Feeling Connected: Designing Instruments and Haptic Feedback for Collaborative Music Exhibits

Paul Preuschoff
preuschoff@cs.rwth-aachen.de
RWTH Aachen university
Aachen, Germany

Karl Deilmann
deilmann@cs.rwth-aachen.de
RWTH Aachen University
Aachen, Germany

Lea Emilia Schirp
schirp@cs.rwth-aachen.de
RWTH Aachen University
Aachen, Germany

Jan Borchers
borchers@cs.rwth-aachen.de
RWTH Aachen University
Aachen, Germany

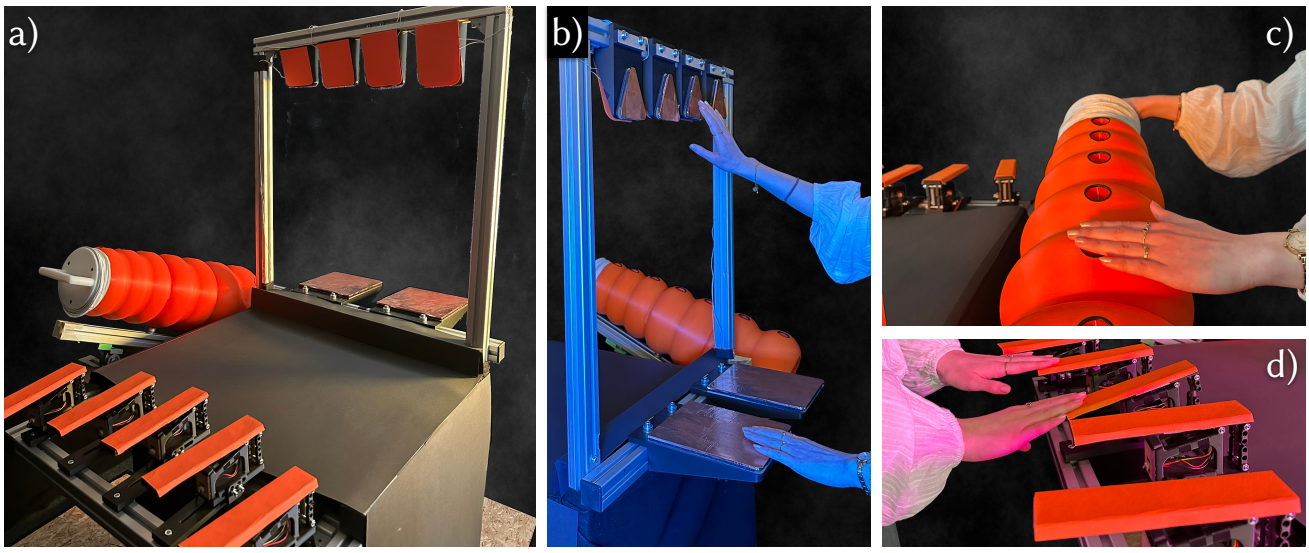

Figure 1: We built a collaborative music exhibit for three players and evaluated different modes of haptic feedback in a user study (n=21). The exhibit (a) comprises three abstract instruments: *Drums* (b) to trigger percussive sounds, the *Bellow-Pipe* (c) to continuously modulate textured pads, and *Keys* (d) to play chords and melodies.

Abstract

Walk-up music exhibits promise inclusive, social music-making, yet ad-hoc groups of novices often struggle to understand agency, coordinate timing, and stay aware of one another. To address this, we created an interactive exhibit for three visitors that features partially abstract instruments with distinct roles (*Drums*, *Keys*, and *Bellow-Pipe*) and multimodal feedback coupling audio with vibrotactile cues via floor plates and instrument-mounted actuators. Following a Research Through Design process, we conducted a participatory design workshop ($n = 7$) that led to one of the instruments using a wind-instrument-inspired interface. A subsequent user study ($n = 21$) of our refined system compared three haptic feedback modes during backing-track performances: a metronomic floor pulse, individual action feedback, and combined action feedback that merged co-players' signals. Using observations, questionnaires, and reflexive thematic analysis of interviews, we found that groups transitioned rapidly from self-focused exploration to coordinated call-and-response play, reporting high levels of enjoyment and largely balanced participation. While participants consistently noticed the shared beat, perceived awareness of co-players increased over time. Haptic support was experienced as both guidance and potential overload: the metronomic pulse was seen as most helpful, whereas global feedback could increase group awareness but blur source separation. We discuss design implications for similar exhibits, highlighting trade-offs between scaffolding and freedom, individual clarity and group awareness, and feedback richness and perceptual load.

Keywords

haptic feedback, collaborative music-making, public interactive exhibits, Research Through Design (RtD)

1 Introduction

Improvising together is a unique and connecting musical experience [17], but it usually requires significant skill and practice to succeed. To enable even novices with little or no musical background to experience this, we investigated how to build an interactive music exhibit that brings people together to improvise. We followed a Research through Design (RtD) approach

NIME '26, June 23–26, 2026, London, UK

and grounded early decisions in a participatory design workshop ($n = 7$). This resulted in an exhibit-scale installation designed for three co-located visitors. The system combines a three-role instrument set (*Drums*, *Keys*, and *Bellow-Pipe*) with a multimodal feedback design that couples audio output with vibrotactile cues delivered through floor plates and instrument-mounted actuators. The core idea is to use instruments with complementing roles, a constrained note space, and shared temporal anchors to minimize errors and "wrong note" anxiety. We focused on keeping the experience socially engaging and meaningful for novice groups and evaluated the system and different paradigms of tactile feedback in a user study ($n = 21$). From this, we derive learnings for designing collaborative music interfaces that deliver a social and meaningful experience for novices. We contribute:

- Learnings and design implications from a design case of an exhibit-scale, three-role instrument set with integrated vibrotactile feedback for walk-up trios.
- Empirical findings from a collaborative evaluation of our prototype in a lab study, comparing metronomic, individual, and group-focused haptic feedback modes.

