Peripersonal Modular Interfaces for Care Ecologies: Decoupling Sensing and Surface in Accessible Digital Musical Instruments

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Abstract

Accessible Digital Musical Instruments (ADMIs) are often assessed for individual access, yet community workshops depend on facilitation labour, hygiene, rapid setup, and shared authorship. We report a collaboration with a London-based community music charity to co-design a Peripersonal Modular Interface that supports ensemble music-making across diverse motor profiles. The system comprises wireless sensing tiles with TPU lattice structures, mechanically decoupling non-contact Hall-effect sensing from the deformable surface so compliance can be tuned without compromising robustness or cleaning. Treating each tile as an independent network node enables participants and facilitators to reconfigure the instrument across tabletops, wheelchair trays, or floors and to negotiate “where the instrument is” in situ within a care ecology. We present findings from a co-design study (N=12) spanning musicians, facilitators, support workers, and volunteers, alongside end-to-end latency benchmarking of a private haptic–audio loop. Results show $\approx$ 7 ms average latency (max <12 ms) and reports of immediate sonic response, cable-free safety, and maintainability via replaceable tactile layers, exemplifying structural agency beyond screen-based administration.

CCS Concepts

• **Human-centered computing** → **Accessibility systems and tools**; • **Applied computing** → *Sound and music computing*.

Keywords

ADMI, inclusive design, community music, tangible user interfaces, accessibility, materiality, IoMusT

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1 Introduction

In inclusive music practice, accessibility is often conflated with mere participation rather than meaningful authorship. Although assistive music technologies have broadened access, a critical gap remains: a “crisis of agency” in which disabled musicians are present in the music-making process but possess limited control over sound and structure.

For musicians with complex motor impairments, performance is often mediated through highly scripted interactions or reductive interface design strategies. In an effort to lower the barrier to entry, expressive agency is often stripped away, constraining timing, dynamics, and phrasing. This blurs the boundary between the musician’s intent and the system’s behaviour [7, 11], positioning the musician as a passive recipient rather than an active author of sound. Furthermore, there is a material mismatch between rigid interface standards and the diverse embodied realities of users [9]. Traditional acoustic instruments often demand exclusionary fine motor dexterity, while many Accessible Digital Musical Instruments (ADMIs) lack the physical resistance needed for proprioception, weakening the haptic loop that underpins situated attention and musical agency [10].

1.1 Beyond the User: Care Ecologies

Crucially, these challenges extend beyond the individual. HCI research often abstracts the instrument away from the “care ecologies” in which they are deployed [2]. In post-pandemic community settings, instruments must meet rigorous infection control, rapid setup times, and safety constraints. Devices that are fragile, cable-heavy, or historically reliant on one-to-one facilitation introduce logistical friction that discourages their use in sustainable music-making [13]. Consequently, inclusivity must account not only for the embodied needs of the musician but also for the practical realities of the facilitators and support workers who sustain the ecosystem.

1.2 A Modular Peripersonal Interface

In response, we present a modular, reconfigurable, and haptically responsive system co-designed with a London-based community music organisation. Based on a disability social model , the system shifts the burden of adaptation from the individual to the material environment, treating the instrument as part of a wider care infrastructure.

We argue that designing for structural agency can remove physical and environmental barriers to independent expression. We achieve this through:

- **Material Intelligence:** Customisable haptic resistance via tunable thermoplastic polyurethane (TPU) lattice structures;
- **Decentralised Architecture:** A low-latency wireless network that eliminates cabling constraints for rapid deployment; and
- **Multimodal Feedback:** Integrated vibrotactile and bone-conduction audio to restore the private haptic loop.

Our contributions are three-fold:

(1) **A Design Case:** A modular bio-haptic system that integrates non-contact Hall-effect sensing with variable-stiffness TPU structures. This architecture establishes a

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low-latency physical force pair, balancing logistical durability with fine-grained tactile sensitivity.

(2) **A Methodological Framework:** A triangulated validation approach utilising expert proxies and situated observation to design with musicians who use limited or non-verbal communication.

(3) **A Theoretical Proposition:** The concept of *structural agency*, where the physical and organisational scaffolding of an instrument is treated as a primary site for redistributing power and enabling autonomy.

2 Related Work

Current research in Accessible Digital Musical Instruments (ADMIs) has primarily focused on lowering the barrier to entry for users with physical impairments. However, a distinction must be drawn between adaptive design, modifying existing paradigms for specific deficits, and inclusive design, which seeks to create modular interfaces that foster agency and social cohesion regardless of ability. This section reviews existing approaches through the lens of haptics, autonomy, and organological metaphors.

2.1 The Limitations of Screen-Based Interfaces

While ubiquitous in music therapy, tablet-based interfaces introduce a "reduced causality" where the absence of mechanical compliance disconnects gesture from sound [10]. This haptic void necessitates restrictive software interventions, such as "Guided Access," to prevent accidental triggers during enthusiastic play [6]. Consequently, standard touchscreens lack the physical affordances required for safe, uninhibited exploration, diminishing the embodied agency essential for expressive performance.

2.2 Tangible Interfaces and the "Tethered" Problem

To address the haptic void, commercial controllers like Skoog have been developed. Although their soft, squeezable interfaces provide an ergonomic entry point for limited fine motor skills, they operate primarily as "tethered controllers" [26]. Crucially, reliance on an external host (e.g., iPad) creates a *bifurcation of agency*: while the participant holds the physical interface to *actuate* sound, the *configuration* (timbre, scale, sensitivity) remains sequestered in a separate graphical interface (Figure 1). In care ecologies, this "administrative" separation often defaults the instrument's control to the facilitator's custody, reducing the device to a mere remote control. In contrast, our work argues for *instrumental autonomy*, embedding synthesis and power within the object to ensure the locus of control resides entirely with the player.

