CollabJam: Studying Collaborative Haptic Experience Design for On-Body Vibrotactile Patterns

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Abstract

Designing vibrotactile experiences collaboratively requires communicating using multiple senses. This is challenging in remote scenarios as designers need to effectively express and communicate their intention while iteratively building and refining experiences, ideally in real-time. We formulate design considerations for collaborative haptic design tools, and propose *CollabJam*, a collaborative prototyping suite enabling remote synchronous design of vibrotactile experiences for on-body applications. We first outline *CollabJam*'s features and present a technical evaluation. Second, we use *CollabJam* to understand communication and design patterns used during haptic experience design. We performed an in-depth design evaluation spanning four sessions in which four pairs of participants designed and reviewed vibrotactile experiences remotely. A qualitative content analysis revealed how multi-sensory communication is essential to convey ideas, how stimulating the tactile sense can interfere with personal boundaries, and how freely placing actuators on the skin can provide both benefits and challenges.

CCS Concepts

• **Human-centered computing → Collaborative interaction**; *Haptic devices*; Open source software.

Keywords

vibrotactile design, vibrotactile patterns, tacton, collaborative design

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1 Introduction

Vibrotactile actuation lies at the core of communicating through the sense of touch. By modulating vibrations, a wide range of devices employ actuators to convey meaningful information and enhance

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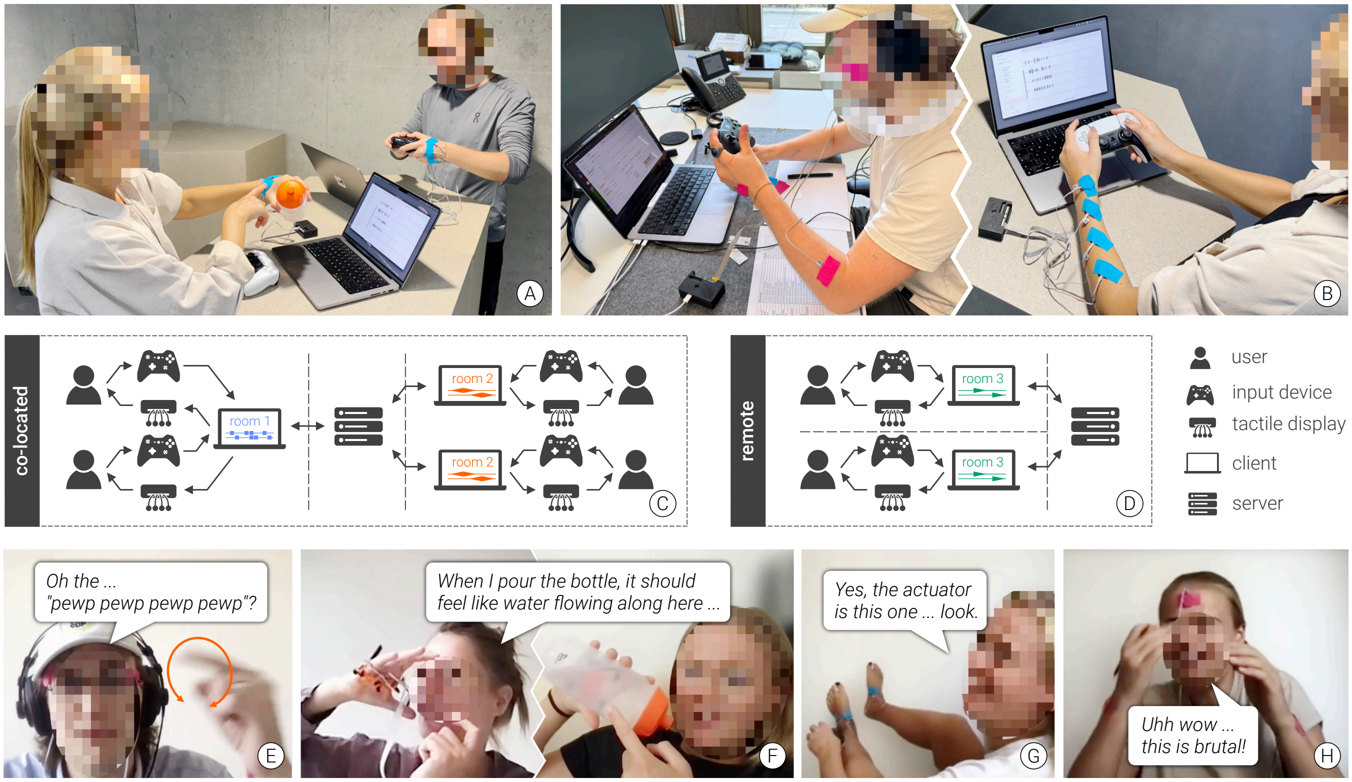

Figure 1: *CollabJam* is a prototyping suite for collaborative vibrotactile experience design. It enables collaborators to design in co-located Ⓐ Ⓒ and remote scenarios Ⓑ Ⓓ with actuators they can place freely on their bodies. We studied communication patterns when collaboratively designing vibrotactile experiences in an empirical study. A qualitative analysis revealed in part that multisensory communication was essential to communicate through gestures Ⓕ and sometimes onomatopoeia Ⓔ, that communication about and reproducing actuator placement was challenging Ⓖ, and that tactile actuation could interfere with personal boundaries and required to be adjusted to one's sensitivity Ⓗ.

multi-sensory experiences, spanning from notifications and directional cues in smartphones [97] to simulating textures [15, 65, 84], weight [83], and stiffness [30] in mixed reality.

However, designing vibrotactile experiences remains a challenging, thoughtful process [41]. Basic modulation of amplitude and frequency to generate vibrotactile signals is unintuitive [72]. Users need approaches that build vibrotactile signals from emotional qualities [78] and enable interactive, iterative generation [72]. Additionally, successful expression of desired tactile experiences requires considering human understanding of tactile sensations [17]. Here, low-fidelity prototyping tools may provide solutions by enabling to test design ideas early to assess their potential [6, 46]. Additionally, haptic experience design (HaXD) is interwoven with other design processes involving different designers and stakeholders [70]. While haptic design methods are improving, this collaborative, multidisciplinary aspect remains largely unexplored. Testing experiences with different users is essential to ensure they convey the right information without disturbing them, however this often requires building entire systems with the risk of ultimately lacking efficacy [70]. These issues stem from three core challenges that HaXD needs to address, namely (1) building tools and technologies that enable collaborative design and sharing of haptic experiences [16], (2) enabling quick and iterative design cycles to feel experiences when creating them [17, 72], and (3) supporting design and communication patterns that enable effective collaboration [46].

This work investigates communication and design patterns used by remote collaborators when designing vibrotactile feedback synchronously. As literature is currently missing tools to support these design scenarios (i.e., synchronous, remote design), we formulated design considerations that led to the creation of a novel prototyping suite called *CollabJam*. This suite extends the state-of-the-art on prototyping on-body vibrotactile experiences [50, 95] with direct and shared controls of actuators to create vibration patterns with co-located or remote collaborators. It consists of a software design tool (Figure 1, Ⓐ to Ⓓ) connected to a global server and a hardware device controlling four independent actuators that one can place on their body. Users can connect to *virtual rooms* to share a remote-tactile space, feel vibrations synchronously, and mute others if needed. They can create vibrotactile patterns by pressing buttons on a keyboard or game-pad, record sequences for playback, and edit these patterns using visual representations or by overdubbing new tactile inputs. Additionally, users can document their patterns and provide feedback on their experiences.

To uncover communication and design patterns, we studied 4 pairs of (haptic) designers working with *CollabJam* during 4 one-hour design sessions. Participants collaborated remotely to design and review vibrotactile experiences based on video prompts of video game sequences. We targeted this theme because designers were free to use any element of the sequences as inspirations for emotions, physical sensations, or any kind of metaphors. We introduced the system in the first session, then let them design alone and in pairs in the second and the third, and they reviewed and remixed vibrotactile experiences in the last session. We ran an inductive qualitative content analysis [10] from the video of the sessions and their transcripts and found a total of 7 themes (4 to 10 sub-themes each) that highlight challenges in many aspects of the collaborative haptic experience such as multisensory means to communicate intention, conflicts between senses when communicating, and cognitive efforts to communicate and reproduce actuator placements on the body (Figure 1, Ⓔ to Ⓗ). We summarize our findings by reflecting on what aspects of the collaboration *CollabJam* supported, and what it failed at supporting, and list significant insights and design guidelines to avoid caveats when designing systems dedicated to collaborative design of vibrotactile experiences.

In summary, we make the following contributions:

- We propose **design considerations** drawn from related work and our experience of designing software dedicated to collaborative haptic experience design.
- We present the *CollabJam* **open-source prototyping suite** that enables remote, synchronous collaborative design of vibrotactile experiences.
- We present **results of an inductive qualitative content analysis** from an empirical study on the communication and design processes of 4 pairs of (haptic) designers.
- We formulate **insights on this collaborative design process** and **design implications** for on-body, collaborative vibrotactile design tools.

2 Related Work

In this section, we present the concepts of co-design and prototyping, and describe how *CollabJam* supports both. We then review work on haptic experience design with a focus on vibrotactile experiences, and discuss systems and solutions proposed in the literature to support this process, especially when collaborating with others.

2.1 Co-Design and Prototyping: A Collaborative, Iterative Process

Co-design is a form of participatory design including both designers and end-users in an iterative design process to build a product [12, 45, 69, 74, 82]. It is defined by Kleinsmann and Valkenburg as "*the process in which actors from different disciplines share their knowledge about both the design process and the design content*" [42]. Co-design is strongly beneficial for HaXD as it enables sketching, prototyping and feeling experiences with multiple stakeholders to assess their efficacy [70].

Sketching and prototyping are essential stages of co-design. Sketching focuses on idea exploration and does not require an interactive system, while prototyping requires some kind of interaction regardless of the prototype fidelity [12, 53]. The line between these stages is rather well-defined when designing graphical interfaces (i.e., static drawing vs. creating paper or video prototypes) [45], but it is less the case with haptic experience design that requires actuation to test ideas [46].

The fidelity of a prototype can go from low to high [45]; low-fidelity prototypes are easy to create but lack precision, while high-fidelity prototypes are closer to final products. Regarding haptic experiences, Muender et al. [54] proposed a framework to define levels of haptic fidelity when aiming to produce realistic experiences. This framework highlights how abstract or realistic (fidelity) and how specific or generic (versatility) an experience can be.

Various tools have been proposed to quickly prototype haptic experiences. Some focus on vibrotactile actuation with one to several actuators fixed on objects or directly on the skin [39, 52, 58, 95], while others focus on kinesthetic feedback provided by grounded-devices [59] or wearables [51]. While many require users to control actuators through a graphical user interface [50, 58, 73, 84], others adopt a more direct approach by capturing experiences through audio signals [39, 52] or providing hardware components as control devices [72, 95].

We employed a user-centered design approach [1, 48, 55] to design *CollabJam* with the goal to create a system enabling co-design of vibrotactile experiences between both novice and expert hapticians. The system supports both sketching different ideas and designing more complete low-fidelity prototypes of rather abstract experiences, as its output capacities limit the creation of more realistic ones.

