Connected Material Experiences using Bimanual Vibrotactile Crosstalk in Virtual Reality

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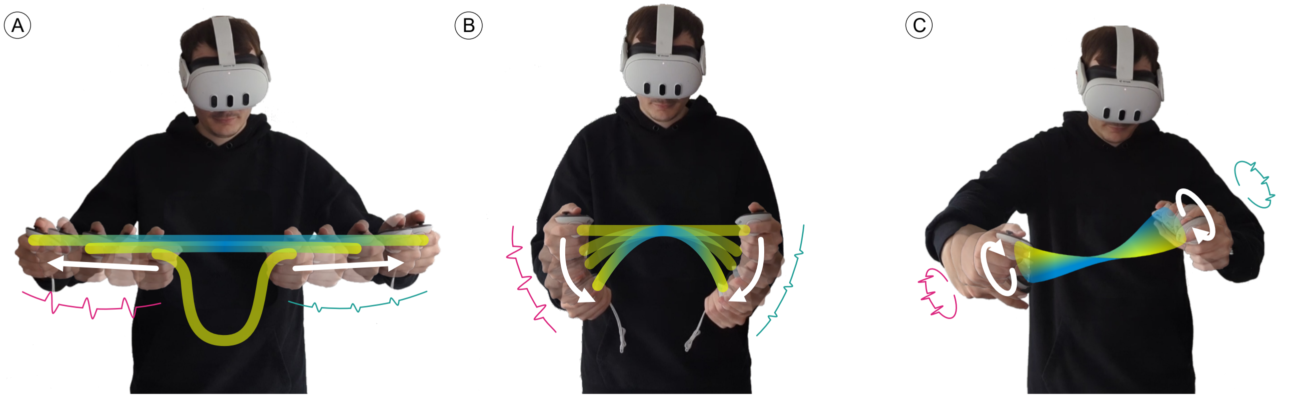

Figure 1: We present a bimanual motion-coupled vibration algorithm capable of creating connected material experiences between two hands. By modulating the parameters of vibrations between the hands, our algorithm can induce material properties of elasticity while stretching Ⓐ, flexibility while bending Ⓑ and torsion while twisting Ⓒ.

Abstract

Perceiving material properties such as elasticity, flexibility, and torsion is inherently bimanual, as we rely on the relative motion of our hands to form a unified sense of materiality. Yet, most vibrotactile material rendering approaches are limited to a single hand or finger. While prior work has explored bimanual haptic interfaces, most depend on specialized hardware for specific interactions. In this paper, we demonstrate design strategies to support bimanual material exploration through motion-coupled vibrotactile feedback. Our technique introduces variable crosstalk between the controllers' vibration to evoke connectedness, making two unconnected devices feel as though they manipulate a single object. The technique generalizes motion-coupled feedback approaches beyond previous single-point explorations. Through two user studies, we show that this approach (1) significantly enhances perceived connectedness and (2) conveys distinct material qualities such as elasticity and torsion. Finally, we present *Dvihastīya*, an authoring tool for designing connected bimanual experiences in virtual reality.

CCS Concepts

• **Human-centered computing** → **User studies**; *Haptic devices*; Virtual reality.

Keywords

bimanual vibrotactile feedback, virtual reality, material perception, motion-coupled vibrations, Consumer VR

CHI '26, Barcelona, Spain

ACM ISBN 979-8-4007-2278-3/2026/04
https://doi.org/10.1145/3772318.3790767

ACM Reference Format:
Nihar Sabnis, André Zenner, Erik Peralta Løvaas, Marco Weiss, Andrea Bianchi, and Paul Strohmeier. 2026. Connected Material Experiences using Bimanual Vibrotactile Crosstalk in Virtual Reality. In *Proceedings of the 2026 CHI Conference on Human Factors in Computing Systems (CHI '26), April 13–17, 2026, Barcelona, Spain.* ACM, New York, NY, USA, 20 pages. https://doi.org/10.1145/3772318.3790767

1 Introduction

During everyday interactions, properties of physical objects, such as their material stiffness, elasticity, and torsion, are typically perceived with both hands performing coordinated manipulations. For example, when twisting a bottle cap, stretching an elastic band, or bending a pool noodle, we perceive connected haptic cues from both hands as they perform orchestrated movements to achieve a shared goal [59]. These interactions are bimanual by nature, as people rely on the relative motion and forces between their hands to probe, compare, and integrate information into a unified sense of an object and its materiality [19]. Research on bimanual interactions shows that our hands do not simply duplicate single-handed movements, but rather involve intricate coordination and tight action-feedback coupling between the hands [42, 50]. Forces or torques on one hand are transmitted as counter-forces to the other hand, offering richer haptic feedback about the object being manipulated [59]. Translating these everyday bimanual object interactions into Virtual Reality (VR) is a core goal of HCI: these interactions in VR must align with real-world expectations to deliver experiences that feel natural and intuitive.

To this end, research has presented various techniques, ranging from special-purpose, hardware-based VR controllers that can provide force feedback [10, 68] to modified commercial VR controllers [51, 60] that aim to simulate the haptic presence and properties of virtual objects. One notable example that refrains from using force-feedback is *PseudoBend* [21], demonstrating a design using vibrotactile feedback that induces bimanual material experiences of stretching, bending, and twisting. Besides *PseudoBend*, only a few previous works have tried to address this gap, and the proposed solutions depend on specialized and custom-designed hardware [45, 53], which mechanically connects controllers or uses body-grounded force feedback devices restricting accessibility [43]. These techniques often depend on custom, specialized hardware with added mechanical degrees of freedom, lack generalization across object sizes, thus restricting the expressive potential of free-hand bimanual interaction, and remain inaccessible for widespread adoption in VR.

On the other hand, vibrotactile feedback is non-grounded, easier to reproduce than custom hardware, and has shown to induce a stronger sense of presence than vision alone [11, 15]. Motion-coupled vibration, a technique where vibrations are synchronized with user action, is capable of inducing material sensations like compliance, texture, and deformation [48]. For instance, vibrations coupled with the pressure applied by a user on rigid objects has shown to induce virtual compliance [28] and vibrations coupled to users' movement over smooth sliders have shown to generate virtual textures on the slider [1, 57]. Yet, most prior work using motion-coupled vibration to render material experiences has only been limited to a single hand [15, 30] or even a single finger [28, 48, 62]. This overlooks how we typically explore material properties, i.e., with both hands, leading to a mismatch between the feedback provided by VR systems and user expectations shaped by real-world experiences. This raises the question addressed in this paper: ***Can motion-coupled vibrations applied to two hands create a sense of connectedness, making users feel like they are exploring a single shared object?***

To address this question, we designed a novel technique aiming to induce a coherent perception of interacting with a single, shared virtual object or material property using both hands, (see Figure 1). Using a motion-coupled vibrotactile rendering approach applied individually to each hand, we create a sense of unison by applying varying levels of crosstalk between the left and right-hand vibration signals, affecting parameters like amplitude, frequency, vibrotactile pulse occurrences (grains), and delay. Through a psychophysical study, we show that this approach can successfully evoke the feeling of connectedness and convey material properties, like elasticity, flexibility, and rigidity. Further, building on the psychophysics study, we conducted a second study to probe the qualitative material and experiential associations induced by different types of crosstalk. Finally, we introduce *Dvihastīya*, a low-level authoring tool that allows users to modulate parameters to design bimanual material experiences for VR. With Dvihastīya, we collected initial user impressions, showcasing the utility and practical value of our novel bimanual vibrotactile rendering approach.

> **Contribution Statement.** Our contribution is threefold: First, we present a technique of designing motion-coupled vibrotactile feedback with tunable crosstalk between hands as a novel approach to induce bimanual material experiences of a single, connected virtual object. Second, through psychophysical and qualitative studies, we provide empirical insights into how crosstalk in amplitude, frequency, grains, and delay influences perceptions of connectedness, material properties, and object structure. Finally, we developed *Dvihastīya*, an authoring tool for creating immersive bimanual material experiences in VR and collected user impressions, highlighting the expressive potential of our approach for natural, intuitive, and accessible bimanual virtual interactions.

2 Related Work

Research on the role of haptic feedback in bimanual interaction dates back to the late 20th century [9, 17, 19, 27]. More recently, work in virtual reality has focused on designing and evaluating bimanual haptic feedback techniques, typically through custom hardware. Vibrotactile feedback, where the vibrotactile stimuli are coupled to user action, shows promise to render material experiences; however, these methods have primarily been limited to feet, hands, or fingertips and have not been explored for inducing bimanual material experiences.

2.1 Bimanual Material Perception

When humans explore materials, they often use bimanual [19], bi-fingeral, or bi-digital gestures [58] typically involving an anchor (support) and a probe (movement, force) point. Crucially, when both hands engage with a single object, the sensory signals are not perceived in isolation, but are integrated into a *unified percept of that object's material properties like elasticity, flexibility, and torsion.* Guiard's kinematic chain model [19] established how humans use both hands together to explore materials bimanually, and remains a primary framework validated in motor control [12, 22, 61] and applied in haptic interface design [59].

Bimanual haptic perception also has several advantages over unimanual exploration, such as the ability to locate our hands with respect to each other even in the absence of visual feedback [59]. Several studies indicated that it is easier to follow the relative position between the hands rather than their individual position in 3D space [4, 22, 23, 63]. This proprioceptive capability proves particularly valuable when visual feedback is absent, inconsistent, or incomplete [4, 63]. Moreover, bimanual exploration enhances stiffness discrimination compared to unimanual exploration, with the combined percept aligning with optimal cue integration models [42]. Similarly, studies have shown that exploring curvature with two hands can reduce discrimination thresholds relative to one-handed touch [38] and symmetric shapes are perceived more accurately with two-handed exploration than with a single hand [5]. For bimanual feedback, studies have shown proprioceptive illusions in one arm induce a measurable motor influence on the other arm [7].

These findings motivate the use of two-handed haptic feedback in VR systems. In particular, providing congruent vibrotactile cues to both hands can exploit the brain's optimal integration strategies, potentially increasing sensitivity and realism [42]. In VR, where visual cues may be incomplete or delayed, reinforcing object properties through bimanual haptics builds on these natural strategies. *This makes rendering material properties such as stretching, bending, and twisting through bimanual haptic feedback especially important, since objects like elastic bands, rods, or wires are most naturally explored with both hands—offering inspiration for designing bimanual material interactions in VR.*

2.2 Motion Coupled Vibrations to Render Material Experiences

Vibration contributes to shaping tactile experiences based on how our tactile receptors respond to different vibration frequencies [26]. Moreover, vibration also helps us distinguish between material and textural properties due to the differences in their frequency spectrum [6, 65]. Using this as the foundation, research has presented prototypes that provide vibrotactile pulses synchronized with user action to induce material experiences during the interaction [48, 49]. For instance, studies by Romano and Kuchenbecker [44] demonstrated that users experience textures on smooth surfaces by rendering vibrotactile pulses proportional to users' movement. Providing vibrotactile pulses at fixed intervals of user movement successfully simulates texture experiences in air [55] and on smooth sliders [1, 48, 57]. Similarly, for isometric actions like applying pressure on objects, vibrotactile cues, coupled to changes in exerted pressure by the user, can induce experiences of compliance (and deformation) [28, 62, 66], even for objects having an inherent base compliance [36]. Furthermore, Ding et al. [15] showed that discrete vibration pulses coupled to user force can create an illusion of movement for the user, even in the absence of motion. Changes in tangential force applied by the user have also been leveraged to create a haptic illusion of compliance [20]. Lee et al. [30] demonstrated that vibrotactile feedback coupled with holding, squeezing, and sliding of fingers can generate experiences of textures and compliance, which helps in precisely manipulating objects in VR.

