sculpture and encourages users to actively engage with the system.

The core of Happy Cycling comprises two bicycle wheels, each serving a distinct role in the musical process. *Wheel 1* is responsible for generating sound through playback of a pre-selected audio file, while *wheel 2* plays the role of a modulator, allowing control over various audio effects. Wheel 1 is securely anchored to the sculpture's body, restricting its motion to rotation. Wheel 2 instead is affixed to the body using a mobile arm, granting players the capability to manipulate its position. This configuration offers a unique opportunity for collaborative play, allowing players to adjust the distance between the wheels, bringing them closer together or moving them apart, and even facilitating direct contact between them. In this setup, the movement of one wheel influences the motion of the other, providing a dynamic platform for shared creative expression and interaction among players.

In essence, Happy Cycling embodies the principles of accessibility, engagement, and collaboration by leveraging everyday objects and providing a versatile interface that accommodates both simple and complex musical interactions. It aims to bring the joy of music creation to public spaces, inviting people of all backgrounds and expertise levels to participate in a harmonious and entertaining musical experience.

3.1.1 A simple interface with a "low entry fee", designed using everyday objects

As demonstrated in previous research, creating a design that resonates with a diverse audience, spanning from musical novices to those with advanced musical skills, is a complex endeavor that requires careful consideration of various elements. This project aims to embrace this diversity by incorporating design elements that appeal to both ends of the spectrum and everyone in between.

To accommodate novices, the sculpture's interface design prioritizes simplicity and approachability, allowing users to derive immediate musical satisfaction. The interaction is designed to be straightforward, with intuitive mappings that connect physical actions to musical outcomes. Additionally, the project employs a high-quality synthesis algorithm that ensures the musical output is pleasant to the ear.

This project addresses the challenges of interface approachability by incorporating bicycle wheels into its design. This choice is rooted in the belief that the audience's pre-constituted familiarity with bicycle wheels will facilitate the immediate establishment of a cognitive link between the wheels' conventional utility and the proposed gestural interaction. We believe that this will serve as a bridge to establish an immediate and profound connection with the musical system.
This hypothesis draws inspiration from Plato's theory of knowledge [16]. Plato posits the existence of a celestial realm called the hyperuranion, where archetypical representations of objects found in the real world, which he terms "ideas," are collected. He also subscribes to the concept of metempsychosis, arguing that our souls have undergone multiple incarnations in different bodies. Throughout these past lives, our souls have experienced the entirety of reality and accumulated knowledge about it. This process culminates in the construction of an internal repository of ideas, but how do we access this repository? Plato contends that we retrieve this pre-existing knowledge through memory, a process he refers to as anamnesis. Therefore, according to Plato, learning essentially involves recollecting what we have acquired in previous lives.
While this project aligns with Plato's idea, it does not delve into debates about metempsychosis. Instead, it contends that the knowledge in question arises from repeated interactions with the object in focus. This perspective aligns with the principles of embodied cognition and the theory of enaction [12]. If we were to accept Plato's theory of the origin of the collection of ideas, we propose that sustained interaction can reinforce and extend these ideas. We posit that this model of ideas can accommodate the addition of new attributes, which are learned through interaction. Therefore, sustained engagement enables us to acquire additional knowledge about the object in question and to build knowledge about its functioning.
The choice of utilizing bicycle wheels in the sculpture is informed by their ubiquitous presence in the urban landscape of Copenhagen, where cycling is a prevalent mode of transportation. As a result, a broad spectrum of individuals possesses a

fundamental understanding of bicycles and their operational principles, primarily being associated with movement and rotation. This project posits that this inherent knowledge about the mechanics of wheels, already ingrained in visitors, will instinctively prompt them to interact with the bicycle wheels by spinning them.

The system deals with the necessity of providing a satisfying musical outcome by employing a high quality playback algorithm and several audio effects. Players can achieve a musically rich and articulated result instantly by merely spinning the sound-producing wheel. This action triggers an immediate and responsive playback of a pre-selected audio file, with the wheel's speed, direction of rotation, and phase all contributing to changes in the produced audio output.

3.1.2 A metaphorical approach to mapping, designed to foster collaboration

The approachability of the system is further determined by the implementation of an intuitive set of mappings. In this regard, the system employs a set of mappings based on metaphors, due to their ability to simplify the understanding of an otherwise complex musical process using familiar terms.

The mappings employed in this interaction are highly intuitive, leveraging the natural spinning properties of the wheel and associating them with sound parameters that are easily correlated with the spinning motion. Players can modulate their performance by adjusting the speed at which they spin the wheel, and these nuanced changes in speed will be accurately translated into alterations in pitch and playback speed. By altering the direction of movement, players can influence the direction of audio playback (forward / reverse). This adds a fun and DJ-like dimension to the experience, akin to spinning a jog wheel forward or backward on DJ equipment. Furthermore, players are able to determine the reading point within the audio file by adjusting the phase of the wheel.

The simplicity and intuitiveness of the mappings in Happy Cycling make it particularly well-suited for novice players, offering an accessible entry point into the musical process. However, its design also recognizes the importance of providing opportunities for players with a more advanced musical background to engage in nuanced and expressive exploration. This approach aligns with the understanding that more expert players often seek to cultivate virtuosity over time and unlock more sophisticated expressive capabilities through dedicated practice [30].

In this regard, Happy Cycling serves as a versatile platform for advanced players to express themselves with a higher level of sophistication, allowing for more articulated and expressive gestures resulting in more nuanced musical results. These aspects of the music-making process come to the forefront in collaborative scenarios. We argue that it is this collaborative potential of the interface, reflected in a nuanced expressive dialogue between players, that constitutes the advanced element that can appeal to more expert players. In scenarios involving multiple players, a natural tendency emerges for them to interact with each other. This interaction often manifests as a dialogue using verbal and non-verbal communication channels — a form of interplay focused on the exchange of information, with the purpose of establishing a set of shared musical intentions that can effectively guide their collaborative music-making process. This separation encourages collaborative exploration as users can coordinate their actions, engage in call-and-response interactions, or mirror each other's movements. The system's primary objective is to promote the establishment of such a dialogue, and to facilitate the coordination of movements, joint action, and collaborative thinking, encouraging players to respond to or mirror each other's movements, engage in call and response interactions, and explore various other patterns of coordinated engagement aimed at conveying shared expressiveness. The set of mappings was meticulously designed and implemented to encourage collaboration and communication between players. Therefore, the most gratifying sonic results are achieved through the combined gestural input to both wheels, as manipulation of the second wheel and of the mobile arm add a layer of complexity to the interaction and sonic outcomes by enabling real-time control over several audio effects. For many of these effects, it is the synergy between the gestural input to both wheels that produces the most rewarding sonic results. This design seeks to encourage collaborative exploration and the formulation of shared musical ideas, promoting a sense of unity in the music-making process

The design strategy implemented in Happy Cycling deeply integrates the elements of collaboration and embeds them into the fundamental principles and mechanisms of the interface, aligning with Symons' vision of entangled instruments [27]. This integration is evident in the way the two wheels are interdependent. One wheel alone would not suffice for sustained interaction, as the sound it generates is too simplistic and might lead to players losing interest quickly. Conversely, the second wheel, responsible for modulating sound, cannot function in isolation as it doesn't produce any sound by itself. These mutually dependent roles make it so the two wheels are deeply dependent on each other, and so are the players. Since the individual actions of each player hold a modest impact on the combined outcome, effective communication between players becomes crucial. Players might find themselves in situations where they need to request their fellow player to perform a specific gesture or halt a particular action in order to produce a desired sound. Effective communication lays the foundation for the development of collaborative musical ideas that are conceived and implemented jointly. As a result, the two players function as a unified entity, thinking, performing, and reacting in sync with the interface's behavior. In the early stages of proficiency, communication will likely take the form of verbal interaction, with players engaging in spoken conversation. However, as players gain experience and spend more time playing together, it is anticipated that they will develop a set of communicative gestures specific to this interface, enhancing their collaborative capabilities.

In this project, collaboration serves a dual purpose: it enhances the music making experience by promoting a nuanced expressive dialogue between the players; and it increases expressivity, complexity and nuance in the musical result.

3.1.3 Promoting collaboration: an interdependent system with a sense of agency

Interdependency plays a crucial role in promoting collaboration and enhancing mutual engagement among players [29]. In the context of Happy Cycling, interdependency can be observed at two levels: between the two wheels and among the players themselves. While the interdependency between the wheels primarily serves the functional aspects of the sound-producing algorithm, the interdependency among players contributes to a rich and fulfilling collaborative experience. Let's delve into both aspects.

The system's network structure is highly *centralized*, with component 1 at the core. Component 1 takes charge of sound generation, it measures wheel 1's speed, rotation direction, and relative position within the cycle, it executes mapping functions, and it outputs the sound to the speakers. Additionally, it receives measurements of wheel 2 via OSC in a wireless configuration.

The network is *local*, as all system elements are physically located in the same place. This proximity facilitates immediate and seamless interaction.

The network operates *synchronously*, enabling real-time interaction between the players and the instrument.

The network is *process-oriented*, with a primary focus on providing an enjoyable and engaging musical process rather than solely emphasizing the final musical outcome. Nonetheless, the goal remains to generate music that is both sonically pleasing and nuanced.

Another significant factor in enhancing mutual engagement and promoting collaboration is the players' ability to comprehend their own contributions and their respective roles in shaping the final musical output, as demonstrated in previous research [2] [28]. This system effectively addresses this aspect by assigning the job of generating sound to one wheel, and by providing the ability to modulate the sound to the other. Given that the players' roles remain consistent unless they choose to swap their positions to control a different wheel, it becomes exceedingly clear for them to understand their individual contributions. Each player, by staying in their position, can discern that they are responsible for generating a distinct set of modifications within the musical composition. This clarity of intentions serves to reinforce their sense of belonging to the collaborative process, granting them a defined role within the creation of the music, and it heightens their awareness of the contributions made by other players too. These factors collectively contribute to a comprehensive understanding of the musical process and the roles each player plays within it, resulting in a more enjoyable and less stressful experience.

3.2 Technical implementation

3.2.1 Iterative process

The present state of the sculpture is the result of an extensive iterative process, which will be detailed in the following paragraphs. This sculpture has transitioned through multiple design phases, progressing from an installation featuring two full-sized bicycles to a single bicycle wheel and eventually to several bicycle wheels arranged in various configurations. From the outset, the primary aim was to create an engaging interactive installation for public spaces, with bicycles (and later bicycle wheels) as the focal point of interaction. The choice of bicycles was motivated not only by their ubiquitous presence in Copenhagen but also by the fact that they require physical effort and movement to function. This emphasis on human agency was integral to the generation and reproduction of sound in this project since the beginning. Collaboration has equally been a central theme, highlighting the significance of teamwork and interpersonal connections in sound production. Furthermore, a core goal from the outset has been to establish a fully embedded networked system of sensors, receivers, and sound generators capable of capturing sensor data, processing it, and producing sound autonomously, without reliance on a laptop and without the use of wires.

The subsequent sections will delve into the various stages of implementation, highlighting both successful aspects and areas that presented challenges or setbacks.

An installation featuring two full-sized bicycles

The original concept revolved around the use of two full-sized bicycles as the focal point of interaction (fig. 3.1).

Initially, the plan was to elevate the two bicycles off the ground to prevent them from moving when people cycled. The idea was to create a support structure for both the front and back wheels, much like in indoor bike setups for indoor training. A design plan was formulated to craft a DIY stand for the rear wheel using wood, and some references where gathered from online sources like Instructables [1].

