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Re-envisioning Touch: Designing Embodied Material and Force Experiences with Motion-Coupled Vibrotactile Feedback

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Saarbrücken, ***December 2025***

gez. / signed

(*Nihar Gurunath Sabnis*)

Re-envisioning Touch: Designing Embodied Material and Force Experiences with Motion-Coupled Vibrotactile Feedback

❧

Notes on Overall Writing Style
Much of the research I present in this thesis was carried out in collaboration with other researchers and students. Therefore, I have used the scientific plural "we" at many places throughout the text. References to online resources (e.g., websites or web articles) are provided as URLs in footnotes. Long URLs have been shortened, and all links were last accessed on 9th October 2025. Additionally, I have URLs to demonstration videos and open-source repositories associated with the respective chapters. References to scientific publications are listed in the Bibliography at the end of the thesis.

Preface

In India, the 10th standard exam is often seen as the moment when one's future takes shape. When I finished mine in 2012, I found myself at the crossroads of two seemingly unrelated passions: science & technology on one side, and badminton on the other. My father even offered to support me in pursuing badminton professionally. But life nudged me down a different path -— one that led to a degree in Mechanical Engineering, with badminton continuing alongside as a semi-professional pursuit.

Whenever someone asked, "What do you want to do in the future?", I always said I wanted to pursue research. Yet, another quiet voice always followed: "But what about badminton?" For years, I carried both questions with me, unsure of how they could ever fit together.

The first real opportunity to merge these questions was when I was undergoing remote physiotherapy for a shoulder injury for Badminton due to COVID-19. I was experimenting whether asymmetric vibrations could provide movement guidance. These vibrations worked for giving directional cues, but they felt dull, external, and disconnected —- nothing like the natural, intuitive feedback you get from stretching a theraband or being guided by a coach's hand. *I knew something was missing.*

But then, on close observation, vibration is present all around us–vibrations occur as you move your hand through sand, crumble the paper or stretch fabric. These vibrations do not feel like artificial signals; they feel one with the material and our method of exploration because they are coupled to our own movements. They are inseparable from the action that generates them. *That single insight opened a door.*

What if we could design vibrations that feel less like alerts and more like the tactile experiences we know from the physical world? What if vibration could help us render textures, compliance, friction, or even guide movement intuitively?

Today, more than a decade later, I see this dissertatio, in some sense, as the bridge and the answer to those questions. It explores how vibrations coupled to user action can fundamentally reshape how we experience virtual materials, forces, and symbolic information. It documents my journey from viewing vibration as a signal to understanding it as an experience; from designing haptic effects to engaging with the perceptual principles that make them meaningful; from thinking about touch as a channel to appreciating it as a fundamental mode of being in the world.

This preface is my personal story of how the idea found me, and how I followed it into a PhD that bridges haptics, engineering and human perception. I invite you to read this thesis primarily as a technical contribution, with personal reflections that guided its direction. I hope the ideas and tools developed here encourage others to explore how vibration and action can together create richer, more intuitive haptic experiences, those that feel natural, responsive and closely aligned with our actions.

Acknowledgements

I take this opportunity to express my gratitude to every person, place, and moment that has shaped the journey leading to this dissertation. I focus here on the past four years: a period of intense learning, collaboration, frustration, discovery, and growth. It has been one of the most transformative phases in my life, and it would not have been possible without the people around me.

I would like to start with people who mentored me in this Ph.D. journey. I begin by thanking the person who shaped this Ph.D. journey most profoundly-—my supervisor, ***Dr. Paul Strohmeier***. Paul, thank you for taking a chance on me when I had no publications to my name, that too as your first Ph.D. student and for trusting that I could grow into a good researcher. Your belief in me laid the foundation for everything that followed. Working with you has taught me far more than academic rigor. You encouraged me to explore ideas I initially resisted—-qualitative research being the biggest example—-and showed me how diverse perspectives enrich haptic inquiry. I have learned from you how to think critically, how to question assumptions, and how to do research with care, integrity, and curiosity. Thank you for guiding me with patience, pushing me when I needed direction, and giving me space when I needed to find my own way. But above all, thank you for making me feel at home. Your check-ins, kindness, and genuine care made this journey lighter, gentler, and far more meaningful than it would have been otherwise.

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Ph.D. is a long journey, and it would have been quite dull if it without the people who walked alongside me. Everyone needs a Ph.D. buddy and I hope that everyone finds someone at least a fraction of what ***Dennis*** is for me. I can write a book about what I learned from him, but the short version is this: he shaped how I think, how I design, how I code. The endless discussions about everything from HCI research to spirituality. Bro, this Ph.D. is as much yours as it is mine. ***Courtney***, thank you for bringing colour to what used to be my black-and-white, quantitative view of research. Despite you leaving SenSInt, every qualitative interview I have conducted still feels like you are speaking through me. And sharing an office with you trained me for life–I can now work in a train station, a flour mill, or amidst absolute chaos without a single complaint. ***Johanna***–our Chief-Breaks-Officer–despite 2000 coffee breaks you made me take during the thesis, this thesis would not have been submitted without you, literally. ***Valentin***, I will miss your warm, home-cooked meals and the excitement of seeing fresh prints emerge from your 3D printer. ***Ata*** and ***Verena***, you were lifelines during this thesis. Knowing that you were in Saarbrücken was like having a second home—complete with the best food in the city. ***Easa***, "Teshachur Eliram" for being the friend I could call in every difficult moment. ***Gabi***, our trip to Spain was one of the best decisions I made during this PhD. Let's plan the next one soon. ***Louis***, thank you for showing that cool racket at Sports HCI-—an unexpected moment that turned into an important step toward embodied vibrotactile feedback for motor learning. ***Donald***, thank you for always being one call away. I still remember how you introduced me to people at CHI—-far better than I introduce myself! ***Bruno***, thanks to the countless hours of online meetings and look forward to many more. ***Don***, conducting foot-augmentation workshops with you and Dennis has been a joy, and now we have almost started a small community around it. To my co-authors—-***André, Erik, Marco, Maelle, Narjes***, and everyone-—thank you for bearing with me, and for consistently doing things not as I asked, but better, with your unique perspectives. Thank you to my colleagues at the Sensorimotor Interaction Group. Even though Paul led the group, he made sure we all feel at home-—something that shaped my experience more than he may realize.

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During my PhD I also had an opportunity to spend six months in South Korea for research. I returned after six months, but a part of me stayed there. *Kamsahamnida* ***JeeYoun, Jungwoo, Heeji, Jiwon, Zocia, Punn, Justin, MJ, Hashra, Ohsung, Tom, Kun-***

woo, Trimbak, my stay in Korea would have been empty if it wasn't for all of you. I would also like to express gratitude to all the secretaries (***Sabine, Petra, Anne, Ellen***) and admin people (***Felix, Maik and the IST Team***) who sorted everything so I could easily focus on research. Thanks Dennis and Prisha for your help with figures.

You can only jump as high as the safety net you know is beneath you–and in my life, that net rests firmly on four pillars. Those pillars are ***Aai, Baba, Shalvi, Jui***. Aai, Baba, thank you for accepting me with open arms every time I returned home. Your love, warmth, and unwavering belief in me made every trip to India refreshing and meaningful. You gave me the courage to move across countries and the reassurance that no matter how far I went, I always had a home to fall back on. ***Shalvi***, thank you for showing your love in your own unique ways. Your visit to Saarbrücken meant more to me than you know. And then there is the fourth pillar—-***Jui***. Well, thank you for being you: steady as a stone when everything else felt uncertain, pushing me forward when I was struggling, and pulling me back to earth when the ego wandered too high. As the Ph.D. journey comes to an end, a far more important one begins, and I am grateful that we will walk together, hand in hand.

The eternal and indefinite net is always provided by friends and family. Thank you ***Ajoba, Aaji, Suju and Sunita Maavshi.*** Even though our conversations were often limited to phone calls, your love, blessings, and warmth crossed continents and reached me unfailingly. I am grateful for our ***Vedanta Study Group***. The Summa Iru retreats–just twice a year–became powerful anchors that helped me reset, regain clarity, and gather the strength to keep going. They were a reminder that even in the intensity of a Ph.D., there is something deeper, much much much more powerful to lean on. Our 'Vishay Ahe Ka' group of ***Tamya, Pandya, Kaushya, Joshya, Jadya, Amdya*** are more than friends, they are family. We grew, debated, laughed, helped each other during all phases, and we continue to do so atleast for another five decades. Same goes with ***Monya, Harshal Patil, Darda, Sammy, Champagne***. With all of you, life was never just about the Ph.D.; it was about learning to grow—individually and collectively. As we move into the next phase of life, I hope we continue supporting one another while also finding ways to give back to society. Thanks ***Romin*** for our trips through Europe and random camping and hiking in Switzerland. Those breaks arrived at exactly the right time. ***Saurabh*** (Stavya's friend) and ***Stavya*** it was fun to walk along the advice we gave to youngsters and ourselves through *Khoj*. The search, as we often reminded each other, has only just begun. I would also like to thank Jnana Prabodhini and especially ***Nachiket Dada*** to have Jnana Prabodhini as a platform to showcase my prototypes, conduct workshops and stay connected to a larger purpose beyond academia. ***Amit Sir***, "I Am That," the book you introduced me to, continues to be my compass.

The pillars, the net and everything above holds because of the ground beneath it. That unwavering, steady and calm ground are my gurus ***Swami Chinmayananda, Subhodhananda, Vivekananda, Swami Maharaj, Swami Samartha, Frank & Paula Spronk***, no matter how high my head goes, it will always be at your auspicious feet.

Hari Om! *All of you raise me up to more than I can ever be!*

Abstract

Vibrations communicated through touch are central to how humans experience material and textural properties and forces when interacting with the world. Yet, most digital systems rely on simple vibrotactile cues that poorly approximate the dynamic tactile feedback of physical interactions. Motion-Coupled Vibration is a method of inducing sensations of materiality, connectedness, and force by rendering vibrotactile pulses generated-by and synchronized-with user action. This dissertation advances the design and understanding of motion-coupled vibrotactile feedback. Through five interconnected studies, the thesis investigates how motion-coupling transforms haptic experience across hands, feet, and whole-body interactions. It begins with Haptic Servos, open-source low-latency (<5 ms) haptic rendering devices that make motion-coupled feedback accessible to non-experts to create rich, embodied tactile experiences. Building on Haptic Servos, the thesis next examines why motion-coupled vibration feels more embodied than conventional vibration. Through a foot-pedal study, I show that motion-coupled feedback increases users' perceived control even when objective performance remains unchanged, revealing a dissociation between physical outcomes and subjective agency. This motivates a deeper investigation into underlying perceptual mechanisms. A follow-up study demonstrates that motion-coupled asymmetric vibration engages sensory attenuation, reducing perceived vibration intensity while preserving the force sensations. This method of rendering pseudo forces improves realism in Virtual Reality force rendering while also providing insight on why motion-coupled vibration is experienced as embodied. The dissertation then turns from perceptual mechanisms to examining how motion-coupled feedback reshape the design of tactile symbols. By contrasting hermeneutic (symbolic) and embodied (intuitive) mediation, the designers integrate material metaphors and lived experiences with motion-coupled feedback. This expands the expressive palette of tactile symbols, enabling tactile symbols that feel intuitive and embodied. Finally extending this approach to bimanual interaction, I demonstrate how introducing tunable vibrotactile crosstalk between two devices can evoke a sense of connectedness between the hands, enabling the rendering of virtual bimanual materials without mechanical linkages. This work culminates in Dvihastīya, an authoring tool for crafting such experiences in VR. Together, these studies position motion-coupled vibrotactile feedback as a ***unifying design principle*** for creating richer, more embodied haptic experiences. This thesis contributes conceptual frameworks, technical tools, and empirical insights that advance a holistic, motion-coupled approach to creating embodied haptic experiences.