2 Related Work

We explore related research on musical interfaces and interactive exhibits. First, we focus on musical interfaces that improve the approachability and playability of instruments, and then present works that inform the design of the exhibit as a whole.

2.1 Musical Interfaces

NIME[1] has long explored the creation of novel, often experimental musical devices, challenging established instrument paradigms by proposing new ways of mapping gestures to sound and feedback. These instruments frequently reimagine how musical expression can be embodied through alternative sensing technologies, unconventional materials, or abstract interaction concepts.

2.1.1 Mappings. In the design of new digital musical instruments, a *mapping* defines how physical gestures translate into sonic outcomes. As such, every mapping creates a tension between expressive freedom and technical precision [24], calling for a trade-off between a performer's sense of causality and their ability to discover [18].

Users further need to be able to evaluate a mapping. Studies of instruments such as the *MR:emin* [12] and the *Bodyharp* [6] have shown that visual cues can improve precision and engagement while reducing learning efficacy [12]. Furthermore, improvisation leads users to develop individual movement–sound vocabularies, which reveal that the perceived quality of a mapping is determined by aesthetics and bodily coherence instead of technical efficiency [6].

These studies highlight that mappings should remain clear and support embodied exploration to preserve low-barrier expressivity.

2.1.2 Feedback Mechanisms. Feedback in digital musical instrument design extends beyond sound, and often includes haptic elements (e.g., [10, 21]). Rather than being merely corrective, feedback becomes a performative partner, continuously mediating control and interpretation [8]. Feedback transforms digital instruments from unidirectional controllers into responsive systems.

[1]https://nime.org *(last accessed February 2026)*

Resistance is a core property of feedback, as it can sustain artistic expression by providing creative friction rather than mere error correction [7]. It can also enhance playability and joy [16] and naturally elicit vibrato and tremolo [11]. Haptic feedback may lower barriers of entry, e.g., for disabled musicians [10, 16].

Additionally, feedback can be either inherent to the sonic actuation or provided by complex external devices, as shown by the *Lorentz Lap Brass* [21]. Its user study showed that haptic cues enhanced intimacy with and playability of the instrument. Combined with artifacts like the *Hapstrument* [14] and the *Sparksichord* [20], this also shows the importance of bidirectional feedback. This motivated our use of vibration to couple sound and touch and to support rhythmic coordination.

2.1.3 Collaboration. Musical improvisation is a process of constant co-regulation of rhythm and phrasing [23] and generates novel musical outcomes from collective timing and responsiveness [19]. We consider supporting this ongoing mutual adaptation essential to the design of our exhibit.

Group improvisation has to preserve both individual agency and collective cohesion. Since novices' satisfaction with their playing experience is linked to their sense of control over their contributions, collaborative exhibits must preserve their agency while providing the right level of restriction [1]. Collaboration is further improved by providing all users with equally powerful, not overly complex means of contributing, allowing them to engage similarly without being overly absorbed in their own interactions [15].

This suggests that collaboration is fostered by mutual visibility, balanced agency, and shared cues rather than explicit instructions. We therefore design for distinct, complementary roles and for feedback that makes both each player's own actions and those of their co-players easy to perceive.

2.2 Exhibit Design

We draw from other public interactive music exhibits to inform our design process. Previous exhibits have increased engagement and approachability, especially for non-musicians, by employing multimodal interactions, like the baton-based interactions of *WorldBeat* [2] and the soft spheres of the *Interactive Musical Fruit* [9]. For multi-user exhibits, *reacTable* [13] explores the potential of tangible interfaces as social mediators to make interactions more symmetrical between users, while integrating tangible, visual, and auditory feedback. We build on HCI design patterns for interactive exhibits such as Domain-Appropriate Devices, Attract–Engage–Deliver, and Cooperative Experience [3]. More recent work further suggests that meaningful interaction with such exhibits relies not on technological novelty but on coherence of sensory modalities between, for example, input and feedback [25].

Together, these projects suggest that effective interaction in public musical exhibits is embodied, social, and supported by coherent multimodal feedback. This motivates our emphasis on large, visible gestures and haptic coupling.

3 Design Goals and Constraints

At the beginning of our design process, we identified high-level design goals and constraints to guide our development. In a walk-up exhibit, visitors arrive with unknown skills, spend limited time, and cannot rehearse or get detailed instruction. In our exhibit, we therefore decided to pay special attention to:

- ***Social Connection***: Social awareness of co-players and their actions should form, ideally, bonding players.
- ***Enjoyment***: The experience should be fun and rewarding, yet reasonably challenging.
- ***Intuitiveness***: Individual agency should become clear quickly and naturally.
- ***Balance***: Players' roles should complement each other, but impact should be equal.
- ***Melodic Support***: Musical outcomes should be constrained enough to be pleasant, while leaving room for exploration.
- ***Rythmic Support***: Groups should establish and maintain a shared tempo and beat.
- ***Inviting***: The whole exhibit should be intriguing and non-threatening to novices, also before use.
- ***Transparency***: Not only the user, but also peers and by-standers should clearly understand what someone is doing and how it sounds.
- ***Power***: Users should feel like what they do has a strong, direct impact, and they should feel in control.