However, most of the motion-coupled vibration methods of creating material experiences are either limited to single-handed interactions [48, 57] or even single-finger interactions [62]. *Building on this foundation, we present algorithms to render bimanual motion-coupled vibrotactile feedback with variable crosstalk to induce a sensation of connectedness and materiality, thus going beyond the single-point rendering of material experiences with motion-coupled vibrations.*

2.3 Bimanual Haptic Feedback in Virtual Reality

Bimanual interaction is central to haptic perception, and many VR systems have explored how to deliver such feedback. Solutions span the active–passive haptics continuum [24, 31], from grounded force-feedback devices [13] to prop-based systems [31, 37, 52], often combined with visual–haptic illusions such as hand redirection [3, 18, 29, 69]. While effective, grounded and prop-based setups face limitations in weight, inertia, and constrained motion, hindering widespread adoption. To address these constraints, researchers have explored ungrounded controllers closer to consumer VR devices. Strasnick et al. [54] introduced *Haptic Links*, where actuated physical connections between two handheld VR controllers varied perceived bimanual stiffness. While effective for rendering interactions, such link-based solutions are limited by added weight and inertia [68] or by constrained ranges of motion [54].

Overcoming these challenges, Ryu et al. [45] presented *GamesBond*, consisting of two ungrounded, non-connected handheld VR controllers rendering the haptic impression of bimanually interacting with a single, deformable virtual object. Similarly, *Hand-to-hand* by Pittera et al. [41], used apparent tactile motion illusions to elicit an experience of passing a ball between hands in VR. *Invisibow* by Yi et al. [67] used vibrotactile illusions of pseudo forces and tendon vibration to simulate an immersive bow-arrow experience in VR. Yet, most of these works overlooked the importance of material rendering through bimanual interactions. *PseudoBend* is a prime example of using bimanual interaction to generate vibrations coupled to differential changes in force and torque applied by the user using both hands to create material experiences of bending, twisting, and stretching [21]. However, *PseudoBend* fixes the distance between hands, assumes all objects are the same size, needs a physical link between the user's hands, and does not support isotonic actions or interactions requiring independent hand movement. These constraints limit its use for other bimanual interactions that require attenuation or magnification of vibrotactile feedback on one hand (e.g., bending a pool noodle with one hand while holding with another; the bending hand would be expected to receive more feedback) or when decoupling is required between the two hands. Our approach is complementary: we focus on creating a sense of connectedness using standard, unconnected VR controllers, enabling flexible and accessible material experiences without constraining hand motion or interaction styles.

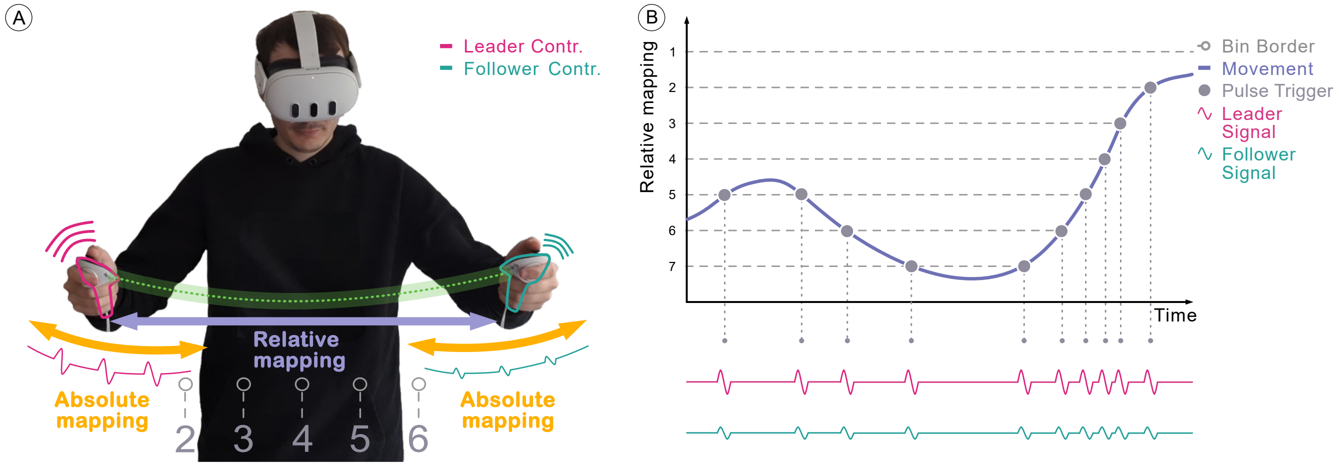

Figure 2: Relative and absolute mapping-Ⓐ: relative mapping triggers vibrotactile pulses synchronously on both hands based on the distance between two controllers, while absolute mapping tracks individual controllers and triggers vibrotactile pulses independently on each hand. The bimanual motion-coupled vibration algorithm-Ⓑ samples these distances to render vibrotactile pulses on both hands at sensor thresholds, with pulse density synchronized to movement and modulated by crosstalk.

As an alternative to existing methods, we address how to render bimanual haptic sensations in VR with only the vibrotactile cues of standard consumer hardware, asking whether two unconnected controllers can convey the unity of a single virtual object. Using commercial controllers with tunable crosstalk adds practical value and brings bimanual material experience rendering closer to real, deployable VR implementations.

3 Bimanual Motion-Coupled Vibration

Motion-coupled vibration, where vibrations are synchronized with user action, has shown to induce material experiences [20, 28, 44]. However, motion-coupled vibrations have been limited to single-handed or single-finger explorations and have not been explored for bimanual interactions where the hands are not physically connected through an object. In the following, we propose to transfer the concept of motion-coupled vibration to the bimanual case. For this, our technique computes for each hand the vibrational pulses triggered by that hand's movement through space. To achieve the feeling of connectedness, the technique further computes how this vibrational signal is to affect the other hand (a concept we call crosstalk), varying, for example, the amplitude, frequency, and timing of the vibrational pulses as they "travel" to the other hand. With this approach we aim to convey the feeling of interacting with a single connected object that can consist, for example, of different types of materials or geometries.

3.1 Algorithmic Approach to Bimanual Motion-Coupled Vibrations

For rendering traditional motion-coupled vibration, the important parameters necessary to induce and vary the material experiences include the occurrence of pulses (grains), also known as granularity [56] and the individual parameters of amplitude, frequency, duration, phase and waveform function to design individual grains [49]. Building on the foundation that the brain naturally binds both hands and explicit haptic coupling strengthens this binding [7], our algorithm links two hands in VR by generating vibrotactile signals based on the movement of either hand and rendering them on both, forming a bidirectional feedback loop. To capture the dynamics of bimanual interaction, we extend the traditional motion-coupled vibration parameters along two additional dimensions:

- ***Mapping type:*** *absolute mapping*, where each hand is tracked relative to its prior position, or *relative mapping*, where the distance between the hands drives the feedback (see Figure 2 Ⓐ). When both hands move together such that the relative distance is constant, relative mapping produces no pulses, whereas absolute mapping does.
- ***Crosstalk:*** the partial or complete transmission and modulation of vibrotactile signals from one hand to the other hand. For instance, when bending a virtual pool noodle, a non-100% crosstalk lets users feel both the initiating hand's action and a corresponding but modified (e.g., attenuated) sensation in the other hand.

Referring to Figure 3, we systematically varied four motion-coupled vibrotactile feedback dimensions for crosstalk as follows:

- *Amplitude Crosstalk:* The vibration intensity on one hand is scaled relative to the other hand, inspired by how forces can be fully or partially transmitted across connected materials (see Figure 3-Ⓐ).
- *Frequency Crosstalk:* The frequency of the vibration on one hand is changed relative to the other hand, inspired by how frequency shapes the perceived texture or pitch of the vibration, allowing differentiation between softer and rougher materials (see Figure 3-Ⓑ).
- *Grain Crosstalk:* One hand receives a fraction of the vibrotactile pulses (grains) of the other hand, modulating whether the experience feels continuous or discrete (see Figure 3-Ⓒ).

- *Delay Crosstalk:* Vibration of one hand is delayed relative to the other, inspired by instantaneous (e.g., rigid objects or rubber bands) versus delayed propagation of forces (e.g., viscoelastic materials like gel or clay) (see Figure 3-Ⓓ).

A crosstalk of zero implies that only the moving hand receives the pulses generated by its movement, whereas maximum crosstalk implies that the full vibrotactile pulse is received on the other hand as well.

Our bimanual motion-coupled vibration algorithm generates vibrotactile pulses from the user's hand movements. Specifically, it continuously monitors changes in the user's hand positions to trigger vibrotactile pulses (grains). These grains are synchronized with user movement such that they feel self-generated and lead to experiences similar to those we feel when exploring material properties. The quality of the material rendering is primarily dependent on the latency between the sensing of the user's bimanual action and the grain rendering, which should be below the perceptual threshold for time-based tactile sensitivity (observed to be between 25 and 60 milliseconds [28, 55, 64]). If both hands are producing pulses and crosstalk transfers pulses from one hand to the other, the system prioritizes pulses generated by the same hand and then renders the pulses generated by the other hand.

To render effective bimanual motion-coupled vibrations, our algorithm thus requires: (a) sensing hand movements either independently *(absolute mapping)* or relative to each other *(relative mapping)*; (b) processing these movements to generate vibrotactile pulses on either or both of the hands based on the crosstalk parameters; and (c) wideband vibration actuators to render vibrotactile stimuli on both the hands.

3.2 Implementation

Following our motivation to propose a rendering approach compatible with consumer hardware, we used a system widely available on the consumer market, the Meta Quest 3 headset with both of its standard vibrational hand controllers, to design and evaluate the bimanual motion-coupled vibration algorithms.

For the studies, the Quest 3 headset was configured to a 120 Hz refresh rate and 1440 × 1600 resolution per eye, connected to a PC (Intel Core i7-9700, 32 GB RAM, NVIDIA RTX 2080 Ti) via Quest Link (serial communication using USB connection) to minimize delays. The sampling interval of the controllers was 16.6 milliseconds, and the latency from the sensing of user movement to the actuation was measured to be 21.5 milliseconds, well below the tactile perceptual threshold (refer to Appendix A for the details). The algorithms were developed in C# and played with Unity (version 2022.3.34f1). All the algorithms can be used directly with the Meta Quest 3 headset and controllers[1]. The Meta XR toolkit was used to generate vibrotactile signals, which were then played using the Voice Coil Actuators (VCAs) in the hand controllers, which have a wide-band frequency response up to 500Hz[2]. VCAs have a stable amplitude response across a broad range of frequencies [33] as opposed to Liner Resonant Actuators (LRAs) which are tuned to operate at specific resonant frequencies. Referring to Appendix A, peak-to-peak vibrations of a single hand controller were measured to be 2.62 G at full amplitude (1.0), 1.83 G at 70% of peak amplitude, and 1.07 G at 40% of peak amplitude for the frequency range we used.