Keywords: touch, motion-coupled vibration, embodied experiences, perceptual mechanisms, vibrotactile feedback, haptic interfaces, haptic interaction, virtual reality.

Zusammenfassung

Durch Berührung wahrgenommene Vibrationen sind zentral dafür, wie Menschen Materialeigenschaften, Texturen und Kräfte erleben. Digitale Systeme nutzen jedoch meist einfache vibrotaktile Signale, die das dynamische Zusammenspiel zwischen Bewegung und taktilem Feedback nur unzureichend wiedergeben. Bewegungsgekoppelte Vibration – vibrotaktile Impulse, die von der Nutzeraktion erzeugt und mit ihr synchronisiert werden – bietet einen Ansatz, um Empfindungen von Materialität, Verbundenheit und Kraft realistischer darzustellen. Diese Dissertation untersucht in fünf miteinander verbundenen Studien, wie bewegungsgekoppeltes vibrotaktiles Feedback die haptische Wahrnehmung über Hände, Füße und bimanuale Interaktion hinweg verändert. Zunächst werden mit den Haptic Servos, quelloffenen Low-Latency Rendering Geräten (<5 ms), neue Werkzeuge bereitgestellt, die solche Feedbackformen für Nicht-Expert*innen zugänglich machen. Darauf aufbauend wird erforscht, weshalb sich bewegungsgekoppelte Vibration verkörperter anfühlt als herkömmliche Vibration: Eine Pedalstudie zeigt, dass sie die wahrgenommene Kontrolle erhöht, selbst ohne Leistungssteigerung, und eine Folgestudie belegt, dass bewegungsgekoppelte asymmetrische Vibration sensorische Dämpfung aktiviert und so Vibrationsintensität reduziert, während Kraftempfindungen erhalten bleiben. Im nächsten Schritt wird untersucht, wie diese Erkenntnisse das Design taktiler Symbole erweitern. Der Vergleich hermeneutischer (symbolischer) und verkörperter (intuitiver) Vermittlung zeigt, dass bewegungsgekoppelte Vibration den Gestaltungsspielraum für haptische Bedeutungen deutlich vergrößert. Abschließend wird demonstriert, wie vibrotaktiles, abstimmbare Übersprechen zwischen zwei Geräten ein Gefühl bimanualer Verbundenheit erzeugt und so virtuelle Materialien ohne mechanische Kopplung erlebbar macht. Dies mündet im Autorentool Dvihastīya für VR. Insgesamt positioniert die Dissertation bewegungsgekoppelte vibrotaktile Rückmeldung als ein einheitliches Designprinzip zur Gestaltung reichhaltiger, verkörperter haptischer Erfahrungen und liefert konzeptionelle, technische und empirische Beiträge zu einem ganzheitlichen haptischen Interaktionsansatz.

Die Schlagwörter: Berührung, bewegungsgekoppelte Vibration, verkörperte Erfahrungen, Wahrnehmungsmechanismen, vibrotaktiles Feedback, haptische Schnittstellen, haptische Interaktion, virtuelle Realität.

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List of Contributions

Here I provide an overview of the contributions made by the author (me) throughout this thesis. The **"Author"** column lists the work conducted solely by the thesis author. The **"Author and Collaborator(s)"** column identifies contributions jointly carried out by the author and collaborators. The **"Collaborator(s) under guidance of author"** column highlights work completed by collaborators such as students and research assistants under the author's supervision. Finally, the **"Collaborator(s) only"** column denotes contributions primarily made by collaborators.

Chapter 7 is where I draw a lot of work done with collaborators where except for the Section 7.2.2, other works were led by the corresponding first authors. For the main chapters of this thesis, the contributions are as follows:

Table 1: *Overview of contributions by the author and collaborators.*

	Contributions of		
Author	**Author and Collaborator(s)**	**Collaborator(s) under Guidance of Author**	**Collaborator(s) only**
PhD thesis writing			
Haptic Servos: Generating Material Experiences Chapter 2 - **References** (Sabnis et al., 2023a) (**Published CHI 2023**)			
PhD thesis writing Implementation Application Development	Idea Paper writing Concept Development Algorithm Study Design Qualitative Analysis	-	Latency Evaluation Conducting Workshops PCB Development
Foot Pedal Control Chapter 3 - **References** (Sabnis et al., 2025a) (**Published TEI 2025**)			
Paper writing PhD thesis writing Concept Development Algorithm Development Study Design Conducting User Studies Application Development	Idea Setup Implementation Quantitative Data Analysis VR Implementation	-	-
Motion-Coupled Asymmetric Vibration Chapter 4 - **References** (Sabnis et al., 2025b) (**Published CHI 2025**)			
Paper writing PhD thesis writing Concept Development Algorithm Development Conducting User Studies Data Analysis (All)	Idea Study Design VR Implementation	Hardware Design	-
Tactile Symbol Design with Continuous and Motion-Coupled Vibration Chapter 5 - **References** (Sabnis et al., 2023b) (**Published CHI 2023**)			
Paper writing PhD thesis writing Concept Development Algorithm Development Study Design Conducting User Studies Application Development	Idea System Development Qualitative Data Analysis	-	-
Bimanual Motion-Coupled Vibration with Crosstalk Chapter 6 - **References** (Sabnis et al., 2026) (**Published CHI 2026**)			
Paper writing PhD thesis writing Concept Development Algorithm Development VR Development Conducting User Studies Application Development	Idea Study Design	Toolkit Evaluation Scene Development	-

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1 Introduction

"The senses are the gateways through which the Self encounters the world."
(Adapted from the Mandukya Upanishad)

The Mandukya Upanishad, one of the cornerstones of Indian Philosophy describes the self (ātman) as moving through three experiential states: waking, dreaming, and deep sleep, each defined by how consciousness relates to the world. In the waking state, the Upanishad says, we encounter the world "outwardly," through the senses, receiving its forms, sounds, smells, and textures. This thought aligns remarkably well with contemporary views in cognitive science: perception is not passive reception but an active encounter, a skilled way of being in the world. Nowhere is this more evident than in the sense of touch.

1.1 Designing With and For the Sense of Touch

Touch is one of the first senses to develop, the last one to fade, and arguably the most fundamental for grounding our bodily existence. From the moment a baby wraps its fingers around a mother's hand, touch becomes the first medium of interacting with the world (Benoit et al., 2018; Addabbo et al., 2015). This earliest tactile gesture is a form of *embodied knowing*: the infant learns the world not by representing it, but by *contacting* it. Long before we learn to speak or see clearly, the tactile contact with the body already enables understanding of pressure, warmth, softness and texture in an immediate, embodied, and profoundly relational way. Moreover, the sense of touch is unique as it simultaneously senses and shapes movement (Serino et al., 2010), and covers the entire body (Van Breda et al., 2017; Culbertson et al., 2018). Thus, we as humans perceive the world and act upon it using the sense of touch.

In our daily life as well, touch remains our primary medium for engaging with the world. While gripping a toothbrush, kneading dough, pushing a door, crumbling a piece of paper, sweeping fingers across grass, or feeling the stretch of fabric between our hands, we interact with the world dynamically using the sense of touch. When we perform these actions, the perceptual experience communicated through our tactile modality is not abstract data. Instead, these actions synchronously create micro-vibrations during the interaction which play a role in creating material experiences of roughness while dragging (Lederman et al., 1999), softness with pressing (Kuchenbecker et al., 2006), etc. Thus, actions generate sensations and these sensations further guide our actions, allowing us to not just observe the world but participate in it.

Through the sense of touch, we perceive a wide range of material properties – softness, compliance, texture, temperature and even pain (Lederman, 1982; Chen et al., 2009; Classen, 2012). Somatosensory research has shown that this richness is supported by the expressive peripheral system and also plays a role in shaping our tactile experiences (Johansson et al., 2009). Material properties like softness, compliance, and texture are primarily conveyed using vibrations and the perceptual variance in material textures can primarily be explained with the vibrational signatures elicited during exploratory movements (Bensmaïa et al., 2005a). Moreover, foundational work by Lederman et al. (1987) showed that humans employ specialized Exploratory Procedures such as pressing for compliance, lateral motion for texture, and static contact for temperature to perceive object properties. These procedures are inherently action-based: to feel texture, we move; to gauge softness, we press; to detect shape, we trace boundaries. This means that tactile perception is not merely sensory input but an ongoing loop between motor activity and sensory feedback. Most of the properties mentioned above like softness, compliance and texture are mediated by vibration (BensmaÏa et al., 2003).

The perceptual benefits of vibrotactile feedback in conveying material properties have led to vibrations being one of the most used modalities in artificial haptic systems (S. Choi et al., 2012). This vibrotactile feedback is primarily conveyed using vibration actuators. Vibrotactile feedback comes with its practical advantages such as the actuators being small, inexpensive, lightweight, power-efficient, and easy to integrate into mobile and wearable devices (Culbertson et al., 2018). Moreover, these actuators can be used to display potentially large amounts of information like tactile instructions and cues to users (Wittchen et al., 2022; Huang et al., 2025). These properties have made it the dominant form of haptic actuation in consumer technologies, from smartphones to game controllers, enabling what Colgate et al. (2025) refer to as the "democratization of haptics". This "democratization of haptics" reflects how accessible, low-cost vibrotactile technologies have broadened who can design, experience, and benefit from haptic interfaces, shifting them from specialized research labs into everyday consumer products. In addition to these pragmatic benefits, vibrotactile feedback stimulates the same mechanoreceptive pathways that encode natural vibrations when exploring surfaces or materials, allowing artificially generated signals to modulate, or shape the material experiences users would normally encounter through physical interaction (Biswas et al., 2021). Thus, *vibrotactile stimulation offers an opportunity to engage with the sensorimotor mechanisms that underlie how people construct material understanding through active touch.*

Despite technical advancements in haptic actuation, the expressive range of digital vibration remains vastly limited in variety and richness compared to the subtle, nuanced, and action-dependent tactile interactions we experience in the natural world (O. Schneider et al., 2017; Klatzky, 2025). The artificial tactile effects produced by digital devices feel monotonic, externally imposed and perceptually detached from the user's action. For instance, consider the "buzz-buzz" vibration of a smartphone which is used when the user unlocks the phone, for a notification, or to indicate a change in direction when using maps. This vibration does not depend on how I move my finger, how I grip the device, nor how I carry my phone. It feels like an externally imposed sensation which is disconnected from my body with the purpose of notifying me of an event originating outside my body. However, this very design illustrates a broader limitation: most vibrotactile feedback in consumer devices is not interactive or action-contingent. Rather than responding to what the user does, it simply delivers a fixed signal, which limits its potential for creating richer, embodied, and dynamically responsive tactile experiences. As a result, such vibrations often remain separate from the user's sensorimotor loop, feeling more like detached alerts than tactile sensations integrated with one's own actions.