2.2 Designing Vibrotactile Patterns

Vibrotactile patterns can convey rich, meaningful information through the sense of touch, acting as a communication channel between users and devices [11]. They can produce expressive haptic experiences which can help in communicating feelings, emotions, and information [70], but vary depending on the rendering methods [31, 68]. To create such patterns, haptic designers (named hapticians [70]) require intuitive tools that enable parameterizing experiences while iterating on various versions of them [70, 75, 77, 78, 88]. Designing such patterns remains a complex task, depending on the need for balancing realism, expressiveness, and the synchronization of tactile feedback with other sensory inputs, such as visual and auditory cues [41]. This challenge is made more complex by the subjective nature of haptic experiences, which can vary widely between individuals.

Most tools for vibrotactile pattern design are built on desktop interfaces [86], enabling designers to control parameters via sliders, response curves, and other casual widgets [18, 50, 67, 84]. They may borrow metaphors from Digital Audio Workstations (DAWs), allowing designers to associate vibrations with sound and other media in a structured way [27, 28, 38, 66]. Furthermore, vibrotactile rendering has relied on demonstration-based authoring methods due to their simplicity and intuitiveness [33]. Although this approach is less common in vibrotactile authoring tools compared to pattern composition or waveform editing, it suits the nature of sketching iterative vibrotactile experiences by integrating fast feedback from the user designing and experiencing the feedback [46, 72]. With respect to rendering vibrotactile feedback, tools like *Syntacts* [60] and *Haptic Servos* [67] support rapid prototyping by reducing the time required to play experiences on hardware devices, whereas others, like the *Hedonic Haptics player* [87], enable users to experience a variety of vibrotactile compositions through an embodied wearable. Another group of systems focus on hands-on approaches enabling direct manipulation of experience parameters through instrument-like input devices [72], dedicated tangible interfaces for on-body experiences [95], or by vocalizing them when performing actions associated to these experiences [17].

CollabJam is grounded in this family of design software; it enables controlling 4 actuators independently through a graphical user interface, and quickly recording vibrotactile patterns that can be overdubbed to produce multiple versions of an experience. Furthermore, *CollabJam* provides a desktop application that shares individual inputs to collaborators over a centralized server, and outputs them using tactile displays connected via Bluetooth. Building on related work in haptics instruments [72], *CollabJam* leverages demonstration-based and direct manipulation authoring methods to design vibrotactile experiences.

2.3 Collaborative and Remote Haptic Experience Design

Remote haptic feedback systems have been explored extensively in teleoperation contexts [76] such as medical operations [63]. The synchronization of tactile feedback is critical in these contexts to support physical actions of remote users. Multi-user environments particularly pose challenges concerning synchronicity that might be mitigated with dedicated protocols [3, 4]. To support effective collaboration in these scenarios, tools must integrate multi-modal communication channels that combine tactile feedback with audio, video, or visual representations [20, 32, 89, 93]. Regarding haptic experience design, these channels allow users with different sensitivities and haptic acuity to test, refine, and improve tactile experiences together [9].

Designing and discussing tactile experiences is inherently challenging due to the difficulty of expressing touch sensations without a well-defined vocabulary [56, 62]. Enabling direct, synchronous feedback between collaborators when sketching and recording ideas might provide them with means to communicate design intentions beyond words. In that regard, TactJam [95] enables collaborators to share on-body vibrotactile experiences using a maximum of 8 actuators. Designers can easily share their designs by saving them online and loading them on their end, but not experience them simultaneously. CoTacs [50] goes a step further by enabling simultaneous playback for all collaborators of parameterized experiences using two vibration motors and a shape-memory alloy fixed to a patch.

CollabJam builds from these two approaches [50, 95] and extends them in three primary ways: (1) each collaborator in a virtual room can control actuators on all ends at the same time by pressing keyboard or controller buttons to experiment hands-on with ideas, (2) collaborators can fine-tune vibration patterns after recording them to better match their expectations, and (3) collaborators can isolate themselves in virtual rooms or mute others to avoid being overwhelmed by vibrations. These features enable synchronous multi-sensory communication and hands-on design between collaborators, as opposed to setting parameters of an experience using time profiles and playing it back. The primary benefit we envision from this approach is to better support sketching ideas, as demonstrated in the empirical study (section 6).

3 Design Considerations to Support Collaborative On-Body Vibrotactile Experience Design

In this section, we discuss challenges we faced when iteratively building design tools for on-body vibrotactile experiences with one or multiple collaborators. We highlight what makes such a design process particularly challenging and emphasize important aspects that interactive systems should support or at least alleviate. We reflected on these challenges through the lens of related work and our experience, and identified a list of design considerations that informed the design of *CollabJam*.

3.1 Communicating Intention through Multi-Sensory Communication

Conveying design ideas demands a clear vocabulary, and simple words might not suffice in all situations [56]. For instance, when trying to communicate a vibration sequence (e.g., a circular pattern [58]) on the body to indicate spatial movements, it may be easier to gesture it to a collaborator than use words (Figure 1,Ⓔ and Ⓕ). Similarly, if a system enables to place the actuator(s) freely on one's body (e.g., independent actuators [95] or a patch [50]), it is likely necessary to reproduce the same placement between collaborators to feel similar experiences and reflect on them. Depending on the actuators' characteristics, using words might be limited to provide instructions on this placement compared to showing (either directly with a camera or using a virtual representation) to a collaborator how they are placed (Figure 1 Ⓖ). Using external resources such as images or videos when designing may also support collaborators by providing them with concepts (e.g., objects, characters) they can use as references to describe feelings or sensations, thus mediate their conversations. Using the sense of touch, they can directly control actuators on their skin to create tactile sensations and convey information through them (e.g., abstract messages [13]) which they can supplement with explanations if necessary.

Overall, vocal communication can be strongly limited to convey a design intention or instructions, and other senses may replace it or be used in combination to convey information. We thus consider the following design consideration:

DC1 *How can the design tool support conveying intentions through any sense?*

3.2 Proxemics: Giving Physical Space to Individuals in Virtual Environments

Proxemics describe the physical, intangible spaces perceived with all senses by people in face-to-face human-to-human interactions to determine a comfortable distance to others [29]. Four zones were originally defined by Hall [29]: the intimate, the personal, the social, and the public zones. Haptics and the tactile sense in particular often requires physical closeness and may breach the intimate space [5]. When collaborating with someone else over a distance or fully remotely, tactile interactions through a haptic setup can conflict with the overall idea of proxemics zones, as this creates a close channel between two designers that may be in two distinct places. To respect privacy and limit the risks of interfering or breaking intimate boundaries, a system should enable modes to control receiving and sending signals to the tactile channel, similar to muting oneself on a video conferencing tool. Interactive means can be used to simulate proxemics spaces in virtual, remote collaboration, such as using spatial metaphors to mute users in specific "floors" [35], or signaling a raised hand as an emoji to show a person wants to speak in a crowded video conference session. Hu et al. [34] propose to request access to virtual rooms with levels of urgency and start personal conversations with collaborators that are nested within group conversation (including transitions from and back to the group conversation). Similar means could be implemented for the communication through the tactile channel, which led to the following consideration:

DC2 *What safeguards does the system need to implement to avoid interfering with or breaking proxemics barriers with the tactile sense?*

3.3 Actuators placement: Individual Sensitivities and Control Mappings

Depending on the kind of haptic experiences targeted with a system, actuators used can be dedicated to a body part and consider a single layout of actuators (e.g., a glove), or, on the contrary, actuators can be independent from each other (e.g., [95]) and placed at any location on the body. This independence can be a strength if the goal is to try out as many actuator placements as possible for a single experience, for instance, but may require to control them all independently too, and ways to easily identify them once fixed to the skin. Several methods can be used to place actuators on the body, ranging from simple tape to elastic bands, garments or dedicated mounts sewn or printed. These methods can be comfortable but limit the body areas actuators can be placed on (e.g., an arm band cannot be used on the torso). Overall, high malleability in the placement and control of actuators can come at the cost of higher mental load for designers. We recommend considering the following points when building design tools:

DC3 *How easily can actuators be (re)placed on the body?*
DC4 *How independently can actuators be controlled and how much cognitive efforts does that require?*

3.4 Input Means: Devices, Degrees of Freedom, and Latency

Wearing actuators might impede physical movements that could limit their control by designers (e.g., wearing actuators on the fingertips). While collaborators could share controls, e.g., one feels while the other actuates, it may impose limitations that can hinder the design process. Devices used to control and record vibration patterns should ideally adapt to actuators' placements and limit their impact. Collaborators may still need to synchronize their actions to split the workload when designing (e.g., each collaborator records a part of the experience in real-time), or to control actuators synchronously with other senses. High system latency (> 200 ms), which considers hardware, software, and network latency, may then strongly impact the design and communication process as well as its UX [70]. Latency between initiating an action and receiving a system response affects user experience due to performance degradation [49]. Furthermore, collaborative tasks suffer from decreased efficiency due to network latency [36]. Huang et al. [36] found that when users collaborate remotely in tasks involving a rigid body movement controlled by the same haptic device, their subjective assessment of operability changes with increasing latency. To summarize, we formulate the following design considerations:

DC5 *Can the placement of actuators impede their control and how?*
DC6 *What impacts can have the system latency on the collaboration process?*

4 *CollabJam*: A Low-Fidelity Prototyping Suite

In this section, we describe the hardware and software components of *CollabJam*. First, we conceptually highlight features we implemented to answer design considerations (section 3), and then describe technical details of the system. All necessary materials, including schematics, fabrication files, and software code can be found in the project's online repository[1], and a tutorial of the system is provided in the supplementary materials[2].

4.1 Communicating and Sharing Information through Virtual Rooms

CollabJam supports co-located scenarios, where designers share the same computer or use their own computer, as well as remote scenarios. We use the metaphor of *virtual rooms* where users design vibrotactile experiences, following analogies from video conferencing tools that offer so called breakout rooms. In *CollabJam*, these *rooms* are work spaces which share a list of vibrotactile experiences as shown in Figure 4. They are configured in a global server that all client applications connect to when launching them. *Rooms* provide shared control to record, playback, and edit vibrotactile patterns as well as shared control for real-time actuation of connected tactile displays, which we refer to as *jamming*. Here, all events are broadcast to all users who joined the same *room* in real-time (cf. Figure 1 Ⓓ). Similar to music jam sessions, haptic designers can jam without the necessity to record vibrotactile patterns to experience specific actuation. This enables synchronous tactile communication that likely supports multi-sensory communication overall (**DC1**).

When multiple designers jam together, the tactile channel can quickly be saturated. As a safeguard for that, we implemented a muting mechanism (**DC2**). Designers can select individual collaborators from the list of users present in the room (Figure 4, bottom left in the GUI) and mute single or all collaborators at once.