A small-scale prototype was constructed using laser-cut HDF, featuring a single bicycle wheel mounted on the stand. It was during this phase that the decision was

[1] https://www.instructables.com/Indoor-Bike-Trainer/

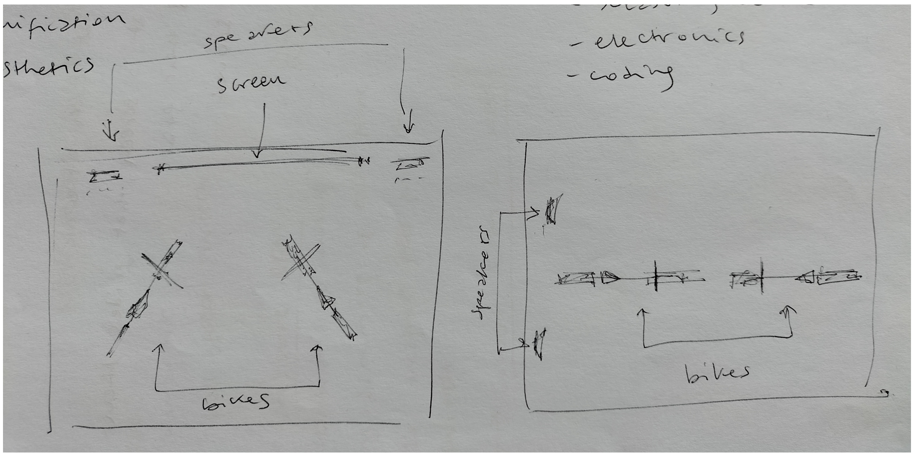

Figure 3.1: An early sketch of the two full-sized bikes installation

made to shift from using entire bicycles to single bicycle wheels. This shift was motivated by various challenges associated with using full-sized bicycles. Firstly, it was logistically challenging to accommodate full-sized bicycles within the limited space of a lab or maker-space for the entire project's duration. Secondly, there was the practical issue of finding full-sized bikes that could cater to a diverse audience with varying physical characteristics. These considerations prompted the transition to single bike wheels as the project's core component.

The bicycle wheel

At this stage, the prototype resembled a DIY home-training bicycle stand, with a single bicycle wheel mounted on it vertically, and it bore a striking resemblance to Duchamp's "Bicycle Wheel" (fig. 3.2). While this early prototype was delicate and fragile, with the stand swaying from side to side when the wheel spun, it served as a foundational starting point for developing the interaction and the initial sensor system. Initially, the idea was to measure the wheel's rotation speed by utilizing a single hall effect magnet switch positioned on the stand and a magnet attached to one of the wheel's spokes. This concept drew inspiration from commercially available bicycle computers, which measure wheel frequency and bike speed using a hall effect switch and a magnet. An early stage prototype of the sensor system was implemented using an Arduino UNO [2] development board. The Arduino was programmed to detect triggers sent by the hall effect switch and calculate the wheel's RPM, which could then be converted into speed through subsequent calculations. Data was transmitted to the laptop via OSC messages over UDP. However, this initial system suffered from measurement inconsistencies due to the low-quality

[2]https://store.arduino.cc/products/arduino-uno-rev3

oscillators driving Arduino's internal clock, and it also experienced latency issues caused by the time intervals needed to count triggers and by performing the calculations. Consequently, the system was slow, unresponsive, and inaccurate. To address these issues, a new sensor was introduced, the M5 ATOM Matrix [3]. This sensor is a robust 6-DOF IMU integrated with an ESP32 featuring WiFi and Bluetooth connectivity and an a 3x3 LED matrix. Its consistent and relatively noise-free measurements, it's built-in network connectivity, its low power consumption and its built-in led screen for visual feedback made it a central component of the system that remains in use. At this point, the fragility of the stand prototype had become a limitation, posing challenges in spinning the wheel at higher frequencies and hindering the intended interaction. Consequently, there arose a need for a more stable and robust structure capable of supporting a forceful and dynamic interaction.

Figure 3.2: A picture of the wheel and its fragile HDF stand

The horizontal wheel

At this stage of the prototype, some of the system's core that remain in the current implementation could be observed, including the use of a bicycle wheel detached

[3] https://shop.m5stack.com/products/atom-matrix-esp32-development-kit

from the body, equipped with an ATOM Matrix IMU and a power bank to power it. However, significant modifications were made to address the need for a more robust structure, which had a profound impact on subsequent implementations. To enhance stability, an approximately 1 cm thick, 1 m tall, and 50 cm wide wooden plate was employed. A hole was drilled in the middle of the plate, and the bicycle wheel was affixed to it by screwing its axle through the hole and securing it with a nut on the other side. For added structural stability, half of an L-shaped metal angle was inserted between the wheel and the wooden plate. It was during this phase that the idea to place the wheel horizontally was realized (figure 3.3).

This phase also saw significant developments in the wheel's generated sound. A click-free monophonic granular synthesizer was implemented in Max MSP, based on classical granular synthesis techniques available online. The bicycle's speed was mapped to the buffer's playback speed, pitch, and grain size, creating a direct relationship between speed and these sound parameters. Additionally, the direction of rotation was mapped to the playback direction. A novel element was introduced in the form of a clock that triggered grain playback. To further reduce clicks, the clock was set to trigger playback with a slightly longer interval than the grain size. This not only eliminated clicks but also created a dynamic gate-like effect, similar to a sidechain compressor, adding character to the sound.

With the granular sound engine in place, there was a desire to dynamically control the reading position within the buffer during playback. This led to the reintroduction of the hall effect magnetic switch. Sixteen hall effect switches were arranged in a circular pattern on the wooden panel, evenly spaced around the point where the wheel's axle was attached (figure 3.3). Placing a magnet on one of the wheel's spokes allowed the magnet to hover over the sensors in sequence as the wheel spun. Each sensor represented a reading position within the audio buffer, enabling users to dynamically change the reading position by turning the wheel. The sensors were strategically positioned to overlap their ranges, creating new virtual resolution points between them. This resulted in a relatively high-resolution 32-point set of positions to choose from.

At this stage, the prototype had achieved a level of robustness and interactive and sonic sophistication. It provided a glimpse of the current interaction and sonic possibilities, although still in the early stages. The system was now ready to be expanded to accommodate collaborative interaction.

Figure 3.3: A picture of the horizontal wheel. The "crown" of hall effect switches can be observed, together with the multitude of wires connecting it to the ESP32 development board

Back to collaboration

At this point, the need to expand the system to accommodate multi-user input and collaboration resurfaced. The concept revolved around the creation of a playground of wheels, each positioned differently to facilitate various gestural inputs and interactions that would result in distinct musical outputs. The original inspiration for this concept stemmed from Tim Murray-Brown's 'Cave of Sounds' installation [23], featuring eight distinct sound objects designed by eight different individuals. Each sound object operated independently, exploring diverse types of interactions, and their collective sounds would harmonize into a unique composition. The initial plan involved incorporating three distinct wheels scattered throughout the exhibition space, each with its own set of interactions and sounds. In addition to the single horizontal wheel described earlier, a vertical wheel suspended from the ceiling was envisioned. This vertical wheel had the capacity not only to spin but also to swing both back and forth and left to right when manipulated and the swinging motion was to be measured by an ATOM Matrix. Fig. 3.4 shows a sketch of this design. A prototype was developed for this purpose. The wheel was attached between the legs of a tall ladder using two steel wires secured with safety locks designed to allow wire adjustment for variable height. The swinging motion was intended to be mapped to the frequency bins of a custom-programmed FFT equalizer, which was partially implemented. The current position of the wheel within its swinging range determined the active frequency bin, muting all other bins. As the wheel moved, it would traverse the frequency spectrum. While the spinning and swinging movements of the wheel were recorded by an IMU, it became apparent that one motion affected the measurement of the other, and vice versa, rendering the data unusable for this case.

Figure 3.4: A picture portraying the "FFT Wheel" while hanging from the ladder it was attached to. In the background, the Max MSP patch that enabled the reception of the movement data

Furthermore, the aspiration for this project was to create an installation that would seamlessly integrate the audience into a shared interactive and sonic realm, nurturing profound physical, cognitive, and creative connections among audience members. It was during this phase that the works of Steve Symons, particularly Stickatron and Elastiphon, and his innovative concept of 'entangled instruments' [27] were discovered. This captivating concept underscores the interconnectedness of players as an integral element of design, and it soon began to cast its influence over this project. As the project continued to evolve, novel wheel configurations emerged, each designed to underscore the interconnectedness of the system and encourage collaborative engagement among the audience. The need to introduce elements of interdependency among the wheels, uniting the players into a cohesive entity of shared mind and body, became increasingly evident. Various options were explored, including one involving two wheels, with one controlling sound generation and the other managing sound spatialization across four or eight speakers. Another configuration, dubbed 'Granular Talks,' entailed two players facing each other, each controlling their own wheel. They engaged in a conversation brought about by rhythmically triggering playback of granular sounds, responding to each other's actions while maintaining visual contact. Another set of ideas revolved around using the wheels as 'sort keyboards' or word selectors. This concept allowed participants to spell words and playback sentences, with playback parameters determined by their performance factors. Fig. 3.5 shows some of the early collaborative designs described above. However, an innovative idea began to take shape during this process: the physical connection of the two wheels, enabling them to touch and influence each other's movements. In this configuration, the movement of one wheel would impact the rotation of the other, causing it to spin in the opposite direction. This element formed the core of the current implementation.

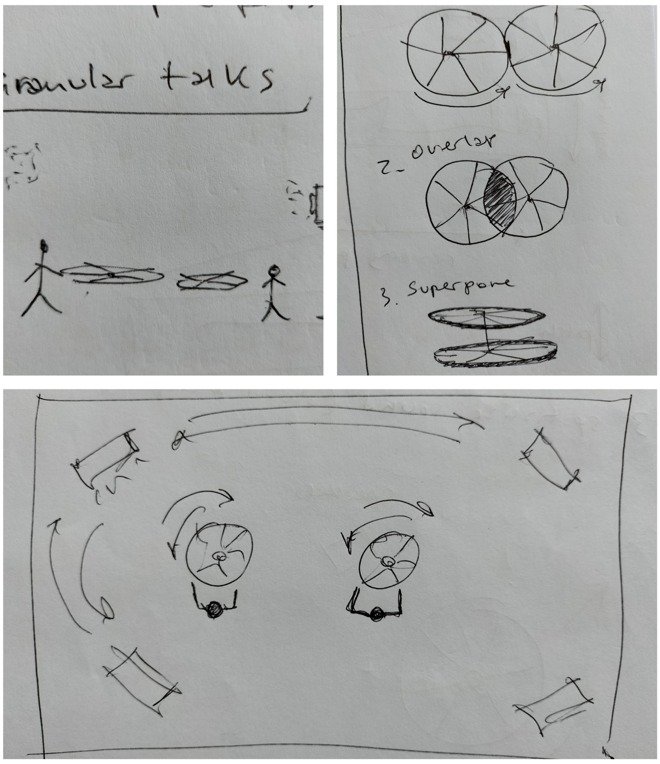

Figure 3.5: A series of sketches portraying some of the early collaborative designs. The "Granular Talks" can be observed in the top-left corner, while in the top-right corner, early sketches of the touching wheels are presented; the bottom section displays a multichannel installation, with one of the wheels controlling the spatialization

Connecting the wheels

The development process of connecting and configuring the bicycle wheels for the interactive musical sculpture involved a series of creative design explorations. Several approaches were considered, including variations in how the wheels were positioned and connected, all centering around the possibility of separating the wheels from each other if desired Among the options explored were configurations with two wheels placed side by side, wheels overlapping, and wheels set perpendicularly to one another. Furthermore, designs featuring three wheels were also considered.

One prominent design concept, portrayed in fig. 3.6 entailed the placement of three wheels in a vertical arrangement, attached to a vertical wooden panel. In this setup, one wheel remained fixed, serving as the sound generator, while the two side wheels were designed to move and to function as audio effect generators. The innovation lay in the players' ability to push the side wheels away from the wooden panel, with a spring mechanism facilitating their return to the fixed wheels upon release. This design allowed for the manipulation of audio effects by controlling the contact between the wheels, thus influencing the overall mix. Explorations also included the potential to measure the separation distance, using it to represent variables such as the dry/wet ratio between sound and audio effects or the volume of parallel-routed audio effects from the primary sound source. This concept, with a fixed sound-generating wheel and mobile wheels for audio effects and modulations, remained a fundamental aspect of the current implementation.