For decades, the field of vibrotactile haptics has tried to bridge this gap (Van Erp et al., 2002). Research has explored a variety of perceptual illusions such as apparent tactile motion, the cutaneous rabbit, the saltation effect, the rubber hand illusion and pseudo-haptic effects, to render more realistic and expressive sensations using artificial haptic feedback (Culbertson et al., 2018; Ziat et al., 2023). Apparent tactile motion produces the sensation of vibration sweeping continuously across the skin by sequentially activating actuators with controlled timing and spacing (Burtt, 1917), and has been used in wearable navigation devices (Jones et al., 2006) and in 1-dimensional or 2-dimensional handheld arrays (Seo et al., 2013; Seo et al., 2015). Phantom sensations occur when two actuators fire simultaneously: users feel a single "virtual" vibration somewhere between them, with its perceived location determined by the relative amplitudes (Alles, 2007). A related phenomenon, sensory saltation or the cutaneous rabbit effect, creates the impression of a stimulus "hopping" along the skin when discrete vibration pulses are presented in rapid succession at spatially separated locations (Geldard et al., 1972). These illusions show how the brain integrates spatiotemporal patterns of stimulation into coherent tactile experiences, enabling haptic designers to evoke complex sensations without mechanical actuation at every location on the body where the illusion is created.

Despite thoughtful design of vibrotactile patterns, illusions and increasingly sophisticated actuators, these approaches share a fundamental limitation: *they treat perception as a passive process, which is only dependent on how the stimulus is crafted, but is disconnected from how the user acts.* However, this overlooks how sensorimotor principles make touch meaningful in the first place: our perception emerges not from passively receiving signals but from actively generating them through movement. When digital haptic systems deliver vibrations to the skin without accounting for how the users move, modulate force, or explore an object, they break the action-perception loop. As a result, most of these vibrotactile cues often feel external, symbolic, or "buzz-like", lacking the embodied nature of natural touch. This disconnect–between how digital haptic feedback is engineered and how tactile perception actually works–forms the central motivation of this dissertation.

1.2 Positioning my Research

We as humans constantly rely on naturally occurring vibrations when interacting with the physical world, especially when the surface or material is expressed using a tool.

For example, consider Merleau-Ponty's famous illustration of how a blind person's cane becomes an extension of their bodily perception: the cane is not felt as an object in the hand, but rather the world is felt *through* it (Merleau-Ponty et al., 2013). Don Ihde similarly argues that tools mediate and transform perception, allowing the user to "feel" the world at a distance; the cane becomes a channel through which vibrations from surfaces and objects are interpreted as meaningful sensory information. In both accounts, vibration is the medium through which the world becomes intelligible (Ihde, 1990; Ihde, 2002). Building on these philosophical insights, a central challenge for artificial vibrotactile systems is to recreate this same sense of *feeling* through an interface—requiring vibrations that are not merely delivered to the user, but arise in coordination with their actions.

To address this, a stream of research has explored vibration which is tightly coupled with user action to render realistic material experiences. The principle of distal attribution states that for the virtual interaction to realistically mimic the real interaction, the rendered signals must behave in an aligned and coherent manner to match the motions made by the user (Loomis, 1992). Based on this principle, effective rendering of vibrotactile signals requires complex models of pre-recorded data that is created prior to rendering the feedback. Okamura et al. (1998) modeled the vibrotactile feedback from patterned textures as data-driven decaying sinusoids which depends on the user's speed of exploration and applied force. On similar lines, Guruswamy et al. (2009) modeled textures based on a spatial distribution of infinite impulse response filters that are fit with decaying sinusoids. Seminal work by Joseph M Romano et al. (2011) demonstrated that when a pen moves across a surface, vibrations recorded during exploration on different surfaces can be replayed in synchrony with movement to simulate textural experiences on a smooth surface. Work done by Culbertson et al. (2014) is based on developing textures using autoregressive models that are depended on the user's normal force and scanning speed. These approaches, which I classify as high-fidelity rendering of vibrations corresponding to user movements, aim to replicate real-world interactions with rich detail, following the principle that rendered signals should behave physically appropriate if they are to feel realistic.

Parallel to this, a second line of work explores simplified motion-coupled mappings, where vibration pulses are triggered when user's force while pressing or user's displacement while moving crosses certain thresholds. Work done by Kildal (2010) pioneered this method of simplistic motion-coupled mappings to render virtual compliance experiences. More recently there has been research on developing simplified algorithms for mapping the user action to vibrational feedback to create experiences of moving on textural surfaces when moving a slider (Strohmeier et al., 2017) and in midair (Strohmeier et al., 2018), introducing flexible feeling in rigid objects (Strohmeier et al., 2016), as well as creating virtual bending, twisting and stretching effects on a rigid rod (Heo et al., 2019). Moreover, Strohmeier et al. (2020) showed that material experiences can be generated on other body parts such as feet to create experiences of walking on different virtual surfaces. These approaches do not reproduce real materials but approximate the perceptual cues that give rise to material experiences. This low-fidelity, heuristic approach demonstrates that rich material experiences can emerge even from simple, discrete vibrotactile pulses.

Across literature, these methods are referred interchangeably as *Motion-Coupled Vibration (MCV)* (*Strohmeier et al., 2017*), *motion-coupled vibrotactile feedback, grain-based vibrations* (*Heo et al., 2019*) *or grain-based vibrotactile feedback* (*Mun et al., 2025*). In this thesis, I adopt the term Motion-Coupled Vibration to mean: ***vibrotactile pulses, which are generated by and synchronized with, the user's own movement.*** MCV has shown to induce embodied material experiences and shape the way users perceive and interact with objects around them, while fundamentally changing how tactile information is perceived, interpreted, and used for interaction. Crucially, unlike high-fidelity approaches, MCV leverages the tight coupling between user-action and vibrotactile feedback to evoke convincing and engaging tactile experiences using minimal computational or hardware complexity. High-fidelity rendering delivers realism but requires dense data, detailed modeling, and careful calibration, where its realism is dependent on accuracy. In contrast, MCV induces material experiences through responsiveness rather than representational fidelity. Because the feedback emerges directly from the user's movement, even simple pulses can feel meaningful, embodied, and action-relevant.

My goal in this dissertation is therefore not to chase realism or to replicate the tactile nuances of specific materials, but to investigate how simple, movement-dependent vibrotactile cues can transform interaction, perception, and the user's sense of engagement with digital objects. Instead, I focus on understanding why simple vibrotactile pulses, when embedded in the closed-loop of action, can fundamentally alter how material properties are perceived; why they feel perceptually embodied rather than external; and how these mechanisms can be harnessed for new forms of interaction.

To elaborate, much of the existing literature treats MCV primarily as a technical means to render virtual material properties, without fully engaging with the perceptual principles that make such feedback feel embodied. A closer examination reveals three persistent gaps that shape the motivation of this dissertation. First, although MCV can convincingly induce sensations of virtual compliance, friction, and texture, the perceptual mechanisms that make these experiences feel embodied differing profoundly from externally generated vibrations, are not fully understood. Existing explanations are often speculative and lack systematic empirical grounding. Second, the broader domain of vibrotactile pattern design develops symbolic, hermeneutic vibration cues (such as tactons and rhythmic patterns) that must be interpreted, yet remains largely disconnected from research on MCV, which produces direct, embodied, material-like sensations. How these two design spaces relate, how they differ, and if they can be integrated into a combined framework is still unknown. Third, despite the inherently distributed and multi-site nature of natural touch, most MCV research has relied on single-point actuation, limiting our understanding of how motion-coupled feedback behaves when extended across the body or across coordinated limbs.

My dissertation addresses these gaps while merging the research on haptic interaction and interface design with Human-Computer Interaction, psychophysics and human perception. I position my dissertation between haptic material rendering and embodied interaction while bridging the gap between the psychophysics of touch (understanding how we feel) and the engineering of haptic interfaces (building tools to make us feel material experiences). I use MCV as the central concept, not simply as a rendering technique as done in previous research, but to understand the underlying perceptual phenomena with implications for designing haptic interactions.

To address these research gaps, my research expands motion-coupled feedback in four directions. First, I develop a ubiquitous, low-latency platform—Haptic Servos—that allows MCV to be generated across objects, hands, feet, and even electrotactile interfaces. Second, I investigate why MCV feels embodied through two key perceptual mechanisms: Sensory Attenuation (self-generated sensations feel weaker than external ones) and subjective sense of control (the feeling of being in control of one's actions and resulting sensations). Third, I explore how these insights can extend beyond material rendering into tactile symbol design leveraging embodied mediation. Finally, I introduce the use of MCV using crosstalk to go beyond single-point actuation for creating material experiences during bimanual interaction.

Although each chapter presented here relies on the coupling of human action to vibrotactile output and has a philosophical or everyday experience which inspired the scientific investigation, the chapters differ in:

- Modality: Interactions involve a single hand, fingers for grasping, feet based interaction and bimanual coordination.
- Underlying Perceptual Mechanisms: Sense of Agency and Sensory Attenuation
- Application Domain: Ranging from material rendering and tactile symbols to sports equipment and shoes for walking.

Each chapter is structured as a standalone published paper, containing its own related work, methods, and contributions. The only exception is Chapter 7, which highlights the utility of our work. This introductory chapter therefore provides a conceptual overview rather than a detailed literature survey. Together, these investigations bridge embodied interaction with vibrotactile material rendering, moving towards vibrotactile experiences which feel embodied. This conceptual foundation motivates the research questions that structure the dissertation and guide the investigations in the chapters that follow.