Our algorithm maps the relative distance between or absolute distance of the hand controllers to vibrotactile pulses on both the hands based on the ratio and type of crosstalk. As an example, consider applying bimanual motion-coupled vibration algorithm feedback for the action of stretching, see Figure 2 Ⓑ. We first define the range of stretching movement which the user can potentially perform by estimating the maximum distance between the two hands as the upper bound, while the lower bound can be fixed to a few centimeters considering the width of the controllers. This range is then divided into discrete bins, which can follow any desired distribution function. During bimanual interaction, the system continuously measures the relative hand distance and triggers vibrotactile pulses (grains) based on the amount of crosstalk between the hands whenever the user's movement crosses a new bin. Faster changes produce rapid pulses, while slower changes generate sparser pulses, creating a dynamic, material-like sensation.

3.3 Evaluation Rationale

We evaluated our proposed bimanual motion-coupled vibrotactile feedback approach in two studies. In both studies, we focused on stretching, bending, and twisting movements inspired by *PseudoBend* [21] (see Figure 1-Ⓐ,Ⓑ,Ⓒ). These movements engage both hands in coordinated yet distinct actions (manipulating elastic bands, pool noodles, or wringing clothes) while capturing bimanual deformations which help to assess material properties like elasticity, flexibility, and rigidity.

The first study was a principled psychophysics study using magnitude estimation protocols. We evaluated the effect of mapping type and amplitude crosstalk levels to understand if crosstalk and mapping type could evoke a unified sense of connectedness and systematically vary it. The second study explored how specific crosstalk types and ratios influence users' perceived quality of the felt connection. Although Multidimensional Scaling (MDS) is suitable for understanding perceptual dimensions from different stimuli [39, 40], our goal was to collect the users' qualitative associations to capture the richness and nuance of material perception attributes that can be conveyed with our technique, for which we chose inductive qualitative analysis. Finally, we developed an authoring tool to assist users in designing bimanual motion-coupled vibrotactile feedback for immersive VR objects. Testing with users provided insights into how algorithm parameters shape bimanual material rendering.

4 Study 1: Perception of Connectedness and Naturalness

Connectedness between the two hands is a primary requirement to establish a unified sense of materiality in bimanual interaction. Therefore, our first goal was to investigate whether amplitude-based crosstalk for bimanual motion-coupled vibrations could induce this sense of connectedness. Beyond connectedness, we also examined *naturalness*, defined as whether the experience matched expectations from real-world two-handed interaction.

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[1] GitHub repository of Algorithms: https://github.com/sensint/biHaptics

[2] Haptic Feedback (Meta Quest 3 Hand Controllers): https://developers.meta.com/horizon/documentation/native/android/mobile-openxr-haptic/

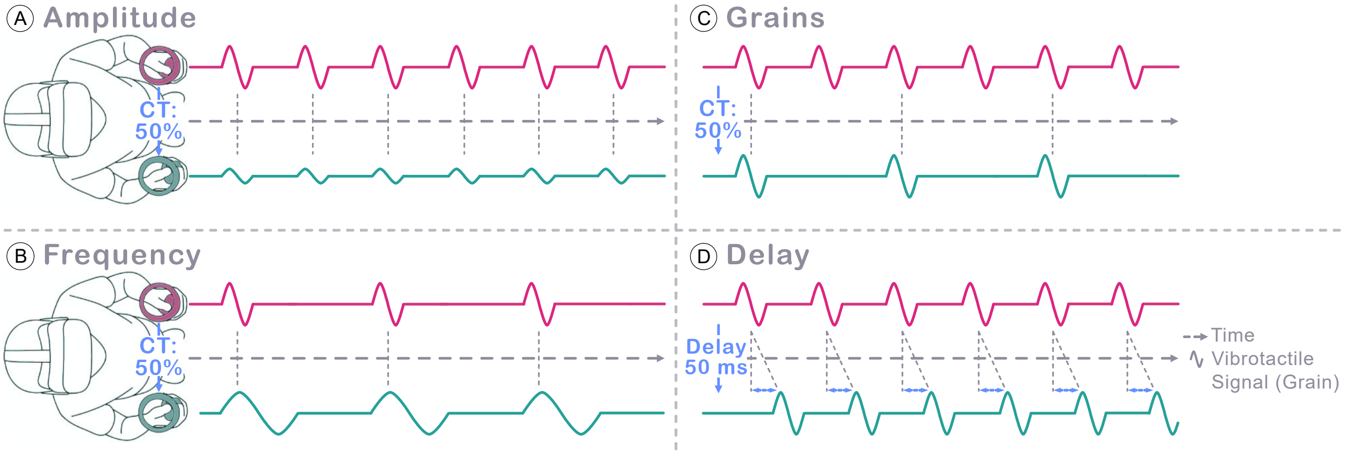

Figure 3: Crosstalk (CT) in amplitude-Ⓐ, frequency-Ⓑ, grains-Ⓒ and delay-Ⓓ is visualized with the vibrotactile pulses (top view of the user is generated using ChatGPT version 5).

While these constructs are not traditional "low-level" psychophysical measures, they follow established practice in haptics and multisensory perception research, where perceptual qualities are often evaluated using subjective magnitude estimation. Prior work has used perceptual descriptors such as softness, compliance, or other induced material qualities to capture emergent percepts that arise from haptic feedback [25, 62]. For example, magnitude estimation has been applied to evaluate perceived salience, depth, and continuity of motion-coupled vibration [56] as well as magnitude and naturalness of induced movement [15]. Our use of connectedness and naturalness fits within this assessment of higher-level perceptual qualities that cannot be captured by thresholds or Just Noticeable Differences alone.

Following the distinction between salience (strength or intensity of the percept) and qualia (the subjective character of the percept) [56], we evaluated both dimensions using absolute magnitude estimation and qualitative insights across different levels of amplitude crosstalk. Throughout the study, participants were blindfolded using a VR headset. To further clarify our methodological grounding, we situate our measures within the method of magnitude estimation from psychophysics [16], to assess perceptual properties of connectedness and naturalness, important for bimanual haptics. Such methods of using magnitude estimation for evaluating perceptual qualities have been previously used in Strohmeier et al. [56] and Ding et al. [15].

4.1 Study Design

We conducted a single-blind within-subject study. The independent variables were:

- Manuality: unimanual (one hand moving, one stationary) vs. bimanual (both moving),
- Movement Primitive: stretching, bending, twisting, (see subsection 3.1)
- Mapping Type: relative vs. absolute. (see subsection 3.1),
- Amplitude Crosstalk Level: 0%, 33%, 66%, 100% crosstalk between the controllers. (see subsection 3.1)

Both absolute and relative mappings used the same grain density; they differed only in the displacement, which was used to trigger the pulses. For *absolute mapping*, the vibrotactile pulses were triggered based on each hand's own displacement relative to its previous position. Thus, each controller maintains its changes in position, so pulses are generated independently for the left and right hands. Absolute mapping is inspired by the motion-coupled vibration rendering methods used for unimanual material rendering [48, 57]. In contrast, relative mapping triggers vibrotactile pulses based on the change in distance between the two hands. The bin is updated whenever the inter-hand distance changes. Thus, if both hands move together while maintaining a constant separation, the relative bin does not change, and hence, no pulses are triggered—analogous to how stretching a single object would work. Since the scaling was identical across mappings, observed differences would arise from the distinct motion sources (individual vs. inter-hand displacement), and not from differences in mapping strategy. For each mapping type, participants experienced four crosstalk levels. With zero crosstalk, only the moving hand vibrated; with full crosstalk, both hands vibrated at equal amplitude. Non-zero crosstalk always produced feedback on both hands, regardless of whether the second hand was moving. This resulted in 2×3×2×4 conditions, each repeated twice. To reduce order effects, we used a balanced Latin square for mapping type × crosstalk level. A balanced Latin square was used for the dimensions of mapping type and crosstalk level because of our hypothesis that *'relative mapping would induce a stronger sense of connectedness compared to absolute mapping, and the crosstalk will be proportional to the strength of connectedness.'* Moreover, as mentioned in subsection 3.1, we aim to capture the dynamics of bimanual interaction with these two dimensions, which extend the scope of single-pointed motion-coupled vibration parameters. A no-vibration baseline was inserted randomly twice per block to understand the effect of vibration.

The dependent variables measured during the study were:

- **[Connectedness]** (Y/N): whether the interaction felt holistic, as if both hands acted on the same object. This was cumulatively answered over all actions.
- **[StrengthConnection]** (magnitude estimation): how strongly the two hands feel connected.
- **[StrengthNaturalness]** (magnitude estimation): how close the interaction resembled real-world expectations.
- Qualitative Descriptors or Associations (verbal).

Besides **Connectedness**, all other dependent variables were measured individually for each movement primitive.

For both mappings, the leader hand (the one that moves the most in bimanual or which moves in unimanual) was rendered with vibrotactile pulses of amplitude = 1.0, frequency = 120 Hz, granularity = 100 pulses/m, delay = 0 ms, ϕ=0 and a sine wave. A single cycle of the sine waveform was used, and hence the duration of the pulse corresponded to 8.33 milliseconds. Although prior work such as Heo et al. [21] and Sabnis et al. [47] used decaying sine wave and asymmetric waveform respectively to generate vibrotactile pulses, other work has shown that sine waves are more promising at rendering material experiences like compliance [62, 66] and texture [48, 55]. Moreover, a sine waveform was chosen as it provides a smooth, artifact-free signal that avoids the sharp onsets or irregularities that can occur with more complex waveforms, making it a reliable baseline for conveying consistent vibrotactile pulses across conditions. Thus, we could isolate the effects of crosstalk parameters on perceived connectedness. Finally, the frequency of 120Hz lies in the sensitivity of the pacinian corpuscles, ensuring a clear and perceivable vibration from the controllers [32]. An amplitude of 1.0 corresponded to the maximum amplitude from the controllers measured at 2.62G, and the amplitude level was kept constant for each pulse of a particular amplitude level. For bending and twisting actions, the angular changes between the controllers were used to trigger the grains.