Based on these goals, we derived more concrete ideas that were later discussed as part of the workshop: Because of *Intuitiveness* and *Balance*, we decided that each instrument should support a specific type of interaction with sound and allow us to map different kinds of sounds to each instrument. We organized the space of potential sounds into three groups.

- **Single-point interaction**: Sounds are triggered once, then fade out, as on percussive instruments like drums or xylophones, and are designed to play rhythmic accents.
- **Two-point interaction**: Sounds are triggered and stopped actively, as on an organ, and are designed to play melodies and chords.
- **Continuous interaction**: Sounds can be modulated at any point while they play, as on a violin or trombone, and are designed to play textured, underlying sounds.

For better *Transparency*, the instruments should encourage large, highly visible gestures that clearly communicate what someone is doing. We also want to balance *Social Connection* and sense of *Power*. This led us to build the instruments so they could be played eyes-free, and we arranged them to encourage eye contact. We also decided against visible feedback, like blinking lights, which would draw the player's attention away from their peers and towards their own instrument. Placing vibrotactile floor panels under each player enabled us to provide strong yet intimate individual feedback. For *Melodic Support* and *Rythmic Support*, and to increase *Enjoyment* and *Intuitiveness*, we constrained the musical space (e.g., restricted pitch sets) and introduced an external temporal and harmonic scaffold via a shared background track reference that included a simple drum beat and baseline.

4 Design Workshop

We conducted a design workshop with seven musicians recruited via university mailing lists and local creative communities. The goal of the workshop was to reflect on our design goals and early prototypes, to gather and evaluate instrument ideas from diverse musical perspectives, and to inform subsequent, more detailed design decisions. Participants were aged 21 to 26 (M = 23.9, SD = 2.6), 5 of whom had a background in playing classical instruments and 2 in being a DJ. The workshop took place in a controlled lab environment and used low-fidelity prototyping materials to foster abstract-level ideation.

The session consisted of three stages:

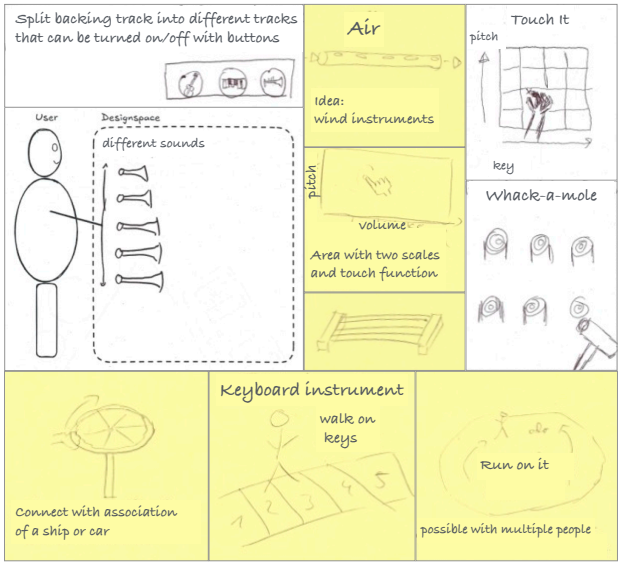

Figure 2: Example ideas and sketches from the workshop. The idea regarding airflow (top middle) inspired the *Bellow-Pipe* instrument.

(1) Introduction to the project context, individual brainstorming on interfaces for collaborative music-making that are approachable for novices, followed by a short discussion.
(2) Presentation of our early concepts and a hands-on experience with prototypes, afterwards gathering feedback and discussing them.
(3) Group design phase in teams of two to three participants to develop more concrete concepts based on our prototypes and their own ideas.

We recorded the workshop and conducted end-of-session interviews to capture reflections on playability and collaboration. Interview data were analyzed inductively using reflexive thematic analysis [4, 5], with attention to themes around intuitiveness, bodily engagement, and social coordination.

Overall, the workshop backed up most of our early design assumptions. Participants suggested that, to be *Inviting*, the instruments should not look like real instruments, as this would convey the impression that they require specific practice and skill. However, similarities to existing instruments might improve *Intuitiveness*. In the workshop, we also collected ideas for concrete interfaces, some of which are presented in Figure 2. Participants also discussed early non-functional prototypes we had created. We had considered a wheel-based continuous controller, as this offered a seemingly natural motion-to-sound mapping, but workshop feedback suggested that this interaction was not intuitive enough, as the concept deviated too much from classical instruments. We therefore abandoned this direction and explored a more familiar wind-instrument-inspired metaphor suggested in the workshop.

5 Final Design: Instruments and Haptic Platforms

The final system consists of three complementary instruments designed for simultaneous play by a trio (Figure 3), three directed speakers, and vibrotactile feedback modules.