Figure 1: Skoog 2.0 connected to IPad.

2.3 Adaptation vs. Inclusion: The Trap of Skeuomorphism

A significant portion of ADMI development focuses on *adaptation*, re-engineering traditional instruments for limb differences. While venues like the OHMI Trust showcase exemplary adaptations such as the Strummi (Figure 2) [8, 24], these often preserve the high cognitive load of the original paradigm. This tendency persists in digital skeuomorphism, notably in the Nordoff Robbins ReHarp (Figure 3) [14]. Although designed to reduce physical exertion for stroke rehabilitation, ReHarp retains a bimanual organological metaphor, separating "selection" (chords) from "excitation" (strumming). For musicians with complex cognitive needs, this separation creates a fundamental *mismatch* [9] between the rigid structure of the interface and the user's need for immediate gestural engagement. Our design moves away from adapting these traditional metaphors, removing abstract cognitive layers to facilitate direct, embodied inclusion.

2.4 Networked Music: From Telematics to Co-located Care

Although Networked Music Performance (NMP) is central to NIME, research has historically prioritised *telematic* solutions that connect distant musicians over wide-area networks [19]. The emerging "Internet of Musical Things" (IoMusT), meanwhile, envisions connected smart instruments for collaborative performance [25].

However, current IoMusT applications still focus mainly on virtuosic expression or concert audience participation and often assume high technical knowledge. Far less research applies these architectures to co-located music therapy. Unlike ADMIs that typically operate as standalone units, our system deploys a local IoMusT architecture. Rather than conquering *geographic* distance, our network aims to bridge *social* isolation, using distributed haptics to support rhythmic cohesion without the distraction of screens.

Figure 2: Musician playing on Strummi with fine motor control.

3 Design Methodology

This section details the iterative co-design process and the technical considerations behind a modular interface for the peripersonal space of musicians in a community-based care ecosystem.

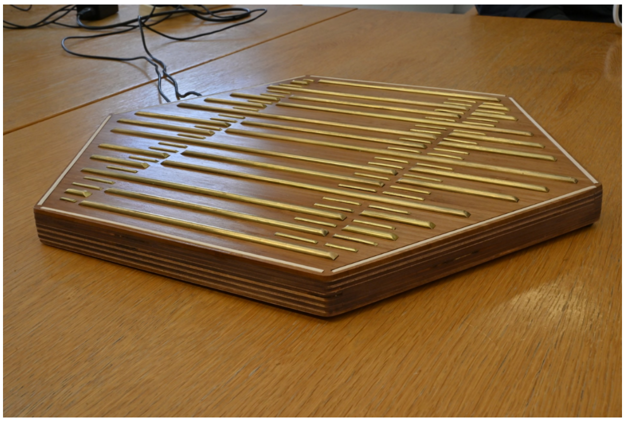


Figure 3: Design of Reharp, where sound triggered by touching the metal rods

3.1 A Triadic Co-Design Framework

We adopted a Research through Design (RtD) methodology grounded in a triadic co-design framework. This approach triangulates the priorities of three stakeholder groups to ensure ecological validity in everyday care settings and improvisational workshops:

- **The Musicians (End-users):** Individuals with diverse motor and cognitive profiles (e.g., tremors and visual impairments). Their primary focus is on achieving embodied agency through immediate haptic–auditory confirmation.
- **The Facilitators (Pedagogical leaders):** Practitioners who prioritise open-endedness and robust, "plug-and-play" workflows to support spontaneous musical interaction.
- **The Support Ecosystem (Carers, support workers and trustees):** Stakeholders who focus on the sustainability of the intervention, prioritising safety, hygiene and long-term durability.

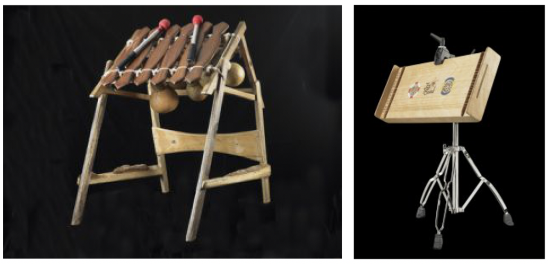
3.2 Phase 1: Situated Observation and Baseline Analysis

A six-month ethnographic phase (Dec 2024 – June 2025) at a community music organisation revealed that existing adapted musical instruments (AMIs) often inadvertently exclude musicians with complex motor impairments by imposing high physical barriers. For example, several adapted plucked string instruments(see Figure 4) require fine motor control and micro-movements of the fingers or the precise use of a plectrum. For musicians with limited muscle control, these interfaces offer limited expressive agency. Similarly, percussive tools like the adaptive marimba(see Figure 5(a)) utilise heavy, felted mallets that demand significant upper-body strength and coordination, which can be fatiguing or inaccessible for many.

Furthermore, the physical infrastructure of these tools(see Figure 5(b)), often mounted on stainless steel stands weighing 2kg to 4kg, presents significant logistical challenges. While providing a sturdy base, the sheer weight hinders spontaneous setup and teardown within a care ecology.

These observations, combined with semi-structured interviews with facilitators and trustees, established three core hardware constraints:

Figure 4: Adaptive plucked string instrument designed by the community music organisation



a. b.

Figure 5: (a) Adaptive marimba (b)Adaptive zither on stand

- **Wireless Operation:** To eliminate cable clutter and trip hazards, ensuring safety in a wheelchair-accessible environment.
- **Material Hygiene:** Sanitisable thermoplastic surfaces to facilitate rigorous infection control and cleaning between participants.
- **High-Sensitivity Feedback:** Reduced physical inertia coupled with immediate tactile response to accommodate users with limited muscle tone.