4.2 Procedure

Participants were informed about the study, and were asked to sign a consent form and complete a demographic questionnaire. They were also explained what 'unimanual' and 'bimanual' interaction mean in the context of the study. Moreover, they were explained what is meant by connectedness as 'both hands interacting with the same object or material to create a unified experience, even if physically disconnected—for example, two hands moving over the same surface.' For the task, they were instructed to perform the three movements (stretching, bending, twisting) and were shown the movements and asked to repeat them during the instructional briefing. To avoid bias, these movements were not mentioned to the participants, as they inherently imply bimanual coordination. The participants were not shown the hand controllers throughout the experiment, and they were described neutrally as hand-held devices. The participants were briefed about the questions they would be asked after each condition. Finally, the participants were told how they should rate on the magnitude estimation scale, with a score of zero for strength of connection meaning that the hands are not connected, whereas a score of zero for naturalness means that the interaction is not natural. With that as the baseline, they could assign any values to the perceived strength of connection and naturalness, keeping in mind that the higher the values, the stronger and more natural the connection.

4.2.1 Task. While seated, each participant completed two sets of trials: one unimanual and one bimanual. In each set, they were exposed twice to crosstalk × mapping conditions for which they performed three movements. As they were exploring each condition, participants answered if their hands felt connected, and for each movement they had to rate the level of connectedness, naturalness and provide optional verbal descriptors. After assigning scores to all the dependent variables, the next condition was presented.

4.2.2 Participants. Sixteen right-handed participants (8M, 8F) aged 22 to 32 years ($M = 26.06, SD = 2.79$), with no known neuromuscular disorders, participated in the study. All participants were naïve to the task; two had prior expert-level experience with VR and three had beginner-level experience (the experiences were self-proclaimed), and one had limited exposure to vibrotactile feedback ($\sim$ 6 months), and one actively worked in the field of haptics. The study duration was about 1 hour 30 minutes, depending upon the participant responses to each condition and the final qualitative interviews. Participants were seated throughout the study and compensated with 18 euros for participation. White noise was played through the headset to mask audio-cues of the controller vibrations.

4.2.3 Data Collection and Analysis. All the responses to the dependent variables were recorded in an Excel file, structured by participant, condition, and movement type. For each condition, participants provided ratings for the dependent variables (Connectedness [Y/N], StrengthConnection, StrengthNaturalness) across the three predefined movement primitives. Thus, each condition had 32 responses (16 participants x 2 repetitions). Scores were standardized per participant and per manuality (unimanual vs. bimanual) to account for individual scale differences and allow comparisons across participants. We used z-score standardization, which rescales each participant's ratings by subtracting their mean and dividing by their standard deviation for that manuality condition. This transforms the scores to have a mean of 0 and a standard deviation of 1, meaning most values naturally fall within roughly ±1.5 standard deviations for subjective responses, although the theoretical range is unbounded. Post-standardization, a four-way RM-ANOVA was conducted to assess the effects of crosstalk, mapping type, movement primitive, and manuality. We performed Shapiro–Wilk tests for normality on each of the 48 within-subject condition cells, and overall, normality was not violated for StrengthConnection or StrengthNaturalness. Sphericity measured using Mauchly's test is not defined for a single within-subject factor with less than three levels (i.e. *Handedness, Mapping* [2]. For the factors *Action* and *Crosstalk Level,* sphericity was assumed because the conditions were randomly presented and can be considered conceptually equivalent. Mauchly's test supported this assumption for both dependent variables. For *StrengthConnection*, sphericity was met for *Action* (W = 0.846, p = 2.343) and *Crosstalk Level* (W = 0.661, p = 5.676). Sphericity was also met for *StrengthNaturalness* for *Action* (W = 0.377, p = 13.660) and *Crosstalk Level* (W = 0.644, p = 6.046). As all p-values were > .05, no violations were detected, and uncorrected degrees of freedom were used in reporting the RM-ANOVA analyses. Qualitative feedback was collected alongside ratings if participants could associate any

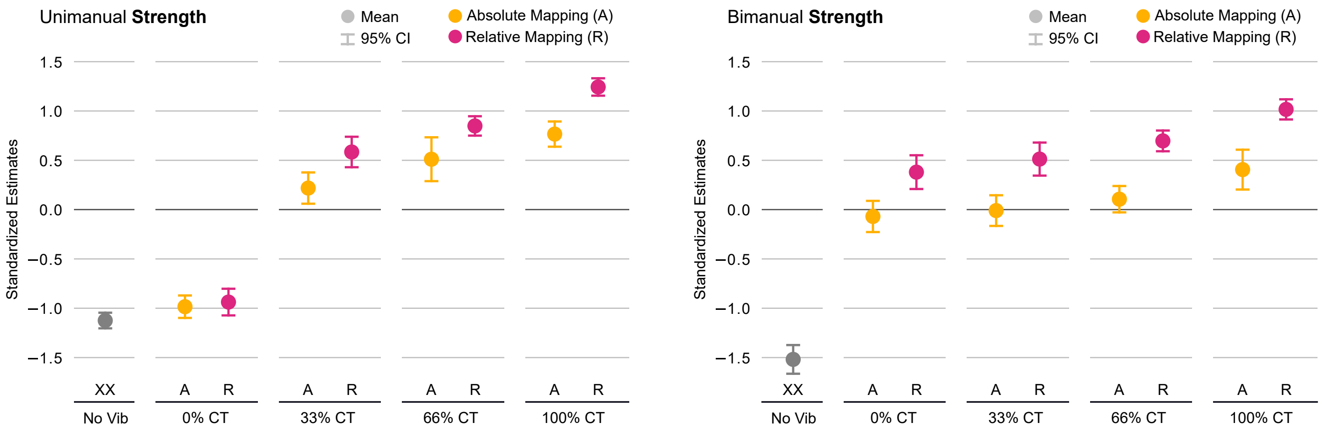

Figure 4: Estimates of connectedness strength for unimanual Ⓐ and bimanual Ⓑ configurations over different amplitude crosstalk levels and relative, absolute mapping types. Each confidence interval bar corresponds to 96 data points (16 participants * 3 actions * 2 repetitions).

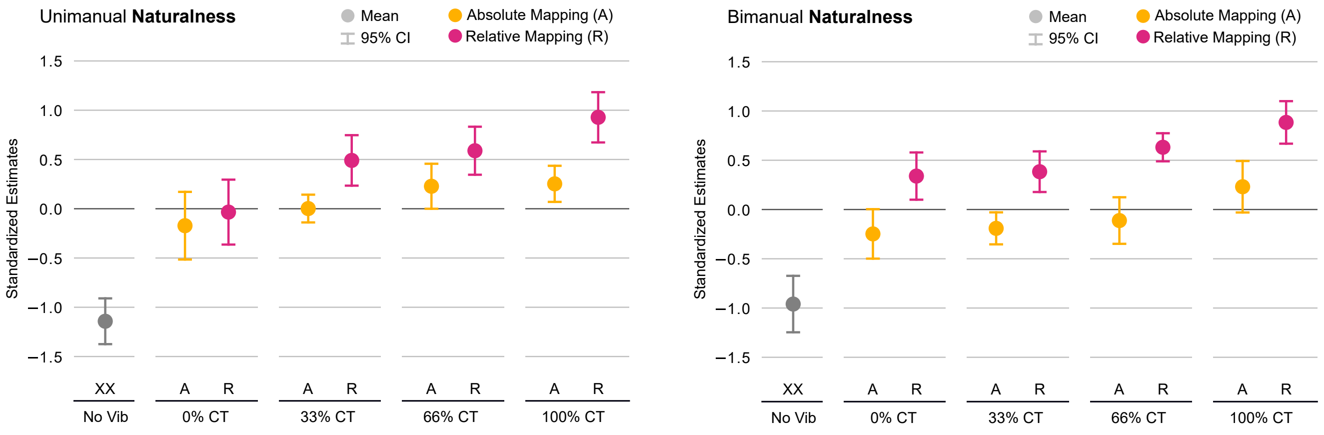

Figure 5: Estimates of StrengthNaturalness for unimanual Ⓐ and bimanual Ⓑ configurations over different amplitude crosstalk levels and relative, absolute mapping types. Each confidence interval bar corresponds to 96 data points (16 participants * 3 actions * 2 repetitions).

object, material, or experiential qualities to the conditions. These responses were coded and clustered using flexible coding approaches to identify recurring themes, similar to [34, 46].

4.3 Results

Results showed that amplitude crosstalk induced connectedness in both mapping types, with relative mapping yielding stronger and more natural experiences, and higher crosstalk levels amplifying both effects. Next, we report on the effects of *Handedness, MappingType, Action, CrosstalkLevel* on **Connectedness, StrengthConnection, StrengthNaturalness** alongside qualitative results.

4.3.1 Connectedness: Positive responses in the unimanual condition were rare with no vibration (3.1%) and absent in the bimanual condition (0%). With crosstalk, unimanual connectedness rose sharply to 87.5% across all levels (A33, R33, A66, R66, A100, R100), except A0 and R0, which showed positive only for 0% and 12.5%, respectively. In the bimanual condition, connectedness was already high: 87.5% (A0), 96.9% (R0), 90.6% (A33), 96.9% (R33), 93.8% (A66), and 96.9% for R66, A100, and R100.

4.3.2 Magnitude Estimation. The four-way RM-ANOVA was conducted on the data of 16 participants for two repetitions to assess the effects of *Handedness, MappingType, Action*, and *CrosstalkLevel* on **StrengthConnection** and **NaturalnessConnection**.

StrengthConnection: Referring to Figure 4 Ⓐ,Ⓑ, and Figure 10 Ⓐ, Ⓑ (Appendix B) RM-ANOVA revealed significant main effects for *MappingType* (F(1, 15) = 77.26, p < 0.01), *CrosstalkLevel* (F(3, 45) = 123.56, p < 0.01), *Action* (F(2, 30) = 8.82, p < 0.01), and *Handedness* (F(1, 15) = 50.53, p < 0.01). Significant interactions (p < 0.01) emerged for *Handedness* x *CrosstalkLevel* (F(3, 45) = 67.00, p < 0.01), *MappingType* x *CrosstalkLevel* (F(3, 45) = 5.00, p < 0.01) and *Action* x *CrosstalkLevel* (F(6, 90) = 3.81, p < 0.01). Significant *Handedness* × *CrosstalkLevel* interaction showed that crosstalk effects on strength depended on whether one or both hands moved, with single-handed movement amplifying its benefits.

Post-hoc comparisons showed that the bimanual interactions elicited significantly stronger connectedness than the unimanual condition (t(15) = -7.11, p < 0.01, g = -1.61). Relative mapping outperformed Absolute mapping in producing a coherent shared-object sensation (t(15) = −8.79, p < 0.01, g = −3.76). Connectedness increased systematically with crosstalk: 0% was lower than 33% (t(15) = −11.75, p < 0.01, g = −4.24), 0% < 66% (t(15) = −11.14, p < 0.01, g = −4.89), and 0% < 100% (t(15) = −17.23, p < 0.01, g = −7.52); similarly, 33% < 100% (t(15) = −7.9, p < 0.01, g = −3.22) and 66% < 100% (t(15) = −5.29, p < 0.01, g = −1.7). Finally, among the action types, stretching was rated as more connected than bending (t(15) = 3.36, p < 0.01, g = 1.53) and twisting (t(15) = 3.81, p < 0.01, g = 1.44).