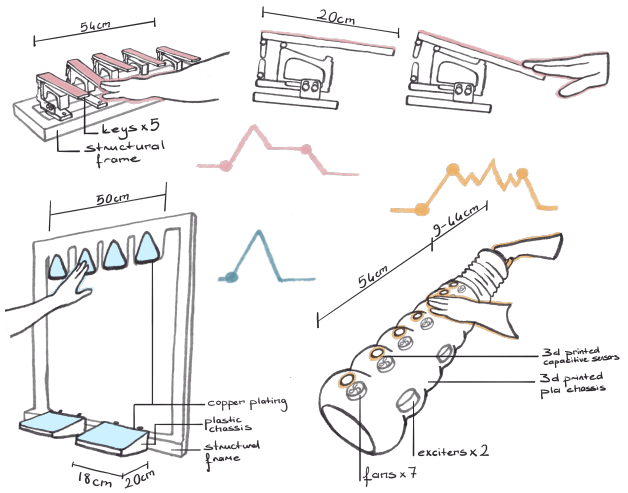

Figure 3: Sketches of the three instruments. Graphs visualize points of interaction with the sound over time. Each instrument is designed to play a specific role.

The *Drums* instrument (Figure 3, blue) was created for *single-point* sound interaction. It consists of six drum-like surfaces: four suspended above the user's head and two larger ones in front of them. They are capacitive touch pads connected to an MPR121[2] controller. This design did not detect attack velocity, but provided robust on/off triggering. Earlier iterations used velocity-sensitive piezo elements, but these frequently misfired. We mapped the sounds of the four top surfaces to four ascending glockenspiel notes and the two bottom surfaces to a cymbal and a kettledrum.

The *Keys* instrument (Figure 3, pink) was designed for the role of two-point sound interaction (start and stop). It uses five large spring-loaded keys with optical distance sensors (QRD1114[3]). This enables note-on and note-off triggering and velocity detection. We mapped this instrument to the sound of an electrical organ.

The *Bellow-Pipe* (Figure 3, orange) provides a third, more abstract role of continuously interacting with the sound by combining discrete pitch selection with continuous modulation. It features seven holes arranged along a wavy body profile that supports eyes-free play; the waves become smaller along the instrument, providing a simple cue for a low-to-high pitch mapping. Each hole is framed by a conductive ring, again connected to an MPR121 controller. For modulation, we placed a bellows-like controller at the narrow end; its position is measured with a VL53L1X[4] distance sensor and mapped to timbral modulation. To enrich tactile feedback and strengthen the metaphor of an air-powered instrument, each hole contains a small fan. As users touch it continuously, we added small haptic exciters inside.

For each player, we introduced additional vibrotactile feedback through floor modules to stand on. Each floor module is a 60 $cm \times$ 60 cm plate driven by a high-power exciter that can produce rather strong vibrations in the approximate range of 30–300 Hz.

[2]https://cdn-shop.adafruit.com/datasheets/MPR121.pdf *(last accessed February 2026)*
[3]https://www.onsemi.com/download/data-sheet/pdf/qrd1114-d.pdf *(last accessed February 2026)*
[4]https://cdn-learn.adafruit.com/downloads/pdf/adafruit-vl53l1x.pdf *(last accessed February 2026)*

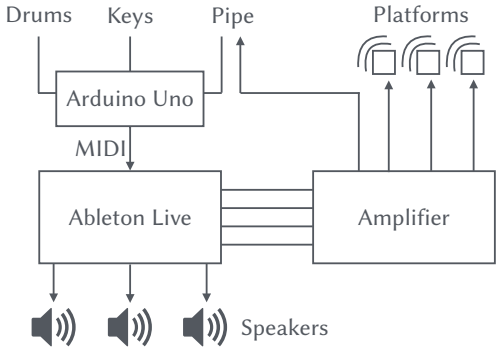

Figure 4: Schematic overview of the exhibit. The instruments are connected to an Arduino Uno, which sends corresponding MIDI signals to Ableton Live. This generates the audio and sends it to speakers and a power amplifier, which powers the vibrating platforms and the haptic feedback of the *Bellow-Pipe*.

All sensor signals are unified via a common MIDI pipeline (Figure 4): an Arduino Uno[5] reads sensor data and applies basic debouncing/filtering, then transmits notes and control values to a host computer. On the host, *Ableton Live*[6] maps these events to synthesize tones. It also produces low-frequency audio for the vibrotactile feedback system.

6 Methods: Collaborative Evaluation Study

This study evaluates our design and compares different modes of haptic feedback. Seven trios ($n = 21$) each completed a 60-minute session. They were 20 to 42 years old ($M = 26.0, SD = 5.5$) and from diverse musical backgrounds, ranging from 0 to 19 years of active music making ($M = 8.8; SD = 6.4$), with moderate self-rated experience in active music making ($M = 3.1$ of 5; $SD = 1.3$). Most participants were students (15 of 19), with the remainder reporting diverse occupations. Because the data for two participants were corrupted, we report findings for only 19 participants for some survey items.

Each group completed four parts. Every part paired an active playing task with an individual questionnaire and a brief semi-structured interview.