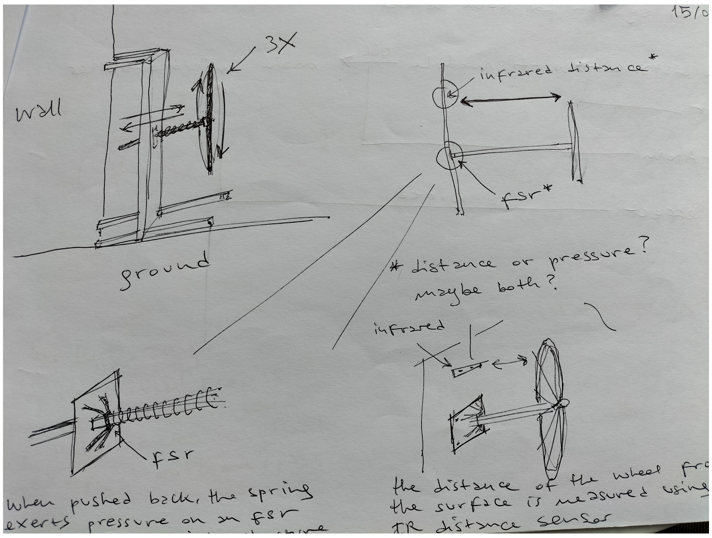

Figure 3.6: A sketch illustrating the spring mechanism designed to enable players to temporarily disengage the side wheels from contact with the central wheel. This mechanism is depicted along with the body to which it was attached, and a couple of different sensing mechanism to measure the distance between the wheels

As the design focus shifted to the mechanics of separating the wheels, another design was conceived. This design retained the central fixed wheel but introduced a pendulum mechanism/hinge, which allowed players to swing the side wheels out of contact to the right or left. The weight of the wheels would have been leveraged to naturally press them against the central wheel when in the resting position, and to force them to return to this position when released from a "distanced" position. A key challenge was how to lock the side wheels in the distanced position, avoiding excessive effort and enabling players to concentrate on spinning the wheel they were controlling. This challenge led to the inception of a pivotal element that remains integral to the current implementation: the "mobile arm." The concept of using steel or aluminum pipes to construct this mobile arm was quickly established. The design required addressing the lateral movement of the wheels and the capability to lock them in distinct positions. Three variations of the mobile arm were explored. The first involved attaching the wheel to a steel or aluminum pipe that connected perpendicularly to a hinge or pendulum mechanism (fig 3.7). However, the challenge of finding a mechanism that could withstand the weight and wear over time without industrial-grade components led to the end of this direction. The second design featured the mobile wheel connected to a straight pipe passing through two wooden panels, placed one behind the other and spaced about half a meter apart. The front panel included a reverse U-shaped hole that allowed players to lock the wheel in two different positions but required a non-fluid and effortful movement to move them, which did not translate well to direct sound control. The third and ultimately successful design mirrored the lateral movement of a pendulum mechanism. It featured a segmented pipe, one part passing through the two wooden panels and attaching the wheel to the body, while the other part extended downward vertically in front of the front panel. The wheel was fixed to the lower end of this section of the pipe. This design met the criteria for a smooth, comfortable, and effortless sideways movement, and the weight of the wheel naturally returned it to the resting position when released. The only remaining issue was how to lock the wheel in the distanced position, ultimately leading to the decision to transition from a vertical to a horizontal arrangement. This design evolution culminated in the current implementation, which is further detailed in the subsequent sections.

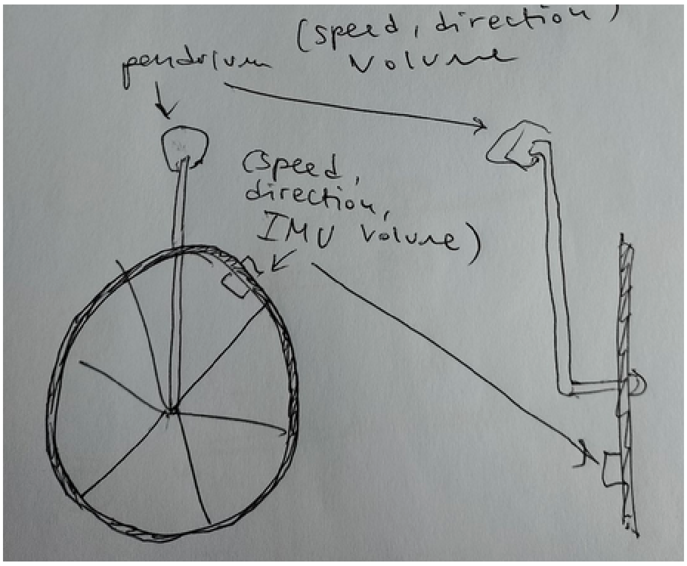

Figure 3.7: A sketch of the pendulum mechanism that would enable the sideways movement of the wheel

3.3 The current implementation

3.3.1 The sculpture

As of the current implementation, the sculpture comprises two main components: an interactive part represented by the two bicycle wheels and a non-interactive body designed to support and stabilize these wheels. The two wheels are connected to the body through two distinct arms. The wheels themselves were repurposed from old bicycles, while the body consists of an office table with some structural modifications to accommodate the interactive elements. The arms, essential for connecting the wheels to the body, are custom-shaped steel pipes.

The two wheels are positioned horizontally above the tabletop, resembling the layout of a traditional DJ set up. The fixed wheel is affixed to its arm, a standard steel pipe that passes perpendicularly through the body of the sculpture. In contrast, the mobile wheel is attached to an L-shaped steel pipe that traverses the body and possesses the capability to rotate on its axis. This rotational feature allows players to move the mobile wheel away from or closer to the fixed wheel.

For a more comprehensive understanding of the sculpture's visual appearance and the specific design of the bike arms, please refer to figures 3.8 and 3.9.

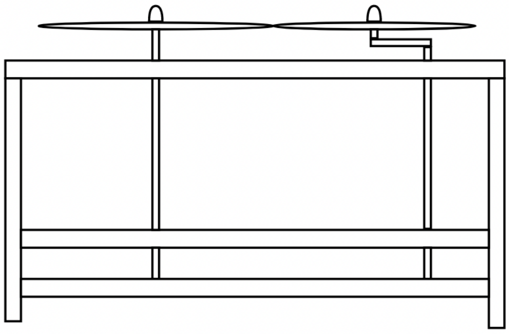

Figure 3.8: A sketch of the sculpture made with draw.io

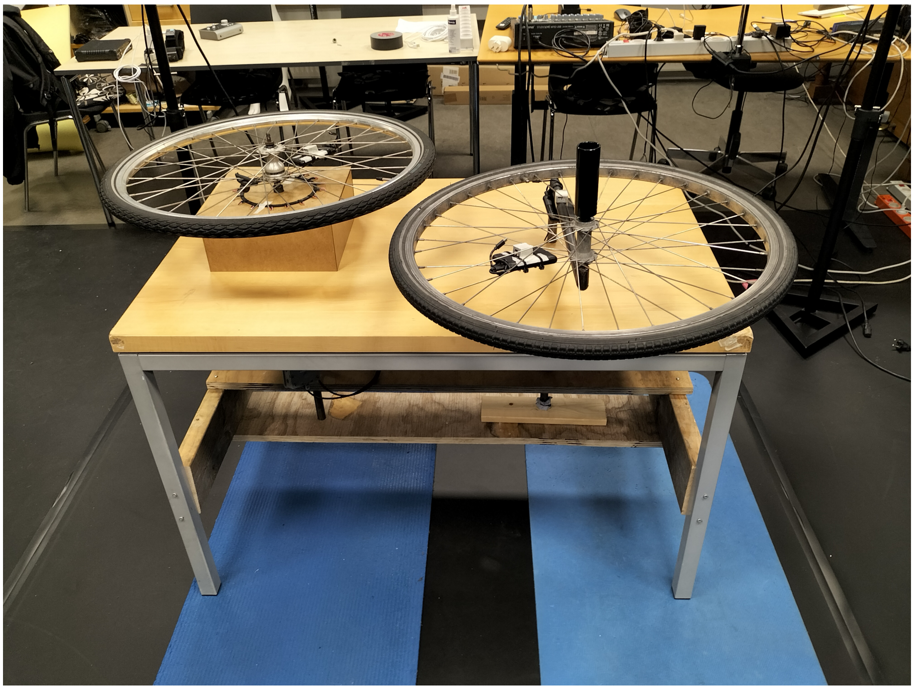

Figure 3.9: A front view of the interactive sculpture

3.3.2 The sensor system

The sculpture is electronically augmented through various sensors, a development board, and a laptop. Each of these components performs a different task, measuring the rotation movement of the wheels, processing these measurements, generating sound, and outputting the results. The sensor system is detailed in fig. 3.10 and consists of:

- 3x ATOM Matrix - placed on the two wheels and on the mobile arm, they measure the wheel's angular velocity and direction of rotation. These measurements serve as the basis for subsequent calculations carried out in Max MSP, allowing to determine the wheel's speed (m/s), its frequency (Hz), and the jerkiness of its movement (m/s^3).

- 16x non-latching hall effect switch - arranged in a circular layout around the fixed wheel, they provide the wheel's current absolute position within its revolution cycle (which we'll call *phase*)
- 1x ESP32 - it collects data from the hall effect switches and is configured as an access point, providing a network for the transmission of data among the various system components
- 1x laptop - using Max MSP, it collects all the data from the sensors, scales and processes it, maps it to sound parameters, and generates sound and audio effects. Additionally, it handles the output of the sound to the speakers.

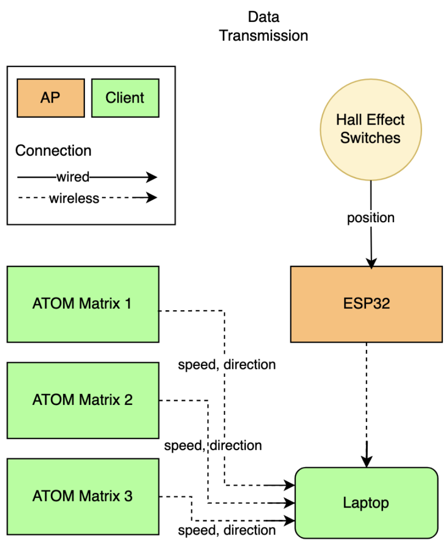

Figure 3.10: Diagram of the data network

The focus of interaction revolves around the two bicycle wheels, which players manually spin using their hands. Each wheel is equipped with an ATOM Matrix IMU [4], individually powered by a compact 5V 5000 mAh power bank that fits in the palm of your hand. The ATOM Matrix was selected over other IMUs primarily due to its high level of accuracy and its ability to transmit data over WiFi, facilitated by the built-in ESP32 module. The three ATOM Matrix measure the rotation of the wheels by reading gyro data along the z-axis, providing a value for the wheel's angular velocity in degrees. Depending on the direction of rotation, this value

[4] $https://docs.m5stack.com/en/core/atom_matrix$

can be either positive or negative. Once converted to angular velocity in radians (rad/s) using the formula,

$$angularvelocity(rad/s) = angularvelocity(deg/s) * (\pi/180) \tag{3.1}$$

this parameter can be used to derive other meaningful parameters of the wheel's rotation movement, such as the wheel's speed (m/s), using the formula:

$$speed(m/s) = angularvelocity(rad/s) * radius(m) \tag{3.2}$$

the wheel's rotation frequency (Hz), using the formula:

$$frequency(Hz) = angularvelocity(rad/s) * 2\pi \tag{3.3}$$

and the jerkiness of the rotation movement (rad/s^3) through two steps: first by differentiating the angular velocity in radians (rad/s) with respect to time to obtain the angular acceleration (rad/s^2), and then differentiating the angular acceleration with respect to time to obtain the rotation jerkiness (rad/s^3).

In addition to measuring the wheel's rotation movement, the system is able to monitor the wheel's phase within its revolution cycle. This is achieved through a set of 16 non-latching hall effect switches arranged in a circular layout around the point where the wheel's arm connects to the body (fig. 3.11). A magnet is positioned on a reference point on the wheel. As the wheel rotates, the magnet hovers above the array of sensors, triggering each sensor individually and returning its position within the cycle. The sensors were ingeniously laid out at a distance that would allow their ranges to overlap. This design effectively doubles the resolution to 32 resolution points.

As shown in fig. 3.10, data from all the sensors is transmitted wirelessly within a custom network via Open Sound Control (OSC) messages over the User Datagram Protocol (UDP). This network is established by the ESP32, which has been specifically configured as a "soft" access point, meaning it doesn't provide internet access. The choice of relying on a custom network and not on regular WiFi was driven by the requirements for reliability and adaptability, particularly in exhibition settings where conventional WiFi access may not be available.