StrengthNaturalness: Referring to Figure 5 Ⓐ, Ⓑ and Figure 10 Ⓒ, Ⓓ (Appendix B) for *StrengthNaturalness* estimates, significant main effects were found for *MappingType* (F(1, 15) = 85.80, p < 0.01), *CrosstalkLevel* (F(3, 45) = 16.55, p < 0.01) and *Action* (F(2, 30) = 6.73, p < 0.01). Unlike **StrengthConnection**, the main effect of *Handedness* on *StrengthNaturalness* was not significant (F(1, 15) = 2.61, p = 0.127). No other statistically significant interaction effects were found, suggesting that naturalness depends primarily on the independent contributions of mapping, action, and crosstalk.

Similar to connectedness, relative mapping was rated as significantly more natural than absolute mapping (t(15) = −9.26, p < 0.01, g = −3.10). Crosstalk effects showed a graded trend: 0% was lower than 66% (t(15) = −3.81, p < 0.01, g = −1.48), 0% < 100% (t(15) = −6.86, p < 0.01, g = −2.31), 33% lower than 100% (t(15) = −4.05, p < 0.01, g = −1.52) and 66% lower than 100% (t(15) = −3.45, p < 0.01, g = −0.93). For actions, stretching felt more natural than bending (t(15) = 3.07, p < 0.01, g = 1.27) and twisting (t(15) = 4.96, p < 0.01, g = 1.07).

4.3.3 Qualitative Descriptor Results. The qualitative feedback was clustered based on flexible coding approaches for the descriptors (if any) given by the participants.

Associations to Metaphorical Objects: Across both unimanual and bimanual conditions, participants frequently described interactions using metaphors rooted in everyday object manipulation, primarily for twisting and stretching actions. For instance, twisting was compared to “squeezing a mop” (P7-A66), “screwing a loose screw with some resistance” (P6-R100), “cloth twisting” (P7-A33, P15-R66) or “bar/stick-twisting” (P9-R100, P11-A66). Stretch actions were associated with “pulling a rubber band” (P7) “stretching a piece of rubber string” (P2), and “resistance/ exercise bands” (P4, P9, P10) for multiple conditions. Bending also evoked associations such as “rubber band fixed to a fixture” (P2-A66) and “bending rubber stick” (P11-A66), reflecting a tangible perception of coordinated effort and shared task between hands. Moreover, at higher crosstalk levels (100), particularly during twist actions, participant feedback shifted toward mechanical or systemic metaphors—e.g., “rusty chain” (P4-A100) “screwdriver spin in hard things” (P3-A100) “using 2 hands to hold a simulated spring”. Descriptions like “rubber band fixed to a fixture” (P2-A66) “pulling something fixed to a post/ rope from left-hand,”(P2-R100, P11-R33) and “resistance band holding in left hand” (P5-A33) point toward the participants perceiving dynamic tension and resistance due to the motion-coupled vibrations. Participants also consistently described interactions in which one hand influenced or responded to the other, especially for relative mapping conditions at all crosstalk levels for unimanual and bimanual configurations.

4.4 Concluding Thoughts

Generally speaking, non-zero crosstalk induced a sense of connectedness, with the strength more pronounced for relative mappings and proportional to the amount of crosstalk. This effect was more evident in unimanual exploration over bimanual exploration showing that the stationary hand relied on crosstalk to infer shared material experiences; in bimanual configuration, the movement of each hand already provided necessary material information, making crosstalk less critical. This is evident in the low connectedness reported at 0% crosstalk for unimanual interactions, compared to the high connectedness for bimanual interactions. Finally, there was no statistical difference in perceived naturalness based on unimanual or bimanual configuration indicating that the naturalness of the material experience was independent of whether single or both hands were used for exploration. Participants also associated bimanual motion-coupled vibrations with real-world experiences, particularly when the relative mapping was used. As participants not only spoke about the strength of connection but also what this connection was like, we decided that the subjective properties of the connection should be the focus of our next study.

5 Study 2: Variable Crosstalk-induced Material Associations

After establishing connectedness during the first study, to understand how different parameter crosstalk induce object, material and experiential associations, we conduct a qualitative study. We focused on unimanual interactions (one hand moving, one hand stationary, both receive vibrotactile feedback depending on the level of crosstalk) to more clearly understand the association elicited based on the different types and levels of crosstalk. Building on the first study, we only used relative mapping, as it yielded stronger connection and naturalness than absolute mapping, and excluded zero crosstalk since it did not support a unified material experience in unimanual configuration. Similar to the first study, participants were also blindfolded in this study using the VR headset, as we wanted to understand the material associations elicited with crosstalk-based bimanual vibrotactile feedback.

5.1 Study Design

We explored qualitative material associations elicited under different crosstalk conditions, assuming the two hands were connected. A leader–follower paradigm was used: the moving hand was the leader hand, and the stationary hand ‘was the follower hand. The leader hand’s vibration parameters were kept constant across all conditions (amplitude = 1.0, frequency = 120 Hz, granularity = 100 pulses/m, delay = 0 ms), matching the first study. Crosstalk levels for each type were decided based on pilot-trials, Quest controller specifications and the authors’ combined experience in designing vibrotactile feedback (>20 years). We examined four types of crosstalk (refer subsection 3.1) with different levels: *amplitude CT* (A33, A66, A100); *frequency CT*: frequency set to 80 or 170Hz (F80, F170); *grain CT*: G10 = every 10th pulse, G25 = every 4th, G50 = every 2nd pulse was triggered with every pulse of the leader hand; *delay CT*: (D50, D100, D200, D400 ms) For each condition and movement primitive, participants were asked: *'Can you describe your experience? What did the experience feel like? Does it remind you of any material and/ or object?'*.

5.2 Procedure

Similar to the first study, we provided information about the study to the participants and asked them to sign the consent form and respond to the demographic questionnaire. We further clarified what bimanuality means and what is implied by connectedness, similar to subsection 4.2. To reduce ordering effects, the sequences of conditions were decided using a balanced Latin square approach. Each condition was played once and the participants had to perform the movements and provide qualitative descriptions if the condition reminded them of anything. After they provided descriptions for each movement primitive, the next condition was presented.

5.2.1 Task. **Assuming that both hands of the participants were connected**, they were instructed to perform a set of movements with their right hand while keeping their left hand stationary. Specifically, they were asked to carry out *stretching, bending*, and *twisting* movements, to intermittently stop and restart their movement, and to maintain a noticeable separation between their two hands. They could perform the movements as fast or slow as they would like. For stretching in particular, participants were encouraged to make relatively large movements. In addition to the prescribed motions, participants were also free to explore other hand movements, provided they remained aware of the assumption that both their hands are connected.

5.2.2 Participants. Twelve participants (6 F, 6 M) took part in the study, aged between 20 and 33 years (M = 26.42, SD = 4.27). Eleven participants were right-handed and one left-handed. Participants always used their dominant hand to perform the movements because, consistent with Guiard's model, it naturally serves as the primary manipulator for precise, controlled movements, while the non-dominant hand provides a stable reference. Most participants had little to no prior experience with vibrotactile haptics, while one participant reported intermediate experience (10 months). Regarding experience in virtual reality, ten participants were beginners and two reported an experience of 6 months. Participants were compensated with 10 Euros for their participation. During the experiment, white noise from the headset was used to cancel any audio cues from the hand controller vibrations and participants were blindfolded using the VR headset.

5.2.3 Data Collection and Analysis. The entire study session for all participants was audio-video recorded using a web camera. Recordings were transcribed and coded by two authors using Taguette[3]. Post transcription, all the relevant codes including the material and object associations as well as the described experiences were collected in Miro to get familiarized with the data. Two authors familiarized themselves with the data during transcription and highlighted an initial code set of the material associations over a two-week period. Finally, we conducted an inductive qualitative content analysis for each crosstalk parameter, following a process of looking at individual codes and contextualizing the elicited associations with respect to the crosstalk parameters.

5.3 Results: Qualitative Analysis

We present themes from the qualitative content analysis done per crosstalk type for different levels and three movement primitives (Figure 6 shows visual overview). For the last three participants, almost all the induced associations were mentioned by the nine participants before them, indicating that the themes saturated around the ninth participant.

5.3.1 Amplitude Crosstalk: Solidity and effort. Amplitude emerged as a central factor in shaping participants' perceptions of material solidity, strength, and effort required for interaction. Increasing the amount of amplitude crosstalk altered the quality of resistance and the object associations participants drew upon. Low amplitude crosstalk (A33) suggested fragile, loose, or worn materials. Medium-amplitude crosstalk (A66) evoked stability, control, and chain-like pull. High-amplitude crosstalk (A100) was associated with tight rubber band, and robust mechanisms, accompanied by descriptions of greater physical effort.

During stretching movements, low crosstalk was described as fragile, loose, or slipping, often evoking materials that lacked structural integrity, with P8 comparing A33 stretching to "a metal pipe… but my right hand is a bit wet and slips on it". In bending movements, amplitude was interpreted as scaling the rigidity of the hinge or arc. At A33, bending was experienced as weak or yielding, almost as if the joint was worn or unstable. At A66, participants described bending as reliable but flexible, akin to working through a stable chain-link or belt mechanism. At A100, bending took on the qualities of a stiff or heavily engineered hinge, requiring more exertion to bend and evoking imagery of gears locking into place. For twisting movements, amplitude strongly modulated the sense of twisting strength. At A33, twisting was experienced as slack or under-tensioned, where the twist lacked robustness and sometimes felt as if it might "slip." At A66, twisting became controlled and chain-like, with participants noting that the twist pulled cleanly and predictably. At A100, twisting was associated with requiring effort with one participant mentioning that twisting felt like "something with gears resisting— not just rubber, but a mechanism." Additional participants confirmed this: P9 likened A100 twisting to turning "a normal screw… an old one," and P11 compared it to "shaking a gym shaker," both conveying dense, gear-like torque and substantial effort.

5.3.2 Delay Crosstalk: Temporal Propagation and Lag. Duration emerged as a critical parameter in shaping how crosstalk was experienced through stretching, bending, and twisting. Changes in duration were able to alter the temporal coupling between the two hands, producing a progressive shift in material associations: from immediate elastic bands and taut couplings (D50) to layered or coiled mechanisms, especially in bending and twisting (D100,

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[3] https://app.taguette.org/

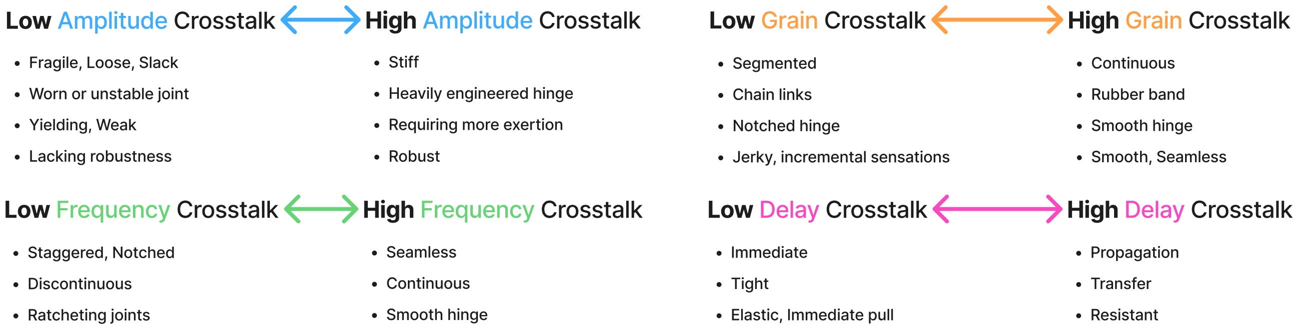

Figure 6: Selected descriptors representative of the qualities associated by participants for different crosstalk types and levels. Refer to subsection 5.3 for the complete qualitative analysis

D200). Long durations (D400) transformed all movements into experiences of propagation, transfer, and slack, evoking analogies to pipes, springs, yo-yos, and granular fluids.