(1) **Free exploration**: The group freely explored and moved between instruments for 5 minutes, mimicking the free exploration setting in a museum. After this phase, each participant committed to one instrument for the remainder of the session to enable within-role comparisons.
(2) **Backing track and Metronome Pulse**: Participants improvised to a 2-minute backing track, with a haptic metronome delivered via the floor plates.
(3) **Backing track and Individual Instrument Feedback**: Like phase 2, but floor plates provided haptic feedback for the player's own actions instead. This feedback was a pitched-down, low-pass-filtered version of the instrument audio.
(4) **Backing track and Combined Instruments Feedback**: Like phase 3, but floor plates provided haptic feedback for the whole group's actions instead.

[5]https://docs.arduino.cc/resources/datasheets/A000066-datasheet.pdf *(last accessed February 2026)*
[6]https://www.ableton.com/en/ *(last accessed February 2026)*

The order of the haptic conditions (Parts 2–4) was counterbalanced. We compared how the feedback modes affected perceived synchrony, awareness of co-players, immersion, and perceived support.

In addition to questionnaires (Appendix A), recordings, and interviews, we collected observational notes on group dynamics and communication. We analyzed interview data with reflexive thematic analysis [4, 5], and summarized questionnaire and log data using descriptive statistics.

7 Study Results: Collaboration and Haptic Feedback

Our study evaluated the final prototypes and three modes of haptic feedback. We translated and shortened quotes where necessary. Our survey used 5-point Likert scales.

7.1 Observed Trajectory of Group Play

Across all seven sessions, groups exhibited a strong learning effect and followed a similar trajectory: In the initial phase, participants explored instruments in a self-focused manner with little attention to co-players. Later, groups introduced more varied motifs and call-and-response interactions, often resembling short "musical conversations" with one participant initiating a phrase and others responding. In a third phase, some groups amplified these dynamics, while in two cases, players introduced chaos, including occasional disruptive behavior to provoke reactions or explore the system.

7.2 Haptic Feedback

Haptic feedback modes noticeably shaped behavior and made the instruments feel more natural.

> "*It feels weird when the melody is without vibration [...] because with classical instruments there is usually some kind of vibration.*" (Group 3)

Participants also stated that Metronome Pulse often stabilized synchronicity. They further felt that Combined Instruments Feedback tended to increase awareness of others, but could also increase cognitive load when sources became difficult to separate. Meanwhile, Individual Instrument Feedback reduced perceived awareness of others and, for some participants, produced a feeling of playing alone. For others, it also helped them understand what sound they created.

> "*It helps with [...] my own sound, to sort it out. To feel my own sound better.*" (Group 5)

Ratings of the general helpfulness of haptic feedback were mixed and overall neutral (Metr.: $M = 3.7, SD = 1.4$, Indiv.: $M = 3.2, SD = 1.4$, Comb.: $M = 3.1, SD = 1.4$). Metronome Pulse tended to be rated as most helpful, whereas perceived control was higher in the Individual Instrument Feedback and Combined Instruments Feedback conditions (Metr.: $M = 3.7, SD = 0.8$, Indiv.: $M = 4.2, SD = 0.8$, Comb.: $M = 4.1, SD = 0.9$). A post-session comparison did not identify a single feedback mode that consistently made collaboration easiest across groups. Friedman testing showed no significant differences between the modes for any questionnaire items.

7.3 Learning and Participation

Perceived awareness of co-players and coordination tended to increase over time, while perceived "fit" of one's contribution to the group remained consistently positive. Similarly, self-reported synchrony increased and perceived collaboration effort decreased across rounds. Finally, responses suggested largely equal participation and little perceived leadership. Enjoyment remained high across rounds and feedback conditions (Metr.: $M = 4.3, SD = 0.7$, Indiv.: $M = 4.3, SD = 0.9$, Comb.: $M = 4.6, SD = 0.8$). Participants also reported a high willingness to play again in the same setup ($M = 4.2, SD = 0.9$), consistent with observations of playful discovery and shared moments of synchrony.

7.4 Interviews

Here, we describe the most relevant themes we identified in the interviews.

Active Coordination. Participants had to coordinate actively by combining auditory and haptic cues with visual monitoring of co-players. In unclear moments, vision became a dominant synchronization channel.

> "*So as soon as I got it for myself, I could look at the others a bit. I looked at what they did, but especially how they moved.*" (Group 1)

Scaffolding supports entry and constrains later. Many participants experienced the beat reference and reduced note range as helpful scaffolding for starting quickly and staying together, but also as prescribing what to play and limiting personal rhythmic or melodic ideas.

> "*I find the beat rather restrictive. So I would say, for the creativity, it didn't necessarily help me now, but for playing together, it did.*" (Group 3)

Cognitive load decreased. Early interaction was frequently described as cognitively demanding because attention had to be split between the beat reference, one's own actions, and the co-players.

> "*It took me a moment at the beginning before I could even pay attention to [other players].*" (Group 1)

Haptics as guidance and risk. Haptic feedback was experienced as both stabilizing guidance and a potential source of sensory overload. Coherent vibrations were described as intuitive, while global mixtures could blur source separation and reduce interpretability during dense group play.

> "*The first thing I noticed was the bass beat on the floor plate [Metronome Pulse]. I think that made it much easier to always know where the beat starts. You didn't have to listen so attentively anymore to both the backing track and the others. One just really felt it.*" (Group 4)

Enjoyment and connection. Participants showed repeated signs of enjoyment, like laughing together at the beginning or end of their performance, for example, when a cymbal hit was used as a dramatic finishing accent (Group 7). Participants felt like the experience was meaningful.