3.3 Phase 2: Pivoting from E-Textiles to Material Intelligence

Initial prototyping explored the use of conductive e-textiles. However, technical stress tests and stakeholder critiques identified three critical failures that necessitated a pivot in our design strategy:

- **The "Midas Touch":** The capacitive nature of the fabric lacked a programmable force threshold, causing accidental sound triggering upon any contact, regardless of user intent [5].
- **Signal Instability and Hygiene Constraints:** High electrical resistance in conductive threads and vulnerability to electromagnetic interference compromised data accuracy over extended periods. Technical benchmarks indicate that even high-quality silver threads (with a resistance of approximately $85\ \Omega\ \mathrm{ft}^{-1}$) are highly sensitive to humidity and aging [3, 20]. Crucially, the textile-based interface failed to meet the Support Ecosystem's priority for hygiene; the porous nature of the fabric precluded frequent disinfection with alcohol or industrial washing, which would lead to rapid material and signal degradation.
- **Haptic Void:** The fabric failed to provide a perceptible "action–reaction" force, resulting in what we term a "haptic void." As explored by Zheng [28], haptic materiality is not merely an aesthetic choice but a fundamental requirement for establishing a sense of instrumentalness. For musicians with diverse motor profiles, the lack of physical confirmation hinders their ability to establish embodied agency and precise control over the digital sound engine.

3.4 Phase 3: Iterative Refinement – "Force Pairs" and Tuning Compliance

3.4.1 The Physical Force Pair Mechanism. To restore the proprioceptive loop, we developed the concept of a "physical force pair." As illustrated in Figure 6, the TPU lattice at resting position maintains a maximum height ($d_{\max}$), where the elastic force (F_{elastic}) is zero. Upon interaction, the musician's input force (F_{input}) creates a displacement ($d < d_{\max}$), triggering a proportional $F_{\text{elastic}} > 0$. This creates a direct action–reaction pair that offers an immediate sense of "instrumental identity." Unlike artificial vibration, this natural resistance provides inherent, zero-latency haptic feedback that allows musicians to "feel" the sound engine's state through physical resistance.

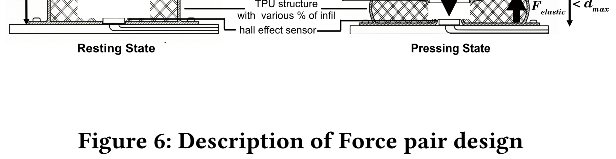


Figure 6: Description of Force pair design

These challenges shifted our focus from surface-level sensing to internal material intelligence. To provide a sturdy yet responsive interface, we moved towards a mechanical structure capable of generating a "Force Pair": a natural, passive haptic feedback loop where the material's intrinsic mechanical resistance matches the user's input force.

3.4.2 Material Optimization: Durability and Adaptive Compliance. The material selection and internal geometry were iteratively refined to satisfy the dual requirements of long-term durability and inclusive accessibility.

Material Resilience and Hygiene. The selection of TPU95 was predicated on its high elastic recovery rate (exceeding 95%) and low hysteresis. According to Qi et al.[18], the micro-phase structure of thermoplastic polyurethanes allows for significant reversible deformation, ensuring that the interface maintains its structural integrity and "spring-back" response even under high-frequency use in communal workshops. Furthermore, the non-porous nature of TPU95 aligns with the Support Ecosystem's priority for stringent hygiene, allowing for frequent disinfection with alcohol without the material degradation associated with porous e-textiles.

Lattice Geometry and Linear Resistance. To complement the material's resilience, we experimented with various lattice geometries to tune the interface's compliance. While *Gyroid* infill provides isotropic strength, offering uniform resistance across all axes, *Adaptive Cubic* infill is more suitable for the final prototype. According to technical specifications, the Adaptive Cubic pattern becomes increasingly sparse towards the center of the structure[17]. Our tests confirmed that this structural gradient results in a more linear resistance curve at low-to-mid densities. Zheng et al. [29] identifies such predictability as crucial for providing reliable haptic feedback to musicians with varying muscle tone, as it avoids sudden jumps in mechanical resistance.

Optimising for Low Force Thresholds. To lower the physical barrier for entry, we established a specific printing protocol to minimize the interface's stiffness. The final prototype utilises TPU95 (selected for its higher printability success rate compared to softer TPUs) with an infill density varying between 8% and 15%. Crucially, the perimeter walls (shells) were disabled in the slicer settings. Removing the rigid outer walls eliminates the structural "crust," ensuring that the mechanical resistance is derived solely from the internal lattice. This setup effectively lowers the trigger threshold, allowing the "Force Pair" to be activated with minimal effort and granting expressive agency to musicians previously excluded by high-resistance interfaces.

3.4.3 Multi-User Centred Infrastructure. Responding to feedback from a workshop facilitator, we transitioned from a binary compliance model (soft/hard) to a five-level lattice density gradient. This allows the instrument to accommodate a wider spectrum of motor capabilities, from musicians with hypertonia (requiring high resistance) to those with minimal muscle engagement. This shift marks a move from a generic user-centred approach to a multi-user-centred infrastructure, prioritising equitable access to musical expression.

3.4.4 Multimodal Feedback and Self-Esteem. Based on a trustee's suggestion about the noise floor of ensemble settings, we integrated a bone-conduction channel. Together with the force pair, this creates a multimodal haptic feedback loop with three layers:

- **Proprioceptive confirmation:** Physical resistance from the TPU lattice.
- **Private vibrotactile and audio monitoring:** Bone-conduction earphones provide a personalised audio-tactile feed, allowing musicians to distinguish their own contribution from the ensemble's collective sound.