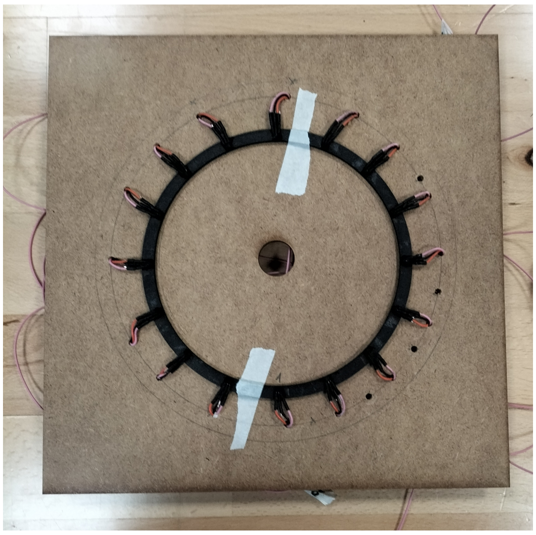

Figure 3.11: The "crown" of hall effect sensors, measuring the wheel's phase

3.3.3 The sound engine

The sculpture's sound is created through a powerful combination of a single audio player, a noise generator and several audio effects, implemented in Max MSP. Most effects are set up in parallel to the looper's dry audio signal, preserving the integrity of the original sound while preventing consistent changes in volume. This approach not only maintains the clarity of the dry signal but also lends a subtler, cleaner quality to the applied effects. The signal routing is illustrated in detail in fig. 3.12.

Below is a detailed description of each element and their implementation:

- **Audio Looper:** the audio looper is the main sound source, and it was implemented using a combination of the *buffer˜* and *groove˜* objects.

  The *buffer˜* object creates a memory buffer to store an audio file. It's name is used by other objects to access and modify its contents. The *groove ˜* object handles the file's playback. It accesses the file by referencing the correct buffer using the *buffer ˜*'s name and it enables control over the number of output channels and over various aspects of the playback, including speed, direction and looping.

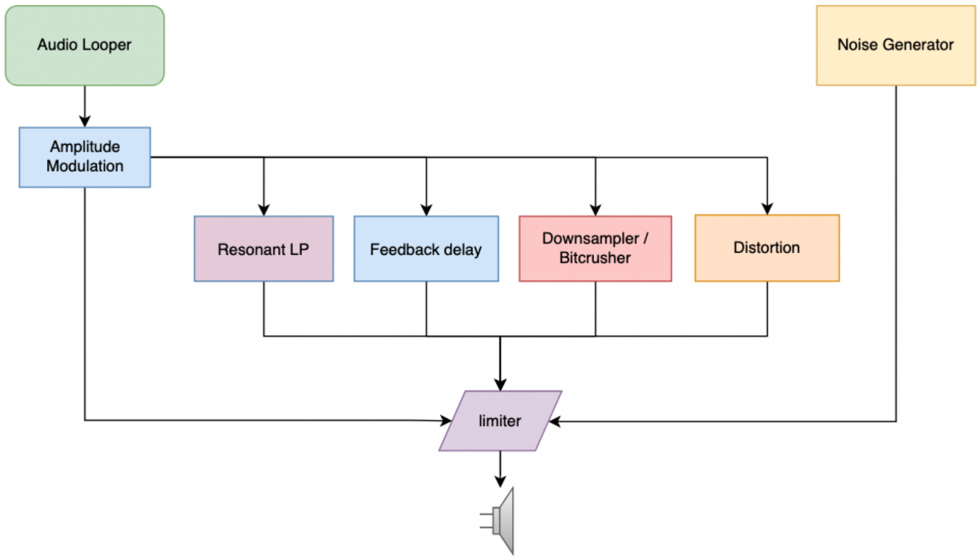

Figure 3.12: The sound generator's and the audio effects' signal chain

- **Feedback delay:** the feedback delay is a powerful audio effect that generates multiple audible repetitions of an input signal. The number of repetitions is controlled by the feedback factor, and the time interval between these repetitions is determined by the delay time. In this implementation, a parallel stereo feedback delay has been created within a Max MSP *gen* ˜ patch. Control over the input gain is available, and high-pass filtering is performed on the input signal at 200 Hz. This filtering helps clean the signal and prevents an excessive representation of low frequencies. A simple diagram of the feedback delay and its control parameters is detailed in fig. 3.13 Finally, the delay's output is routed through a stereo limiter (*limi* ˜), ensuring that the resulting audio remains within desired amplitude bounds, preventing clipping and maintaining consistent output levels. At the core of this implementation is the delay object, which operates as a traditional delay line, much like the combination of Max MSP's *tapin* ˜ and *tapout* ˜ objects. The feedback loop is implemented using the history object, with the feedback intensity adjustable via user input. However, a notable challenge arises when attempting to modify the delay time while audio playback is in progress. This challenge is rooted in discontinuities, which manifest as abrupt changes in the reading position within the audio buffer, leading to audible clicks or pops. To address this issue, the system employs a clever approach involving crossfading between two parallel delay. The sah (sample and hold) object plays a crucial role in this process. It samples the user-controlled delay time and releases it to a silent delay line, which is then introduced into the audio signal. Simultaneously, the old delay line with the previous delay time value is smoothly phased out. This transition is facilitated by a sinusoidal interpolation function running at 5 Hz with a phase offset of +1 * 0.5, ensuring that changes in delay time occur seamlessly and free from disruptive artifacts.

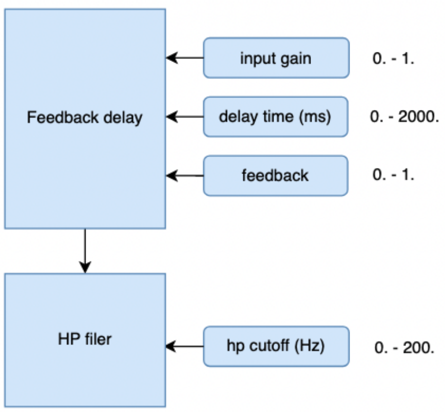

Figure 3.13: A simple sketch of the feedback delay and its control parameters

- **Bitcrusher / Downsampler:** bitcrushing and downsampling are two audio processing techniques that reduce the bit depth and sample rate of audio samples respectively. Both processes create a lo-fi, crunchy, and distorted sound, often associated with vintage digital equipment. A simple diagram of the bitcrusher / downsampler and its control parameters is detailed in fig. 3.14. The bitcrusher implementation offers a novel approach by providing precise control over the signal's bitmask. This implementation follows a structured three-step process: (1) the incoming audio signal undergoes rounding to eliminate any decimal components, a task efficiently carried out by the *trunc ˜* object; (2) following rounding, a bitwise XOR operation takes place. It involves comparing the rounded audio signal with a 32-bit binary sequence. The content of this sequence dynamically adjusts based on a user-modifiable input parameter. This operation enables fine-tuned alteration of the audio signal's bitmask, allowing for controlled variations; (3) to achieve the desired bitcrushing effect, the resulting output undergoes an additional rounding process.

  In contrast, the downsampler implementation centers around the *degrade ˜* object, which takes any given audio signal and reduces its sampling rate as specified. While *degrade ˜* could potentially serve for bitcrushing too, the chosen implementation stands out due to its precision in bitmask modification, offering users a highly controlled and customizable approach.

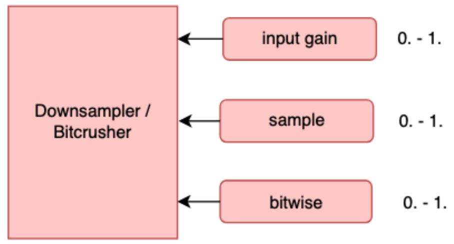

Figure 3.14: A simple sketch of the bitcrusher / downsampler and its control parameters

- **Distortion:** distortion is a widespread audio effect capable of generating additional harmonics in the input sound. Various types of distortion exist, including saturation, clipping, and waveshaping. What these methods share is their ability to reshape the incoming signal's waveform, leading to a crunchy and more aggressive output. In this particular implementation, a simple clipping technique has been employed. The input audio signal is amplified until it exceeds the maximum amplitude that a Max MSP audio channel can handle. When this threshold is exceeded, the waveform is clipped at both the higher and lower edges, resulting in a distinctive distorted sound. The degree of distortion is determined by the amount of gain applied; higher gain settings lead to more pronounced clipping. To manage the resulting distorted output, the *tahn* ˜ object is used to reduce the signal's amplitude, preventing clipping at the master output. The distorted signal then passes through a biquad peak/notch filter. This filter dynamically 'tunes' itself to the fundamental frequency of the incoming audio signal. This dynamic tuning is achieved by modulating the filter's cutoff frequency and gain based on estimations of the fundamental frequency and amplitude of the incoming signal. While more complex FFT techniques could have been employed for pitch estimation, this implementation utilizes the *fzero* ˜ object. *fzero* ˜ estimates the fundamental frequency by performing multiple layers of wavelet transforms and comparing the spaces between peaks. The resulting modulation signals are interpolated to ensure a smooth and pleasing transition between different cutoff frequencies and gains. This results in a more harmonic and sonically pleasing modulation of the distorted signal. A simple diagram of the distortion unit and its control parameters is detailed in fig. 3.15.

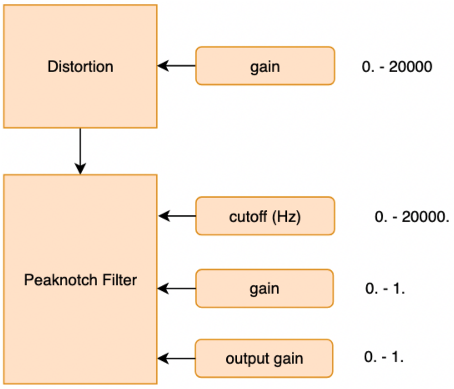

Figure 3.15: A simple sketch of the distortion unit and its control parameters

- **Noise:** in this implementation, noise takes on the role to infuse high frequency content into the overall sound. The noise component is a blend of pink and white noise generators; its output is fed into a biquad peak/notch filter similar to the one used for distortion. Once again, this filter is dynamically tuned to the fundamental frequency of the main audio signal, and its gain is determined by the audio signal's current amplitude. A simple diagram of the noise generator and its control parameters is detailed in fig. 3.16.

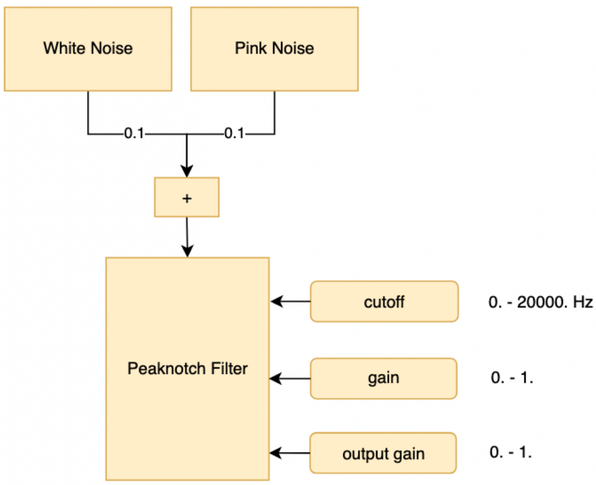

Figure 3.16: A simple sketch of the noise generator and its control parameters

3.3.4 Mappings

Table 3.17 explores the sculpture's mapping configuration.

A brief note regarding the mappings: during the evaluation tests, the "crown" of hall effect switches was not included due to functioning issues. As a result, it remained unplugged and inactive. However, it is important to note that this component will be reintegrated into the system during future developments.

	Parameter	Source	Scale
Audio Looper	Playback speed + pitch	Wheel 1 speed	exponential (5), 0. 5.5 -> 0. 5.5
	Playback direction	Wheel 1 direction of rotation	-
Noise Generator	Filter cutoff	Audio sample's f0 * 10.	-
	Output gain	Wheel 2 jerk (if Wheel 1's speed = 0, gain = 0)	linear; 0. 25. -> 0. 1.
Amplitude Modulation	Modulation frequency	Wheel 2 frequency	exponential (4.5), 0. 60. -> 0. 120.
	Modulation amplitude	Wheel 2 frequency (if Wheel 2 is spinning backwards, mod. amp. = 0)	linear, 0. 60. -> 0. 1
Feedback Delay	Delay Time	(1 / Wheel 1 frequency) * 10000	-
	Input gain	0.14	-
	Feedback	0.31	-
Bitcrusher / Downsampler	Bitwise	Wheel 2 jerk	linear, 0. 40. -> 0. 0.3
	Downsample	0.28	-
	Input gain	Arm jerk	linear, 0. 60. -> 0. 0.6
Distortion	Gain	Wheel 2 acceleration (abs)	exponential (8), 0. 12. -> 0. 20000.
	Volume	0 if Wheel 2 is spinning forward	-
	Cutoff frequency	Audio sample's f0 * 10.	-
	Cutoff gain	Audio sample's amplitude * 5.	-
Resonant LP	Cutoff frequency	Arm acceleration	linear, -2.5 2.5 -> 20000. 20.
	Resonance	if Arm acc = 0 then 0, else Wheel 1 speed	linear, 0. 3. -> 0. 1.