> "*I learned something about myself and could just be creative and try things out.*" (Group 6)

Finally, they reported enjoying the experience and finding comfort in the presence of other players.

> "*I thought it was fun. I was also glad that I was not alone here, because I first used it completely wrong, and then I oriented myself with the others.*" (Group 3)

8 Overall Design Implications

Throughout our design process, we iteratively refined and verified our assumptions, resulting in a set of recommended principles and learnings.

8.1 Abstract Instrument Apperance

We learned from our workshop that abstraction should still keep instruments related to recognizable metaphors. This supports playful discovery [22] and allows simplification while still using familiar interaction metaphors, without making them as intimidating to novices as real instruments.

8.2 Visual Connection to Other Players

Our user study suggests that being visually oriented towards their co-players is vital for players to recover from confusing situations, build connections, and experience mutual affirmation. Large instruments that require clearly discernible gestures support this naturally. The line of sight between players should not be blocked, and each instrument should not bind the visual attention of its player.

8.3 Limited Complexity

The more constrained the space for interaction and expression is, the more the experience can be simplified, but this can also cap exploration and agency. Constraints were essential for early success, reduced "wrong note" anxiety, and helped groups coordinate quickly. However, participants learned quickly and sometimes grew bored, suggesting that restrictions could be stronger at the beginning and become broader as players gain confidence.

8.4 Haptic Feedback

As the visual channel should be used for social coordination, and the auditory channel is occupied by the music, the haptic channel should anchor players in the experience and provide individual feedback. Instruments should have a distinct feel and be played by directly touching, pressing, or hitting them. In our exhibit, we included different surface finishes, vibrating instruments, mechanical movable parts, and air flow to provide a rich haptic experience and strengthen metaphors. Taking this a step further, we observed that vibrating floor modules can offer valuable support, like temporal synchronization, an improved feeling of the instrument, or stronger awareness of others.

8.5 Different Roles

By encouraging different musical roles, conflicting situations become less likely, and each role can be crafted more meaningfully. Roles should not be separated strictly, as interaction between them is necessary. Participants often developed call-and-response patterns and reported largely balanced participation.

9 Limitations and Future Work

Our study was conducted with a prototype in a controlled setup and not in a museum. When more people, especially children, use our exhibit, we expect a wider set of behavioral patterns and edge cases to become apparent. The sounds, note-space, and backing track also have a high potential to increase expressiveness. Our current choices in this regard also make assumptions about what is musically pleasant, coming from a Western cultural background. Different sounds and modulation options might improve the overall experience. Based on our findings, it seems feasible to look deeper into the overall flow of the experience, including a short tutorial sequence, introducing additional complexity, or dynamically offering support or affirmation when needed.

10 Conclusion

The goal of this work was to make the social experience of cooperative musical experimentation accessible to novices without musical background. We used Research through Design and a workshop to iteratively develop a prototype for a walk-up music exhibit that allows visitors to perform in trios on different instruments. Based on three different paradigms of interaction with sound, we developed corresponding instruments that are abstract to appear approachable, but also lean on instrument metaphors to be self-explanatory. We found that vibrotactile feedback via floor panels can support timing and action sensing, but can also overwhelm players. We evaluated our instruments and three different modes of haptic feedback in a lab study with 21 participants. Based on our process, we suggest a set of design considerations to improve social connection, empower players, and create an intuitive and enjoyable musical collaboration experience for novices. An updated version of our exhibit will be on permanent display in the *House of Music* museum in Vienna.

11 Ethical Standards

This work is in line with the ethical standards of the authors' institution. Participants were informed about audio/video recording and provided written informed consent before the study. All data was anonymized. Study participation was voluntary; participants were not compensated.

Acknowledgments

We would like to thank the participants in our study and workshop, Doğa Su Kıralioğlu and Nele Preuß for their support with the figures, and Sarah Sahabi for proofreading. This work was funded in part by the German B-IT foundation.

References

[1] Ben Bengler and Nick Bryan-Kinns. 2013. Designing Collaborative Musical Experiences for Broad Audiences. In *Proceedings of the 9th ACM Conference on Creativity & Cognition (C&C '13)* (Sydney, Australia, 2013-06-17). ACM, New York, NY, USA, 234–242. https://doi.org/10.1145/2466627.2466633

[2] Jan Borchers. 1997. WorldBeat: Designing a Baton-based Interface for an Interactive Music Exhibit. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI '97)* (Atlanta, GA, USA, 1997-03-27). ACM, New York, NY, USA, 131–138. https://doi.org/10.1145/258549.258632

[3] Jan Borchers. 2000. A Pattern Approach to Interaction Design. *Proceedings of the 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods and Techniques (DIS '00)* (August 2000), 369–378. https://doi.org/10.1145/347642.347795

[4] Virginia Braun and Victoria Clarke. 2006. Using Thematic Analysis in Psychology. *Qualitative Research in Psychology* 3, 2 (2006), 77–101. https://doi.org/10.1191/1478088706qp063oa

[5] Virginia Braun and Victoria Clarke. 2021. *Thematic Analysis : A Practical Guide.* SAGE Publications Ltd, London, UK. https://uk.sagepub.com/en-gb/eur/thematic-analysis/book248481