Table 1: Mapping of lattice infill density to resistance levels and target user profiles.

Infill (%)	Resistance	Target User Profile
8%	Super Low	Severe hypotonia; requires minimal activation force.
10%	Low	Low muscle tone; early rehabilitation.
12%	Medium	Standard hand interaction.
14%	Medium High	Improved motor control; requiring distinct feedback.
15%	High	High muscle tone or foot interaction (Stomping).

- **Collective auditory response:** The live acoustic feedback from the group.

This multimodal setup fosters self-monitoring and agency, which are crucial for building musical self-esteem [7, 29]. By clearly perceiving their role within the ensemble, musicians move from passive attendance to active, confident participation.

3.5 Decoupling Without Delay: The Latency Challenge

A primary challenge in designing for care ecologies is decoupling the interface from the sound engine without introducing debilitating latency. While Bluetooth solutions offer convenience, standard protocols often incur delays of 100-200ms, falling within the critical window of Delayed Auditory Feedback (DAF) that disrupts rhythmic synchronisation[4].For inclusive ensemble play, maintaining an "action-reaction" latency below 10ms is crucial to preserve the illusion of a direct physical force pair [27].

3.6 Designing for Logistics and Hygiene

Beyond musical expression, the instrument must survive the logistical realities of a care ecology. Drawing inspiration from modular kinetic flooring [12], we designed the system as a constellation of independent tiles rather than a monolithic unit.

Decentralised Power and Safety. Each sensing tile is powered by independent rechargeable lithium-ion batteries. This decentralised power strategy eliminates the need for power cables between tiles, mitigating trip hazards, a critical safety requirement in care environments with high foot traffic or mobility aids. This autonomy allows facilitators to arrange tiles in bespoke configurations (e.g., across wheelchair trays, tables, or floors) to meet the diverse ergonomic and motor needs of individual musicians, fostering a sense of embodied agency (see Figure 7).

Maintenance and Hygiene. Components are assembled using hook-and-loop fasteners (see Figure 8), allowing facilitators to rapidly detach the key and the TPU lattice from the base. This modularity serves two functions:

- **Hygiene:** The tactile surface can be removed for thorough cleaning or sterilisation without exposing electronics to moisture.
- **Sustainability:** If a specific part wears out (e.g., the TPU lattice loses elasticity), it can be swapped out individually without replacing the entire unit. As most structural components are 3D-printed and the electronics rely on low-costcommodity microcontrollers, the system is straightforward to maintain, duplicate, and augment over time.

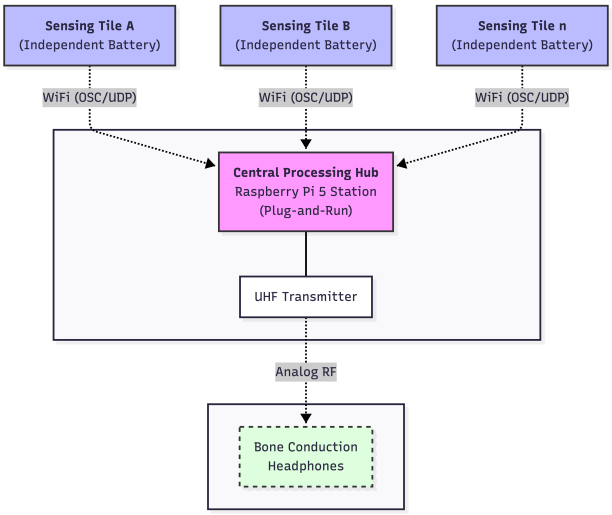


Figure 7: Sensor tiles and central processing hub

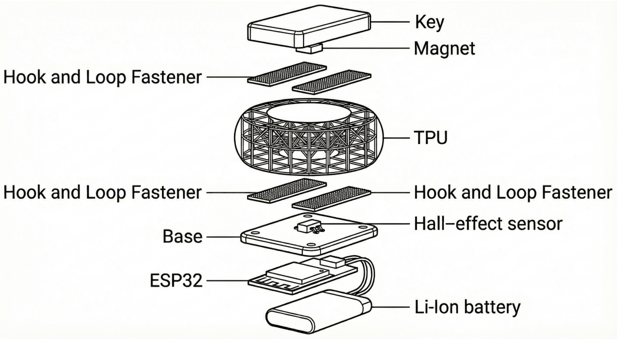


Figure 8: Explosion diagram of sensor tile

Rapid Deployment ("Plug-and-Play"). While heavy computational tasks (sound synthesis, signal processing) and RF transmission are offloaded to the Raspberry Pi 5 Station (see Figure 7), the user-facing tiles are completely wireless. This separation allows for a "plug-and-play" workflow: facilitators, volunteers, or support workers simply power on the central station and place the wireless tiles on any flat surface. The system automatically pairs and calibrates, significantly reducing setup time and technical barriers for non-specialist staff.

3.7 Sonic Mapping: Psychoacoustic Grounding

To complement the organisation's acoustic environment, we mapped the four-tile prototype to a custom Additive Synthesis engine tuned to a low bass register (Eb2, G2, Bb2, D3). Designed to emulate the spectral characteristics of Himalayan singing bowls, the engine generates inharmonic partials characterised by harmonic richness and long, sustaining decays. This timbral choice serves a dual psychoacoustic function:

- **Sensory Regulation:** Drawing on vibroacoustic principles [1], the synthesised "soft onset" (gradual attack of 50–100ms) avoids triggering the startle reflex. This creates a sensory-friendly auditory environment that prevents over-stimulation [22], particularly for musicians with sensory processing challenges.