There may be phases in the design process, where designers want to individually develop and record ideas. They can jump in another empty room to try out design ideas without receiving or sending tactile messages to collaborators. When they finished the solo design phase, there are two ways users can collaboratively proceed; they invite collaborators to join the room they are in or transfer (i.e., *moving*) vibrotactile experiences to other rooms with

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[1] GitHub repository: https://github.com/TactileVision/CollabJam
[2] OSF repository [94]: https://osf.io/bqw4t

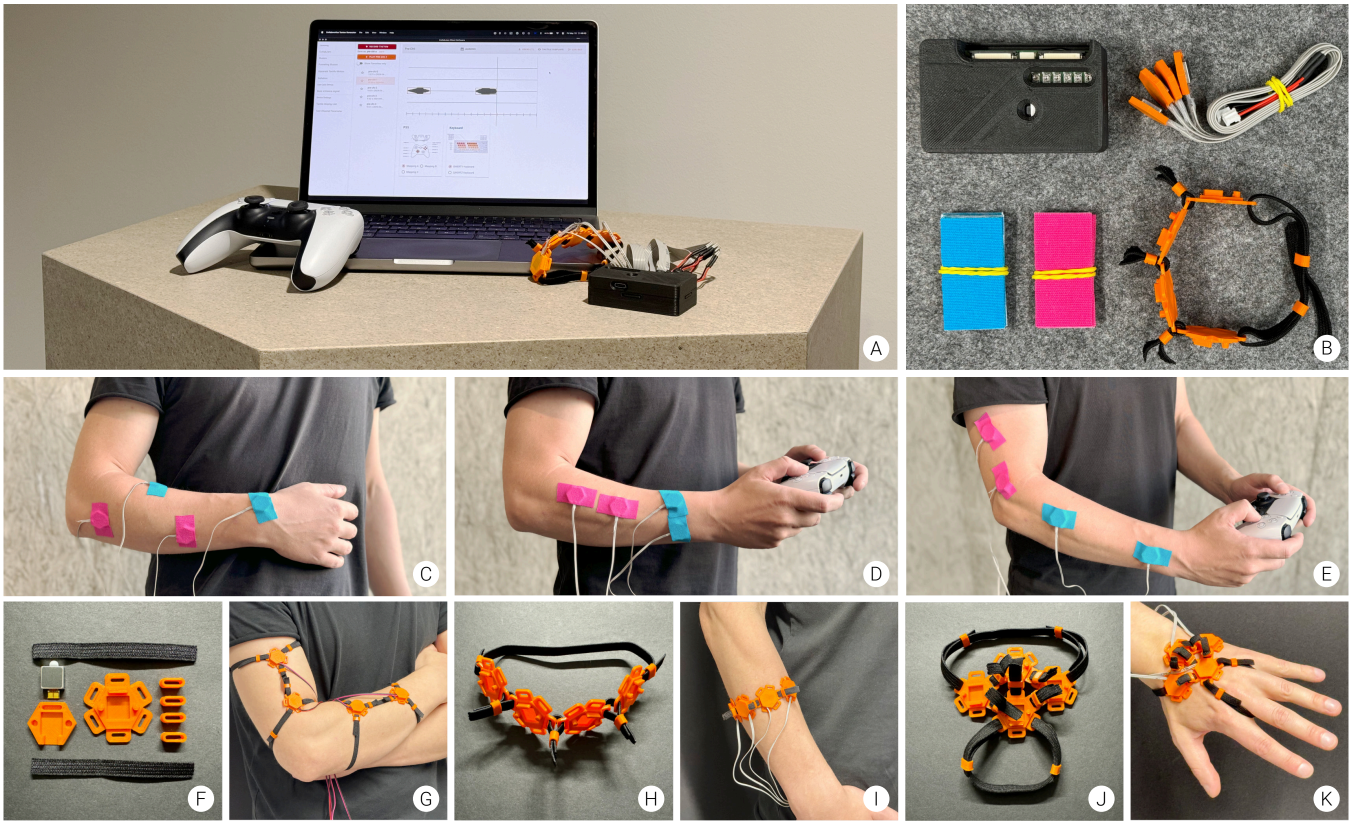

Figure 2: *CollabJam* consists of a software application, a tactile display, and a keyboard or gamepad to control the actuation Ⓐ. The tactile display consists of a custom PCB, four LRAs, and means to attach actuators on the skin (kinesio tape, modular harness) Ⓑ. Both, the kinesio tape (Ⓒ to Ⓔ) as well as the harness (Ⓕ to Ⓚ) can be used to freely create on-body actuator arrangements.

collaborators. If designers want to keep a copy of a pattern in their private room, they need to *clone* the pattern before *moving* it to another room. Since we planned to evaluate our system only with pairs of designers, we did not implement more mechanisms to control what information is carried over different virtual rooms. Such mechanisms could be more relevant for larger groups of collaborators (cf. [34]).

In addition to the vibrotactile experience itself, designers can add textual information including intention, notes, actuator placements, and tags, to document vibrotactile experiences overall (**DC1**). However, we did not implement means to annotate or tag specific vibrotactile blocks to provide contextual information. Instead, we prioritized facilitating direct communication during the design process and chose to keep the feature set streamlined to maintain simplicity.

4.2 Jamming, Recording, and Overdubbing Vibrotactile Experiences

With *CollabJam*, we mainly address the early stages of the design process, namely sketching and prototyping [45, 46]. The system focuses on features that allow both rapid sketching of ideas and refining experiences to create more complete prototypes through fine-tuning actions.

Designers can control individually timing and intensity of vibrations, but not their frequencies, using keyboard or gamepad input (**DC4**, **DC5**), and place actuators independently on the skin (**DC3**). Pressing keys on the controllers actuates single or groups of actuators at a given intensity, which becomes handy when actuation needs to be synchronized. We leverage the pressure sensitivity of gamepads' triggers to enable modulating intensity of actuators or targeting each of them separately to create spatial animations.

Typical Workflow with CollabJam. First, designers can jam to sketch ideas. As soon as all collaborators have their tactile displays connected to the client application and have joined the same virtual room, they can start jamming. In this mode, all user inputs (such as button presses) are broadcasted in real-time to all clients that are present in the same virtual room.

During jamming, designers can split their efforts (**DC4**); for instance, one designer could play a basic rhythm while another adds vibration patterns on top of it. To identify who is actuating what at a given time, the dot on the left of an actuator's line is colored with the distinct color assigned to the user actuating it,

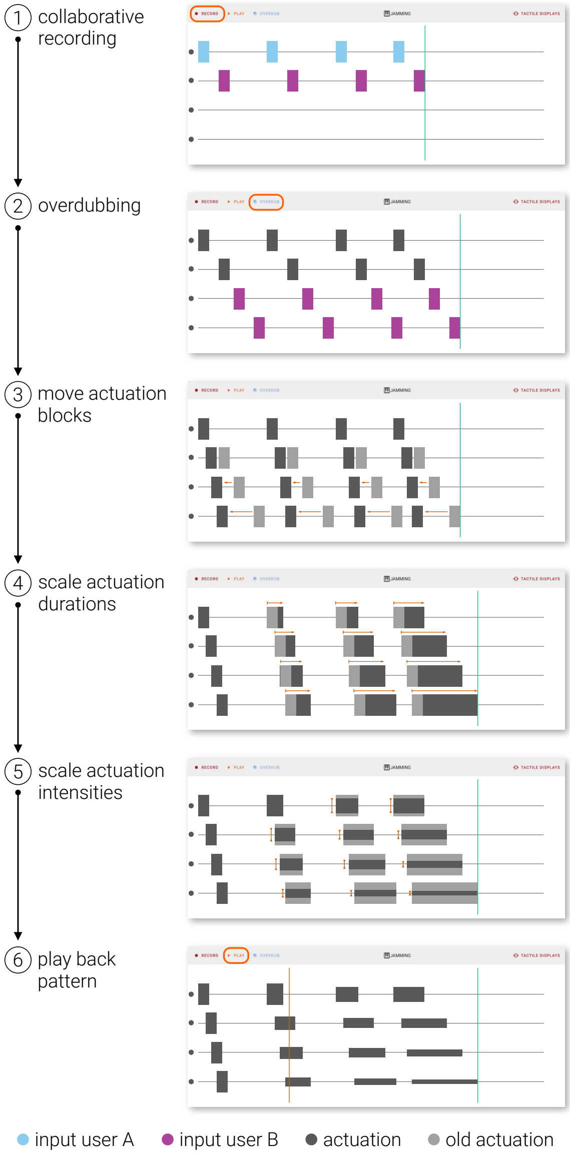

Figure 3: This is an example of a workflow where two designers collaboratively record a vibrotactile pattern using shared control. During recording, each designer's contribution (i.e., actuation blocks) is visually represented in the timeline using their assigned user-color ①. After finishing the recording, all blocks are colored in dark gray to minimize visual clutter. One designer then enhances the pattern by overdubbing, adding more complexity ②. Afterwards, they refine the pattern by adjusting the onset time of actuations by moving blocks ③, scaling the duration of individual blocks ④, and tweaking the intensity levels of specific blocks ⑤. Finally, they play back the pattern and experience it synchronously ⑥.

as there are no actuation blocks recorded and visualized during jamming (Figure 4, on the left of the actuation timeline).

Once they feel comfortable, they can *record* the vibrotactile pattern and edit it afterward, which is depicted in Figure 3. During recording, designers can distinguish their contributions by colored actuation blocks in the timeline (Figure 3, top left). If the planned experience is more complex than what designers can record in one go, they can *overdub* new patterns, which consists in playing back recorded vibrotactile patterns while designers can record new patterns on top of them. This may overall lower the cognitive efforts and require less motor skills by focusing on specific aspects of the experience at each step (**DC4**). Overdubbing can also be planned in advance by simply playing back the current pattern and jamming over the playback. If the timing or intensity of certain actuation in the recorded pattern does not match the designers' expectation, they can adjust this with mouse interactions by drag-and-dropping corresponding blocks in the timeline, scaling blocks to the desired duration horizontally, or fine-tuning their intensity by scaling them vertically. Individual blocks can be deleted by selecting them and pressing the delete key, but not duplicated.

To enable quick comparison of multiple vibrotactile experiences, we implemented *cloning* them, which duplicates all information (including all metadata). Designers can then apply adjustments to vibration blocks and compare versions. All vibrotactile patterns with the same name are grouped in a collapsible list, which helps keeping them organized (Figure 4).

4.3 Software Implementation Details

We implemented *CollabJam* using a server-client architecture (Figure 1 Ⓒ and Ⓓ). The client software is a cross-platform[3] desktop application. It handles all inputs through a keyboard or gamepad, and outputs vibration through the tactile display. The central server handles the real-time interaction of clients that are connected to the same virtual room and manages data such as users, virtual rooms, and vibrotactile experiences in a MongoDB [37] database.

4.3.1 Client Application. The client application is built using Electron [24], which provides an architecture comprising a *renderer process* and a *main process*. These processes communicate through Electron's Inter-Process Communication (IPC) mechanism [25], enabling interaction between the user interface and underlying system processes such as Bluetooth. We developed the renderer process using the Vue [98] framework in combination with the Vuetify [90] component framework to create the user interface. The tactile feedback visualization (i.e., actuation timeline, see Figure 4) was implemented using PixiJS [61].