1.3 Research Questions

The primary research question at the core of the thesis is, "**RQ0: How can motion-coupled vibrotactile feedback (MCV) be used to design tactile experiences that feel embodied, realistic and perceptually integrated with human action?**". This overarching question ties together all chapters: the technical foundation (Chapter 2), the underlying perceptual questions (Chapter 3, Chapter 4), the tactile symbol design questions (Chapter 5), and the questions on extending MCV beyond single-point rendering (Chapter 6).

1.3.1 Technical and Perceptual Foundation of Motion-Coupled Vibration

Motion-Coupled Vibration has been established in research as a method of rendering virtual material experiences. Despite this shared goal, most prototypes, systems, devices or algorithms developed in these research papers use their own sensing, processing and vibrotactile actuation pipelines. However, when we press into a sponge, move our hand over a texture or stretch fabric between our hands, these actions – though physically different – share a common underlying mechanism: interaction with a material generates micro-vibrations that help us perceive its properties. This suggests the possibility of a unified approach, where a single system could adaptively render material experiences across diverse user actions. Hence, we ask:

RQ1: How can we develop a system which is able to render corresponding material experiences across different user actions, such as compliance for pressure and texture for movement? This question is answered in Chapter 2.

This question can be unpacked into 4 sub-questions:

- **RQ1-1:** What hardware and software principles can enable low-latency mapping from human action to vibrotactile output? (answered in Chapter 2).
- **RQ1-2:** What are the experiential differences when interacting with motion-coupled vibration compared to continuous vibration? (answered in Chapter 2).
- **RQ1-3:** How can motion-coupled feedback be made usable for non-experts, lowering the barrier for designers and researchers to experiment with embodied haptic rendering? (answered in Chapter 2).
- **RQ1-4:** How can such a system be applied across different human-body modalities and applications? (answered in Chapter 7).

1.3.2 Understanding Perceptual Mechanisms which make MCV Embodied

Research on Motion-Coupled Vibration shows that the vibration often "feel embodied" and is able to render virtual material experiences (Strohmeier et al., 2016; Strohmeier et al., 2020). However, the field lacks grounded empirical understanding of *why Motion-Coupled Vibration feels embodied*. Theories of predictive processing and motor-based attenuation suggest that self-generated sensations are processed differently, but this has not been systematically tested for MCV. This leads us to the question:

RQ2: How do perceptual mechanisms such as Sense of Agency and Sensory Attenuation play a role in perceiving motion-coupled vibrations as embodied? This question is answered in Chapter 3 and Chapter 4.

We further subdivide this question into sub-questions:

- **RQ2-1:** Does coupling vibration to user action suppress the perceived intensity of the signal, while maintaining the induced material quality? (answered in Chapter 4).
- **RQ2-2:** Asymmetric vibrations shown to induce sensations of force, are inherently linked to vibrations. By coupling asymmetric vibrations with user action, can we detach the vibration experience of vibration from the experience of induced pseudo force? (answered in Chapter 4).
- **RQ2-3:** How do material experiences rendered using MCV influence the user's subjective sense of agency and objective performance? (answered in Chapter 3).

1.3.3 Designing Tactile Symbols with MCV

Traditionally tactile symbols rely on abstract, discrete and rhythmic patterns. For instance, mobile phone vibrating for a notification is an example of a traditional tactile symbol. However, these tactile symbols feel disconnected, disruptive and even annoying to the users (Strohmeier et al., 2018; E. Kim et al., 2020). With MCV, we are able to render material experiences that emerge through interaction between user action and the corresponding vibrotactile feedback. Hence, we ask,

RQ3: How can motion-coupled vibrations be used to design tactile symbols along with continuous vibration, bridging Embodied and Hermeneutic Mediation? This question is answered in Chapter 5.

1.3.4 Beyond Single-Pointed MCV:

Until and including Chapter 5 in my dissertation and also in literature, MCV rendering focuses on a single fingertip, hand or device. Yet many real-world activities such as wringing clothes, stretching a theraband, bending a stick or opening a jar are inherently bimanual. This leads us to the question,

RQ4: How can we design motion-coupled vibrotactile feedback for rendering material experiences such as stretching, bending and twisting which are primarily experienced in bimanual interactions?

Together, these questions move from building a platform and applications using this platform, to explaining why it works, how it can be used for designing tactile symbols, and finally to understanding its scaling for bimanual applications. At each stage, the inquiry is grounded not only in technical development, but also evaluated using empirical studies.

1.4 Methods and Approach

To answer the above-mentioned research questions, I leverage established methods in the fields of Human-Computer Interaction (HCI), qualitative analysis and psychophysics.

Throughout this thesis, I present several individual research projects, each following an approach structured around three central phases:

1. **Concept Development/ Research Rationale:** I develop concepts for novel vibrotactile rendering approaches for creating material experiences based on new ideas, identified requirements, underlying perceptual mechanisms, and insights from related work.
2. **Implementation:** These concepts are transformed into high-fidelity prototypes, devices, and algorithms involving the creation of novel hardware and/or software components.
3. **Evaluation:** The developed systems, prototypes and algorithms are investigated through structured user studies and experiments, aiming to evaluate their effectiveness or to derive psychophysical insights.

Specifically we develop one system to render MCV to answer research questions **RQ1-1, RQ1-2, RQ1-3** in Chapter 2, and demonstrate the applications of the developed system to answer question **RQ1-4** in Chapter 7. The development of systems in Chapter 2 and Chapter 7, included an extensive development of the technology stack. Implementation ranged from hardware development (e.g., 3D printing, laser cutting, optimization, electronic circuits and PCBs) to low-level software engineering (e.g., microcontroller programming), signal design and processing. To address **RQ2-1, RQ2-2** we developed a motion-coupled asymmetric vibration algorithm and compared the perceived vibration and pseudo force with continuous asymmetric vibration. **RQ2-3** was addressed by evaluating MCV on a foot-pedal interface and measuring performance and subjective sense of control. Along with developing hardware similar to Chapter 2, we also focused on the low-level software engineering of designing novel algorithms along with interactive VR applications. In Chapter 5, we address **RQ3** by developing Graphical User Interface (GUI) and Tangible User Interface (TUI) along with the required electronics and low-level software development. Finally in Chapter 6, we used commercial hardware and developed novel algorithms using high-level software development (e.g., programming with 3D-engines, development of VR applications, user interfaces, and setup for conducting experiments and collecting data) for addressing **RQ4**. We also developed an authoring tool for designing crosstalk-based bimanual vibrotactile feedback.

Primarily, evaluations were conducted as controlled laboratory user studies for all the projects. Exceptions include a workshop study conducted for Chapter 2, real-world user impressions for 'Tactile Augmented Shoes' (Section 7.2.1) and a demo at a conference for VibRacket (Section 7.2.2). We collected data using both qualitative and quantitative methods. More specifically, Microphenomenology inspired interviews were conducted for understanding the structure of experience when interacting with MCV in Chapter 2 (Claire Petitmengin et al., 2018). Semi-structured Interview interviews were conducted for all the chapters where Chapter 2 and Chapter 5 were analyzed using established methods such as thematic analysis (Braun et al., 2012), whereas the interviews in Chapter 4, Chapter 3 and Chapter 6 were analyzed using qualitative content analysis. For the quantitative measurements, we predominantly used psychophysics analysis of magnitude estimation (George A Gescheider, 1988; George A. Gescheider, 2013) in Chapter 4, Chapter 3 and Chapter 6. 2-Alternative Forced Choice protocol to evaluate design preferences in Chapter 5. System measures including latency measurement and signal analysis were done in Chapter 2, Chapter 4 and Chapter 6.

1.5 Contributions

The overall goal of my thesis is to advance our understanding of motion-coupled vibrotactile feedback. I show that this seemingly minimal form of haptic rendering can serve as a foundation for designing material experiences, explaining embodied perception, building new vibrotactile feedback systems, shaping the way we interact with the world around us, exploring bimanual material experiences and designing tactile symbols grounded in both Embodied and Hermeneutic modes of Mediation. This thesis makes a threefold contribution to the field of HCI, advancing the theoretical foundations, technical capabilities, and empirical understanding of motion-coupled vibrotactile feedback. Each chapter describes the individual contribution made with that chapter, however here I describe synthesized contributions across the thesis:

Theoretical Contributions

A major contribution of this thesis lies in extending the theoretical foundations of how Motion-Coupled Vibration interact with human perception, embodiment, and tactile sense-making. The dissertation advances theory through:

- *Coupling sensing and actuation for creating material experiences:* Although this has been shown throughout the thesis, in Chapter 2, I provide empirical evidence that tight temporal coupling between movement and vibration is sufficient to shift tactile experience from “buzzing actuator” to “material-like response,” thus contributing to an empirical theory of embodied haptics.
- *Exploratory Research for why motion-coupled vibrations feel embodied:* I provide experimental evidence of how the embodied nature of motion-coupled vibration can be attributed to the perceptual mechanisms of Sense of Agency (Chapter 3) and Sensory Attenuation (Chapter 4).
- *Sensory Attenuation as a Design Tool:* While showing that Sensory Attenuation plays a key role in mitigating the perceived vibrations in motion-coupled vibration renderings, we present it as a tool which can be leveraged to design vibrotactile feedback, while also using it as a metric to quantify embodiment (Chapter 4).
- *Advancing pseudo-force rendering:* By coupling asymmetric vibrations with user action, I refine how pseudo forces can be rendered—maintaining the force sensations while reducing unwanted vibratory sensation (Chapter 4).

- *Qualitative evidence for material perception illusions:* The studies in all the chapters contribute to a growing body of qualitative observations, (as well as Microphenomenology inspired observations in Chapter 2, Chapter 5, showing how haptic illusions emerge from the closed-loop interplay of sensing and action.
- *Broadening the Tactile Symbol Design Space:* With Chapter 5, I provide a framework for designing tactile symbols with motion-coupled vibrotactile feedback along with conventional method of designing them as rhythmic vibrotactile patterns.
- *Insights of Input-Output mappings for rendering effective Motion-Coupled Vibration:* In Chapter 8, I discuss how specific input parameters of MCV structure the creation of material experience and how the corresponding output parameters of the vibration shape the tactile experiences.

Technical Contributions

Besides advancing theories, this thesis also makes several contributions which are more technical in nature.

- *Haptic Servos Platform:* We developed a low-latency (<5 milliseconds) sensing to actuation pipeline for generating motion-coupled vibrotactile pulses, enabling real-time, high-fidelity material rendering (Chapter 2). Haptic Servos take care of all the timing critical components and input-mapping to enable designers to focus on designing the haptic experience. We present Haptic Servos in two form-factors: an elaborate one for hobbyists and a compact one for embedded development.
- *Vibrotactile Augmentation Platform for Embodied and Hermeneutic Feedback:* We introduce a tactile augmentation platform which can be interfaced with a Graphical User Interface to design tactile symbols that integrate both motion-coupled grains and symbolically structured rhythms, expanding the tactile symbol design space available to haptic designers (See Chapter 5).
- *Crosstalk-based bimanual motion-coupled vibrotactile feedback:* I present a crosstalk-based extension of grain-based rendering for bimanual material rendering in Chapter 6. By introducing crosstalk in amplitude, grains, frequency and duration, the algorithm enables designing material experiences between the two hands. This method advances the established research on single-point motion-coupled vibrotactile feedback rendering.