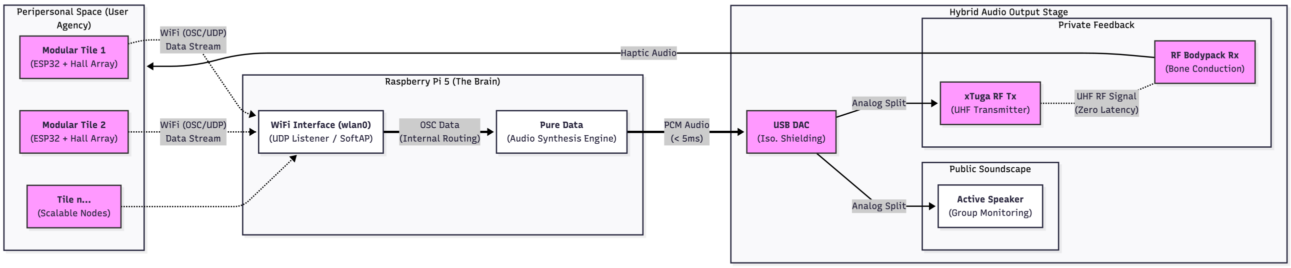


Figure 9: Network structure of Multimodal system

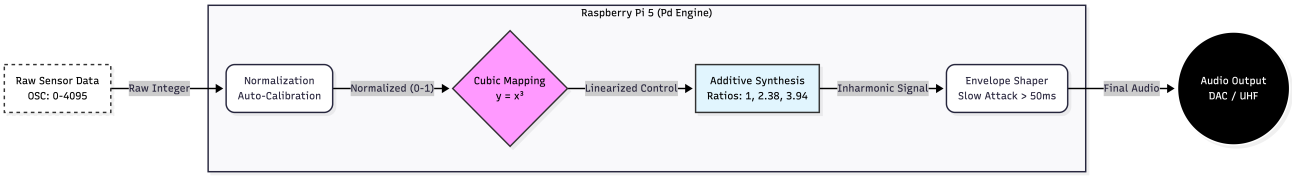


Figure 10: Signal flow from raw sensor input to synthesized output, illustrating the cubic mapping stage and additive oscillator stack.

- **Sonic Holding Environment:** The long decay (> 3s) functions as a "sonic holding environment". Unlike staccato percussion, these sustaining textures fill the silence between rhythmic events, providing a continuous safety net. This allows the instrument to act as a calming anchor, balancing the chaotic energy of group improvisation with a grounding presence.

4 Technical Implementation

4.1 System Architecture & Hardware

The system employs a star-network topology centred around a Raspberry Pi 5 hub, interfacing with distributed sensing nodes (tiles) and a hybrid audio output system (see Figure 9). This heterogeneous architecture explicitly separates control data from audio monitoring to minimise latency.

Modular Sensing Tiles (The Agency). Each tile functions as an independent sensing unit driven by the ESP32-WROOM-32 microcontroller, selected for its dual-core architecture and integrated Wi-Fi stack.

- **Sensing:** A KY-024 Linear Hall Effect sensor captures the lattice displacement at a polling rate of 200Hz, capturing fast percussive gestures with high resolution.
- **Power Safety:** To ensure safety compliance in care environments, each tile is powered by a CE/UKCA-certified 5V USB power bank, providing a stable, regulated current compared to DIY lithium circuits.
- **Protocol:** Data is transmitted as raw 12-bit ADC integers (0–4095) via OSC over UDP. The addressing scheme follows the format `/tile/{id}`. Offloading the scaling logic to the central hub allows for dynamic calibration without re-flashing firmware.

Central Processing Hub (The Brain). A **Raspberry Pi 5 (8GB RAM)** running a headless Linux distribution acts as a dedicated SoftAP to minimise network congestion. To prevent CPU throttling during real-time synthesis, the hub is powered by the official Raspberry Pi 27W USB-C supply, ensuring sufficient amperage (5V/5A) to sustain peak computational loads.

Hybrid Audio Output (The Latency Solution). As the Pi 5 lacks a native analog output, a USB DAC splits the signal into two paths:

(1) **Public:** Line-out to active speakers for the shared acoustic space.
(2) **Private (Force Pair Feedback):** Crucially, to bypass Bluetooth buffering, audio is transmitted via an analog **UHF Wireless IEM system** (XTUGA J02S) to bone-conduction headphones.

Performance: This analog link enables an end-to-end latency of ≈ 7 ms (measured), satisfying the temporal precision required for intimate musical control [27].

4.2 Software and Synthesis Architecture

The core signal processing and sound generation are handled within a custom Pure Data (Pd) environment running on the Raspberry Pi 5. The software architecture prioritises psychoacoustic predictability to support the "Safe Exploration Zone" design.

Signal Conditioning and Calibration. Upon receiving the raw OSC integer ($0 \leq x \leq 4095$), the system performs an auto-calibration routine on startup to establish a noise floor ($x_{\min}$). The normalized force F_{norm} is calculated as:

$$F_{\text{norm}} = \frac{x_{\text{raw}} - x_{\min}}{x_{\max} - x_{\min}} \tag{1}$$

Psychoacoustic Mapping Strategy. Instead of linear mapping, which can cause abrupt volume jumps for users with tremors, we implemented a cubic transfer function ($y = x^3$). This decision is grounded in Stevens' Power Law, which states that loudness perception follows a power function with an exponent of approximately 0.3 [21, 23].