At short durations (D50), participants described sensations as tight, immediate, and elastic, often resembling rubber bands or direct mechanical couplings; in stretching this felt like an immediate pull with no lag, while P3 likened bending to "like opening a very old very rusty gate," showing that even minimal lag could be read as hinge resistance, and twisting was typically felt as synchronous between hands, reinforcing taut or direct link associations. Several participants additionally described D50 stretching as "instantaneous," with one comparing it to the quick flick of a thin metal strip and another noting that twisting at D50 felt like turning a pen cap where "both ends move together," underscoring the absence of delay. At medium durations (D100, D200), participants noticed temporal offsets suggesting layering or coiling: several participants while stretching described that vibrations seemed slower to reach the left hand, evoking springs with multiple coils or joint links; bending reinforced resistance across layers as if movement passed through stiff segments; and twisting at D200 produced slight slack or delayed return, compared to wind-up toys or mechanical lag. Stretching at D100 was described as "first on the right, then the left catching up" (P12) and one participant noted that D200 felt like "a rope where the wave travels along before the other hand reacts." (P4) For bending at these durations, participants reported "lag building up across the bend,". During twisting, D200 was described as "the twist coming back late" (P9) or like twisting a kitchen towel "where the tension travels before settling" (P11) indicating a perceived delay in torsional coupling. At long duration (D400), delay was experienced as propagation through material: stretching was likened to routed transfer, such as P2's analogy of "passing water from my right hand to the left hand… through a curved pipe," and P1 noting "even after I stop I still feel some of the vibration on this [other] hand" highlighting sense of residual persistence and lagging transfer; bending felt highly layered, with P2 describing it as "either very long or it has a lot of layers in between," like multi-coiled springs; and twisting introduced the clearest sense of slack, with P2 comparing it to a yo-yo where feedback trailed behind action. Additionally, participants described D400 stretching as "pushing sand through a long tube," with P8 noting that the sensation "lingers even after motion stops," and P10 adding that it felt like "a long cable where the signal takes time to travel."

5.3.3 Grain Crosstalk: Discreteness vs. Continuity. Grain crosstalk affected the perception of connectedness by shifting sensations between discrete, mechanical and continuous, fluid experiences across all movement types. Low grain crosstalk consistently generated mechanical associations — chains, gears, ratchets — while higher grain fostered elastic and fluid interpretations, such as rubber or water. This transition, modulated further by the movement type, highlights grain as a key factor structuring the experience of discreteness versus continuity across gesture contexts.

At low grain crosstalk level (G10), stretching felt segmented and mechanical; participants compared it to "chain links or gear teeth clicking into place" (P3) and described it as "chunks… like stepping on gravel, not smooth" (P4) and "small clicks, like pulling something over ridges" (P9) emphasizing a ratcheting, stepwise transfer of force. Bending at low grain felt like resistance in steps, "like a ratchet," producing the impression of notched hinges or material that catches rather than moves smoothly. For twisting, low grain produced jerky, incremental sensations analogous to cogs and ratchets, with P7 describing it as "little jolts, like something catching — like a ratchet," and P8 mentioning "a tube twisting but getting stuck every few degrees," echoing the mechanical segmentation. With higher grain crosstalk (G25, G50), these sensations shifted significantly. Stretching became smooth and continuous, linked to elastic or fluid associations, such as rubber bands or water, as P1 noted: "it was more like water, as if it flows evenly… not broken." Bending at higher grain crosstalk felt more like a uniform sweep, mirroring the impression of a smooth joint or a rubber hinge rather than a mechanical linkage. While performing twisting movements, participants described higher grain as yielding seamless, elastic resistance, "smoother, more like stretching rubber than separate parts" (P2), supporting metaphors of fluid or viscous media.

5.3.4 Frequency Crosstalk: Rhythm and Pacing. Collectively, participants interpreted low frequencies as incremental, ratcheted motion across all gestures, while high frequencies evoked continuous media such as rubber, liquid, or smooth elastic winding, highlighting frequency as a distinct parameter governing the pacing and temporal texture of material experience. In stretching, low-frequency conditions were consistently described as staggered and effortful, with P2 noting it felt like "pulling in pulses, almost like each tug had to restart" and "tiny bumps which interrupt the pull" (P9) while higher frequencies were likened to continuous flow, as P6 explained: "the stretch feels uninterrupted, like pulling something liquid." In bending movements, low frequency was mapped onto mechanical resistance, as P4 remarked that "it catches in steps, like bending through notches," whereas higher frequency produced more seamless arcs, which P7 described as "a single sweep, no breaks." For twisting, low frequency evoked strong associations with gear-like mechanics, with P3 stating, "it's like turning through teeth, each click makes it advance," while higher frequency was experienced as elastic and organic, "the twist feels like rubber winding up smoothly without stops" (P1) and P11 felt like "stirring thick paint".

5.4 Concluding Thoughts

While this study presented a rich overview of the types of experiences users have when engaging with bimanual motion-coupled vibration with crosstalk, there is another interesting observation that can be made in the data. The *amplitude crosstalk* condition provided participants with the same stimulus as in **study 1**, yet the qualitative associations were quite different. These differences are not only based on the questions asked but more importantly on how this study was framed for the participant. In study 1, the participant was asked to judge *if* there is a connection between two controllers. In study 2, participants were asked to assume that the two controllers are connected by a material and, given this assumption, to judge what the material is like. This highlights that the a priori expectations of the user shape how the stimulus is experienced. One way of shaping such a priori expectations is through visual information. For example, as a user approaches an object that they *see* in VR, they form a priori expectations of what it will feel like. These expectations then shape the context within which the tactile stimuli are interpreted, which we explore in the next section of multimodal explorations that include visual information.

6 Dvihastīya Authoring Tool: Design and Initial User Impressions

Based on our observations around the importance of multimodality, our final explorations were conducted in VR. To receive a different type of insight, we did not provide fixed stimuli to the user, but we instead observed if our approach was robust enough to allow users to independently design bimanual experiences. Thus, we designed *Dvihastīya*, an authoring tool that enables users to design bimanual motion-coupled vibrotactile feedback for different demo applications in VR (Figure 7-Ⓑ). *Dvihastīya* was provided to the users directly in the virtual environment, allowing them to quickly iterate between designing and testing the bimanual feedback designs. Users were presented with interactive visual demonstrations of objects with known material properties that involved two-hand interaction. Each of the interactive demonstrations changed their state from unstretched to stretched, straight to bent and untwisted to twisted.

The focus was on how users design with *Dvihastīya* to create bimanual vibrotactile feedback across these demos of virtual objects and actions. We deliberately exposed low-level vibration parameters rather than allowing designers to specify high-level material descriptions as our goal with this exploration was to understand *how* users make sense of and manipulate bimanual motion-coupled vibrotactile crosstalk parameters. With *Dvihastīya*, we also wanted to clarify which perceptual dimensions (e.g., amplitude for stiffness, grain for resistance, delay for realism) are most meaningful.

6.1 Designing Bimanual Motion-Coupled Vibrotactile Feedback with Crosstalk

Dvihastīya is a Sanskrit word meaning "with two hands" referring to actions performed bimanually. *Dvihastīya* enables the users to design the bimanual motion-coupled vibrotactile feedback in VR environments. Users primarily need to configure the parameter values relating to the feedback provided to the leader hand: **grain amount/ per 2 meters** (value range: 0-400), **frequency** (value range: 80-200 Hz) and **amplitude** (value range: 0.0-1.0). Since the synchronization of the hands is assumed by the authoring tool, users can simply choose the feedback provided to the one hand relative to the one they designed using base parameters by adjusting **crosstalk** multipliers for each parameter (value range: 0.0-1.0). Finally, the user can also choose the propagation **delay** length (value range: 0-500 ms). The authoring tool is open-source and can be used with Meta Quest 3 and hand controllers[4].

6.2 Exploration with Dvihastīya

We explored how users design bimanual vibrotactile feedback for familiar bimanual demo interactions using Dvihastīya in a semi-realistic VR environment, designed to resemble the interior of a space station with ambient lighting and minimal distractions (Figure 7 Ⓐ). The setup used the hardware described in subsection 3.2.

Users: We recruited 3 male and 2 female users, aged 25-32 (M=28), to participate in this exploration. The user's experience of designing haptics ranged from no experience (U4, U5), six months (U2), 2 years (U1), and 4 years (U3). U2 worked on vibrotactile feedback for texture rendering, whereas U1 was developing vibrotactile feedback for movement guidance. U3 worked in the fields of passive haptic feedback, audio-haptic feedback and vibrotactile haptics.

Virtual Objects: Participants interacted with four virtual objects: an *elastic band* (Figure 7 Ⓒ), a *pool noodle* (Figure 7 Ⓓ), a *braided wire* (Figure 7 Ⓔ), and *table-tennis rackets.* The first three demo applications mapped directly to stretching (elastic band), bending (pool noodle), and twisting (braided wire). All three demos were suggested by previous study participants (see subsubsection 4.3.3). Objects (except table tennis rackets) were simulated in real time using the Obi Rope[5] (inspired by GamesBond [45]), with parameter values tuned to reflect their distinct physical properties (Appendix C). For example, the braided wire was modeled as semi-rigid for twisting, the pool noodle as a foam-like structure with both elastic and plastic deformation, and the elastic band as a tension-based object deforming primarily through stretch. One racket was rendered in each hand for the table tennis rackets, and users were asked to design for a disconnected experience.