Design Contributions

Thirdly, this thesis also contributes to design guidelines, devices and application-driven demonstrations based on the theoretical and technical contributions.

- *A suite of applications built on Haptic Servos:* Across six projects (Chapter 7), I was involved in or led, I demonstrate how motion-coupled vibrotactile feedback can be adapted to different body locations and wearable interfaces, along with demonstrating experiences for as well as using electrotactile feedback, sports equipment, and kinesthetic illusions.

- *Invisibow: Combining two haptic illusions* Although not the focus of Chapter 4, the Invisibow project demonstrates how combining tendon vibration with asymmetric vibration creates a compelling overall sensation of drawing an arrow with a bow, illustrating the potential of combining two classical illusions.
- *Design guidelines for tactile symbol creation.* I derive actionable guidelines for designing tactile symbols that combine embodied (motion-coupled) with hermeneutic (continuous) vibrotactile feedback, grounded in empirical user data and qualitative interviews (Chapter 5).
- *Authoring Tool for designing bimanual motion-coupled vibrotactile feedback:* Based on the insights of the studies of bimanual motion-coupled vibrotactile feedback with crosstalk, we develop and evaluate a design tool to enable users to design bimanual vibrotactile feedback for different applications (Chapter 6).

Chapter 9 discusses the overall implications of the work presented in this dissertation by contributing to how this research informs the design of devices, advances the establishment of tactile perception as closed-loop perceptual process, relates to mediation theory and promotes the frontier of more responsive and expressive consumer haptic interfaces. Finally, Chapter 10 proposes two concrete future directions of expanding this work to the fields of Motor Learning and Universal tactile displays.

1.6 Synopsis

I have organized my dissertation into six separate chapters. Together, they investigate how motion-coupled vibrotactile feedback—vibrations generated by and synchronized with user action, can be understood, engineered, and creatively applied to produce embodied material experiences. Although each chapter stands as an independent contribution, I present how these works are coherent and span over the fields of haptic interfaces and interaction, human perception, and haptic interaction design.

Foundation of Motion-Coupled Vibration and Applications

I address **RQ1** and the corresponding sub-questions **RQ1-1** to **RQ1-4** in Chapter 2 and Chapter 7. Chapter 2 introduces *Haptic Servos*, a platform for rendering real-time motion-coupled vibrations through simple sensor-actuator coupling pipeline. This chapter describes the algorithmic, engineering, and perceptual rationale behind the system. I describe how vibrotactile pulses generated by and coupled with user action can be used as a building block for rendering material experiences such as softness, friction, and texture. Rather than aiming for high-fidelity physical replication (such as Joseph M Romano et al. (2011)), Haptic Servos embraces a low-parameter, heuristic approach that emphasizes the *why* behind rendering material experiences over the *how* of realistic material reproduction.

In Chapter 7, I present six projects that extend Haptic Servos into different domains such as interactive shoes, electrotactile compliance, embodied illusions, sports interfaces, and hand redirection. Each project demonstrates a distinct way in which real-time motion-coupled feedback can be adapted to new form factors, perceptual goals, or interaction contexts. Collectively, these works show how a simple principle scales into a versatile design space for on-body, object-mounted, and action-shaping haptic interaction.

Perceptual Investigations Underlying MCV

RQ2 and the corresponding sub-questions **RQ2-1** to **RQ2-3** are addressed in Chapter 3 and Chapter 4. These chapters shift from technology design to perceptual inquiry, asking ***why*** motion-coupled feedback feels embodied and how it interacts with fundamental mechanisms of human perception. In Chapter 3, whether motion-coupled vibrotactile feedback influences users performance and subjective experience of control using a foot-operated pedal interface. The findings showed that motion-coupled vibrotactile feedback enhances the feeling of control (Sense of Agency) without significantly changing the objective performance.

Chapter 4 investigates Motion-Coupled Vibration through a lens of the perceptual mechanism of Sensory Attenuation, the phenomenon by which self-generated sensations feel weaker than externally generated ones. Building on prior work that uses asymmetric vibrations to simulate directional force or pseudo-force, in our study, we show that when these asymmetric pulses are coupled to user movement, their perceived vibration intensity decreases while the pseudo force intensity is preserved. By systematically comparing externally triggered and motion-coupled asymmetric vibrations, the chapter argues that sensory attenuation is a key mechanism explaining why motion-coupled vibrotactile feedback can yield convincing, embodied material qualities while masking much of the “vibration-ness” of the signal. This provides a perceptual foundation for understanding why MCV feel less intrusive, more self-generated, and embodied compared to conventional open-loop vibrotactile cues.

Designing Tactile Symbols: Embodied and Hermeneutic Mediation

Chapter 5 moves from understanding perceptual mechanisms which make vibrotactile feedback feel embodied to design theory, while addressing **RQ3**. I ask whether tactile symbols which are traditionally abstract, rhythmic vibrotactile patterns can be designed in a way that does not rely solely on hermeneutic (symbolic) mediation, but instead draws on material associations and embodied familiarity. Offering hapticians to design tactile symbols with motion-coupled vibration along with continuous vibration, this chapter examines how tactile symbols can be designed to feel like material sensations and lived experiences, complementing the existing tactile symbol design space.

Beyond Single-point Motion-Coupled Vibrations

I address **RQ4** in Chapter 6 which extends motion-coupled vibrotactile rendering into the bimanual haptics domain, to explore if the same principle can be used to create bimanual tactile experiences such as stretching, bending and twisting. I introduce a novel crosstalk based approach that investigates how different mapping strategies across both hands can generate a sense of connectedness, and a shared material experience. By studying how motion-coupled vibrations induce bimanual material experiences, this chapter is aimed at expanding the theoretical and design space for embodied haptics beyond single-point actuation and toward distributed bodily experience.

Together, these four sections go from the foundations of motion-coupled vibrotactile feedback, to its perceptual underpinnings, to its expressive use in tactile communication, and finally to its extension into bimanual haptic interaction.

In the final part of the dissertation, I gather the insights that emerged across these investigations (Chapter 8), articulate how they collectively advance our understanding of embodied haptics, and summarize the conceptual, technical, and empirical contributions of this work (Chapter 9). I close by reflecting on how the pragmatic findings and theoretical considerations developed here may support the design of new haptic experiences and deepen our scientific understanding of touch within HCI and by outlining promising avenues for future research (Chapter 10).

2 Haptic Servos: Creating Virtual Material Experiences

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Nihar Sabnis, Dennis Wittchen, Courtney N. Reed, Narjes Pourjafarian, Jürgen Steimle, and Paul Strohmeier. *Haptic servos: Self-contained vibrotactile rendering system for creating or augmenting material experiences.* In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, pp. 1-17. 2023. *This paper was awarded an Honourable Mention Award (top 5% of all papers) at CHI 2023.*

Vibrotactile Haptics has been influential in creating virtual material experiences. Common material experiences such as friction (similar to what we feel when exploring wood or metal), texture (roughness and smoothness), compliance (similar to what we experience when we press or squeeze objects) can be induced by carefully orchestrating vibrations. Across HCI and haptics research, these experiences are typically achieved through Motion-Coupled Vibration (MCV): vibrotactile signals whose timing and structure are precisely synchronized with the user's movement. When implemented successfully, such systems can produce compelling illusions of materiality, enabling designers to prototype, modify, or augment perceived tactile properties without altering their physical form.

Despite a rich body of work demonstrating these capabilities, existing systems almost universally rely on bespoke, highly specialized pipelines. Implementations are specialized to handle high-frequency sensing, real-time signal processing, and low-latency output generation, often demanding expertise in embedded systems, audio processing and actuation hardware. As a result, literature has focused on the effects these systems can produce, rather than interrogating the mechanisms that allow such experiences to emerge. Besides the research questions mentioned in Section 1.3.1, questions such as, 'What is the underlying perceptual mechanism for the material expe-

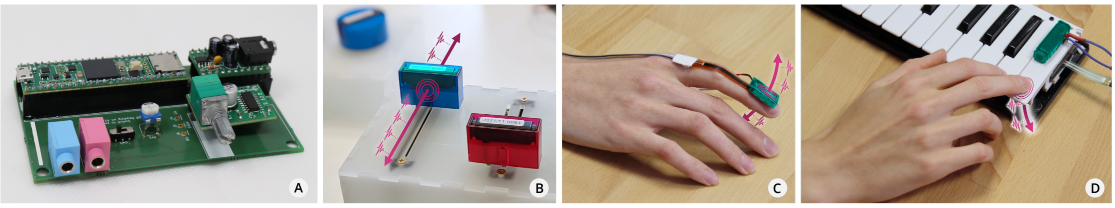

Figure 2.1: *Haptic Servos enable rapid rendering of diverse material experiences. (a) The open source Haptic Servo shield, compatible with the Arduino IDE, encapsulates all timing-sensitive elements, to create a rich variety of material experiences. We demonstrate how Haptic Servos can be deployed by example of (b) dynamically rendering the material experience on tangible user interfaces, (c) creating on-body material experiences, and (d) augmenting the experience of everyday objects (here piano key).*

rience to emerge?', 'How perception is mediated through vibration?', 'What are the experiential differences between continuous and motion-coupled vibration?', have remained implicit and unexplored. Moreover, for designers, novice hapticians and even haptic enthusiasts, the technical barrier to building reliable MCV systems, limits both, experimentation and adoption.

This chapter introduces **Haptic Servos** [1] which are self-contained, open-source haptic rendering devices designed to lower this barrier and make motion-coupled vibrotactile experiences accessible, reproducible, and conceptually tractable. Inspired by the metaphor of RC servo motors, *Haptic Servos* encapsulate all timing-critical operations including, high-speed sampling, low-latency digital signal generation, and high-fidelity actuation. When users interact with the system, human-action is continuously measured using analog sensors and are converted into discrete vibrotactile pulses ("grains") whose density and dynamics correspond to movement speed, pressure changes, or other sensor inputs. Haptic Servos achieve end-to-end latencies under 5 ms, satisfying the temporal requirements necessary for rendering high-fidelity material sensations.