By applying a cubic curve (an exponent of 3, roughly the reciprocal of 0.3), we effectively linearise the user's perceived control:

$$\text{Perceived Loudness} \propto (F_{\text{norm}}^3)^{0.33} \approx F_{\text{norm}} \tag{2}$$

This ensures that the acoustic response feels perceptually linear and predictable. Furthermore, the cubic curve naturally creates a "dead zone" of low sensitivity at the onset of a press. This provides the "Safe Exploration Zone" where users can rest their hands on the interface without triggering loud sounds, preventing sensory overload.

Additive Synthesis Engine. To replicate the soothing timbre of Himalayan Singing Bowls, we developed a custom Additive Synthesis engine (see Figure 10).

- **Inharmonic Partials:** The oscillators are tuned to inharmonic ratios (fundamental f, $2.38f$, $3.94f$) rather than a harmonic series. This generates the characteristic metallic “beating” textures.
- **Temporal Shaping:** Amplitude envelopes are shaped with a soft attack (50–100ms). Crucially, while the sonic onset is immediate (preserving perceived agency), the gradual rise to peak amplitude mimics the physics of a resonant metal bowl struck by a soft mallet. This avoids the “startle reflex” associated with percussive transients. Additionally, a long decay (> 3s) is applied to create the “sonic holding environment,” filling the silence between physical gestures to ground the ensemble.

5 Evaluation

To validate the system’s performance and usability, we conducted a mixed-methods evaluation comprising a technical latency benchmark and a qualitative user study involving stakeholders from the community music workshop ecosystem.

5.1 Technical Validation: End-to-End Latency and Jitter

As established in Section 3.5, maintaining low latency is critical for preserving the user’s sense of agency in a haptic loop. However, network-based architectures (IoMusT) often introduce variable latency (jitter) due to packet collisions. To mitigate this, our system utilises the Raspberry Pi 5 as a dedicated SoftAP, isolating the sensor traffic from external network congestion.

We measured the end-to-end latency (Δt), defined as the time difference between the physical actuation of the TPU lattice (t_1, captured via a contact microphone) and the onset of the bone-conduction audio output (t_2, captured via a measuring microphone).

Results. Using an oscillogram analysis method (see Figure 11) over 50 trial actuations, the system demonstrated:

$$\Delta t_{\text{avg}} \approx 7\text{ms} \quad (\sigma \approx \pm 2\text{ms}) \tag{3}$$

This 7ms average comprises the accumulation of the ESP32 ADC time, WiFi UDP transmission, Pd audio buffering (64 samples), and the USB DAC output buffer.

Crucially, while UDP over WiFi introduces inherent jitter, the use of a dedicated local hotspot kept the maximum observed latency below 12ms. This performance consistently falls within the 10–20ms perceptual threshold for “intimate control” [27], confirming that the heterogeneous link (UDP + Analog UHF) successfully preserves the illusion of instantaneous physical interaction.

Results. Using the oscillogram analysis method(see Figure 11), the system demonstrated an average latency of:

$$\Delta t = t_2 - t_1 \approx 7\text{ms} \tag{4}$$

The latency is well below the 10 ms perceptual threshold for “intimate control” [16, 27], confirming that the heterogeneous link (UDP + UHF) successfully eliminates perceived lag and supports tight rhythmic synchronisation.

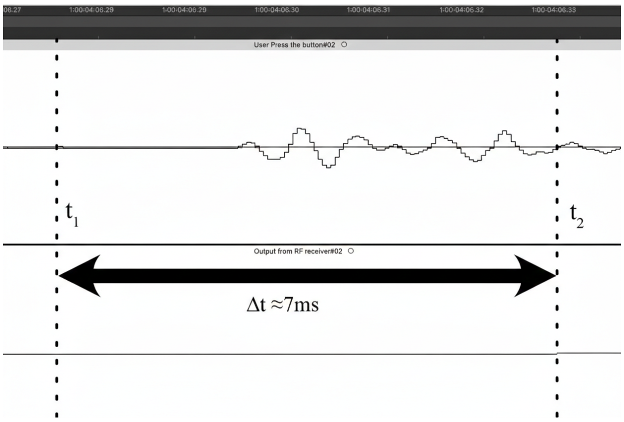


Figure 11: Oscillogram analysis

5.2 User Study Methodology

We conducted three rounds of participatory evaluation sessions at the community music making workshop. The goal was to assess the instrument’s usability, haptic feel, and integration into the existing care workflow.

Participants ($n = 12$). A diverse group of 12 stakeholders participated, representing the full spectrum of the support ecosystem (see Table 2).

Table 2: Participant Demographics and Roles.

ID	Role	Background / Expertise
P1	Trustee / Facilitator	Musician & Instrument Designer
P2	Trustee / Facilitator	Occupational Therapist (OT)
P3	Trustee / Facilitator	Sound Therapist / Tai Chi Teacher
P4	Trustee / Facilitator	General Facilitation
P5–7	Volunteer	Retired Community Members
P8	Support Worker	General Care Support
P9	Support Worker	Dedicated support for P11
P10	Support Worker	Dedicated support for P12
P11	Participant	Visually Impaired, Verbal
P12	Participant	Visually Impaired, Motor & Cognitive Impairments, Non-verbal

5.3 Qualitative Findings

The feedback was transcribed, coded, and categorised into four foci.

5.3.1 Haptic Materiality and Agency. The “Force Pair” mechanism received positive validation across all groups. Participants (P1–4, P5–10, P11) described the keys as having a “great touch,” noting that the physical resistance provided a natural sense of pressing that is often lacking in flat touchscreens.