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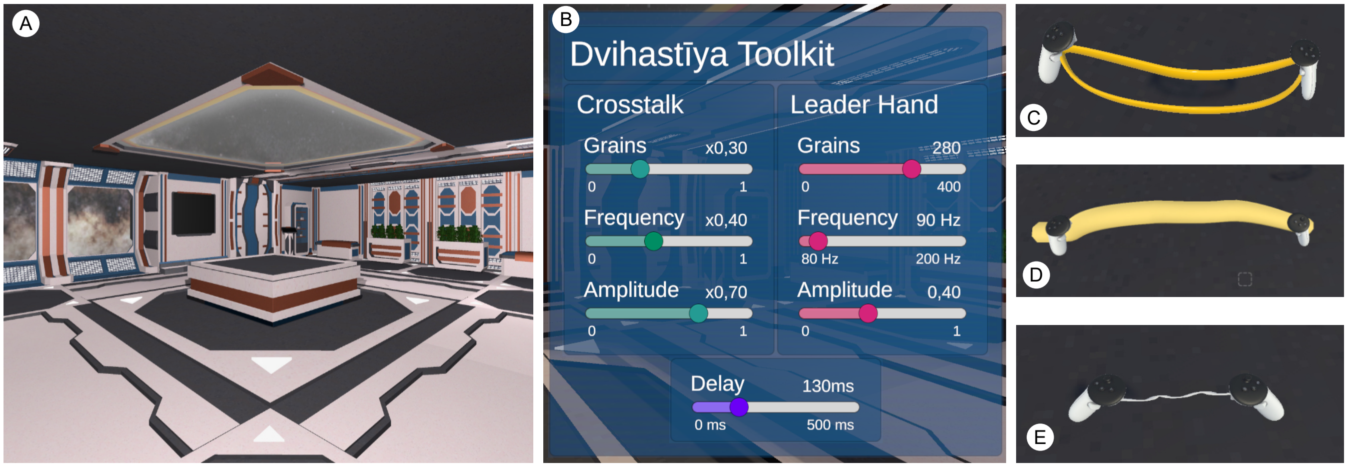
[4] GitHub repository of Crosstalk Algorithms: https://github.com/sensint/biHaptics

[5] Obi Rope Asset on Unity Asset Store: https://tinyurl.com/obiAsset



Crosstalk: Grains x0,30 (0–1); Frequency x0,40 (0–1); Amplitude x0,70 (0–1)

Leader Hand: Grains 280 (0–400); Frequency 90 Hz (80 Hz–200 Hz); Amplitude 0,40 (0–1)

Delay 130ms (0 ms–500 ms)

Figure 7: The virtual room used for the exploration Ⓐ, the Dvihastīya authoring tool Ⓑ and three of four interactive demo objects that were designed for in VR are shown (elastic band-stretching Ⓒ, pool noodle-bending Ⓓ, and braided wire-twisting Ⓔ).

Procedure: At the start, each user was introduced to the central theme of the session: to design bimanual vibrotactile feedback to suit a known, visually represented object. They were explained the Dvihastīya parameters which they could change and were shown how to adjust vibrotactile parameters through a VR-based GUI. In addition, users were encouraged to think aloud while designing. Each user then created seven designs: tight and loose elastic bands (stretching), stiff and flexible pool noodles (bending), stiff and flexible braided wires (twisting), and table tennis rackets (with free choice of action for non-connected interaction). The designs were done one after the other and the order between the objects was presented pseudo-randomly to each user. After each design, users were asked to report their chosen parameter values and reflect on

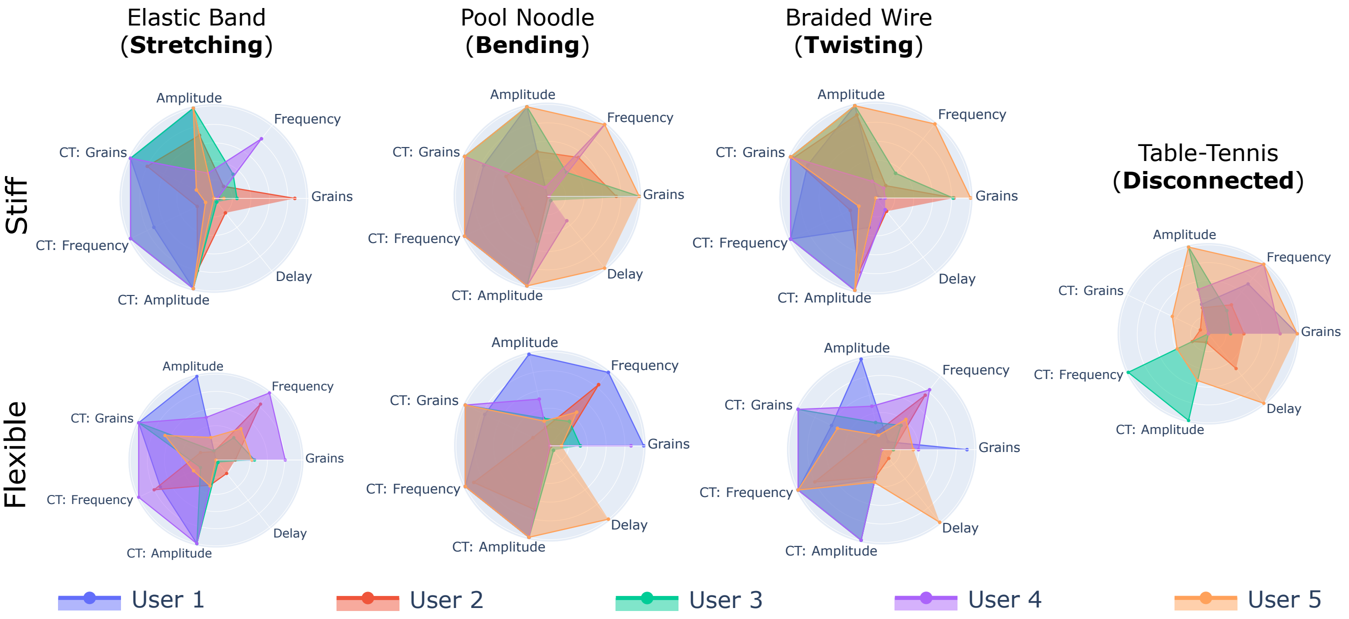


Figure 8: Parameter configurations showing seven haptic designs made by five users using the Dvihastīya authoring tool. Designs for the elastic band, pool noodle, and braided wire were created to fit both flexible and stiff material properties. For the table tennis rackets, the users were instructed to make the hands feel disconnected. A clear contrast is seen between the use of crosstalk for bimanual actions like stretching, bending, twisting and the absence of it for disconnected table-tennis hand movements. Grain crosstalk of zero means that there are no vibrotactile pulses being played on the stationary hand (despite the pulses having an amplitude and frequency) as seen in the design for table-tennis.

the relative importance of visual versus haptic cues in shaping their experience of interacting with the object.

6.3 User Impressions of Designing with Dvihastīya

Users described that Dvihastīya was intuitive to use for bimanual haptic design, even with little prior experience. However, U2 and U4 noted that definitions of 'Crosstalk,' 'Grains,' and 'Leader Hand' when pointing at the words in VR would help to make the authoring tool more user-friendly. Referring to Figure 8, amplitude was an effective parameter: U1, U3, and U5 found high amplitude conveyed stiffness (primarily for stretching), while low amplitude indicated looseness; grain was linked to resistance and stretch (U1, U5), with U4 noting that distinct pulses implied incremental stretch. Frequency played a subtler role: U2 associated higher frequency with flexibility, while P5 used it for fine-tuning. Delay divided users: U3 preferred small delay for realism, but U2 and U4 wanted minimal delay for connection, and U5 favored higher delays for flexibility.

Users often adjusted amplitude crosstalk in ways that aligned with their interpretation of connectedness, tending to lower it when designing interactions they perceived as independent (e.g., U1, U2, U4, U5 for table tennis) and increasing it for shared-material interactions, with mid-range values often described as most natural (U5), though preferences varied across users. Similar patterns were observed for grain and frequency crosstalk, where the crosstalk was lowered to zero for designing *disconnected* table tennis rackets, which made one hand feel disengaged (U1, U4). Moderate or high crosstalk values supported flexible material experiences while bending the pool noodle (U1, U5). Minimal delay crosstalk was preferred to maintain unity (U2, U4), but moderate delays sometimes enhanced realism or alignment with visuals (U3, U5). *Overall, participants tuned crosstalk selectively: reducing it to emphasize independence and increasing or balancing it to reinforce material connectedness.* For twisting (braided wire), users described different roles for grain and amplitude crosstalk shaped the experience such as using lower amplitude for localized stiffness (U1) or mid-level grain crosstalk to support a twisting feel (U5), and frequency changes helped or hindered realism depending on values (U2, U3). For stretching (elastic band), users preferred to tune amplitude to adjust tightness (all users), while grain crosstalk was used to refine continuity of the bend (U1, U2, U4). These observations suggest preliminary ways users tune crosstalk to convey either connected material experiences or independence, with users preferring non-zero crosstalk when designing bimanual connected experiences.

Regarding the design process, novices (U4, U5) made broad, noticeable changes and often relied on amplitude first, while experienced designers (U1, U3) experimented with interactions between parameters and discussed non-linear or multi-frequency effects. These impressions highlight that Dvihastīya supports quick prototyping and fine-tuning. Finally, no user noted visual–haptic mismatch while interacting with the virtual objects, suggesting that the demos were immersive and stable enough to let them focus entirely on designing and tuning the haptic parameters.

Dvihastīya enables users to configure bimanual motion-coupled vibrotactile feedback for VR demonstrations illustrating its real-time usage. Beyond the above applications, Dvihastīya can be used to design a wide range of bimanual interactions, such as collaborative object manipulation (e.g., deforming clay, kneading dough, or stabilizing flexible materials) and training scenarios involving two-handed tools (e.g., operating pliers, tightening bolts with a wrench, tuning haptics for rowing or manipulating surgical instruments). Concrete movement-specific examples for which bimanual feedback can be designed include pulling exercise bands or tightening straps for stretching; bending semi-flexible materials, breaking sticks, or equivalent using both hands; wringing fabric, opening bottles, or coiling wires for twisting movements.

7 Discussion

We reflect on how findings from the studies extend our understanding of bimanual vibrotactile motion-coupled vibrations and the material experiences rendered with it.

7.1 Validating Bimanual Motion-Coupled Vibration Algorithm

The results of the psychophysics study show that vibrotactile crosstalk alone is sufficient to induce bimanual haptic experiences and a strong sense of connectedness between two unconnected controllers, thus eliminating the need for complex hardware. Even low crosstalk levels (33%) evoked a strong sense of connectedness, while higher levels (66%, 100%) progressively amplified the perceived strength of the connection. Crosstalk effects were more prominent in unimanual configurations (one hand stationary, one moving), where the stationary hand relied on crosstalk to perceive shared material experiences, whereas in bimanual configurations, the movement of both hands already generated motion-coupled feedback, reducing the need for additional crosstalk. Moreover, relative mapping outperformed absolute mapping in both connectedness (Figure 4) and naturalness (Figure 5), consistent with Guiard's model, which emphasizes that bimanual actions depend on the relationship between hands rather than their absolute positions [19], while also closely matching how humans naturally perceive bimanual interactions with strong inter-hand relationships than individual hand positions [23].

Although crosstalk was able to elicit connectedness in all three movement primitives, stretching was perceived to have stronger connection than bending or twisting. This suggests that vibrotactile grains are more readily interpreted as counterforces in isotonic actions such as stretching [55], whereas bending and twisting involve more complex torque and differential hand movements, which might have made the feedback harder to interpret. These findings are also seen in the JND differences for the three movements with *pseudobend* [21], indicating a strong need for having a physical prop to provide resistance and opposing force for bending and twisting actions.