Input Handling. The system currently supports keyboards (default device, see Figure 1 Ⓑ) and gamepads, using respectively the Web KeyboardEvent [23] and Web Gamepad [22] APIs. Gamepads particularly allow more degree of control than a keyboard through pressure sensitivity. We leverage it by enabling intensity sweeps. Connected gamepads[4] are detected automatically and get a default key mapping assigned (refer to Appendix A for more details). We defined three different mappings for gamepads defined in JSON files

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[3] We successfully tested the application on macOS (v14 and v15), Windows (v10 and v11), and Linux (Ubuntu 24 LTS).

[4] We successfully tested the system with different gamepads such as PS3/4/5, XboxOne/360, and Steam. Other controllers can be added easily as long as they are compatible with the Gamepad API [22].

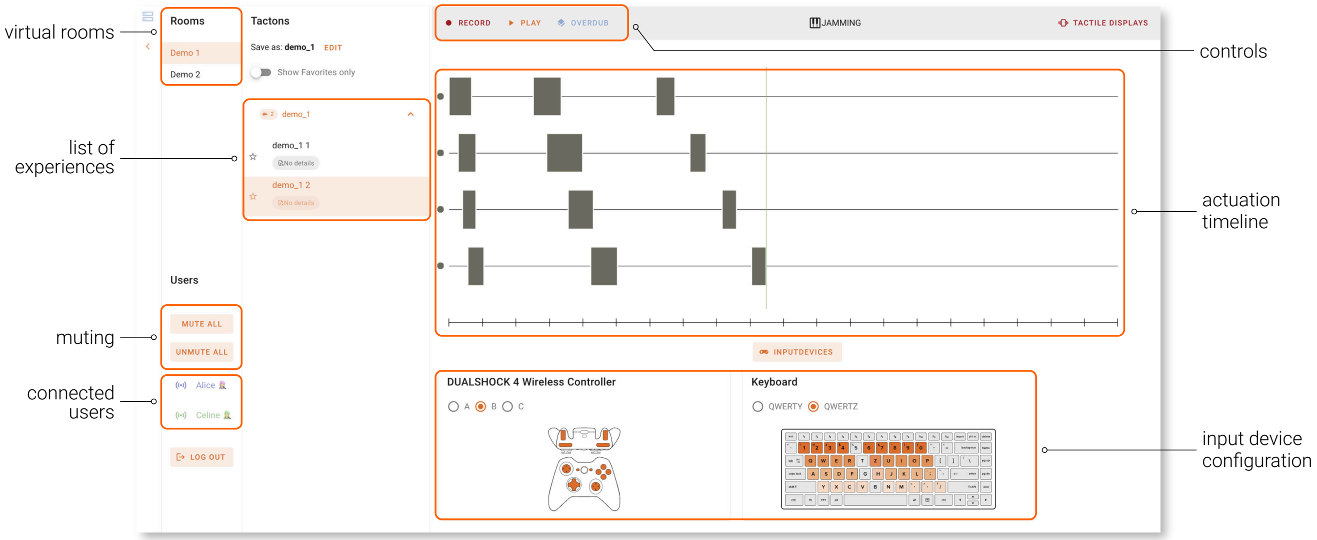

Figure 4: *CollabJam*'s graphical user interface. Here, the actuation timeline visualizes vibrotactile patterns in blocks on timelines for different actuators. Users can join virtual rooms and record, play and overdub experiences. Connected users are visualized and can be muted, while different input device configurations can be selected.

that can be edited for customization. To ensure efficient handling of user input, a debouncing system aggregates vibration-related commands at 20 ms intervals before being sent to the main process for further processing, and we limited the trigger input to 24 discrete levels to reduce the data-transfer load between the client and the server.

Communication between Components. The main process, running in Node.js [26], handles all communication with external systems, including the central server and tactile display. To manage server interactions, we used the Socket.IO [80] library. For direct communication with tactile displays, the main process integrates Bluetooth Low Energy (BLE) technology (refer to subsection B.2 for details on the transferred data). Through this integration, the system can scan for and connect to compatible BLE devices, manage these connections, and write amplitude characteristics to the devices based on instructions received from the input system or the server in case of actuations triggered by a collaborator. All user actions originating from the renderer process are sent to the server, ensuring that all clients remain synchronized.

4.3.2 Server. We implemented the server as a Node.js [26] application that enables: 1) real-time broadcasting of vibrotactile patterns (i.e., input events from clients and playback), 2) managing patterns in a database, and 3) managing users as well as virtual rooms. For real-time collaboration, the server receives input signals (e.g., gamepad triggers) from individual clients that joined the same room and broadcasts these signals to the others. When one of the clients starts recording, the server samples input signals from all clients, compiles them into a list of instructions, and stores them as JSON file in a MongoDB [37] database. An example of such a file can be found in subsection B.1 of the appendix. When a user starts the playback of a pattern, the server manages the playback timer and broadcasts actuation signals to all clients in the same room, ensuring a synchronized experience.

4.4 Rendering vibrations

The tactile display consists of a custom PCB featuring an ESP32 microcontroller (M5Stamp ESP32S3 Module [44]), that interfaces with motor controllers (Renesas DA7282 [64]). The PCB supports four actuators of different types, including Eccentric Rotating Mass (ERM) motors, Linear Resonant Actuators (LRAs), and Voice Coil Actuators (VCAs).

We chose the Vybronics VLV101040A [91] LRAs in this work due to their low rise time (≤ 10 ms), compact form factor (10 × 10 × 4 mm), and sufficient amplitude (2.75 Grms) at their resonance frequency (170 Hz). While these LRAs offer a controllable frequency, we preferred to maximize their amplitude range, thus fixed the operating frequency at 170 Hz.

Actuators are connected to the PCB using 60 cm long wires, providing flexibility in placement across different body parts (**DC3**). For attachment to the body, Kinesio tape was used, ensuring the actuators could be easily re-positioned as needed (see Figure 2 Ⓒ to Ⓔ). Additionally, we designed a modular harness inspired by Kollannur et al. [43] (see Figure 2 Ⓕ to Ⓚ). This allows to assemble re-usable actuator arrangements with control over distances between actuators.

The tactile display is self-contained, powered by a LiPo battery (power supply via USB-C is also possible), and communicates wirelessly with the client application via Bluetooth Low Energy (BLE) 5. This allows designers to freely move in the room, which might be valuable while testing the vibrotactile experiences in interactive applications. The client application is capable of connecting to multiple devices simultaneously, enabling shared experiences in co-located scenarios, as well as using multiple devices on the body.

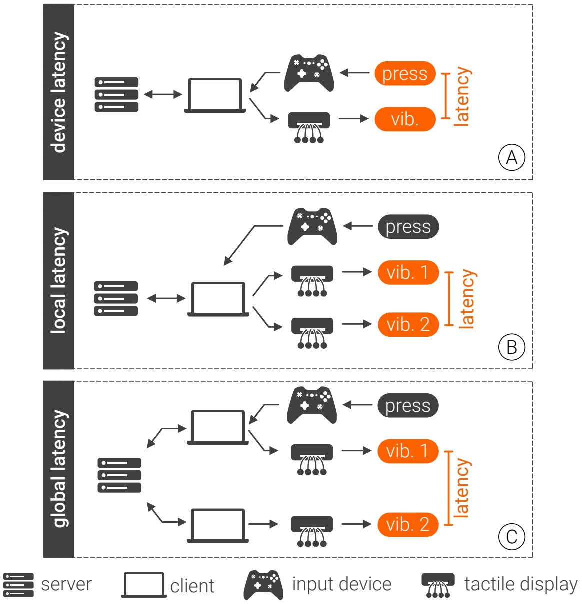

Figure 5: We evaluated three types of latency: *device latency* for a single user Ⓐ, *local latency* for two users working on the same computer Ⓑ, and *global latency* for co-located and remotely collaborating users Ⓒ, i.e. working on different computers.

Such a distributed setup could be useful when attaching actuators to the upper and lower limbs, which would otherwise require long cables along the body and could interfere with movements.

5 Evaluating the End-to-End Latency of *CollabJam*

We designed *CollabJam* to support synchronous multi-sensory communication. A system with high latency, however, has the potential to strongly limit such communication, especially in remote scenarios [36, 70]. In this section, we present a technical evaluation of *CollabJam*'s latency for co-located and remote scenarios.

5.1 Types of Latency

We evaluated three types of latency, i.e. *device latency*, *local latency*, *global latency*. The latter can be further divided into co-located and remote scenarios. Figure 5 illustrates the signal path for each type.

Device Latency. We define *device latency* as the **absolute** time difference between a button press and the onset of vibration at the tactile display (Figure 5, left). To quantify this, an additional button was attached to the gamepad for capturing button presses, while an Inertial Measurement Unit (IMU; MPU6050) was attached to the actuator to detect the vibration onset.

Local Latency. We define *local latency* as the **relative** time difference between the onset of vibrations at two tactile displays that are **connected to the same computer** (Figure 5, middle). To quantify this, an Inertial Measurement Unit (IMU; MPU6050) was attached to each actuator on the respective tactile display.

Global Latency. We define *global latency* as the **relative** time difference between the onset of vibrations at two tactile displays that are **connected to different computers** which are co-located or remotely connected (Figure 5, right). We first performed simulations of remote scenarios using VPN connections to different countries, but realized measurements included worldwide networks latency that we do not control within the system and provide little information on its inherent latency. We thus opted for a setup of two co-located computers connected via WiFi to the same network in the reported evaluation. We quantified the latency using the same evaluation hardware setup as for *local latency*.

5.2 Procedure

We utilized a microcontroller to collect signals (i.e., button press and vibration onset) and calculated latency with precision at the microsecond level (refer to Appendix C for details regarding the hardware setup). The threshold for vibration onset was defined as the RMS acceleration taken from reference measurements while driving the actuator with at resonance frequency (170 Hz) at maximum intensity (supplying 2.5 Vrms). For each type of latency, we conducted 200 measurements.

5.3 Results

Our analysis revealed an average absolute *device latency* of 64.81 ± 13.92 milliseconds, a *local latency* averaged at 9.78 ± 8.08 milliseconds, and an average relative *global latency* of 53.25 ± 56.51 milliseconds (Figure 6).

5.3.1 Contextualization of Results. To understand *CollabJam*'s latency, we frame the obtained results in terms of latency perception of tactile impressions for different scenarios. For *device latency*, we consider the perception of visual–tactile latency where JNDs have been established in the order of 35 to 65 milliseconds [40]. *CollabJam* average *device latency* of 64.81 ms can be found at the upper bound of this range.