Figure 3.17: A simple sketch of the noise generator and its control parameters

Chapter 4

Evaluation

This chapter guides the reader through the comprehensive evaluation of the project. It covers various facets of the evaluation process, including the methodologies employed and the underlying research, the implementation of data collection and analysis systems, the interpretation of questionnaire responses, as well as the presentation of the test results.

To begin this evaluation journey, it's crucial to clarify the key areas under scrutiny. The evaluation process focuses on two primary dimensions:

1. **the interface and its affordances:** this dimension delves into the instrument itself, exploring its interface and the opportunities it offers for interaction and for achieving meaningful musical results.

2. **quality of the collaboration:** this dimension aims to assess the collaborative dynamics that emerge between two players while playing the instrument. It aims to gauge how effectively the instrument facilitates collaboration, fostering meaningful musical interactions.

Both of these dimensions are multifaceted, encompassing various variables and aspects that are pertinent to this evaluation. In the following sections, we will explore these elements in greater detail.

4.0.1 The interface and its affordances

When evaluating the interface and its affordances, our primary objective is to assess its appeal to a diverse audience with varying levels of musical expertise. Specifically, the evaluation aims to determine the extent to which the interface delivers an enjoyable and coherent experience for both musical novices and more advanced users. We base our evaluation on elements and terminology from the NIME [1] and

[1] https://www.nime.org/

DMI literature [21] [26], while also introducing our own elements inspired by the author's prior work in DMI design [17].

To assess the interface's suitability for a diverse user base, we focus on several clue aspects, including:

- **explorability:** which entails examining the interface's ability to offer a diverse set of interactions. This includes both obvious and less obvious ways for users to engage with the system, leading to a broad spectrum of sonic outputs [17];
- **expressiveness or expressivity:** which measures the extent to which the interface allows users to convey their musical intentions and emotions. It involves assessing how effectively users can manipulate the interface to produce a wide range of musical expressions [21];
- **learnability:** which pertains to the level of challenge presented by the interaction, and it involves assessing how easily and intuitively users can learn to use the interface and become capable of implementing their musical intentions [26];
- **the quality of musical outcome:** which evaluates the meaningfulness, expressivity, aesthetic quality and emotional impact of the final musical result.

4.0.2 Quality of the collaboration

Assessing the quality of the collaboration is an even more multifaceted and intricate endeavour. It involves examining the development of coordination and synchronized execution between players, the cultivation of shared musical intentions, the formulation of strategies to realize those intentions, and the establishment of effective communication cues for implementing these shared musical intentions. The primary objective of this evaluation is to observe the *emergence* of new musical ideas resulting from collaborative work, as defined by Bishop as ideas that cannot be attributed to any single individual but arise from the collective mind [3]. Additionally, we aim to assess whether participants will develop specific gestural communication cues unique to the instrument to express their collective musical intentions and coordinate their collaborative efforts. To conduct this evaluation, we will draw insights from various fields, including literature related to traditional music ensembles [3], contemporary DMIs and collaborative musical systems [9], teamwork, games, and sports [22].

4.1 Methods

The evaluation of this project took place at Aalborg University's AP Lab in Copenhagen. A total of 18 participants were recruited from the author's personal network, with an effort to include individuals with diverse musical backgrounds.

The test consisted of three phases:

1. Introduction phase
2. Testing phase
3. Assessment phase

4.1.1 Introduction phase

During the introduction phase, participants were invited in pairs into the AP Lab. They provided their informed consent for video recording of their performances and the use of their video captured and questionnaire data for discussing the evaluation of this project. Participants then completed a brief questionnaire aimed at assessing their level of musical background. These few questions were partially adapted from the Goldsmiths Musical Sophistication Index (Gold-MSI) [2], a widely-used tool for assessing a participant's experience with traditional musical instruments, and were modified to include electronic musical instruments as well. The questionnaire was divided into two parts. In the first part, participants used a 7-point Likert Scale to rate their responses to general questions about their involvement with music. This scale ranged from strong disagreement (1) to strong agreement (7) and included questions tailored to gauge their familiarity with contemporary interactive musical systems, as well as their attendance at exhibitions featuring such systems. The questions included in this part of the questionnaire were:

1. I spend a lot of my free time doing music-related activities
2. I often read or search the internet for things related to music
3. I often visit public cultural spaces exhibiting interactive musical systems
4. I have often engaged in interaction with interactive musical systems in public spaces

In the second part, participants completed a series of sentences to provide information about their musical education, by completing them with the missing information, choosing between 7 different options. Below are the questions included in the second part of the questionnaire:

1. I engaged in regular, daily practice of a musical instrument (including electronic instruments) for *X* years

[2] https://www.gold.ac.uk/music-mind-brain/gold-msi/

2. I have had X years of formal training on a musical instrument (including electronic instruments) during my lifetime
3. I can play X musical instruments (including electronic instruments)

Participants were then given a brief introduction to the instrument and the subsequent testing phases. They were informed that they would be evaluating the prototype of an interactive sound sculpture designed for exhibition in museums and public spaces. The sculpture was described as being designed for multi-user input, with the aim of encouraging collaboration between the players.

4.1.2 Testing phase

No prior information about the sculpture's functioning was provided to the participants. Instead, they were given the opportunity to explore and discover the sculpture's functionality on their own during a 5-minute exploratory phase. They were encouraged to discuss and exchange information about their understanding of the interface and interaction while playing, with the aim to reinforce the collaborative aspect. It was hoped that by working together to understand the interaction, they would establish a connection that would carry through the rest of their collaborative experience.

Following the exploratory phase, participants were given a set of three brief assignments that had to be completed within a few minutes. These assignments were deliberately designed to encourage communication and stimulate discussions on how to approach and solve them. Therefore, to successfully fulfill these tasks, participants needed to combine gestural input on both wheels. This approach aimed to foster the development of collaborative strategies and shared musical intentions in order to successfully complete the assignments. The three tasks were presented as follows:

- Try to make the sound's volume fluctuate in a wave-like pattern
- Try to play a reversed sound with a gritty texture and a lower pitch;
- Try to find the "bell" tone in the sound you're producing;

Participants received assistance if the terminology of the tasks was unclear, and they were provided confirmation upon the completion of each task.

After completing the tasks, participants were given the opportunity to continue playing as long as they desired. The majority of them continued playing for an additional 10 minutes, resulting in a total average playtime of 20 minutes.

4.1.3 Assessment phase

During the assessment phase, participants were provided with a questionnaire aimed at evaluating their experience with the interface and their collaborative experience with their partner. To ensure balanced feedback and minimize response bias, a combination of questions with both positive and negative connotations was used. This strategy helps mitigate response bias and ensures a more accurate assessment of the participants' experiences [7]. Participants were asked to rate their responses using a 7-point Likert Scale, ranging from strong disagreement (1) to strong agreement (7).

The first part of the questionnaire focused on evaluating the participants' overall playing experience and their understanding of the interface. This assessment targeted the aspects of interface design and affordances mentioned in subsection 4.0.1. The questions were partially adapted from the System Usability Scale (SUS) [3] [7], which had been employed in some of the author's previous work [17], and from Schmid's recently developed evaluation questionnaire [26] emphasizing the experiential qualities of the interaction. Other questions were also created specifically for this evaluation. Below is the list of questions used in the first part of the questionnaire:

Table 4.1: Questions relative to the interface and its affordances

1	I appreciate the musical outcomes I was able to produce
2	I perceived the interaction with the sculpture as too basic
3	The sculpture offers me new possibilities to express myself musically
4	I exhausted the sculpture's creative and expressive capabilities too fast
5	I felt in control of the sculpture
6	The interaction with the bicycle wheels yielded different results than I anticipated
7	The sculpture offered me enough creative freedom and precise control to formulate musical ideas, even if they were basic
8	perceived the sculpture's response to my actions as awkward and unresponsive
9	The sculpture's interface provides room for learning more complex interaction techniques
10	I think I would've needed some more guidance before performing with the sculpture
11	As soon as I saw the wheels, it was clear what I had to do
12	I couldn't achieve the musical results I had hoped for

[3] https://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html

The second part of the questionnaire focused on assessing the quality of the collaboration between pairs of participants. All questions in this section were specifically designed for this evaluation, with a focus on identifying emergence [3] and the establishment of mutual engagement [9] between players. Below is the list of questions used in the second part of the questionnaire:

Table 4.2: Questions relative to the interface and its affordances

1	I enjoyed playing together with my partner
2	I had a hard time communicating with my partner
3	I discovered that collaborating with my partner expanded my creative potential
4	My partner and I failed to discuss strategies for completing the tasks
5	I found that the sculpture enabled clear and efficient communication with my partner
6	I found that playing together with my partner restrained my creative possibilities
7	I found that my partner successfully attuned to my musical intentions
8	I didn't feel like interacting with my partner
9	I borrowed lots of musical ideas from my partner
10	I could not understand my partner's musical intentions
11	My partner and I exchanged several ideas on how to tackle the tasks
12	I tried not to look at what my partner was doing, to focus on my own thing

4.2 Data Analysis

Data analysis was conducted in MATLAB [4]. The evaluation was entirely based upon the ratings from the questionnaires. The data collected from the questionnaires had a multifaceted purpose. It aimed to assess specific design aspects and gauge each participant's overall satisfaction with their interface experience and collaborative engagement. Additionally, it sought to inquire about potential effects that the participants' musical background could have on their overall experience and on specific aspects of the design. The analysis was conducted using both statistical and comparative methods.

4.2.1 Statistical analysis

The data collected from the questionnaires primarily served to evaluate specific design aspects by analyzing responses to individual questions across all participants, as well as each participant's overall satisfaction with their interface experience and collaborative engagement, through what we refer to as their *appreciation index*. The

[4]https://se.mathworks.com/

data analysis was conducted separately for the interface and collaborative aspects. It's important to note that the analysis was carried out both on individual participants' responses (participant-based) and on specific questions aggregated across all participants (question-based). Below are the cues used for the analysis derived from the questionnaire ratings:

- Mean rating (question-based)
- Standard deviation of mean rating (participant-based)
- Interface appreciation index (participant-based)
- Collaboration appreciation index (participant-based)
- Mean interface appreciation index (participant-based)
- Mean collaboration appreciation index (participant-based)
- Standard deviation of interface appreciation index (participant-based)
- Standard deviation of collaborative appreciation index (participant-based)

Mean ratings per question were separately computed for all positive and all negative questions. This method allowed for the evaluation of particular design and collaboration aspects, emphasizing strengths and addressing weaknesses. The standard deviation for each question was calculated to assess the degree of consensus in the responses. The mean ratings were categorized in custom-defined groups expressing a *bad* rating for scores between *1* and *2.5*, *moderate* rating for scores between *2.5* and *5*, *good* rating for scores between *5* and *6.5* and *excellent* rating for scores at *6.5+*. These categories were used to assess the various aspects of the implementation and assign them to different levels of success, including *unsuccessful* (bad), *fair* (neutral), *successful* (good) and *outstanding* (excellent).

Each participant's appreciation index, consisting of a single value between 0 and 100, was calculated to assess each participant's overall appreciation for both the interface and the collaborative experience. The calculation of this index was adapted from the System Usability Scale (SUS) score [7], which had been used in the author's previous work [17], with modifications to suit the specific questionnaire in this evaluation. The traditional SUS questionnaire includes 10 questions (5 positive and 5 negative), rated on a scale from 1 to 5. It uses the following formula to compute the score:

$$SUSScore = ((p1 + p2 + p3 + p4 + p5) - 5) + (25 - (n1 + n2 + n3 + n4 + n5)) * 2.5$$

In this evaluation, the questionnaire consisted of 12 questions (6 positive and 6 negative) and used a rating scale from 1 to 7. Therefore, the formula was implemented as follows:

$$A.I. = ((p1 + p2 + p3 + p4 + p5 + p6) - 6) + (42 - (n1 + n2 + n3 + n4 + n5 + n6)) * 1.42855$$

The mean appreciation index was also calculated to provide an overview of the general level of appreciation across all participants, while the standard deviation of the appreciation index was computed to determine the presence or absence of a consensus in the responses. Participants were categorized into four distinct groups based on their individual appreciation index. These categories were developed separately for the evaluation of the interface and the collaborative experience. This categorization system was adapted from the author's previous work [17], which was rooted in the SUS score rating. Participants with an appreciation index below 68 were classified as showing *low* appreciation, those between 68 and 75 were considered to show *moderate* appreciation, those between 75 and 90 were categorized as showing *high* appreciation, and those with an index above 90 were categorized as showing *extremely high* appreciation.