Finally, bimanual motion-coupled vibrotactile rendering method where the pulses are simultaneously presented in sync on both hands, plays a part in rendering a unified material experience between the two hands, going beyond the established single-point material rendering [57, 62]. This finding directly supports the observation by Squeri et al. [50] that the brain integrates bilateral haptic information into a unified percept. Our results show that the brain's integration mechanisms extend from natural bimanual exploration to artificially coupled vibrotactile stimuli, enabling connected experiences through vibrotactile crosstalk alone, without requiring physical object sharing or specialized hardware. This finding is particularly significant given that previous bimanual haptic systems in VR have relied on either grounded force feedback devices [13] or physical connectors between controllers [54], which limit accessibility and natural movement.

7.2 Material Perception through Parametric Crosstalk

We found that different crosstalk parameters map onto distinct perceptual dimensions of bimanual material interaction: amplitude for structural integrity, delay for propagation, grain for discreteness versus continuity and frequency for rhythm and pacing. These findings extend previous work on single-handed vibrotactile material rendering [47, 48] by showing how bimanual crosstalk can convey material properties. The amplitude crosstalk results demonstrate a clear progression from fragile/loose materials (A33) to robust/mechanical systems (A100), suggesting that amplitude primarily modulates perceived structural integrity and required effort. The differences in qualitative associations between studies highlight that a-priori user expectations play an important role in how crosstalk is interpreted, influencing whether users perceive hand connectedness or infer shared material properties. This underscores the value of thoughtful visual design in immersive bimanual VR experiences. The temporal dimension introduced by delay crosstalk reveals particularly rich material associations. The progression from immediate elastic coupling (D50) to propagative, viscous media (D400) demonstrates that temporal delays can effectively simulate the transmission of force through different material types, beyond moving a ball between two hands [41]. This finding is relevant to VR applications where realistic material behavior is crucial, as it suggests that simple temporal manipulation of vibrotactile signals between the hands can evoke complex material experiences without requiring sophisticated physics simulation [8, 35]. The dichotomy of frequency and grain crosstalk suggests that these parameters primarily influence the perceived granularity of material structure rather than overall material properties, with frequency affecting material character, as already touched upon in previous research for single-point material rendering with motion-coupled vibrations [49, 56]. Thus, different crosstalk parameters systematically influence material associations, providing insights into the perceptual dimensions of vibrotactile material rendering. User designs for connected bimanual experiences vs. unconnected ones (Figure 8) further highlighted that crosstalk plays an important role in establishing a shared experience in the presence of visual cues as well.

7.3 Implications of Bimanual Motion-Coupled Vibrations

Our findings have several important implications for the design of bimanual material experiences in VR. First, we showed that vibration crosstalk alone can create a sense of connectedness between the hands as well as convey material experiences for stretching, bending and twisting movements, showing that vibrotactile feedback can capture important aspects of bimanual interaction without relying on physical connections. Moreover, the superior performance of relative mapping suggests that bimanual haptic interfaces should prioritize inter-hand relationships over absolute positioning. This finding supports the design philosophy of *PseudoBend* [21], which focuses on relative deformations between hands using purely vibrotactile implementations and extends it to creating material experiences that do not require rigid physical connections. Second, the perceptual effects we observed follow consistent patterns: amplitude influenced how robust or solid a material felt, duration shaped how forces seemed to propagate, and grain or frequency affected the sense of texture and continuity. These relationships offer a clearer basis for design than trial-and-error approaches.

Finally, these mappings could inform authoring tools (beyond *Dvihastīya*) or heuristics that combine parameters into recognizable material experiences such as elastic bands, flexible rods, or coiled springs, thus making it easier and accessible for designers to create meaningful bimanual feedback with existing VR hardware.

7.4 Limitations and Future Work

While our approach demonstrates the potential of bimanual motion-coupled vibrations, some limitations must be acknowledged. We only formally investigated amplitude crosstalk, assuming other parameter crosstalk would similarly influence connectedness. While our method induces a sense of connectedness between the user's hands we did not compare our results to established research prototypes such as *gamesBond* [45] and *PseudoBend* [21]. Moreover, relying solely on vibrotactile feedback limits fidelity: real bimanual material exploration involves complex force transmission, proprioceptive integration, and kinesthetic cues that our approach cannot fully capture. In the unimanual tasks of both studies, participants used their dominant hand, which aligns with natural coordination patterns; however, the generalizability for the non-dominant hand is limited. Using the non-dominant hand might yield different levels of perceived connectedness and associated material experiences, and future work should examine whether the effects hold across hands. Along with differences in the users' knowledge of haptic design, the low-level parametric design space provided by *Dvihastīya* authoring tool was the reason for diverging designs for similar material properties. Moreover, insights from designing with our authoring tool are of an exploratory nature and should be considered as preliminary patterns for bimanual haptic design rather than generalizable guidelines. Another version of the authoring tool could explore the relationship between feedback parameters and their material qualities established in the qualitative study (section 5) and allow users to directly modulate material qualities and observe if the designs match their expectations.

Future research could combine our vibrotactile bimanual rendering with mechanically connected haptic devices [45, 54] to strengthen connectedness through both cutaneous and kinesthetic cues. Integrating multimodal feedback, such as audio or audio-haptic cues [14], could further enhance material perception. While we focused on isotonic actions like stretching, exploring isometric actions (to create experiences such as pushing into a virtual pillow with both hands), multi-point interactions, or bipedal/hand-foot combinations can extend the applicability of our approach. Moreover, our qualitative analysis can be extended with a quantitative perceptual mapping approach such as Multidimensional Scaling (MDS) to examine whether the systematic parameter variations produce similar dimensions across crosstalk conditions. An important next step is to examine how visual or multimodal cues interact with haptic cues in bimanual contexts. Because visual perception strongly shapes overall interaction percepts, studying combined visual–haptic feedback can clarify the individual and joint contributions of each sense to creating more immersive and coherent experiences. Theoretically, studies could investigate how the brain integrates spatially and temporally offset vibrotactile crosstalk to better understand multisensory mechanisms underlying perceived material unity. Furthermore, higher-level material-driven authoring tools based on the qualitative findings that allow designers to specify the desired material qualities need to be developed to enable personalized bimanual haptic design as well as for application-specific scenarios, including medical training, teleoperation, and collaborative VR.

8 Conclusion

Our work challenges the dominant trend of treating vibrotactile feedback in VR as an independent experience across hands by introducing an ungrounded bimanual motion-coupled vibration algorithm with crosstalk that links two unconnected hands to create a unified material experience. With two studies, we demonstrate that our algorithm induces a sense of connectedness even with low levels of crosstalk while higher levels shape the perceived quality of the interaction, inducing bimanual material qualities without specialized hardware. These findings extend motion-coupled vibrotactile rendering beyond single-point interactions and offer a flexible, accessible approach for designing cohesive bimanual experiences in VR. Finally with *Dvihastīya* authoring tool, we provide user impressions of designing bimanual vibrotactile experiences. This work opens opportunities for more immersive, intuitive, and widely deployable bimanual interactions in virtual environments.

Acknowledgments

This work is funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. This work is supported by ERC grant Kinesthetic Displays, Grant agreement ID: 101165100. This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 521601028. Andrea Bianchi was supported by the National Research Foundation (NRF), Korea, under Grant RS-2024-00436931.

Funded by the European Union

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A Technical Evaluation

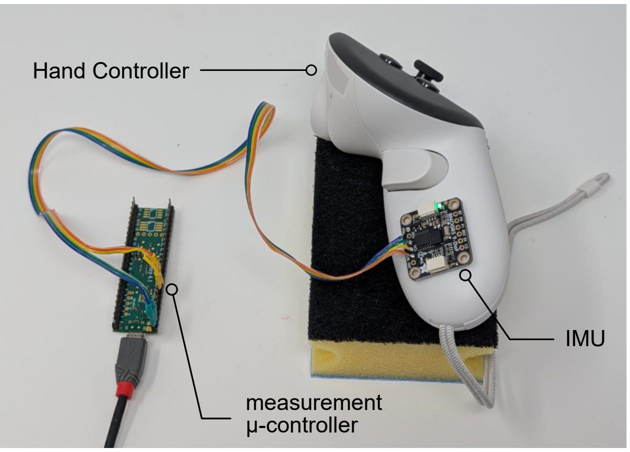

Figure 9: Technical setup used for measuring the latency between sensing and actuation as well as output acceleration of the Meta Quest 3 hand controller.

The latency between sensing the user movement to actuation was measured by placing an inertial measurement unit (IMU)-BNO085 with the accelerometer sampling frequency of 500Hz [6] on one of the hand controllers. The IMU was connected to a Teensy 4.1 microcontroller, which has a sampling rate of 600MHz. A physical tap was applied to the controller, producing an inertial spike that was simultaneously detected by the headset's in-built controller-tracking system and the external accelerometer. The hand controller and the accelerometer system were placed on a sponge to isolate the system from any environmental vibrations as shown in Figure 9. The controller vibrated when it received the tap. The vibration response produced by the controller's haptic motor was then captured as a second distinct spike in acceleration in the IMU trace. Latency was computed as the temporal difference between the onset of the physical tap and the onset of the resulting haptic pulse. All measurements were sampled at 500Hz and averaged over 30 trials. The latency was measured at 21.486 ± 1.426 milliseconds.

For measuring the peak-to-peak accelerations, we used the same setup and recorded for a controller frequency of 120Hz and three amplitude levels, corresponding to 100%, 70% and 40% of maximum amplitude. The signal at each amplitude level was recorded for 10 seconds (120 cycles of the waveform) and the peaks in positive and negative accelerations were averaged. The mean and standard deviations of the peak-to-peak accelerations at 100%, 70% and 40% of maximum amplitude were 2.62 ± 0.24G , 1.83 ± 0.17G, 1.07 ± 0.12G respectively.

B Details: Study 1 All plots

C VR Rendering Parameters

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[6] Referring to the datasheet of BNO08X: https://www.ceva-ip.com/wp-content/uploads/BNO080_085-Datasheet.pdf

Figure 10: Results of study 1 for strength of connectedness Ⓐ,Ⓑ and naturalness Ⓒ,Ⓓ for unimanual and bimanual configuration with action, mapping type and crosstalk.

Table 1: Obi Rope and Rod Implementation Parameters for the Elastic Band, Braided Wire, and Pool Noodle Objects.

Object	Type	Thickness	Stretch Compliance	Bend/Twist Compliance	Solver Substeps / Iterations
Braided Wire	Obi Rod (Chain)	0.02m	0	0.001	16 substeps; Bend/Twist: 20; Distance: 1
Pool Noodle	Obi Rod (Chain)	0.06m	0	0.02 (+ plastic 0.05)	16 substeps; Bend/Twist: 25; Distance: 1
Elastic Band	Obi Rope	0.03m	0.01	0	5 substeps; Distance: 20