To frame *local latency*, we considered the perception of tactile impressions between users. To the best of our knowledge, there are no clear perceptual latency investigations only considering the tactile modality in this context. Therefore, for *local latency*, we consider the perception of latency between two different tactile

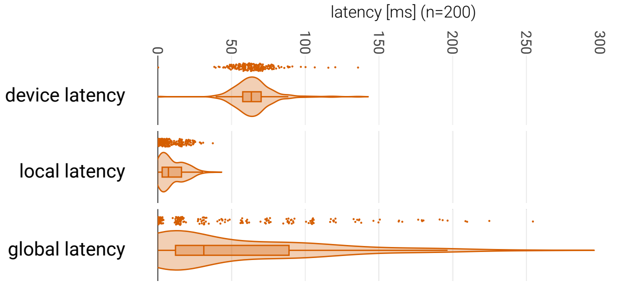

Figure 6: Results of latency measurements $(n = 200)$ of *device latency* (left, $M = 64.81 \pm 13.92ms$), *local latency* between two tactile displays connected to the same client (middle, $M = 9.78 \pm 8.08ms$), and *global latency* between two co-located clients (right, $M = 53.25 \pm 56.51ms$).

actuations on a single user's body. In a directed attention task, Spence et al. [81] noted the perceived JND for tactile actuation on the left side and the right side of their body was 48 ms. *CollabJam* average *local latency* of 9.78 ms clearly falls below this threshold.

Lastly, for *global latency*, we consider latency in the context of teleconferencing scenarios. Here, when listening to voice and reacting within a conversation, latency of up to 100 ms was found to be non-observable [21]. *CollabJam* average *global latency* falls below this threshold.

In summary, our empirical results suggest that *CollabJam* 's latency is unlikely to negatively impact the collaborative design process (**DC6**).

6 Empirical Study: Designing Vibrotactile Patterns in Pairs

We conducted an empirical study with two distinct goals in mind: (1) identify communication and design patterns used by participants when designing on-body vibrotactile patterns collaboratively, and (2) study whether *CollabJam*'s solutions to the design considerations exposed in section 3 would support participants in their task. To gain insights of longer-term usage of our system and understand *CollabJam*'s learning curve, we invited 4 pairs of participants to use *CollabJam* over the course of 4 sessions. The sessions lasted an hour each and consisted in introducing the system (1), designing alone and in pairs (2-3), and reviewing and improving vibrotactile experiences from other teams (4). We collected qualitative data in the form of videos and transcripts, and quantitative data by capturing the Creativity Support Index (CSI) through questionnaires [14] and capturing actuator placements and vibrotactile patterns of the experiences designed. This study has received ethical approval from University of Duisburg-Essen (ID 2406MCDD0242).

6.1 Participants

We recruited 8 participants from our local universities and surrounding community with an expertise in the fields of haptics (industry or academia), human-computer interaction, and product/interaction design. We recruited participants by pairs to prevent any discomfort or awkwardness that might arise from working with unfamiliar partners. Table 1 summarizes their demographics and self-declared expertise. Participants were aged between 23 and 39 years (M = 27.88, SD = 5.25). Each participant was paid 15 Euro per session (60 Euro in total).

6.2 Task

We used open-ended tasks with little to no constraints to let participants decide on how they wanted to proceed with their design process. We defined 4 types of tasks used in the various sessions: (1) designing alone, (2) designing in pairs, (3) documenting experiences, (4) reviewing vibrotactile experiences. When designing alone, participants would connect to private virtual rooms set up for them, and design quietly or explain their process out loud. When designing in pairs, they would connect to the same virtual room, but had the possibility to access their private room to try out ideas alone. When documenting experiences, they would input textual metadata and were free to discuss. Lastly, when reviewing others' experiences, they would use the same setup as when designing collaboratively.

To inspire their designs, we provided participants a set of video prompts[5] extracted from video games sequences that showed characters or objects interacting with each other or the environment. We chose this scenario as haptic experiences are becoming more prevalent in video games and on-body technologies are gaining in popularity [2, 57]. We felt that participants would more easily identify with such a use-case. Furthermore, the video sequences were selected as references to physical sensations (e.g., walking in snow), emotional messages (e.g., hugging someone), or metaphorical representations (e.g., providing spatial directions). We specified that vibrotactile experiences did not have to be synchronized with the videos, as *CollabJam* focuses on low-fidelity prototyping and was not designed to integrate synchronization features. When designing in pairs, participants would work on the same experience, and always used the same video prompt. It is worth noting that participants were free to use these prompts as guidance for their designs or disregard them, with no specific constraints imposed. For instance, they could design for any interaction or event of their interest and describe this in the metadata (i.e., intention) of the designed pattern. During the study, however, all participants only used the provided prompts for designing vibrotactile experiences.

6.3 Procedure

The study lasted about a month in total, with sessions spanning over a few weeks (see Figure 7).

Session 1. The initial session consisted of a comprehensive onboarding process. We first introduced the study, obtaining participants' informed consent, and collected demographic information through a survey. Next, we presented the *CollabJam* software and demonstrated its capabilities. Participants were then given 15 minutes to individually explore and familiarize themselves with the software, hardware, and video prompts, using their private virtual rooms within the *CollabJam* software. Subsequently, participants joined the same virtual room and designed in collaboration for 15 minutes. Throughout the session, they were encouraged to consult the experimenter for technical assistance or to ask questions regarding the procedure. The session concluded with a debriefing, during which participants were invited to provide initial feedback.

Session 2. The first task of this second session was to design alone for 15 minutes. Afterward, participants teamed up to collaborate on designing vibrotactile experiences for 25 minutes. They could design based on new prompts or the ones they already used. We

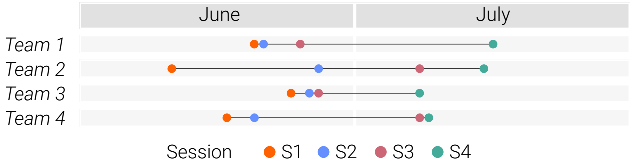

Figure 7: Distribution of study sessions per team.

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[5] We provide a list of video prompts with descriptions and links to the original sources on YouTube in the supplementary material (OSF repository [94]).

Table 1: Participant demographics.

ID	Occupation	Experience with haptics (years)	Level of expertise	Experience with vibrotactile design	Age	Gender
T1P1	Designer and founder of a (haptics) startup	4-6	Expert	Yes	31	M
T1P2	UI/UX Designer and researcher	1-3	Intermediate	Yes	29	F
T2P1	Product designer, research associate	4-6	Intermediate	No	26	F
T2P2	Design researcher	4-6	Intermediate	No	39	F
T3P1	Haptics researcher, PhD student	1-3	Intermediate	No	24	F
T3P2	Master student (Media informatics)	1-3	Intermediate	No	24	F
T4P1	Master student (Design)	<1	Beginner	No	27	M
T4P2	Master student (Design)	<1	Beginner	No	23	M

asked them to document their design(s) before the end of the task. We finished the session with a semi-structured interview and the completion of the Creativity Support Index (CSI) [14] questionnaire. Questions used in the interview were (similar to [50]):

- *What were the challenges you faced when working with the tool solely and with each other?*
- *What things helped you the most to solely work with the tool and with each other?*
- *What could have helped you to work more effectively with the tool solely and with each other?*

Session 3. This session followed the same structure as the previous one, but participants worked exclusively in collaboration for 40 minutes. After documenting their designs, participants were then asked to select as many vibrotactile patterns as they wished (3 to 5 depending on the team) to be reviewed by another team.

Session 4. In this last session, participants reviewed tactons designed by other teams and rated them based on the same procedure proposed by Messerschmidt et al. [50]. They evaluated *Goodness of Fit* (i.e., how well the haptic experience fits the prompt and written intent) and *Goodness of Feel* (i.e., how good the haptic experience feels independent of how well it fits to the prompt and written intent) on 5-point scales. We manually created flashcards[6] for each experience (see Figure 8) and a printed form to input their ratings. Participants first evaluated and rated the experiences individually, and then shared their opinions to provide team ratings. Following the rating process, participants were given the opportunity to improve the experiences. The review and improvement phase was limited to 45 minutes. Afterward, we conducted a short semi-structured interview with similar questions as in session 2 but regarding the review phase this time, and the completion of the CSI questionnaire.

6.4 Apparatus

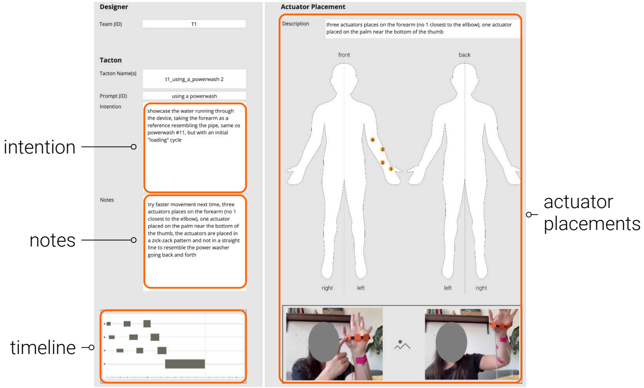
We conducted the study in our lab's offices for two teams, and the two other participated remotely from their homes due to personal circumstances. The participants were always in separate rooms. Each participant was provided a laptop (with remote participants using their own computers), a gamepad, a tactile display with four actuators, a harness (bracelet), and strips of kinesio tape for attaching the actuators to the body (Figure 2, Ⓐ and Ⓑ). We provided executable binaries of the *CollabJam* client software and a VLC playlist containing the 21 video prompts. Zoom was used for video conferencing throughout the interactive parts of the study. Participants completed the demographics survey and the CSI questionnaire through a browser interface (LimeSurvey).

6.5 Data Collection

We collected two types of video recordings: screen recordings from participants' computers and the video feeds on the video conferencing tool, including in both cases spoken conversations. To document the placement of actuators, we took pictures of participants (either directly or through the video conferencing tool). Demographics data and responses from the CSI questionnaires were recorded using LimeSurvey.

6.6 Qualitative Analysis

We transcribed all conversations 4 × 4 (4 teams, 4 sessions) using Aiko[7] (v1.7.4). We verified all automatic transcripts manually and



Team (ID): T1

Tacton Name(s): t1_using_a_powerwash 2

Prompt (ID): using a powerwash

Intention: showcase the water running through the device, taking the forearm as a reference resembling the pipe, same os powerwash #11, but with an initial "loading" cycle

Notes: try faster movement next time, three actuators places on the forearm (no 1 closest to the ellbow), one actuator placed on the palm near the bottom of the thumb, the actuators are placed in a zick-zack pattern and not in a straight line to resemble the power washer going back and forth

Description: three actuators places on the forearm (no 1 closest to the ellbow), one actuator placed on the palm near the bottom of the thumb

Figure 8: Example of a vibrotactile experience flashcard, which we provided participants with for the review session.

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[6] We provide all flashcards in the supplementary material (OSF repository [94]).

[7] Aiko (https://sindresorhus.com/aiko, accessed September 5, 2024) is a free AI-based transcription tool, which uses OpenAI's Whisper model and runs locally in order to protect data privacy.

edited them when necessary. We performed a qualitative content analysis [10] on these transcripts and the videos, as some interactions from participants were non-verbal (e.g., gesturing in front of the camera). We used a top-down approach involving 4 co-authors. We split the dataset (of videos and their transcripts) in 4 and started coding inductively using the MaxQDA (v24) software. After a first iteration, we discussed and compared our individual codebooks to identify themes and sub-themes in the data. After completing a comprehensive set of themes including all significant codes, 2 co-authors iterated once more on the dataset to assign them and verify their coherence and comprehensiveness (deductive coding).