4.2.2 Comparative analysis

The comparative analysis consisted of three main comparisons:

- responses to the same question between pair members, to investigate the correlations between their individual perceptions and impressions of their collaborative experience;
- between each participant's musical background and their appreciation index, to determine whether musical experience has an impact on their appreciation and understanding of the interface and of the collaborative experience;
- between each participant's musical background and their response to specific questions, to determine which aspects of the implementation and collaborative experience are influenced by their level of musical expertise.

Participants were categorized into groups based on two factors: their musical experience (measured in years spent playing a musical instrument, including electronic instruments) and their familiarity with interactive musical systems in public spaces (determined by the sum of their ratings to the two questions out of a total score of 14).

For their musical experience, participants were classified into three categories: *novices* (0 - 3 years), *practitioners* (4 - 9 years), and *experts* (9+ years). As for their level of acquaintance with interactive musical systems, they were divided into *newcomers* (0 - 3 points), *explorers* (4 - 9 points), and *acquainted* (10+ points).

4.3 Results

This section of the paper explores the result of the evaluation tests, following the methods of data analysis and interpretation exposed in section 4.2. For the data plots, please click on the links to the Appendix next to the corresponding subsection title.

4.3.1 Results of the statistical analysis

Aspects of the interface and its affordances , A.0.1

This section of the statistical analysis uses questionnaire data to examine the quality of the design and implementation of specific aspects of the interface and its affordances based on questionnaire responses. It does so by analyzing mean ratings for individual responses. Furthermore, it evaluates the participants' overall appreciation of the interface and its affordances by providing an overview of the appreciation index for each participant.

Upon delving deeper into the data and examining the mean rating for each question, we can pinpoint the strengths and weaknesses of the implementation. Please refer to fig. A.1 for the data plots.

The most noteworthy success emerges from the participants' appreciation of the musical outcome, which received a high rating of 5.94. The remarkably low standard deviation of 0.8 indicates a substantial consensus among all participants regarding this aspect. In contrast, the aspect that appears to have encountered the least success is the efficiency of the chosen interactive medium in establishing an immediate cognitive link with the proposed interaction. Notably, the mean rating of 4.83 assigned to question number 6, which inquires, "The interaction with the bicycle wheels yielded different results than I anticipated," might suggest that the bicycle wheels did not naturally prompt a specific type of interaction. However, when compared to question 11, which states, "As soon as I saw the wheels, it was clear what I had to do" and received a higher rating of 5.33, an inconsistency becomes evident. This discrepancy implies that question number 6 may not have been well formulated and was widely misinterpreted by the participants. Additional support for this hypothesis can be found in the participants' low rating of 2.83 for question 10, "I think I would've needed some more guidance before performing with the sculpture." This suggests that most participants felt comfortable playing the instrument right away, indicating that the bicycle wheels were indeed successful in facilitating spontaneous and unguided interaction.

Another aspect that displays mixed results pertains to the interface's learnability, expressivity, and explorability. A predominant trend in the data suggests that the interface functions as a highly responsive instrument, providing abundant opportunities for exploration and artistic expression. This observation is substantiated by the positive ratings assigned to questions 2 (2.89), 3 (5.22), 5 (5.22), 7 (5.55), 8 (2.22), 9 (5.72), and 12 (2.5). Collectively, these ratings underscore the notion that the interface effectively accommodates a wide spectrum of gestural interactions, facilitating a diverse range of sonic possibilities. Moreover, these ratings indicate that the interface affords ample creative potential and nuanced control, enabling participants to formulate and implement musical ideas, even at a fundamental level. However, question number 4, which reads, "I exhausted the sculpture's creative and expressive capabilities too fast," received a relatively high rating of 3.78. This rating challenges the notion of the instrument's extensive explorability, indicating that some participants believed they reached the limits of its creative and expressive potential rather quickly. The relatively low standard deviation of 1.26 indicates a significant level of agreement among the participants regarding this aspect.

Examining the data from a broader perspective allows us to provide an overview of the participants' opinions. Please refer to fig. A.2 for the data plots.

In particular, an overall mean rating for the interface design and implementation can be determined. To ensure a consistent interpretation where higher ratings represent a more positive response, all negatively-connotated questions were converted into their positive equivalent and their individual mean ratings (x) were reversed to obtain a positive value (7 - x). The overall mean rating was then calculated as the mean of the mean ratings per question. The result indicates that the interface and its affordances received an overall rating of 4.71 out of 7, signifying a "fair" level of success in the design and technical implementation of the sculpture. It's worth noting that the standard deviation of the mean ratings, which is 0.24 out of 7, reflects a high level of consensus among all participants. The mean appreciation index reports a value of 72.14 out of 100, aligning with the overall mean rating and affirming the "fair" success rating assigned to the interface and its affordances. Additionally, the standard deviation of the appreciation index, rated at 10.76 out of 100, once again indicates a substantial consensus of opinions among participants.

Aspects of the collaborative experience, A.0.3

This section of the statistical analysis uses questionnaire data to examine the quality of the participant's collaborative experience and of the communication driving such collaboration. It does so by analyzing mean ratings for individual responses. Furthermore, it evaluates the participants' overall appreciation of their collaborative experience by providing an overview of the appreciation index for each participant.

Overall, the data relative to the collaborative experience emphasize that most participants had an enjoyable time playing together and exhibited high levels of communication between each other.

To provide a detailed analysis of the collaborative experience, let's begin by examining the mean rating for each question in the survey. A.3 for the data plots. The most striking observation is that participants thoroughly enjoyed playing together, as reflected in the highest-rated question, with a rating of 6.17. This positive and enjoyable experience can be attributed to several factors: participants demonstrated a high level of communication, as indicated by the positive ratings for questions 2, 4, 5, and 11; participants seemed to have the general impression that collaboration enriched their creative possibilities, as evidenced by the positive ratings for questions 3 and 6; a relatively high level of mutual engagement was observed during the collaboration. The observations regarding mutual engagement among participants are noteworthy. On the whole, participants felt that their partners successfully attuned to their musical intentions, found their partner's musical intentions to be clear, and made conscientious efforts to collaborate and communicate effectively. The only area where mutual engagement seemed to receive a lower rating was in the extent of borrowing musical ideas from each other.This observation does raise questions about the interface's capacity to facilitate the generation of musical ideas, and this aspect certainly deserves further investigation. From a comparative analysis between the questionnaire responses related to the interface and the collaborative experience, it emerges that the interface provided the potential for formulating basic musical ideas (as indicated by question 7). However, the lower rating for the extent of borrowing musical ideas suggests that participants might not have fully exploited the interface's capabilities, and their individual resources for borrowing musical ideas from each other. However if we look at the other data about exchanging musical ideas and discussing strategies to accomplish all the tasks we can be reassured. Indeed, when considering the data related to exchanging musical ideas and discussing strategies to accomplish the tasks, there appears to be a more positive picture. This suggests that despite the lower rating in terms of borrowing musical ideas, participants engaged in meaningful discussions and exchanges to work together effectively and achieve their collaborative goals. It reinforces the idea that successful collaboration involves multiple facets, and the dynamics of interpersonal interactions can be multifaceted and nuanced, touching upon aspects of personality, sociability, mood and more.

Taking a broader perspective, it becomes evident that participants had a highly enjoyable and collaborative experience. A.4 for the data plots.

The appreciation index data demonstrates extremely high levels of appreciation for the collaborative aspects of the sculpture, with peaks at 97.14 out of 100. Notably, three participants, constituting 16.67 percent of all participants, reported appreciation indices exceeding 90, and 11 others, constituting 61.11 percent of all participants, reported scores ranging from 75 to 90. However, it's also intriguing to note that two participants rated their collaborative experience between 68 and 75, and two participants rated it below 68, with a lower peak at 52.86, as reported by participant number 16. It's particularly interesting to observe that participant number 16's appreciation index was 22.85 points lower than that of their partner. This observation underlines the multifaceted nature of successful collaboration, influenced by individual factors such as personality, sociability, and mood.

Ultimately, the collaborative experience appears to outshine the interface, with 88.89 percent of participants rating the collaborative experience above 68, compared to 72.22 percent rating the interface and its affordances above 68. It is also worth noting that while 27.77 percent of participants rated the interface and its affordances lower than 68, only 11.11 percent rated the collaborative experience below 68. The overall mean appreciation index for the collaborative aspect was 79.60, against the 72.14 attributed to the interface and its affordances also seem to point in this direction. Once again, the relatively low standard deviation of 10.63 out of 100 underscores a general consensus in the responses.

4.3.2 Results of the comparative analysis

A comparative analysis was conducted to investigate the potential relationship between participants' individual levels of musical background and their responses to the questionnaires. In particular, the primary objective was to determine whether a connection exists between their musical background and their overall level of appreciation both for the interface and the collaborative aspects. Furthermore, the analysis aims at digging deeper into the interplay between the participants' musical background and specific issues related to the interface.

With regard to the primary objective of the comparative analysis, several significant trends are observable. Firstly, participants with limited musical experience, such as novice participant 6, who has only one year of practice and a familiarity score of 2, tended to give the lowest appreciation index for the interface (47.12) and the second lowest to the collaborative experience (64.28). However, it is interesting to notice that participants 6 (a novice) and 16 (an expert and explorer) rated both the interface and collaborative experience below 68, indicating a less favourable perception of the system.

Consistently with the results shown above, experts predominantly provided the highest ratings for both the interface and collaborative experience, with only a single practitioner falling into this category. For instance, experts like participants 1, 4, 8, and 17 gave high marks to both the interface and collaboration, reflecting a strong positive sentiment. In particular, participants 1, 4, and 8 stand out as those who appreciated the interface and the collaborative experience the most, giving scores with peaks at 88.57 for the interface and 97.14 for the collaborative experience. It's noteworthy that all three participants rated their collaborative experience above 90. However, there are also some participants who displayed a nuanced perspective. For instance, participants 7 (practitioner and acquainted), 13 (novice and explorer), and 18 (practitioner and explorer) expressed low ratings for the interface but rated the collaborative experience positively, highlighting a potential divergence in their experiences, and their preference for the collaborative experience over the implementation and affordances of the interface. As for the interplay between the participants' musical background and specific issues related to the interface,the comparative analysis of individual responses to single questions shows an intricate interplay between participants' musical backgrounds, familiarity with interactive systems, and their perceptions of the sculpture. Although some discernible patterns arise, the presence of exceptions and varying opinions within each category underscores the significance of individual preferences and expectations in shaping their assessments. It is interesting to notice that participants with limited musical experience, such as Participant 6 (novice, with minimal exposure to interactive systems) presented the lowest ratings. Particularly,aspects related to the sculpture's capacity for musical expression, the sense of control it offered, and the level of creative freedom it provided garnered notably lower scores. In stark contrast, Participant 1, an expert well-acquainted with interactive systems, expressed the most favorable opinion. Moreover, it was observed that experts generally felt in control of the sculpture. A diverse spectrum of opinions arises when assessing the efficiency of the bicycle wheels as an interaction medium. Participants' ratings concerning whether it was immediately apparent what to do upon seeing the wheels and whether the interaction yielded unexpected outcomes varied significantly. Curiously, participants'musical backgrounds and familiarity with interactive systems did not display a clear pattern in this context, as novices and experts alike showed diverse opinions. Another salient observation revolves around the perception of exhausting creative possibilities too swiftly. Practitioners, individuals with 4 to 9 years of musical experience, assigned higher ratings (approximately 5) to this sentiment. Conversely, experts and novices consistently provided lower ratings (ranging from 1 to 3), suggesting that practitioners found the instrument somewhat limiting in terms of expressive capabilities.Participant 7, a practitioner acquainted with interactive systems, stands out for rating the instrument's response negatively (5), deviating from the highly positive evaluations given by other participants (with 61.11 percent rating it as 1 or 2).Notably, many participants held the instrument's responsiveness in high regard.