[6] Doga Cavdir. 2024. Creative Practice as an Evaluation Method: A Case Study with a Movement-based Musical Instrument. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '24)* (2024-10-08). Zenodo, Geneva, Switzerland, 456–464. https://doi.org/10.5281/ZENODO.13904909

[7] Robert Ek. 2024. Playing With Resistance. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '24)* (2024-10-08). Zenodo, Geneva, Switzerland, 154–159. https://doi.org/10.5281/ZENODO.13904814

[8] Alice Eldridge, Chris Kiefer, Dan Overholt, and Halldor Ulfarsson. 2021. Self-resonating Vibrotactile Feedback Instruments ||: Making, Playing, Conceptualising :||. *International Conference on New Interfaces for Musical Expression (NIME '21)* (jun 9 2021). https://doi.org/10.21428/92fbeb44.1f29a09e

[9] Cumhur Erkut, Stefania Serafin, Jonas Fehr, Henrique M.R. Fernandes Figueira, Theis B. Hansen, Nicholas J. Kirwan, and Mariam R. Zakarian. 2014. Design and

Evaluation of Interactive Musical Fruit. In *Proceedings of the 2014 Conference on Interaction Design and Children (IDC '14)* (Aarhus, Denmark, 2014-06-17). ACM, New York, NY, USA, 197–200. https://doi.org/10.1145/2593968.2610451

[10] Andreas Förster, Alarith Uhde, Mathias Komesker, Christina Komesker, and Irina Schmidt. 2023. LoopBoxes - Evaluation of a Collaborative Accessible Digital Musical Instrument. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '23)* (2023-05-31). Zenodo, Geneva, Switzerland, 30–39. https://doi.org/10.5281/ZENODO.11189094

[11] Jack E Hardwick, Stefano Fasciani, and Çağrı Erdem. 2024. CordChord: A String Instrument with Optical Sensing. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '24)* (2024-10-08). Zenodo, Geneva, Switzerland, 104–109. https://doi.org/10.5281/ZENODO.13904796

[12] David Johnson, Daniela Damian, and George Tzanetakis. 2020. Evaluating the Effectiveness of Mixed Reality Music Instrument Learning With the Theremin. *Virtual Reality* 24, 2 (2020), 303–317. https://doi.org/10.1007/s10055-019-00388-8

[13] Sergi Jordà, Günter Geiger, Marcos Alonso, and Martin Kaltenbrunner. 2007. The reacTable: Exploring the Synergy Between Live Music Performance and Tabletop Tangible Interfaces. In *Proceedings of the 1st international conference on Tangible and Embedded Interaction (TEI '07)* (Baton Rouge, LA, USA, 2007-02-15). ACM, New York, NY, USA, 139–146. https://doi.org/10.1145/1226969.1226998

[14] Jonathan Lane-Smith, Derrek Chow, Sahand Ajami, and Jeremy Cooperstock. 2023. The Hapstrument: A Bimanual Haptic Interface for Musical Expression. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '23)* (2023-05-31). Zenodo, Geneva, Switzerland, 549–553. https://doi.org/10.5281/ZENODO.11189284

[15] Leilah Lyons. 2009. Designing Opportunistic User Interfaces to Support a Collaborative Museum Exhibit. In *Proceedings of the 9th International Conference on Computer Supported Collaborative Learning (CSCL'09)* (Rhodes, Greece, 2009), Vol. 1. Association for Computational Linguistics, 375–384. https://doi.org/10.3115/1600053.1600110

[16] Lloyd May, Lateef McLeod, and Michael Mulshine. 2024. Bishop BoomBox: A Physically Accessible Drum Machine. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '24)* (2024-10-08). Zenodo, Geneva, Switzerland, 33–39. https://doi.org/10.5281/ZENODO.13904774

[17] Edward A. Roth. 2025. Shared flow and Emotional Synchrony Through Group Instrumental Improvisation: A Feasibility Study of Music-based Social Connection. *Frontiers in Psychiatry* 16 (2025). https://doi.org/10.3389/fpsyt.2025.1648873

[18] Lawrence Sasaki, Guy Fedorkow, William A.S. Buxton, C. Retterath, and Kenneth C. Smith. 1981. A Touch-Sensitive Input Device. In *International Conference on Mathematics and Computing*. https://api.semanticscholar.org/CorpusID:11340666

[19] R. Keith Sawyer. 2006. Group Creativity: Musical Performance and Collaboration. *Psychology of Music* 34, 2 (2006), 148–165. https://doi.org/10.1177/0305735606061850

[20] Adam Schmidt, Jeffrey Snyder, Gian Torrano Jacobs, Joseph Gascho, Joyce Chen, and Andrew McPherson. 2025. The Sparksichord: Practical Implementation of a Lorentz Force Electromagnetic Actuation and Feedback System. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '25)* (2025-06-19). Zenodo, Geneva, Switzerland, 268–279. https://doi.org/10.5281/ZENODO.15698857

[21] Adam G Schmidt and Michael Gurevich. 2024. The Lorentz Lap Brass: Method for Frugal Integrated Sonic/Haptic Interaction. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '24)* (2024-10-08). Zenodo, Geneva, Switzerland, 568–573. https://doi.org/10.5281/ZENODO.13904953