7 Empirical Results: Communication Patterns, Actuator Placement and Creativity Support Index

This section presents all themes and sub-themes identified by the qualitative content analysis, discusses broadly the vibrotactile experiences produced by the 4 teams, and summarizes results of the CSI questionnaires filled out by participants in sessions 2, 3, and 4.

7.1 Qualitative Content Analysis

We found a total of 7 themes from our qualitative analysis, containing each from 4 to 10 sub-themes. We summarize all of them in a table in the supplementary material (OSF repository). We provide quotes to illustrate each entry and list identifying indices we use in the paper to refer to them. In the following, we describe each theme in a subsection and expose each of their sub-theme to provide a comprehensive view of our findings.

7.1.1 Designing and Reflecting on the Haptic Experience. Participants faced several challenges when harmonizing their intention to design in collaboration. They had to specify their goal such as the intention of the haptic experience; they designed to *simulate physical sensations* [RD6.1][8], *induce emotions* [RD6.2], or *convey abstract messages such as directions to follow* [RD6.3]. Sometimes they had to decide on and specify the *experience point-of-view* [RD3], because the video prompt could include multiple characters and give the choice to incarnate one or the other (*"I kind of just tried to imagine myself as like Mario and hopping" T3P1*). Participants often relied on the prompts to *provide the context of their experience* [RD4.2] (*"I think having the prompts [...] is quite important because if you're just talking about some speculative scenario [...] it's quite difficult to make the other person understand what you are trying to achieve." T2P1*) but also to *synchronize vibration patterns with the video* [RD4.1] (*"I will delete them because they are not in sync with the video" T3P2*) underlining the importance of visuo-haptic congruence. They also sometimes *performed physical motions* [RD5] to contextualize their experiences beyond the video prompts.

Regarding the participants' design intentions, they did *not always maximize goodness of feel but rather aimed at inducing negative emotions or feelings to match a prompt (e.g., create anxiety)* [RD2]. Lastly, *their expectations of a vibrotactile experience were at times significantly different from the actual physical experience* [RD1] (*"the neck and in the chest where some places which had completely different experience than I expected" T4P2*), pointing out the importance of low-fidelity prototyping to test ideas.

7.1.2 Placing and Identifying Actuators on the Skin. Once intentions were identified, the second step was often to place actuators on the skin to start designing the experience. This stage was time-consuming and required *detailed discussions to share and reproduce placements* [PIA1] (*"One was on my right thumb [...]. Two on the index finger [...]. Three on the ring finger [...]. And then four is at the base of the little finger" T2P2*), as well as specific *methods to validate that the placement was correct* [PIA3]. Without support, participants were sometimes missing such methods and ended up with discrepancies (*"do you have actuator four in the neck? [...] I think it's the other way around. So, four on the chest and three in the neck." Exp*) – we observed only *little impact on the design process overall* [PIA4] however (*"oh we have different placement but it kind of works [...] yeah it's symmetric it's a machine" T3P1*). To match actuators' placement, participants used *body landmarks as references* [PIA2] and identified actuators through *discussion* [PIA6.2], *by looking at them* [PIA6.3], by *actuating them* [PIA6.4], or by *looking at their positions on a 2D visualization* [PIA6.1] in sessions 4 (see Figure 8).

In general, beyond the experience's intention, the actuators' placement was influenced by the *sensitivity of the body parts* [PIA5], and *worn accessories on the skin* [PIA7] (*"it's also vibrating my glasses" T4P2*). We observed participants placing actuators on *unconventional body areas* [PIA9] for haptic experiences, such as the feet or the spine, compared to commercially available devices (e.g., haptic gloves [7, 47, 79] or vests [2, 8, 57]), and they sometimes *iterated on the placement* [PIA10] for the same experience. The placements they adopted were at times unpleasant or even hurtful: *attaching actuators with kinesio tape could be hurtful when removing them* [PIA8.2] (*"I also am not really willing to put a new piece of tape, especially on my legs." T4P2*), and some participants *would feel uncomfortable with some actuators on body parts that were too sensitive* [PIA8.1].

7.1.3 Conveying Intentions and Instructions through Multi-Sensory Communication. Participants leveraged the visual channel when discussing actuators' placements to *demonstrate the position of actuators on the body* [MC2.1] by showing them to the camera, by *pointing at their body* [MC2.3] to provide context to sentences spoken, or to *gesture a specific movement describing a vibrotactile pattern* [MC2.2].

The tactile channel was often dominant and would *induce strong, immediate reactions* [MC3.1] (*"oh wow, it's really strong *laughs*" T3P2*) when participants were not expecting stimulation, and easily become a *hindrance when using other senses to communicate* [MC3.3] (*"I just want to show... oh, are you playing something?" T3P1*). This led participants to *ask explicitly for consent before using this channel* [MC3.2] (*"Can I play already or...?" T4P2*).

Both the auditory and tactile channels were often used sequentially by participants to *substitute vibrations to words to convey their intention* [MC1] (*"Ah, so we can do like... *actuates actuators*" T4P1*).

7.1.4 Communication Means to Discuss and Reflect on the Experience. When discussing the haptic experiences, participants used means such as *metaphors* [CMDR2] (*"The vibration is very subtle that feels like the character is just a tiny like piece here jumping." T3P2*)

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[8] We use identification number of sub-themes from the complete list available in supplementary material (OSF repository [94]).

to convey their ideas, and often *referred to vibrations or actuators with high-level concepts* [CMDR3] such as objects or sensations (*"I really like the second cloud it's very soft but it's hard to control" T3P1*) to simplify the transmission of information and lower cognitive efforts. They sometimes preferred *using onomatopoeia* [CMDR1] to describe the feeling or the goal of vibrations, and tended to *ask verbally their partner to share their feelings and sensations* [CMDR4] to grasp their perception of the haptic experience.

7.1.5 Designing Vibration Patterns: Recording and Fine-Tuning. Participants enjoyed *trying out ideas in their own rooms before sharing them with a collaborator* [DVP1] (*"we have [...] more time to explore and maybe we [produce] different ideas than [when] exploring together" T3P1*). They designed vibrations with either a keyboard or a game controller, and using the latter *enabled more degrees-of-freedom to control parameters of vibrations* [DVP7] and led to more subtle control of their amplitude, but *required motor skills* [DVP6] to time vibrations and set the right levels of amplitudes in one go (*"it's hard, I have to practice to make this small" T3P2*). *Timing vibrations when recording* [DVP8] was often an issue to match specific design goals that *fine-tuning means* [DVP3] could solve to a certain degree (*"Let's shift it over here" T4P1*), as participants were missing more functionalities *to design experiences with finer details* [DVP2] (*"I kind of want to slice the haptic signals" T3P1*). They sometimes timed vibrations by *pressing buttons simultaneously or by using dedicated buttons for that (i.e., mapped to a group of actuators)* [DVP5]. Lastly, participants were missing *means to adapt the range of vibrations to their own sensitivity* [DVP4] (*"So even the lowest vibration was a bit too much for me" T2P2*).

7.1.6 Planning and Coordinating Collaborative Actions. To record vibration patterns efficiently, participants often *harmonized their intentions before recording* [PSC1] (*"I think you could [...] add the pushback from the Kärcher" T4P2 "Yeah, we can do that" T4P1*) and *assigned roles to themselves to perform categories of actions* (e.g., trigger the recording, play vibration patterns when recording) [PSC4.2] (*"I will click record and then you play" T3P2*). Concretely, participants often *asked for the collaborator's consent* [PSC3] to perform an action with significant impact on the collaborative space (*"I just play once. Is that okay?" T1P2*). They sometimes *shared initiative on actions by asking the partner to perform some actions and split the work load* [PSC4.1] (*"Do you want to be the person creating this time?" T3P1*, and used similar strategies when recording vibration patterns by *assigning actuators to collaborators* [PSC4.3] (*"one person can take charge of the soft movement and [...] I can take care of [the] jumping" T3P1*). They used *means to time their actions* [PSC2] like counting down verbally before pressing record or overdub buttons, which was sometimes unnecessary (recording would start on the first actuation action), but sometimes a compromise to software flaws (overdub would start right away).

7.1.7 Context Awareness while Performing Collaborative Actions. Despite using means to coordinate actions, participants often faced caveats, either introduced by the software or by the nature of the collaborative task. Participants did not seem to always *grasp the impact of their actions on the collaborative space* [CA3] (*"Ah, ah, what's happening? That was not my intention. *recording patterns when overdubbing*" T2P2*), and felt the *need to report their actions* [CA2] to the collaborator at times to likely prepare them about the results of these actions (e.g., moving a vibration pattern in time). We observed several situations in which a participant was *not aware of their partner's actions or situation* [CA1] and could be surprised (*"Are you on it now?" T2P2 "No, wait a second." T2P1*). Isolating oneself in an empty room proved useful to *avoid disturbing a collaborator* [CA4] but sometimes led to a lack of awareness of the collaborator's interaction with the system.

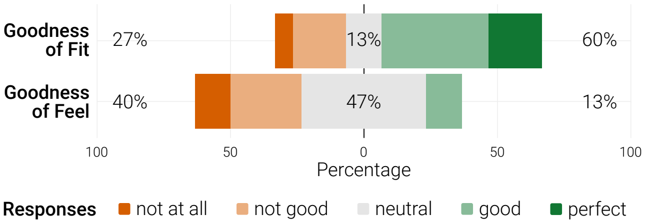

Figure 9: Team ratings of *Goodness of Fit* and *Goodness of Feel for all* experiences reviewed in session 4.

7.2 Reviewing Vibrotactile Experiences

7.2.1 Goodness of Fit and Feel. Across all teams, 15 vibrotactile experiences were reviewed, corresponding to 15 team ratings (Figure 9). In the majority (n=9, 60%) of 15 *Goodness of Fit* ratings participants indicated a good or perfect fit (Mdn=4, IQR=1.50), whereas four ratings (27%) indicated that the experience did not fit well or not at all. For the *Goodness of Feel*, only two experiences (13%) were evaluated as feeling good, and six (40%) were evaluated negatively, with almost half of the patterns (n=7, 47%) being neutral (Mdn=3, IQR=1.00).

7.2.2 Actuators Placements on the Body. Figure 10 depicts the 37 different actuator placements used by participants in the study. Teams used between 7 and 12 placements (Mdn=9) across all four sessions. As observed in previous work [95], participants tend to use many different areas of their bodies to place actuators, with higher frequencies on hands. While some placements could easily be demonstrated to the collaborator (e.g., showing the forearm to the camera), others led to restrictions in the available communication channels. For instance, placing actuators on the feet or on the back of the shoulder required participants to raise their legs or turn around to show the actuators to the camera, or default to describing the placement with words (*"maybe we do like top of the foot, like [...] left and right. Argh... I don't know how to contort my body to show that into the camera" T2P1*, see Figure 1 Ⓒ). Furthermore, a team decided to adapt the location of certain actuators when reviewing experiences for personal reasons (e.g., not wanting to remove their shoes: *"I'm not really ready to [...] to get out of my shoes" T4P2*), demonstrating the importance to test experiences with several people in various contexts.