- **Perceived Immediacy:** A recurring comment from musicians and volunteers (P1–3, P5–6, P9–10) was that the instrument “sounds instantly.” They noted it “does not feel like playing a digital instrument,” suggesting that the low latency and haptic feedback successfully bridged the gap between digital processing and acoustic feel.
- **Bone Conduction:** Support workers and trustees confirmed that bone conduction feedback provided a necessary private monitoring channel without isolating the user from the group.

5.3.2 Ergonomic Inclusivity. The physical design was praised for its adaptability to diverse physical needs:

- **"Moon-shape" Ergonomics:** Trustees (P1, P2, P4) highlighted that the curved base board allowed keys to be positioned closer to the user's torso, facilitating play for individuals who cannot fully straighten their arms.
- **Accessibility Suggestions:** The Occupational Therapist (P2) and Musician (P1) noted the system's potential for wheelchair integration due to its modularity. P1 suggested a future iteration could include a clamp mechanism to attach tiles directly to existing music stands or wheelchair trays.

5.3.3 Psychoacoustic Regulation. The sound design choices (see Section 4.3) were validated by the Sound Therapist (P3) and volunteers. Participants (P2, P3, P5, P6) described the synthesised audio as "resonating with the sound of singing bowls," explicitly stating that it provided a "calm feeling." This confirms that the synthesis engine successfully functions as a tool for sensory regulation.

- **Sonic Familiarity (P11):** Participant P11, whose primary instrument is the cello, specifically praised the system's timbre. She noted that the lower register resonated with her preference for the cello, invoking a sense of calm and enjoyment. Consequently, she expressed a strong willingness to adopt this interface alongside her acoustic instrument in future workshops.

5.3.4 Ecosystem and Deployment. From a logistical perspective, the "plug-and-play" architecture was highly effective:

- **Safety:** Facilitators (P1–4, P5–7) expressed feeling "safe and confident" setting up the system, citing the absence of cables as a major relief for trip-hazard anxiety.
- **Hygiene and Maintenance:** The modular "sandwich" design was universally praised. Participants (P1–10) highlighted the ease of detaching the TPU layer via the hook-and-loop system for wiping and sterilisation.
- **Design Trade-off:** While the modularity was praised, the Instrument Designer (P1) and the occupational therapist (P2) identified a specific trade-off. They observed that the current open-edge design might allow users to pry or "tip" the keys off the base from the bottom edge during enthusiastic play. To prevent unintended disassembly, they suggested integrating a protective barrier in future iterations to secure the interface while retaining cleanability.

5.4 Observational Case Study: Participant P12

As Participant P12 (Non-verbal, severe motor and cognitive impairments) could not provide verbal feedback, we relied on interaction analysis and proxy-reporting via their support worker (P10) and the Occupational Therapist (P2).

Affective Engagement: P12 displayed visible signs of pleasure, wearing a smile throughout the interaction, indicating a positive emotional response to the instrument.

Exploratory Behaviour: P12 actively initiated interaction, exploring the instrument through pressing and touching. Notably, P12 engaged with the textured keys, using touch to differentiate between surfaces, validating the importance of the tactile signals designed into the TPU lattice.

Acceptance of Wearables: Despite potential sensory sensitivities, P12 was willing to wear the bone-conduction headphones, suggesting the headset form factor was comfortable and non-intrusive.

This observation serves as a critical proof-of-concept: the instrument successfully engaged a user with complex needs who is typically excluded from complex digital music interfaces, granting them a medium for expression and joy.

6 Discussion and Limitations

This study set out to bridge the gap between digital flexibility and acoustic materiality. While the evaluation successfully demonstrated the efficacy of the "Force Pair" mechanism, the deployment in a real-world care setting revealed both the strengths of our specific design choices and the limitations inherent in this initial iteration.

6.1 The Tension Between Hygiene and Robustness

The evaluation highlighted a critical design trade-off specific to the care ecosystem: maintenance accessibility versus structural robustness. The modular "sandwich" structure was praised for facilitating rapid sterilisation, a non-negotiable requirement for communal instruments post-COVID. Crucially, the TPU lattice functions as a low-cost, replaceable consumable, mitigating material fatigue and ensuring long-term sustainability within the care ecology. However, as noted by P1 and P2, the open-edge design exposed a vulnerability to unintended disassembly during enthusiastic play (see Section 5.3).

Implication: Inclusive design must account not just for the user's interaction, but for the facilitator's maintenance workflow.

Future Iteration: We propose a magnetic interlocking barrier (see Figure 12) to secure the TPU lattice against "tipping" forces while maintaining the tool-less detachability required for hygiene compliance.

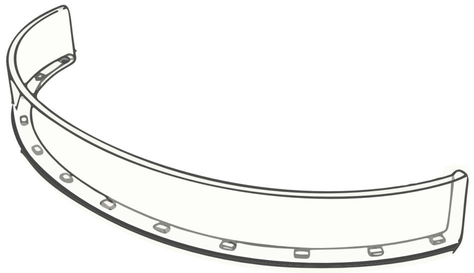


Figure 12: Proposed concept for a magnetic interlocking barrier to prevent unintended disassembly.

6.2 Psychoacoustic Mapping as an Inclusive Bridge

The successful implementation of Stevens' Power Law ($y = x^3$) proved to be more than a technical calibration; it functioned as a safety mechanism for neurodivergent users.

- **The "Safe Exploration Zone":** Mathematically, the cubic curve creates a "dead zone" of very low amplitude at the start of the press. Physically, the TPU lattice provides resistance. Combined, this allows users like P12 to rest

their hands on the keys or engage in "stimming" (repetitive touching) without triggering abrupt and loud sounds.
- **Prevention of Sensory Overload:** Unlike linear switches that might trigger a full sample upon contact, this mapping ensures that sonic intensity is strictly coupled to intentional force. This prevents the "startle reflex" often caused by accidental triggers in digital instruments.
- **Expressive Range:** At higher velocities, the extended dynamic range allowed experienced musicians (P11) to find nuances closer to acoustic instruments. This supports the inclusive design principle that accommodating the "one" can produce a richer instrument for the "many").