[22] Enrique Tomás, Florian Goeschke, and Martin Kaltenbrunner. 2024. Exploring Design Patterns for Spatial Instruments: User-Driven Strategies, Spatialized Synthesis and Loudspeaker Topologies. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '24)* (2024-10-08). Zenodo, Geneva, Switzerland, 127–132. https://doi.org/10.5281/ZENODO.13904804

[23] Ashley E. Walton, Auriel Washburn, Peter Langland-Hassan, Anthony Chemero, Heidi Kloos, and Michael J. Richardson. 2018. Creating Time: Social Collaboration in Music Improvisation. *Topics in Cognitive Science* 10, 1 (2018), 95–119. https://doi.org/10.1111/tops.12306

[24] Marcelo Wanderley. 2023. Prehistoric NIME: Revisiting Research on New Musical Interfaces in the Computer Music Community before NIME. In *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME '23)* (2023-05-31). Zenodo, Geneva, Switzerland, 60–69. https://doi.org/10.5281/ZENODO.11189104

[25] Yanan Wu, Yiyuan Huang, Wenchen Guo, Xiao Li, Zhirui Chen, Zheyu Feng, Yubin Zhu, and Guoyu Sun. 2023. Multi-sensory Interactive Experience Design of Museum Musical Instrument Collections. In *HCI International 2023 – Late Breaking Papers*, Hirohiko Mori, Yumi Asahi, Adela Coman, Simona Vasilache, and Matthias Rauterberg (Eds.). Vol. 14056. Springer Nature Switzerland, Cham, 420–437. https://doi.org/10.1007/978-3-031-48044-7_30

A Collaborative Evaluation Questionnaire

Tables 1–4 list English translations of the questionnaire items used in the Collaborative Evaluation Study. Technical metadata fields, condition assignments, timestamps, and repeated free-text justification prompts are omitted. Unless stated otherwise, agreement items used a five-point Likert scale (1 = strongly disagree, 3 = neutral, 5 = strongly agree).

Table 1: Questionnaire items: demographics and self-assessment. Technical metadata fields, condition assignments, and timestamps are omitted.

Question or statement	Response format
How old are you?	Numeric
What is your current occupation or main activity?	Free text
For how many years have you actively made music or played an instrument?	Numeric
Briefly describe what kind of musical experience you have had (e.g., instruments, bands, ensembles).	Free text
I have a lot of experience in active music-making.	Likert
How often do you actively listen to music per week?	Free text
I rate my teamwork ability as high.	Likert
I can keep several things in view at the same time (multitasking).	Likert

Table 2: Questionnaire items: free exploration phase. Items were answered after the initial free exploration phase; closed items could be followed by an optional free-text explanation.

Question or statement	Response format
It was easy to choose an instrument.	Likert
There were no conflicts when choosing instruments.	Likert
I felt comfortable trying things out spontaneously.	Likert
I actively perceived the other people (e.g., gaze, body language).	Likert
We coordinated well.	Likert
My own actions fit well with the group.	Likert
Participation in the group was equal.	Likert
There was a clear leading person.	Likert
I enjoyed the discovery phase.	Likert
The shared situation seemed to me ...	1 = rather chaotic, 3 = neutral, 5 = rather coordinated
I felt ... while playing.	1 = rather insecure, 3 = neutral, 5 = rather confident
Were there conflicts when choosing the instruments? If so, how were they resolved?	Free text
What helped you most in the first phase?	Free text

Table 3: Questionnaire items: repeated backing-track rounds. Items were answered after each backing-track round: metronomic floor pulse, local action feedback, and global action feedback. Closed items could be followed by an optional free-text explanation.

Question or statement	Response format
In this round, we stayed in time as a group.	Likert
It was easy for me to coordinate with the others.	Likert
I could anticipate the others' timing well.	Likert
I perceived the others (gaze, body movements, timing) well.	Likert
My contribution fit well with the group.	Likert
Participation was equal in this round.	Likert
There was no clear leading person in this round.	Likert
The haptic feedback was helpful in this round.	Likert
The haptic feedback was not distracting or overwhelming.	Likert
I felt in control of my sound.	Likert
I enjoyed this round.	Likert
In this round, we seemed rather ...	1 = independent of one another, 3 = neutral, 5 = closely coordinated
The collaboration in this round felt ...	1 = rather effortful, 3 = neutral, 5 = rather effortless
How would you describe your role in this round?	1–5 agreement scale; role statement shown in questionnaire
I clearly perceived the base beat.	Likert
What helped you most with collaboration in this round?	Free text
Was there anything that disturbed or irritated you in this round?	Free text

Table 4: Questionnaire items: post-session comparison and reflection. After all rounds, participants rated the overall experience and compared the three haptic feedback variants: A = metronomic floor pulse, B = local action feedback, C = global action feedback.

Question or statement	Response format
I felt connected to the group.	Likert
Overall, we were well coordinated.	Likert
Overall, participation was equal.	Likert
Overall, I was in flow.	Likert
I would play together in this setup again.	Likert
Rank variants A, B, and C.	Ranking
In variant [A/B/C], collaboration was easiest.	Likert per variant
In variant [A/B/C], participation was distributed most evenly.	Likert per variant
In which variant was there most clearly a leading person?	Variant choice
The observed leadership in the group was appropriate.	Likert
What was the greatest difference between the variants for you?	Free text
Which one thing should we most improve in your opinion (e.g., haptics, arrangement, interface)?	Free text
Is there anything else you would like to say about the shared experience?	Free text