Chapter 5

Discussion

The evaluation results provide valuable insights into the interface's implementation and the collaborative experience the sculpture provides. This discussion will focus on key findings, strengths, and areas for improvement.

The analysis of the interface reveals several noteworthy findings. Firstly, participants expressed a high degree of appreciation for the musical outcome produced by the sculpture, regardless of their musical background. This is indicative of the success in the design and implementation of this aspect of the sculpture, with a mean rating of 5.94. The remarkable consensus among participants, reflected in the low standard deviation of 0.8, underscores the effectiveness of this aspect. This constitues a good entry level in delivering a meaningful and coherent musical experience for broad audiences.

Another positive aspect of the implementation is highlighted by the general positive trend in assessing the sculpture's learnability, expressivity, and explorability. A predominant trend in the data suggests that the interface functions as a quite highly responsive instrument, accommodating a wide spectrum of gestural interactions and facilitating a diverse range of sonic possibilities. This is indicated by the positive ratings assigned to various questions related to these aspects. However, a challenge arises when participants express that they exhausted the sculpture's creative and expressive capabilities too quickly, as indicated by a relatively high rating of 3.78 for this question. The lower standard deviation of 1.26 implies a significant level of agreement among participants regarding this aspect. This probably has to do with the mappings still being quite raw and undeveloped, and by the fact, observed in the captured videos, that most pairs of participants struggled in finding some of the interactive and sonic easter eggs.

An intriguing discrepancy also emerges regarding the efficiency of the chosen interactive medium in establishing an immediate cognitive link with the proposed interaction. Question 6, which inquired about participants' expectations when interacting with the bicycle wheels, received a rating of 4.83. It is crucial to note that this lower rating could be attributed to the question's formulation, as evidenced by the relatively higher rating of 5.33 for question 11, which focused on the clarity of the interaction upon seeing the wheels. This suggests that question 6 may have been widely misinterpreted by participants.

In summary, the interface of the musical sculpture demonstrates strengths in facilitating an engaging and expressive musical outcome. However, certain aspects related to the immediate cognitive link and the potential for exhausting creative possibilities require further investigation.

The evaluation of the collaborative experience yields positive results. Participants reported a highly enjoyable and communicative experience, characterized by mutual engagement and enriching collaboration. The highest-rated question in this section pertained to the enjoyment of playing together, with a rating of 6.17, highlighting the collaborative aspect's success.

Participants generally displayed a high level of communication, as indicated by positive ratings for questions related to communication quality. They seemed to have the impression that collaboration enriched their creative possibilities and allowed for a high level of mutual engagement.

However, an interesting point of divergence emerged concerning the extent to which participants borrowed musical ideas from each other. While other aspects of mutual engagement received positive ratings, this particular question received a lower rating. This suggests that participants may not have fully utilized the interface's capabilities for sharing musical ideas.

The analysis of individual appreciation indices points towards a highly positive collaborative experience, with most participants providing ratings above 68. The appreciation index data further reinforces this positive perception of collaboration, as reflected in the mean appreciation index of 79.60.

The comparative analysis of participants' musical backgrounds and their responses reveals intriguing trends. In general, it was observed that novice participants tended to rate the interface lower, which is an indication of their struggles at understanding the interaction; while experts consistently provided higher ratings, which is understandable as they draw on their experience with gestural interaction, instrumental gestures, and their musical knowledge. Notably, the novices' lower ratings for the interface may indicate the need for more user-friendly and intuitive elements to improve the overall user experience. On the other hand, the positive evaluations from experts suggest that the interface succeeded in engaging individuals with a deeper understanding of interactive systems.

An aspect deserving examination pertains to the impact of question quality and focus on the overall quality of the analysis. It becomes evident, in hindsight, that the equilibrium and precision of the questions posed in a study wield substantial influence over the collected data and the subsequent analysis. This realization brings several noteworthy considerations into prominence.

An aspect worthy of examination concerns the quality and the focus of the questions included in the questionnaire, and the potential impact it had on the overall accuracy of the evaluation. In hindsight, it becomes evident that the balance and specificity of the questions posed during the evaluation process significantly shaped the data collected and the overall analysis. This realization brings several noteworthy considerations into focus.

First and foremost, the questions' distribution among various categories was notably imbalanced. The majority of the questions were directed towards two primary dimensions, primarily assessing the expressivity and learnability of the interface. In contrast, relatively few questions delved into the explorability and the quality of the musical outcome. This imbalance had distinct repercussions, as the areas receiving less attention reported data that often lacked clarity and exhibited conflicting trends. With regard to the aspect of collaboration, the questions predominantly targeted the level and quality of communication between players. Only one question addressed the overall enjoyment of playing together and the potential for enhanced expressivity. To address this imbalance in future evaluations, it is advisable not only to maintain the existing questions but also to introduce additional inquiries in the underrepresented categories. Striking a greater balance in question distribution will contribute to a more holistic understanding of the subject under investigation. Furthermore, the formulation of the questions requires refinement to enhance comprehension and the quality of the data. For instance, question 6, that reads "The interaction with the bicycle wheels yielded different results than I anticipated", seems to have been misunderstood, leading to unclear data.

Additionally, the evaluation process would benefit from a more comprehensive assessment of participants' musical backgrounds. While playing bicycle wheels may not demand advanced musical skills, such information remains relevant, as musical expertise, or the lack thereof, can influence the participants' ability to perform intricate instrumental gestures and engage in explorative interactions to generate more articulated sounds. Moreover, participants' familiarity with interactive musical systems should be probed in greater depth. The current data indicate a lack of clarity in this aspect, making it challenging to connect the two data categories effectively. Future evaluations should include inquiries about participants' specific familiarity with collaborative musical systems and their prior engagement in collaborative creative experiences. This approach would yield more robust and easily relatable data, particularly in the context of collaborative experiences.

The composition of the participant group can also yeald a significant impact on the evaluation's outcomes and merits careful consideration. The preeminent influence of experienced participants in this evaluation is unmistakable, with the majority having more than four years of practice with traditional and electronic instruments. In contrast, novices constituted only 27.77 percent of the participant pool. The data already illustrate that novices encountered greater challenges in playing the sculpture and comprehending the interaction. Given this observation, it is pertinent to inquire whether a more balanced representation of musical categories, including a greater amount of novices would have yielded different or potentially more adverse results. This emphasizes the need for a more diverse and balanced participant pool in future evaluations to attain a comprehensive perspective on the system's usability and collaborative potential.

Unlike the big impact they had on approaching the interaction and relating to the interface, the participants' musical backgrounds did not appear to significantly impact the collaborative experience, suggesting that other unexplored factors played a more pronounced role. One such factor is the participants' prior familiarity with each other, as previous research has indicated that it can substantially affect collaborative interactions.

Personal observations gathered form the video recordings

The observations of the video recordings reveal key insights into the participants' behaviors and expectations.

First of all, the majority of participants exhibited a passive interaction approach with the sculpture, simply letting the wheels to spin without actively attempting to exert influence over their movement. In contrast, only a few participants engaged in activities that involved creating rhythmical patterns or triggering sounds in a rhythmic manner. This discrepancy in engagement styles highlights the potential influence of the allotted interaction time. It is plausible that the relatively short 20-minute playtime may have shaped participants' behaviors, potentially preventing them from progressing to more complex and articulated instrumental gestures. Notably, this passive behavior was particularly evident among less experienced participants, who also appeared to be less at ease with the sculpture's operation within the initial five minutes. This unease was reflected in their greater struggle to complete the tasks. While the tasks did necessitate a basic level of technical knowledge, an effort was made to ensure clarity for all participants by referring to audible and easily discernible sound qualities rather than employing technical terminology (e.g., "fast amplitude modulation" was described as finding the "bell" tone).

A significant issue in participants' interactions with the sculpture was the prevailing expectation that they could modulate certain parameters based on the absolute position and orientation of the mobile arm. Consequently, most participants attempted to gently rotate the arm along its axis, investing considerable time and effort in this gesture. However, this approach did not yield the desired results, as the arm's operation relied on abrupt and jerky movements. Notably, none of the participants intuitively performed the "jerky gesture," as described by the author, at least not in the intended manner. Even when explicitly instructed to execute this movement, participants encountered challenges in doing so. Moreover, a considerable number of participants expected that their proximity to the wheel would trigger specific actions, although this was not the case. It is important to recognize that the lack of control over the angle and orientation of the arm can be attributed to a design limitation. This movement, as evidenced by the significant attention it received, is highly intuitive and should have been represented in the interface design.

The tasks set for the participants, while admittedly unclear for some participants, played a significant role in fostering collaborative interactions and proved to be a resounding success in promoting collaborative interactions. These tasks led participants to engage in active discussions, where they openly shared their opinions and ideas on how to accomplish the assigned objectives. The overall level of interaction among participants was remarkably high, characterized by extensive dialogue and the exchange of thoughts. Within these interactions, participants not only deliberated on the tasks at hand but also shared their perspectives on how the instrument operated and why specific sounds were produced. Some common expressions heard during these discussions included: "try to do that"; "I'll do this, you do that"; "that sounded nice, can you do it again"; "how can we play this sound again?"; "try this, I'll try that".

5.1 Future Work

While the current level of interaction exhibits a certain degree of completeness in terms of the variety and quality of sounds it can generate and the collaborative experience it offers, there is ample room for improvement. Several issues warrant attention, and a brief overview of these concerns will be provided.

The interface and its affordances

Significant room for improvement exists across various facets, including the interface, the physical structure, and the interactive capabilities of the sculpture. To address these areas, specific enhancements have been identified.

In terms of the interface and its sonic and interactive affordances, there are several aspects that can be refined. Firstly, there is a plan to re-implement the granular synthesizer to enable a more diverse and expressive sound generation process.

This will involve reintroducing the "crown" of hall effect switches, which will allow real-time control over the reading position in the buffer. This enhancement aims to strike a better balance of control between the two wheels, offering greater exploratory potential to wheel 1. Moreover, an absolute orientation measurement of the arm will be integrated, enriching the set of mappings and the creative possibilities of the interface. This change will meet users' expectations of an intuitive gesture and eliminate the "interactive void" created by the arm's previous lack of influence on the overall sound.

A structural concern was related to the generation of distracting "squeaky" sounds due to the friction between the arm and the wood at the points where the arm was inserted into the body. These sounds discouraged the movement of the mobile arm and disrupted the overall experience. To address this issue, the solution entails enlarging the holes in the wood and integrating two ball bearings around the pipe. This modification aims to ensure smooth rotation and prevent any contact between the pipe and the wood, ultimately eliminating the squeaky sound and enhancing the user's interaction with the sculpture.

The evaluation

To enhance the clarity and accuracy of future evaluations, a new set of questions will be introduced to the questionnaire. The objective is to achieve a more balanced assessment of various implementation aspects, providing a comprehensive evaluation. These new questions may encompass participants' musical experiences, bridging their familiarity with traditional musical instruments and contemporary interactive systems, as well as inquiring about their engagement in collaborative music-making.

Another crucial aspect of improving future evaluations is achieving a better balance in the participants' musical backgrounds. In the current evaluation, there was an overrepresentation of experts and a shortage of novice participants. Ensuring a more diverse participant profile will contribute to a more robust evaluation in the future.

Chapter 6

Conclusion

Happy Cycling embodies a compelling exploration of unconventional and innovative design concepts to facilitate music-making in museums and public spaces. Its core philosophy revolves around extending its reach beyond trained musicians, aiming to embrace a diverse and varied audience. The ultimate goal is to provide a fun, engaging, and meaningful experience for all players. It proposed to do so by: providing an interface with a "low entry fee", that can still provide meaningful interactions and musical outcomes for the more expert players; employing everyday objects to facilitate an intuitive yet novel interaction; placing a strong emphasis on fostering collaboration among audience members. The firm belief backing the entire work is that collaborative efforts can enhance the understanding of the musical process for individuals with limited musical backgrounds, and add a layer of fun and enjoyment that can appeal to more experienced player as well.