6.3 Limitations

Despite the positive qualitative feedback, several limitations regarding the study design and technical constraints must be acknowledged.

6.3.1 Methodological Constraints: Proxy Reporting and Consent. A primary limitation is the reliance on proxy reporting for non-verbal participants. As P12 could not provide first-person verbal feedback, our data relies on the interpretation of support workers and occupational therapists. While these proxies are experts in the participant's behaviour, their interpretation introduces a layer of subjectivity.

Furthermore, the sample size ($N = 12$) was constrained by strict ethical standards regarding informed consent. To ensure the study adhered to high ethical principles, we focused only on participants who could clearly demonstrate willingness (assent) to participate, either verbally or through clear non-verbal cues, alongside institutional and carer consent. This necessary ethical rigour excluded potential participants with more ambiguous communication signals, limiting the breadth of our data on severe disabilities.

6.4 Constraints of Scope: From Individual Agency to Ensemble

For this initial evaluation, the interface was restricted to a four-tile pentatonic configuration. This design choice prioritised establishing individual instrumental agency, a prerequisite for meaningful ensemble interaction [15]—over immediate chromatic scalability. Furthermore, ethical and logistical protocols required separate sessions to accommodate the different sensory profiles of P11 and P12 (auditory focus vs. motor support), prioritising participant comfort over experimental complexity. Consequently, while the system's "perceived immediacy" and closed-loop haptics were validated individually, the technical load and emergent social dynamics of a fully networked, co-located ensemble remain a critical avenue for future work.

6.4.1 Short-term Evaluation. The user study was cross-sectional, consisting of brief 5-minute interactions. While "perceived immediacy" was validated, long-term engagement remains untested. It is unclear if the single timbre (Singing Bowl) would sustain P12's interest over weeks, or if the novelty of the haptic feedback would diminish over time.

6.4.2 Technical Constraints in Spectrum-Dense Environments. While the current architecture achieves autonomy by utilising the Raspberry Pi 5 as a dedicated SoftAP (host), the system relies on the 2.4 GHz WiFi spectrum to communicate with the ESP32 nodes. In controlled environments, this performs flawlessly. However, in crowded public settings, the 2.4 GHz band is often saturated by interference from personal mobile devices and venue infrastructure. This spectrum congestion can lead to packet loss or jitter, degrading the strict timing required for rhythmic cohesion.

6.5 Future Directions

Building on these findings, we intend to expand the system in three critical dimensions:

- **Scalability and Open Science:** We aim to stress-test a larger array (8–12 units). While the lightweight integer protocol minimises bandwidth load, future iterations will explore an ESP-NOW gateway to bypass WiFi stack latency in signal-dense environments. To support the community, we will publish a repository of these benchmarks and modular design files for replication.
- **Granular Synthesis and Sonic Agency:** To address timbral limitations, we will implement granular synthesis modules. This allows users to manipulate environmental recordings or vocal samples, granting non-verbal participants (like P12) a way to "play" with their own voice. This transforms the instrument from a passive resonator into an active sampler, expanding the palette for personal expression.
- **Longitudinal and Demographic Expansion:** Moving beyond the initial novelty, we plan to conduct a 6-week longitudinal study to assess sustained therapeutic value and sensory regulation. Simultaneously, we will expand test sessions to partner community centres, validating our design assumptions across a wider demographic of cognitive and physical impairments.

7 Conclusion

This paper presented the design, implementation, and evaluation of a modular, low-latency tactile musical instrument developed in close collaboration with a London-based inclusive music charity outside the academic sphere. By embedding the design process within a real-world care ecosystem, we addressed the specific challenges of accessibility, hygiene, and creative agency, factors that are often overlooked in laboratory-based NIME research. Technically, the system bridges the "analogue-digital divide" by combining high-performance single-board computing (Raspberry Pi 5) with distributed sensing nodes to achieve a 7 ms response time. However, the instrument's true novelty lies in its participatory origins. The "Force Pair" mechanism and the "sandwich" modularity were not conceived in isolation but were refined through direct feedback from co-designers, including therapists, facilitators, and participants with complex needs. This co-design approach ensured that the interface is not only expressively nuanced for musicians but also structurally robust and hygienically compliant for communal care settings. The evaluation demonstrated that Accessible Digital Musical Instruments (ADMIs) are most effective when they balance technical performance with the "situated knowledge" of practitioners. By restoring the material resistance that gives music its physical soul, we provide a platform for non-verbal participants and those with complex disabilities to assert their agency. Ultimately, this project highlights the vital role of cross-sector collaboration in NIME. We argue that true inclusion requires moving beyond "assistive devices" designed for users, towards shared instruments designed with communities, fostering social cohesion and dignity through sound.

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9 ETHICAL STANDARDS

This research was conducted as an independent study in collaboration with the Joy of Sound. While formal university ethical approval was not required, the study protocol strictly adhered to the ethical principles outlined in the Declaration of Helsinki regarding research involving human subjects. Informed consent was obtained from all verbal participants prior to the sessions. For the participant with severe cognitive and motor impairments, a rigorous two-stage consent protocol was implemented, comprising written proxy consent from legal guardians and a "process assent" model, where the researcher and support staff continuously monitored non-verbal cues to ensure ongoing willingness to participate. All data were anonymised, and participants retained the right to withdraw at any time.

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