Beyond technical performance, this chapter demonstrates how Haptic Servos serve as a general-purpose haptic rendering mechanism capable of producing natural, integrated tactile experiences across diverse interaction modalities. Three studies collectively highlight the system's versatility. First, compatibility with the broader Arduino ecosystem supports rapid prototyping and seamless integration into existing workflows. Second, a qualitative Microphenomenology inspired investigation reveals how Haptic Servos generate proximal, self-caused sensations that differ fundamentally from conventional continuous vibration. Participants consistently experienced motion-coupled pulses as part of their own action—an integration of tactile and motor components—while continuous vibrations were perceived as external, distal stimuli. The analysis further uncovers an important distinction between isotonic and isometric actions: sliding and turning interactions tend to evoke sensations of added counterforce, whereas pressing interactions yield experiences akin to reduced resistance or loose mechanical elements. Finally, a workshop with novice hapticians and designers confirms that Haptic Servos can be set up within minutes, enabling rapid exploration of rich material experiences without the need for deep technical expertise.

Taken together, these contributions position Haptic Servos as both a practical tool for designers and a conceptual lens for understanding how vibrotactile material experiences emerge. In this chapter, I detail the conceptual motivation behind Haptic Servos, describe the technical design and implementation, present the evaluation studies, and discuss the implications of this platform for haptic perception, interaction design, and future research on motion-coupled vibration.

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[1] Haptic Servos teaser video: `https://www.youtube.com/watch?v=g50hMcphB5Q`

2.1 Introduction

When we manipulate any object, we experience many of its material properties through vibration (BensmaÏa et al., 2005). For example, when we break a stick or crumple a plastic bottle, information about the consistency of the stick or the rigidity of the bottle is mediated through vibration. These vibrations are typically not consciously perceived as vibration, but rather as material properties of the objects we are interacting with. *Virtual material experiences* can be created or modified by carefully measuring the forces resulting from user motion (such as pressing a finger onto an object) and then designing vibrotactile signals that closely match the motion. We refer to this as motion-coupled vibration.

Researchers have demonstrated a wide range of such *virtual material experiences* (Joseph M. Romano et al., 2012; Kildal, 2010; Strohmeier et al., 2016; Heo et al., 2019). In all these systems, material experiences are rendered in three steps: (1) user actions are measured with high temporal resolution; (2) then based on predetermined parameters and input mappings (Kildal, 2010; Heo et al., 2019; Strohmeier et al., 2016) or through lookup tables (Joseph M. Romano et al., 2012) electrical control signals are generated; (3) which are then used to drive a wide-bandwidth vibrotactile actuator providing the user with corresponding vibrotactile feedback. These systems are exciting because they can haptically provide detailed material information, without actually requiring the user to be handling the corresponding object, much like a display can present colors and shapes of an object, without actually recreating it. Similarly, such systems might allow designers to create an object but determine the material properties later in the process. For instance, like texture mapping in computer graphics or designing virtual objects in AR/VR, material experiences can be rendered based on the application requirements. More specifically, a designer might produce multiple identical 3D printed objects, and then provide each object with unique tactile qualities. However, one key hurdle for implementing such systems lies in their requirements of high-frequency sampling, low system latency, and high-fidelity tactile output which, together, are non-trivial to meet. We address this challenge by proposing that haptic rendering mechanisms can be thought of as servo-mechanisms, encapsulating the demanding hardware aspects and exposing a simple interface that adheres to the standard interface of RC servos.

To enable novice hapticians[2], designers, practitioners, and hobbyists, to easily create diverse *virtual material experiences*, we present **Haptic Servos** (Figure 2.1-A). A *Haptic Servo* handles the details of creating motion-coupled vibration, enabling the haptic designer to instead focus on the higher-level functionality of the device or interaction they are creating. All timing-sensitive elements are contained within the firmware of the *Haptic Servo* to ensure the minimal latency required for creating diverse material experiences. Our approach is conceptually inspired from how a servo motor and its

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[2] we follow the same definition for "novice haptician" as Seifi et al. (Seifi et al., 2020)

corresponding control libraries[3] encapsulate the underlying hardware aspects of driving a geared motor while exposing an easy way for controlling it. This reduces the barriers for designers and novice hapticians to create rich material experiences.

Haptic Servos are compatible with the Arduino IDE and can be easily integrated into an Arduino sketch. Through a lookup table that contains unique combinations of key parameters for vibrotactile rendering, *Haptic Servos* can render 180 parameter combinations, supporting rapid and easy prototyping of material experiences for novice hapticians. Additionally, to provide higher detail of fine-tuning, *Haptic Servos* support individual parameter tweaking, which can further expand the rich vocabulary of material experiences. To help the research community replicate *Haptic Servos*, we open-source our hardware design and firmware[4].

The perception of material experiences generated using motion-coupled vibration is time-sensitive and hence, system latency plays a crucial role (Strohmeier et al., 2018; Wessel et al., 2002; Repp et al., 2013). To ensure that *Haptic Servos* provide a high degree of control for rendering time-sensitive materials experiences, we systematically characterized the overall latency of the system. With a latency of approx. 5 ms, *Haptic Servos* offer high temporal resolution, which can enable the rendering of highly articulated high-fidelity material experiences.

Through two empirical studies, we evaluated the qualitative experience and ease-of-prototyping. In the first experiment, micro-phenomenological analyses of qualitative interviews with expert hapticians show that the material experiences rendered by *Haptic Servos* are perceived as very natural. Since the vibrotactile feedback was tightly coupled with the actions being performed, the participants perceived the integrated experience combining tactile and motor elements. This enables the rendering of rich material properties to objects. In a design workshop, we evaluated the ease with which hapticians, designers, and practitioners can prototype custom material experiences with *Haptic Servos* for three diverse application scenarios: tangible UIs, body feedback, and industrial design. Overall, results from these studies show that *Haptic Servos* can (1) render high-fidelity motion-coupled tactile effects and (2) users with no or little prior experience in hardware design can use *Haptic Servos* to quickly and easily prototype material experiences.

2.2 Context & Related Work

The experience of touch is multifaceted and combines various modalities. For example, thermal receptors mediate temperature and moisture information, open nerve endings mediate pain, bulbous corpuscles and Merkel cells mediate forces, and Pacinian and Meissner corpuscles mediate vibration (Johansson et al., 2009). In our work, we focus solely on experiences mediated through vibration.

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[3] such as the Arduino Servo Library `https://github.com/arduino-libraries/Servo`

[4] `https://github.com/sensint/Servo_Haptics`

2.2.1 How and What We Touch

Tactile experiences are often discussed in terms of *how* the touch is performed (Lederman, 1981; Smith et al., 2009). *Active* touch relates to an exploration of the object or interface initiated by the user, while *passive* touch relates to moments where the user is touched by another person or object. Perceiving an object's properties is ideally performed by active exploratory procedures (Gibson, 1962), while passive touch has less sensory acuity (Heller, 1984).

Touch can also be discussed in the context of *what* is being touched. Interestingly, touch as a sense which enables us to perceive two distinct types of stimuli (Katz et al., 2013). One way of experiencing touch, is as a *distal* stimulus. A distal stimulus origins from a location external to the body; for example, a landslide might cause the ground to rumble, or a kitchen mixer might cause the work-surface of a kitchen to shake. When we perceive these stimuli, they are independent of our actions. We feel the vibrating counter no matter if we scan it or not. These experiences are also public, in the sense, that anyone touching the vibrating object will experience the vibrations. If we wish to shape the material experience of an object, we aim to minimize the *distal experiences*.

The type of tactile stimulus we are more commonly aware of when engaging with physical objects are *proximal*. Here, the stimulus is co-located with our body, for example, if we touch a texture, we experience this texture at the part of the body in contact with it and we experience the texture to exist at the location we are touching it. More importantly, we need to engage with it to experience it: To experience a texture, we require relative motion between our finger and a material, which leads to a stimulus that is synchronized to our actions.

Proximal and distal stimuli appear to relate to active and passive touch, insofar as distal stimuli unfold without synchronization to our actions while proximal stimuli unfold proportionally to the interaction between the body and the stimulus. However, even though proximal stimuli are experienced with higher acuity for active touch, they are also experienced passively, and while active touch might mask elements of distal stimuli, they are still perceivable, even during active touch.

In terms of digital devices, such as a smartphone, we might feel the smooth glass of the distal, or possibly a textured back of the device. These experiences origin where we experience them, where our fingers touch them. What we experience is synchronized to how we scan the device with our finger. The experience is *proximal*. The phone however might start vibrating. Inside the device a motor with an asymmetrical device starts rotating, eventually making the entire phone resonate. This stimulus persists no matter how we touch the device, is independent of our actions, is *distal*.

More recently, the *proximal* and *distal* experiences have been related to active and passive touch, respectively (Lederman, 1981; Smith et al., 2009). *Active* touch relates to an active exploration of the object or interface by the user, and *passive* touch relates to the movement of the object in relation to the user. These *proximal experiences* or *active touch*, which is closely coupled to the user's actions, are what *Haptic Servos* are designed to produce, conveying the experience of new material properties.

2.2.2 Proximal Perception & Vibration

Katz assumed that proximal stimuli are mediated by pressure and the distal stimuli are mediated by vibration (Katz et al., 2013). However, today we understand that proximal touch experiences are also mediated through vibration. For example, when we break a twig, or when we move our fingers over a textured surface, we cause vibrations. These vibrations are experienced as part of the material properties of whatever we might be interacting with. A well understood example is the perception of textures: Bensmaïa and Hollins have shown that the vibration of the finger, caused by touching a texture, accounts for 80% of variability in the similarity rating of the same participants on the same textures (Bensmaïa et al., 2005b). This suggests that the Pacinian corpuscles primarily mediate the experience of texture (Bensmaïa et al., 2005b). Romano and Kuchenbecker demonstrated that users can be made to experience textures on flat surfaces by creating a vibrotactile signal proportional to speed and pressure of the users' actions (Joseph M. Romano et al., 2012). Strohmeier et al. demonstrated that users can even experience such textures in the absence of the normal force that a surface might provide; they created texture experiences in midair (Strohmeier et al., 2018). Another example of proximal experiences mediated through vibration are experiences of compliance. Kappers et al. have demonstrated that there are a plethora of compliance cues, many of which are associated with skin deformation (Bergmann Tiest et al., 2009). It has been shown in practice that vibrotactile cues, closely coupled to changes in exerted pressure, are sufficient for compliance and deformation experiences to emerge (Kildal, 2010; Kildal, 2012). Moreover, Heo et al. used changes in force and torque applied to a device by the user to generate the experiences of bending, twisting and stretching of the device (Heo et al., 2019) and also created a haptic illusion of compliance based on tangential force provided by the user (Heo et al., 2017). Furthermore, Lee et al. demonstrated that vibrotactile feedback coupled to holding, squeezing and sliding of fingers can generate experiences of textures and compliance which helps in precisely manipulating objects in virtual reality (Jaeyeon Lee et al., 2019). Many more examples can be found in the HCI literature (e.g.: (S. Kim et al., 2013; Liao et al., 2018)).