7.3 Reviewing *CollabJam*'s Creativity Support Index

We present a summary of all results to the CSI questionnaires filled out by participants in sessions 2, 3, and 4 in Table 2. To facilitate interpretation of the CSI scores, Cherry and Latulipe [14] mapped

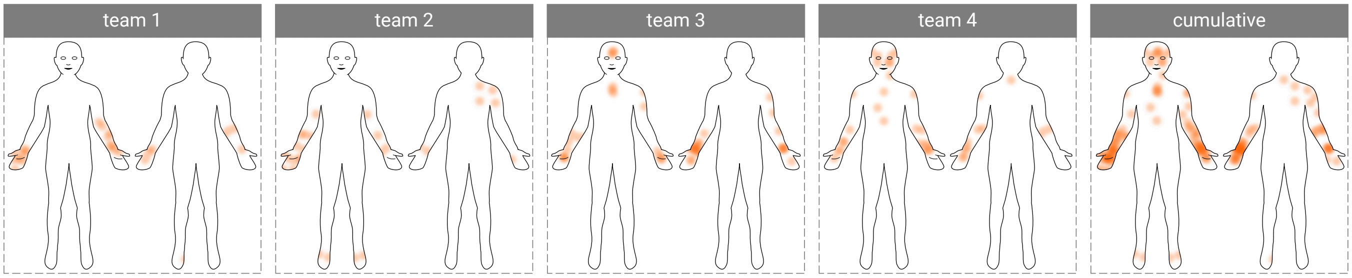

Figure 10: Visualization of actuator placements used during the study; for each team and cumulative (n=37). A colored circle corresponds to an actuator, and circles can overlap, creating more opaque areas.

Table 2: Summary of CSI results for the 3 last sessions.

Scale	**Factor Counts**	**Factor Score**	**Weighted Factor Score**
Measure	M (SD)	M (SD)	M (SD)
Results Worth Effort	2.25 (1.42)	16.00 (3.12)	37.04 (24.30)
Exploration	3.75 (1.19)	15.83 (2.93)	59.46 (22.47)
Collaboration	3.29 (1.43)	16.46 (2.92)	54.75 (26.92)
Immersion	0.83 (0.96)	11.54 (5.36)	10.71 (13.24)
Expressiveness	3.33 (1.09)	14.67 (3.29)	48.13 (18.88)
Enjoyment	1.54 (1.18)	16.46 (2.83)	25.83 (22.58)

them to educational grading systems. Specifically, scores above 90 are assigned an "A" grade, denoting exceptional support for creative work, while scores below 50 receive an "F", indicating inadequate support. Overall, the participants in our study generated an average CSI score of 78.64 (SD=11.90) corresponding to the upper bound of a "C" grade, indicating an acceptable support from *CollabJam* to design vibrotactile experiences collaboratively.

Participants seemed neutral about producing significant results at the cost of efforts using *CollabJam* (Factor Count=2.25, Factor Score=16.00, Weighted Factor Score=37.04), but did not feel the need to be immersed in the creative task to produce vibrotactile experiences (FC=0.83, FS=11.54, WFS=10.71) nor to enjoy doing it (FC=1.54, FS=16.46, WFS=25.83). We observed mixed results on that aspects: some participants really enjoyed designing with *CollabJam* (*"Oh, it was a very nice experience. I kind of don't want to send the stuff back because it's fun to [...] play with it." T2P1* in session 4), while others did not seem interested about vibrotactile stimulation overall (*"I'm not sure if I'm ever going to be really excited about vibrating motors on my body" T2P2* in session 4).

Exploration, *collaboration* and *expressiveness* seemed, on the contrary, to be the focus of participants using *CollabJam*. We calculated respective factor counts of 3.75, 3.29, 3.33 and factor scores of 15.83, 16.46, and 14.67. Their respective weighted factor scores (59.46, 54.75, 48.13) indicate a strong emphasis of participants for these three creativity factors when designing vibrotactile experiences collaboratively, echoing results from the literature for similar design tools [50].

8 Discussion and Design Implications

We discuss insights from the themes produced with our qualitative analysis. We reflect on the solutions implemented in *CollabJam* based on the design considerations in section 3, and evaluate the support they provided participants in completing their tasks, and outline their intrinsic limitations. From our observations, we draw design implications dedicated to the collaborative prototyping of vibrotactile experiences, with a focus on future software implementations.

8.1 *CollabJam* Supports Designing Vibrotactile Patterns Collaboratively and Synchronously

Our user study focused on two aspects: identifying communication and design patterns used by remote collaborators, and evaluating how *CollabJam's* functionalities support designers in their tasks. Empirical results indicate that *CollabJam* supported designers to produce many different experiences over 4 sessions. Participants' answers to the CSI questionnaire demonstrate high scores for *exploration*, *collaboration*, and *expressiveness*, three essential aspects to collaborative design and low-fidelity prototyping. Participants managed to produce at least one vibration pattern for 37 actuator layouts over the course of 4 hours, including time dedicated to learning how to use *CollabJam* and reviewing others' designs (Figure 10). Lastly, we observed participants switching roles to record and manipulate vibration blocks to fine-tune the experiences with ease.

In general, *CollabJam* was well received and supported designers in their tasks to design remotely with a collaborator by sharing controls over actuators. One participant explicitly expressed their interest in the prototype saying *"it was a very nice experience. I kind of don't want to send the stuff [back]" T2P1. CollabJam* only provides control over the sense of touch, however, while most of the conversations between collaborators necessitated visual and auditory communications. While we used the Zoom video-conferencing tool to allow unrestricted communication in the study, future versions could integrate video and audio streaming to fully support collaboration, for instance based on suggestion by Hu et al. [34]. Integrating such features would also enable addressing potential privacy concerns [92, 96] in a multi-sensory context.

We focused this work on live, remote collaboration, a context that tools like CoTacs [50] or TactJam [95] partially support. Two novel features provided by *CollabJam* were particularly exploited by participants in this context, namely its multi-actuator design (Figure 10) (as compared to CoTacs) and the hands-on synchronous jamming functionalities (as compared to TactJam), both to test ideas before recording them and explaining their intentions through vibrotactile messages. We, nevertheless, did not compare our approach to the literature, e.g., parameterized single- or composite-actuator haptic experiences (e.g., [50]) and hands-on multi-actuator vibrotactile experiences (e.g., [95]). We encourage further studies to compare them and better highlight their drawbacks and benefits.

8.2 Controlling the Reach of Tactile Stimulation Without Isolating Oneself

Informed by **DC2**, we implemented *virtual rooms* in *CollabJam* to confine vibrotactile patterns to a specific space. This enabled participants to design individually when needed, but also to feel vibrations synchronously with others when collaborating. We implemented a "muting" feature that allowed users to quiet incoming vibrations when needed, similar to muting audio of an online collaborator in the case of background noises. We did not observe the latter being used, however, and only a single participant joined a room to design alone without being instructed to by experimenters. While expected to, these features did not prevent them from being surprised by unexpected incoming vibrations (*"I think that can work quite well. *collaborator plays vibration* Ah! Wait, wait, wait. No. Ah!" T4P2*). As a compromise, participants seemed to prefer asking directly for consent before playing vibrations to avoid disturbing their collaborator (*"I need to play again. Sorry" T2P2*).

These observations helped identify two major limitations of the system. First, jumping in an empty room would cut tactile connections with the collaborator when participants often wanted to only experiment ideas quickly. Second, our system only enabled duplicating entire vibrotactile experiences and did not facilitate sharing only parts of them, e.g., by only copy/pasting a few vibration blocks that are essential "soft features" among redo/undo [71, p. 207].

Implication 1: The system needs to implement a quick-to-access mode to design and record experiences without "loosing touch" with the collaborators. Like a "push-to-talk" feature on a video conferencing tool, participants needed a mode or truly private virtual rooms to isolate themselves from their collaborator to try ideas out without muting them and losing the design context and their tactile link to their remote collaborators.

Implication 2: The system should facilitate re-using vibrotactile patterns from various experiences without recording them again. Enabling fine-tuning of individual vibration blocks (defined by their timing, duration, and intensity) proved very useful as participants heavily relied on it in the study. *CollabJam* lacked, however, the possibility to copy or move specific vibration blocks across recorded experiences to only retain part of them. If such groups of blocks are differentiable and ideally identifiable, they represent so-called *haptic phonemes* that can be re-used and arranged as basic building blocks of *haptic words* (what we referred to as vibrotactile patterns in this paper) [19]. Thus, design tools should consider haptic phonemes to be re-used anywhere, similarly to audio samples or MIDI messages in Digital Audio Workstations, an approach adopted by a few already [28, 38, 66, 85].

8.3 Synchronous Multi-Sensory Communication is Essential to Convey Design Intentions

A major goal with *CollabJam* was to support synchronous tactile communication (**DC1**). Participants leveraged multiple times this feature to communicate their design intentions (*"Ah, so we can do like... *actuates*" T4P1*, *"We could start like this and then it goes... *actuates*" T1P1*). They also heavily used their voice to speak or use onomatopoeia to reproduce vibration sounds, or create or refer to the sound of a physical experience (e.g., swallowing) (*"I'm having a really quick dip, dip, dip, interesting, I'm drinking that fast" T2P2*). When missing words or to contextualize the information they wanted to convey, they gestured in front of their camera or pointed at positions on their body (e.g., to reference actuators), sometimes asking visual attention from their collaborator (*"I would put it maybe on the palms [...] look into Zoom." T4P2*). Overall, participants heavily relied on several senses, sometimes using them conjointly. While we focused mostly on the tactile sense with *CollabJam*, these observations reveal that all senses are useful in the collaboration process.

Implication 3: The system should not impede communicating with several senses, and ideally include means to communicate vocally and visually with a distant collaborator. We used a video conferencing tool beside *CollabJam* in the study to enable remote communication. Participants could communicate vocally continuously but required at times visual attention from their partners, which implied switching between applications. To facilitate this, the system could, for instance, provide modes to switch between communication and design stages to support collaborators talking face-to-face when ideating (e.g., enlarging the video streams), and focus on the vibration patterns when recording them (e.g., reducing the video streams in a corner of the window).

8.4 Freedom in Placing Actuators creates a Trade-off between Creative Exploration and Reproduction

We designed *CollabJam* to foster creativity with minimal constraints to designers. Therefore, we made actuators independent and easily attachable to the skin with, e.g., using Kinesio tape, to allow designers to explore actuation on any part of their bodies (**DC3**, **DC4**). Participants leveraged these benefits by placing actuators mostly on their upper body (forearms and shoulders) and sometimes on their feet, neck, or rib cage (Figure 10). We provide two interpretations for the focus on the upper body. Firstly, participants were mostly sitting during the sessions, which was not an instruction but may have influenced their choices to use their lower body less. Secondly, beyond participants' sensitivities which informed their choices of body areas to actuate, they did not always feel comfortable with some areas because of the social context; e.g., one participant remarked they would not remove their shoes because the weather was hot (*"we have never done anything on the feet and I'm not really ready to [...] expose my feet" T4P2*).