The project's user-friendly and inherently intriguing interface has been the result of a lengthy iterative process. It all began with two full-sized bicycles, and through a series of deconstructions and refinements, the interactive medium evolved into its current form. This transformation involved converting the two bicycles into two single bicycle wheels, which are horizontally attached to the sculpture's body. The interface leverages its approachability and entertainment value, offering ample opportunities for exploration and expression. The use of repurposed bicycle wheels fosters spontaneous and direct interaction, establishing an immediate connection with the interactive objects. Collaboration is empowered by the fact that the wheels can be comfortably and effortlessly moved further apart or closer to each other at the player's will. A custom-made sensor system placed on the wheels and on the mobile arm, comprising three IMUs and several hall effect magnetic switches, enables real-time control of an audio player and various audio effects programmed in Max MSP.

In the overall assessment, the evaluation has produced positive outcomes, indicating the success of the instrument in delivering a meaningful collaborative musical experience for a diverse group of players with varying musical backgrounds. We posit that the universal success of the instrument can be primarily attributed to the novelty of its interface, both in terms of aesthetics and proposed interaction. However, It is notable that while the instrument appealed to a broad spectrum of musical categories, it was particularly appreciated by more experienced users, while novices encountered challenges in comprehending the interaction and formulating concrete musical ideas. Additionally, it became evident that the creative potential of the sculpture was often quickly exhausted in most cases, regardless of the player's musical background. This observation raises questions about the instrument's long-term engagement potential. Nonetheless, it's important to acknowledge that the evaluation and its resulting data may have been influenced by certain biases. These biases stemmed from an underrepresentation of particular aspects of the implementation process and the collaborative experience, as well as an imbalance among different musical categories.

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Appendix A

Appendix

A.0.1 Mean Rating (Interface), 4.3.1

Table A.1: Questions relative to the interface and its affordances

1	I appreciate the musical outcomes I was able to produce
2	I perceived the interaction with the sculpture as too basic
3	The sculpture offers me new possibilities to express myself musically
4	I exhausted the sculpture's creative and expressive capabilities too fast
5	I felt in control of the sculpture
6	The interaction with the bicycle wheels yielded different results than I anticipated
7	The sculpture offered me enough creative freedom and precise control to formulate musical ideas, even if they were basic
8	perceived the sculpture's response to my actions as awkward and unresponsive
9	The sculpture's interface provides room for learning more complex interaction techniques
10	I think I would've needed some more guidance before performing with the sculpture
11	s soon as I saw the wheels, it was clear what I had to do
12	I couldn't achieve the musical results I had hoped for

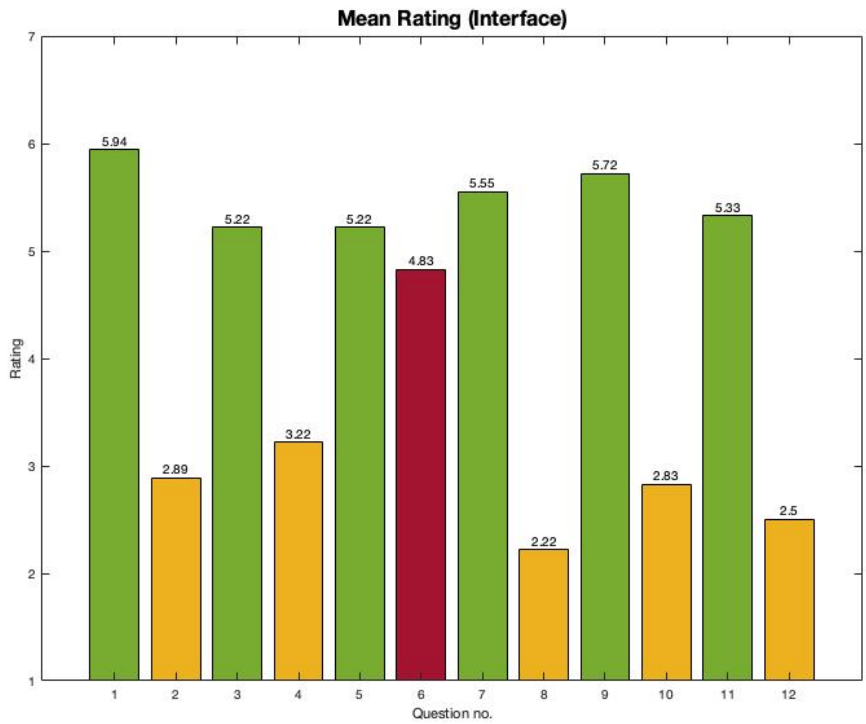

Figure A.1: The mean ratings for each question pertaining to the interface and its affordances. Ratings are color-coded as follows: *red* for *low* ratings, *yellow* for *moderate* ratings, *green* for *good* ratings, and *cyan* for *excellent* ratings. Click here to get back to the Results section 4.3.1.

A.0.2 Appreciation Index (Interface), 4.3.1

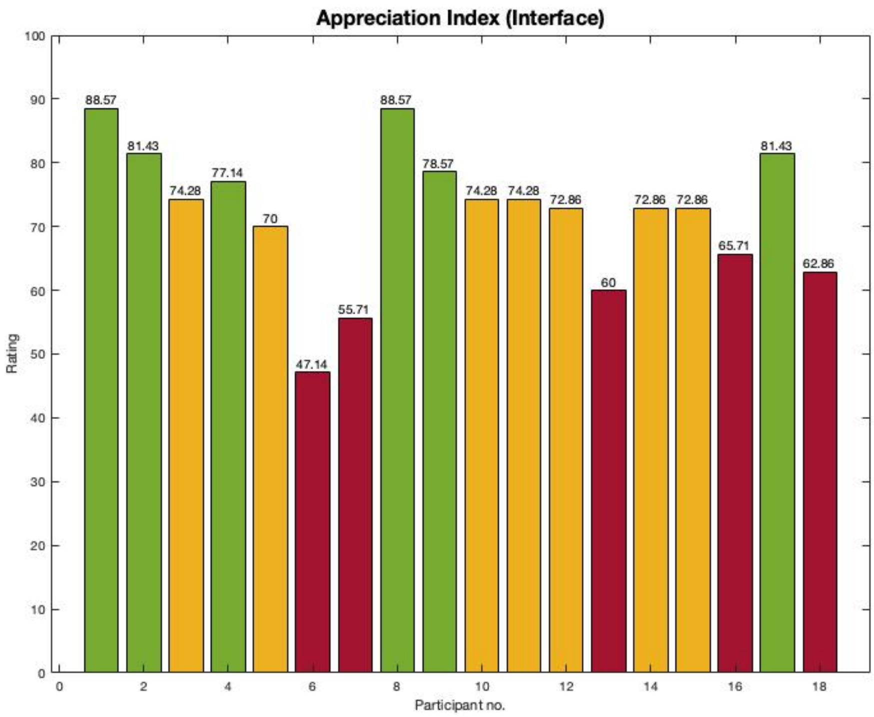

Figure A.2: Each participant's appreciation index pertaining to the interface and its affordances. Ratings are color-coded as follows: *red* for *low* appreciation, *yellow* for *moderate* appreciation, *green* for *high* appreciation, and *cyan* for *outstanding* appreciation. Click here to get back to the Results section 4.3.1.

A.0.3 Mean Rating (Collaboration), 4.3.1

Table A.2: Questions relative to the interface and its affordances

1	I enjoyed playing together with my partner
2	I had a hard time communicating with my partner
3	I discovered that collaborating with my partner expanded my creative potential
4	My partner and I failed to discuss strategies for completing the tasks
5	I found that the sculpture enabled clear and efficient communication with my partner
6	I found that playing together with my partner restrained my creative possibilities
7	I found that my partner successfully attuned to my musical intentions
8	I didn't feel like interacting with my partner
9	I borrowed lots of musical ideas from my partner
10	I could not understand my partner's musical intentions
11	My partner and I exchanged several ideas on how to tackle the tasks
12	I tried not to look at what my partner was doing, to focus on my own thing

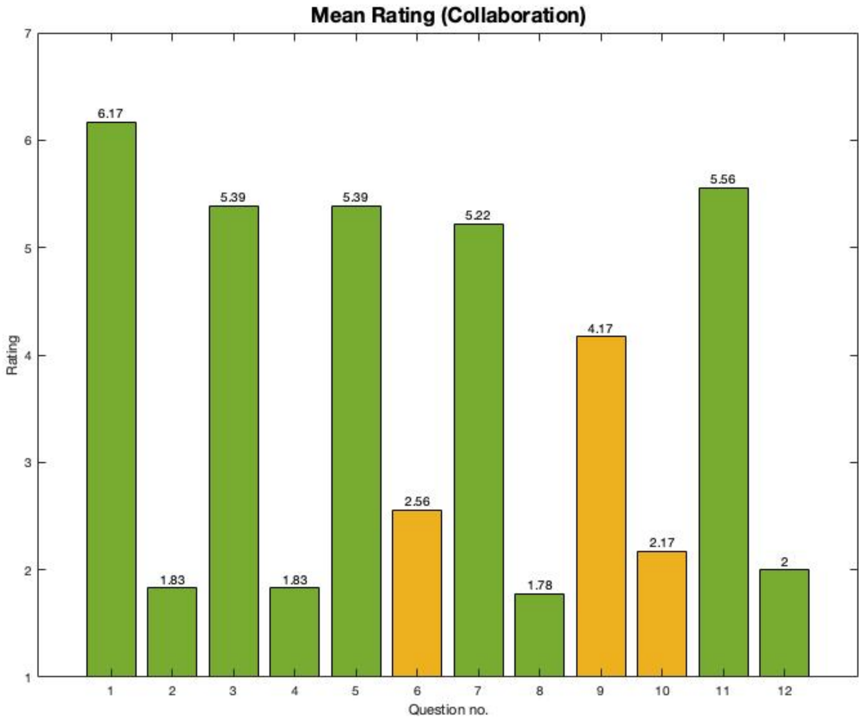

Figure A.3: The mean ratings for each question pertaining to the collaboration experience. Ratings are color-coded as follows: *red* for *low* ratings, *yellow* for *neutral* ratings, *green* for *good* ratings, and *cyan* for *excellent* ratings. Click here to get back to the Results section 4.3.1.

A.0.4 Appreciation Index (Collaboration), 4.3.1

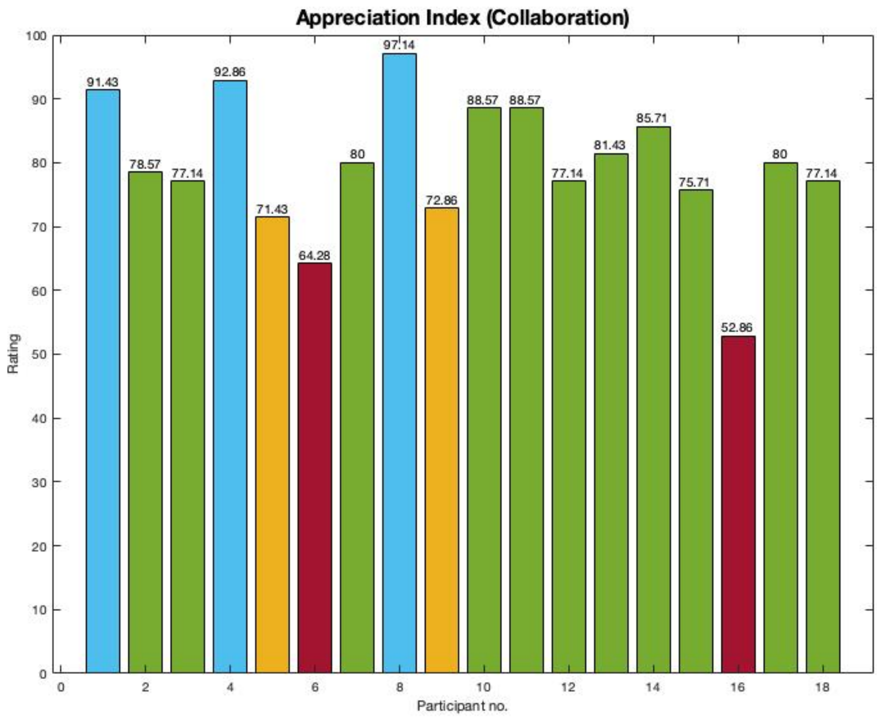

Figure A.4: Each participant's appreciation index pertaining to the collaboration experience. Ratings are color-coded as follows: *red* for *low* appreciation, *yellow* for *moderate* appreciation, *green* for *high* appreciation, and *cyan* for *outstanding* appreciation. Click here to get back to the Results section 4.3.1.