All systems mentioned here, which use vibration for creating proximal stimuli, share many implementation details. They have a method for high resolution sampling of human action and use this information for modulating parameters of a vibrotactile signal. This suggests that these known vibrotactile effects are merely special cases of a larger space of vibrotactile material experiences. It is reasonable to assume that they are in fact all different manifestations of the same underlying perceptual mechanism. Correspondingly, *Haptic Servos* are designed as a generic system, which is not intended to create any specific material experience, but rather address their underlying mechanism, so designers can implement arbitrary systems. This is further explored in the qualitative exploration of Section 2.4.2, where we use *Haptic Servos* to determine how these experiences unfold and if the underlying perceptual mechanism is consistent.

2.2.3 Proximal Output in HCI

If we apply the distinction between distal and proximal experiences to vibrotactile feedback used for HCI purposes, we find that most HCI systems cater to the distal aspect of vibrotactile perception. For example, when a smartphone buzzes (e.g., because we have received a text-message) we experience this vibration originating distally, from the device. Even if we look towards more complex haptic experience design (O. Schneider et al., 2017), the focus on distal experiences remains. For instance, a number of prototyping and design tools for haptic symbols exist (O. S. Schneider et al., 2016b; Wittchen et al., 2022; O. S. Schneider et al., 2016a). However, these are designed along a time dimension. Because their patterns do not interact with human actions, they are perceived as external, distal stimuli. Work exploiting apparent tactile motion where a virtual vibrotactile stimulus is moved over the human body by interpolating the intensity of a grid of actuators (O. S. Schneider et al., 2015; Israr et al., 2011) is also based on distal stimuli. The experience is of a stimulus originating externally, that is moving over one's body. Similarly, actuator systems designed for on-body feedback, such as the epidermal feedback device by Withana et al. (Withana et al., 2018), and recent development in the field of chemical haptics (Lu et al., 2021) currently function independently of user actions. What these systems have in common is that the stimuli are created with fixed parameters, which are not modulated by human action.

Though rare, examples of proximal vibrotactile feedback in consumer devices exist. A well known example is the 3D Touch mechanism used in many Apple devices, which provides a compliance illusion by means of a pressure-synchronized tactile cue[5] Similarly, within HCI and haptics research communities, such proximal feedback can be found, most notably used for vibrotactile feedback in the examples introduced in the previous sections (Strohmeier et al., 2018; Kildal, 2010; Heo et al., 2019; Joseph M. Romano et al., 2012). We design *Haptic Servos* to support the deployment of proximal vibrotactile feedback devices – devices which create material experiences through vibration – as we believe these are currently underrepresented in the literature and have untapped potential both in researching perception and interaction, as well as for improving consumer devices.

2.2.4 Generating Vibrotactile Output

High resolution vibrotactile signals generation is non-trivial and is often done using DAQs (Culbertson et al., 2013; McMahan et al., 2014) or Audio Interfaces (Pezent et al., 2020). More rarely, one can also find systems that use embedded solutions (Strohmeier et al., 2020) using either DAC output or dedicated driver chips[6]. DAQs have both high resolution sensing and output capabilities, but are expensive and do not support a

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[5] https://developer.apple.com/design/human-interface-guidelines/ios/user-interaction/3d-touch/

[6] https://www.ti.com/product/DRV2605L

rapid-prototyping workflow. Audio Interfaces are capable of creating high resolution output, and high-end audio interfaces together with custom software are capable of creating relatively low latency output systems (Pezent et al., 2020). Using commercial audio-pipelines is convenient, enabling users to directly focus on the tactile experience, which is why it is used in many haptic toolkits, such as Stereohaptics (Israr et al., 2019) and Vitaki (Martínez et al., 2014). However, if one wishes to add sensing to such systems, one typically introduces additional hardware in the sensing-actuation loop, which again adds unwanted latency.

Looking towards embedded solutions, most custom driver chips are also not designed or used for the type of continuously modulated signal required for rendering material experiences. Consequently, custom microcontroller based solutions are the ideal path forward for low latency high resolution vibrotactile rendering. An example of this is bARefoot, a vibrotactile shoe (Strohmeier et al., 2020). Here, the authors report the 8 bit DAC used as a limiting factor. The prototyping suite by Wittchen et al. can create 8 independent channels of vibrotactile output, but does not have any mechanism enabling sensor control (Wittchen et al., 2022). In contrast, the system by Dementyev et al. enables such control: Their vibrotactile haptics platform even provides vibration output on 16 channels from a single microcontroller. However, their system uses a relatively low sampling rate of 2kHz (Dementyev et al., 2021) to maximize the concurrent channels of vibrotactile actuation.

Generally speaking, systems based on commercial audio can have output with high resolution and sampling rates, but often with relatively high latency. Microcontroller based systems on the other hand can have very low latency, but often at the cost of low sampling rate and a bit depth. Creating multi-channel systems using custom embedded solutions typically requires reduction in signal fidelity, and for commercial audio-based systems requires purchasing expensive multi-track audio interfaces. *Haptic Servos* address these impracticalities. They provide low latency high resolution audio output, modulated by sensor input.

2.2.5 Haptic Design Tools

The role of haptic designers and their training and education is an active topic of discussion in both industry and academia (O. Schneider et al., 2022), and strategies of how haptic designers work are actively being studied with the intent to develop better tools for novices (Seifi et al., 2020). This has lead to collections and libraries to facilitate discovery of devices (Seifi et al., 2019) or tactile effects (Zhao et al., 2014). Other work provides platforms for sketching and designing haptic designs through direct manipulation (Wittchen et al., 2021; Wittchen et al., 2022; O. S. Schneider et al., 2015) – a particularly creative exploration in this area is the use of vocalizations to sketch out haptic feedback (Degraen et al., 2021). Others have presented design tools for creating haptics using visual metaphors (S. A. Panëels et al., 2010; S. Panëels et al., 2013), software tool-chains for connecting sensors and (remote) actuators in hardware (Y.-W.

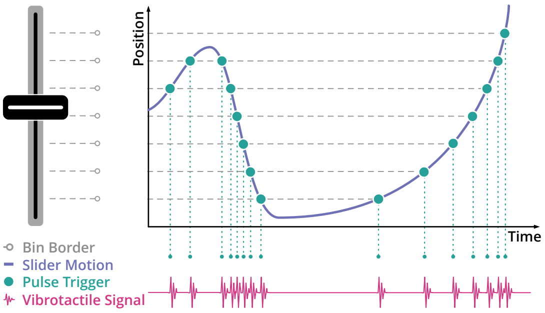

Figure 2.2: *The range of a sensor (e.g., a slider) is divided into bins of equal sizes. While moving the slider, a vibrotactile pulse is triggered at each crossing of a bin-border. Hence, the dynamics of the perceived pulse sequence is coupled to the user's motion.*

Lin et al., 2017; Günther et al., 2021) or the development of dedicated experimental platforms to deploy arbitrary haptic symbols (Dementyev et al., 2020).

Haptic Servos provide a complimentary approach. Rather than creating a new tool-chain for haptic design, the intent is to create a powerful actuator which can be integrated in existing tool chains and devices. This is why we use the servo-motor metaphor in naming our device. In the same way that a servomotor encapsulates a complex control process in a discrete device which the user need not worry about, we abstract away the bulk of the complexities of creating a specific type of haptic feedback, which can be used to create material experiences. While a traditional RC servo-motor controls the position, the haptic servo controls the output waveform, proportionally to human action. While the RC servo measures the error in terms of position, the haptic servo measures the error in terms of correlation between waveform and dynamics of human action.

Haptic Servo also alludes to the final form factor of the device we envision. Our ultimate design goal is a completely self-contained device, which contains actuator, sensors (possibly using inertial measurement, or back-EMF voltage (Dementyev et al., 2020)) and control electronics in a single housing. We imagine such a device (or even multiple) might easily be integrated in many of the existing prototyping tool-chains, multiplying their efficacy.

2.3 Haptic Servos

The purpose of *Haptic Servos* is to create proximal tactile experiences, which include material properties such as compliance and texture as well as physical experiences such as force – from now on, we will simply call these *material experiences*. This is achieved by measuring a human action with an analog sensor and generating a tactile signal based on that action. The resulting tactile signal consists of a series of pulses that occur at a density that correlates with the change in the measured signal (Figure 2.2). For example, when rotating a knob, tactile pulse density correlates with the speed of rotation; when pressing a button, pulses are generated based on changes in applied force. The overall density of the vibrotactile pulses and the vibration parameter of the

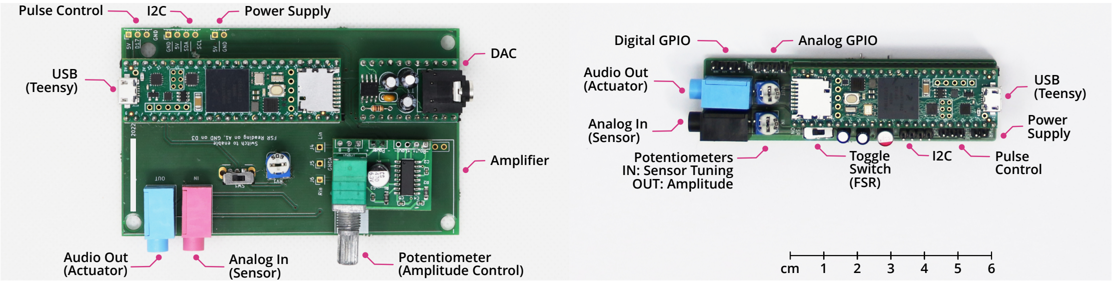

Figure 2.3: *Two instances of the Haptic Servo shield with several ports for I/O, communication, and power supply. Left, a version that can be equipped with off-the-shelf breakout boards, and on the right a version with reduced footprint and surface mounted ICs.*

individual pulse can be controlled by the user. In the future, we imagine *Haptic Servos* to be completely self-contained components. A designer can then easily integrate one or multiple haptic servos into a prototype, in the same way that we can currently deploy RC servo motors in prototypes.

2.3.1 Technical Design Considerations

We envision *Haptic Servos* to be a versatile platform that enables easy prototyping of material experiences. However, for rendering material experiences, several technical requirements need to be considered:

Latency

Anecdotally, when perceiving a virtual material experience, such as a friction rendering, the fidelity of the experience is perceived as highest mid-movement, and lowest at movement onset and when ending the movement. We believe that this is an effect of latency, as latency would be experienced most prominently during changes in movement, and least during constant movement. Prior work has also argued that latency is a crucial metric that can have a significant influence on the overall tactile experience (Strohmeier et al., 2018) and there are reports of latency being experienced as a type of inertia (Strohmeier, 2019). Literature reports multiple values of latency in haptic rendering systems, for instance, $25ms$ (Strohmeier et al., 2018), $45ms$ (Vogels, 2004) and $60ms$ (Kildal, 2010).