Placing actuators revealed itself to be tedious on the other hand. For example, communicating locations of actuators required detailed vocabularies and instructions. Despite the presence of identification numbers on individual actuators, specific body locations, such as the forehead or the back of the shoulder, would render them inaccessible for identification. Furthermore, participants tended to use higher-level concepts to refer to actuators during collaboration, e.g., by referencing them using body landmarks or the sensations they simulated. Additionally, we noticed *CollabJam* was lacking support to mediate actuator placement, as framed by one participant: *"if you had [...] the human body so you can like draw circles [...] you don't have to like do this in the camera especially when it concerns feet or like lower extremities" T2P1*. Similar to previous work [95], one participant hinted that using a dynamic visualization of actuators' placement would help to keep track of their positions, and eventually assist in controlling them: *"it's difficult to remember in which part of the body you place certain [actuators]. So it would be great if in the interface you can have like a body, and then you can add little dots to remind you where it was" T3P2*). Validating a placement was an important part of this process, but participants did not always succeed in this task.

Implication 4: The system should support participants when communicating about and reproducing actuators' placements, and ideally provide means to validate them. An ideal scenario would involve automatic identification and localization of actuators on the skin. Without that, the system should provide means to mediate where actuators are placed and how to support users in communicating such information. While previous work proposed to visualize a 3D avatar to place actuators on [95], such solutions remain to be evaluated in collaborative design contexts to assess benefits and limitations (e.g., disruption of the design process). Furthermore, integrating a 3D avatar into design tools, where actuator positions are synced across clients in real-time, would mitigate potential privacy issues associated with video calls [96] by enabling expressive communication without exposing personal visual or environmental details [92].

8.5 Vibrotactile Experiences can Generate Discomforting Feelings

As noted from our study, there are differences between predicting how vibrotactile experiences might feel and the sensations they elicit [95]: *"in the neck and in the chest where some places which had completely different experience than I expected" T4P2*), *"I didn't expect that placing the [actuator] here *pointing on the chest* give me like anxiety feelings, but it actually did" T3P2*). While some experiences were intended to create uneasy feelings, they also resulted in lower goodness-of-feel ratings (*"Ah! It feels awful [...] the forehead [actuator] is brutal" T2P1*). Regardless of the valence of the designer's intent, experiences could be perceived too strongly, depending on the body parts actuated and the body sensitivity. This was specifically noted by one participant when stating *"I think in general, what we now tried and experienced really shines the light on how everyone perceives haptics differently. So it would be nice to have the possibility to make some adjustments. For example, the intensity level would be the first that I would have adjusted to make it more comfortable" T1P1.*

Implication 5: The system should provide means to adjust vibrotactile patterns parameters based on participants sensitivities without altering the nature of vibrotactile experiences. Several solutions can be implemented to adapt an experience to one's sensitivity, such as linearly normalizing amplitudes, capping peaks of amplitude to a certain amount, etc. The primary challenge in this case is to not alter the nature of the experience with these adjustments; if an experience was designed to be disturbing, tweaking its parameters to make it soothing would create a new experience.

9 Conclusion

We investigated synchronous collaborative design of vibrotactile experiences in remote scenarios with a prototyping suite called *CollabJam*. We designed it with an iterative process that led to the formulation of design considerations informing the design of software dedicated to low-fidelity prototyping of haptic experiences. We performed a technical evaluation to assess the system latency, and later used it in an empirical user study involving 4 pairs of designers over 4 sessions. Using a qualitative content analysis on the videos and their transcripts, we identified several themes on communication and design patterns. We reflected on these themes and proposed a list of design implications as guidelines for future prototyping systems.

This work highlights many different challenges for collaborative haptic experience design that an interactive system cannot overcome alone. It emphasizes that developing low-fidelity systems for haptic design remains challenging, is not cost-free, and implies making important choices that will impact the design process. Design considerations and implications we propose try to encompass various aspects of such design processes and may expand to other types of experiences than just vibrotactile. Therefore, we encourage future work to investigate other types of prototyping tools following these guidelines to challenge them.

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A Input Mappings

Figure 11 shows two examples of input mapping for keyboards and gamepads to control actuation of the tactile display. For instance, pressing keys between 1 and 4 on the keyboard triggers one of the four actuators at the maximum amplitude. The rows below are associated to lower amplitudes (i.e., 80%, 60%, 40%), or combine actuation of multiple actuators. Furthermore, we provide mappings to actuate pairs of actuators or all of them with the press of a single button. Similarly, for gamepads we mapped buttons to single or multiple actuators. Additionally, we utilized the gamepad's pressure sensitive triggers to enable dynamic intensity control (left trigger) or cycle through actuators to create spatial animations (right trigger). The left trigger can be also used in combination with the left shoulder button to select and lock an intensity level. Once the intensity is locked, users can simply use the d-pad buttons to play the vibrotactile pattern at the selected intensity. The intensity level can be unlocked again by pressing the left trigger.

B Data Structures and Data Handling

B.1 Representation of Vibrotactile Patterns

The communication between the client and server are based on JSON-like formatted messages. For instance, to control the actuation of the tactile displays, we implemented the `setParameter` instruction, which specifies the channels (actuators) to address as well as their intensity (range: 0.0—1.0). This instruction can also specify the frequency. However, for the sake of simplicity and because of the LRAs we used, which have a narrow frequency spectrum, we did not provide this feature in the current version of the client application. Listing 1 shows how these instructions are compiled into a persistent format stored in the database for playback. While recording these instructions, the server adds `wait` instructions to represent pauses in the vibrotactile pattern.

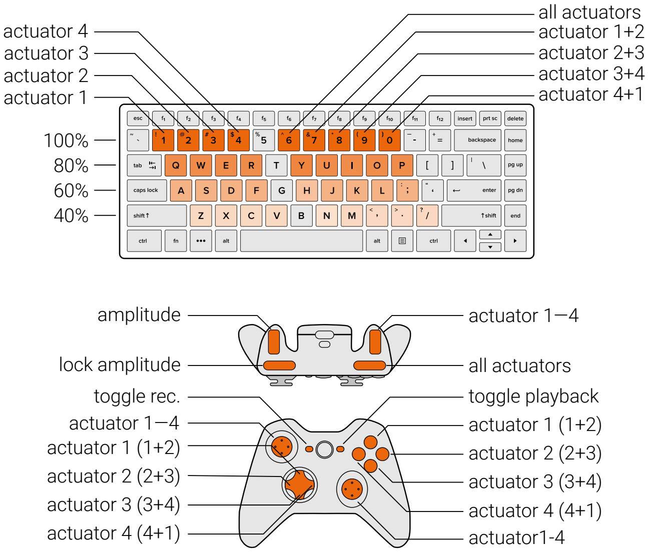

Figure 11: Detailed input mappings for keyboards (top) and gamepads (bottom).

```
{"instructions":[
  {"setParameter":{"channels":[0],"intensity":1}},
  {"wait":{"milliseconds":200}},
  {"setParameter":{"channels":[0],"intensity":0}},
  {"wait":{"milliseconds":400}},
  {"setParameter":{"channels":[0,1,2,3],"intensity":0.5}},
  {"wait":{"milliseconds":400}},
  {"setParameter":{"channels":[0,1,2,3],"intensity":0}}
]}
```

Listing 1: Example of the JSON file structure of vibrotactile experiences stored in the *CollabJam* database. It's a one-second pattern consisting of two buzzes, i.e. 200 ms buzz on one actuator at maximum intensity and 400 ms buzz on all actuators at 50% intensity, and a 400 ms pause inbetween.

B.2 BLE Characteristics

We implemented a custom BLE service that the tactile display provides. This service includes six characteristics, of which four provide details about the tactile display (read only) and two are used to transfer application data, i.e. modifications of the amplitude or frequency on a per-channel basis (Table 3). As the current version of *CollabJam*'s client application does not implement an interaction scheme to dynamically modify the actuators' frequency while designing vibrotactile experiences, we only utilized the amplitude command buffer (*C5*) for this study.

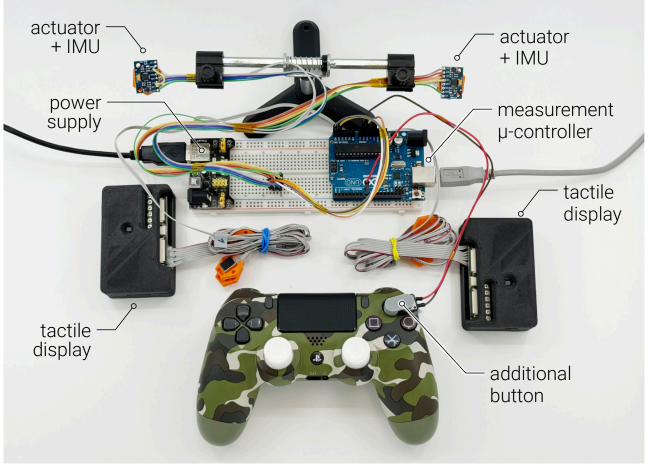

Figure 12: Hardware setup used to take latency measurements.

Table 3: BLE characteristics.

ID	Characteristic	Description	Data Type	Access
C1	Number of actuators	GATT clients can read the number of output channels of the tactile display.	`uint32`	Read
C2	Amplitude modification enabled	GATT clients can read, if the amplitude can be changed (1) or not (0). Each bit represents one channel (max. 32 channels, LSB = channel 1).	`uint32`	Read
C3	Frequency modification enabled	GATT clients can read, if the amplitude can be changed (1) or not (0). Each bit represents one channel (max. 32 channels, LSB = channel 1).	`uint32`	Read
C4	Available frequency range	GATT clients can read the min., max., and resonance frequency of the actuators (in Hz) which are connected to the tactile display, e.g. `{10,300,150}`. Note, all actuators have the same specifications.	`struct`	Read
C5	Amplitude command buffer	GATT clients can set the amplitude for all channels on a per-channel basis (8-bit values). For instance, `{254,0,0,255}` sets channel 1 to its maximum amplitude, channel 2 and 3 are turned off, and channel 4 remains at its current amplitude (indicated by 255).	`struct`	Write
C6	Frequency command buffer	GATT clients can set the frequency for all channels on a per-channel basis (16-bit values). For instance, `{300,10,10,0}` sets channel 1 to its maximum frequency, channel 2 and 3 to its minimum frequency (see *C4*), and channel 4 remains at its current frequency (indicated by 0).	`struct`	Write

C Technical Evaluation Setup

The hardware setup illustrated in Figure 12 was used for measuring latency (see section 5). It consists of a gamepad, two tactile displays of which a single actuator was under test, and a measurement microcontroller (an Arduino Uno), which processes input (i.e., button press) and output signals (i.e., actuation). Each of the two actuators under test was paired with an accelerometer (MPU-6050) to detect the actuation. A separate additional button mounted on a gamepad was used to provide input signals. The gamepad as well as the two tactile displays were connected to the client software via Bluetooth Low Energy.