The timing sensitivity of motion-coupled vibration is similar to issues around the synchronization of sound and action in music (Strohmeier et al., 2020). Hence, we take inspiration from auditory perception, as there are many parallels between acoustic and vibrotactile perception, and the effects of latency on audio perception have been studied extensively (Mäki-patola et al., 2004; DeLiang et al., 2006; Wessel et al., 2002; Repp et al., 2013). Based on the recommendations provided in acoustic perception literature, we aim to have a latency of less than 10ms (<10ms) for *Haptic Servos*.

Sensor Sampling Rate

Previous work has reported sampling rates of 125 Hz (Strohmeier et al., 2017), 240 Hz (Strohmeier et al., 2018) and >2000 Hz (Strohmeier et al., 2016). In anecdotal reports and in our own experience, higher sampling rates result in *crisper* experiences, while lower sampling rates can result in experiences which feel less clearly defined. We therefore intend to sample the human actions as fast as technically possible, i.e. in the current firmware version approx. 125 kHz on a Teensy 3.5. To be clear, vibrotactile perception is most sensitive at comparatively low frequency: Pacinian cells are most sensitive at approx. 250 Hz (Verrillo, 1966) (though different studies find slightly different values for this). The analog sensory processing path, however, is very sensitive to signal onset (Johansson et al., 2009). This high frequency is therefore not required for rendering high-frequency signals, but for optimizing the signal onset of individual pulses. A low sampling rate can lead to something similar to hysteresis, where a specific pulse occurs at different times or locations depending on the direction which the user is moving when encountering it. High sampling rates improve the synchronization between tactile pulse onset and human movement dynamics. Capturing human actions at very high temporal granularity enables us to create material experiences which feel crisp, hard, and exact.

Signal Fidelity

Another important technical consideration that is crucial for rendering realistic material experiences is signal fidelity. Prior work which used embedded systems for generating vibrotactile signals motivates the need for having high signal fidelity (Strohmeier et al., 2020), as the system was limited by the hardware (8-bit DAC on ESP32). This limitation can be overcome by using hardware with higher available bit-depth to produce high-fidelity signals.

Taking these technical details into consideration, we set our target for a latency under 10 ms, while maximizing the sampling rate (>120kHz in our case) and generating high-fidelity control signals that are comparable to commercial audio (16bit, 44.1kHz).

2.3.2 Usability Considerations

The design of *Haptic Servos* is centered around two key considerations about usability:

Simplicity and Discoverability over Control

As we intend *Haptic Servos* to be used in early stages of the design process, the *Haptic Servo* should support designers to rapidly reach a stage where their idea can be tested. Working with *Haptic Servos* should support intuitively discovering and exploring interesting experiences in practice, rather than offline fine-tuning of parameters. This is supported by the explicit choice to *not* give the designer full control over all stimulation parameters. Instead, the goal is to merely provide enough ability for customization to

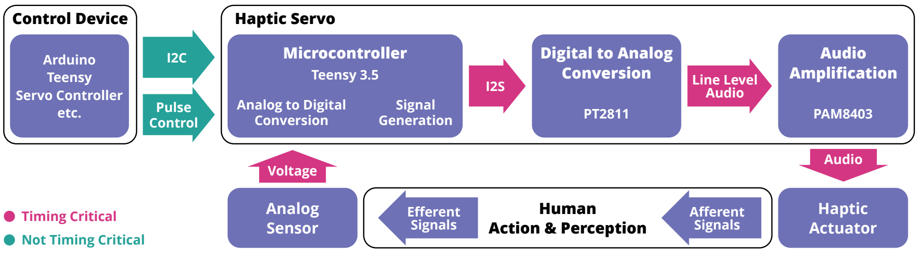

Figure 2.4: *The components needed in the process of rendering material experiences using a Haptic Servo.*

explore variations of a design, similarly to how a servo motor merely allows the designer to set a target value, but not modify the algorithm of how to get there.

Compatibility with Existing Tools

To make integrating *Haptic Servos* into existing projects effortless, maximum compatibility with existing toolkits should be ensured. We do not want designers to require custom control libraries or custom electrical interfaces.

2.3.3 Implementation

A *Haptic Servo* requires a microcontroller that samples a sensor (input) and generates a signal based on specified parameters and sensor dynamics. The *Haptic Servo* must also have a way of transforming this digital signal into an electrical control signal. It then requires an amplification circuit to provide enough power, so the signal can drive a haptic actuator. To keep the *Haptic Servo* as generic as possible, we defined the input as an analog voltage and the output of the *Haptic Servo* as the amplified control signal (AC voltage), making it compatible with a wide range of actuators (LRAs, voice coil actuators and piezos with correct amplification) as well as audio speakers for supporting rapid prototyping.

Hardware

For our proof-of-concept device (Figure 2.3 left), we use off-the-shelf hardware and open source software. This was done to make our system more easily reproducible. We used a Teensy 3.5 microcontroller and generated the signals using the Teensy Audio Library [7]. For full 16 bit analog output, we used the PT8211 Audio Kit by PJRC and for amplification, we used the PAM8403 by AZDelivery. Here, the loop between vibrotactile output and analog sensing is closed by the human, who perceives the feedback and acts accordingly (Figure 2.4).

The PT8211 and the PAM8403 are connected to the Teensy with a hardware shield , together forming the physical *Haptic Servo*. As shown in Figure 2.3, the *Haptic Servo* shield has two primary I/O ports for connecting to the sensor and the haptic actuator.

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[7] https://github.com/PaulStoffregen/Audio

To support tinkering and experimentation, these are implemented with 3.5 mm audio jacks. These are convenient as they are built to mechanically withstand frequent connection and disconnection, while being sturdy enough to not accidentally disconnect.

The *Haptic Servo* also has two communication ports and a power port. These are implemented as regular pin-headers, so a standard servo cable or a 4pin I2C cable can be used. Future versions will include shrouding to hold cables securely and prevent cable rotation. All designs including schematics will be provided open source in our GitHub repository[8] for reproduction.

Form Factor

The device described above is easy for others to reproduce. However, ultimately we wish all elements of the Haptic Servo, including the actuator, to be self-contained. As a step towards this goal, we have also produced a version which saves space by using a custom PCB rather than breakout boards (Figure 2.3 right). Both devices have their benefits and drawbacks (ease of reproduction vs ease of integration) we will provide source materials for both designs. The next step with regard to form-factor is to choose a discrete microcontroller which we will use to replace the Teensy. This shield with a smaller print can be used for handheld and wearable applications.

Servo Compatibility

To maximize the ease with which a *Haptic Servo* can be integrated in existing prototyping ecosystems, we chose to maximize compatibility with regular RC servos. For this purpose, the *Haptic Servo* has a pulse-control port, which is pin-compatible with a standard servo cable. Additionally, the *Haptic Servo's* parameters can be set using Pulse Width Control. In a standard RC servo, the target angle is selected by sending pulses ranging from 544 to 2400 μs for -90 to +90 degree respectively. In a *Haptic Servo*, the values are used to select what the material experience should feel like.

The intention behind this is to leverage the existing infrastructure built for servos. For example, to create a prototype with multiple *Haptic Servos*, one might use an Arduino and a servo shield[9]. The servo shield then correctly powers each *Haptic Servo*. The designer will then be able to control the software aspects of the material experience using the standard Arduino servo library. No special knowledge or special purpose tools are required to use or interface with the *Haptic Servo*.

There are two code examples shown in Appendix A, the first highlights how one might gradually scan through all output parameters on a single *Haptic Servo*. The second shows code that adapts the parameters of three haptic servos.

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[8] `https://github.com/sensint/Servo_Haptics`

[9] such as those provided by Adafruit: https://learn.adafruit.com/adafruit-16-channel-pwm-slash-servo-shield

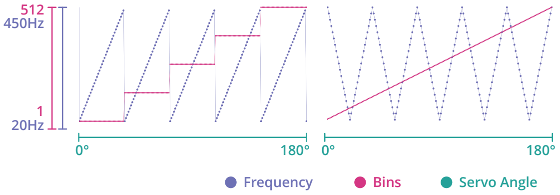

Figure 2.5: *Two models of parameterization considered when mapping angles to vibrotactile parameters. Based on these models, we created lookup tables used in the Haptic Servo firmware to select combinations of the vibrotactile parameters.*

Algorithm

To create the control signal, the resolution of the ADC is divided into a number of discrete bins. When a sampled sensor value changes enough to enter a new bin, an AC pulse (i.e., audio signal) with a given waveform, duration, amplitude, and frequency is generated as shown in Figure 2.2. When the signal changes fast, pulses are generated rapidly. When the signal changes slowly, the pulses are generated proportionally slower.

The relevant variables required for generating the signal are the number of bins, which corresponds to the overall density of pulses (in the sensor range). The vibration specification of each pulse is determined by the type of waveform used, as well as the duration, amplitude, and frequency of that waveform. As the duration should ideally be coupled to the frequency to minimize clipping artifacts (we found that both a full period and a half period work well), duration can be derived from frequency. The amplitude should always be set as high as possible, to leverage the full available bit-depth of the *Haptic Servo*. However, the amplitude of the output signal can be adjusted with a physical potentiometer on the *Haptic Servo*. This leaves the frequency and number of bins as primary parameters to consider when designing a vibrotactile material experience.

Selecting Material Parameters

This strict adherence to RC servo standards creates an interesting point of friction. Pulse Width Control works well for a single parameter, such as position, however the parameter-space for generating the vibrotactile feedback is multidimensional. Here, we take inspiration from systems common in audio design, where a multidimensional device supports a user continuously morphing between presets using a single knob, as for example implemented in the Steinberg Sweet Spot Morphing DSP effects[10].

The simplest way of achieving this for two variables would be to choose an appropriate number of levels for these parameters (such that their product is 180 or less) and have each angle correspond to a unique combination. While this guarantees all possible combinations, it might be confusing for novices to explore as they will experience strong discontinuities in the experience as they increment or decrements the angle

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[10] https://www.youtube.com/watch?v=PzV9k0u0ou4

(Figure 2.5, left). An alternative would be to choose a dominant dimension, which linearly increases with the angle, and a supplemental dimension which oscillates back and forth as the angle increases (Figure 2.5, right). While this does not enable the same strict counterbalancing of values, it has the benefit that neighboring settings will always feel similar. This enables a novice to first roughly explore the experiences (e.g., with 10-step increments) and then, once they have found something that feels good, start fine-tuning it by exploring neighboring settings.

We chose to provide control over the frequency of the pulses and the number of bins. As the effect of frequency has been found to be more important than bin numbers for creating distinct experiences (Strohmeier et al., 2017), we set frequency as the primary parameter and the number of bins as supplementary. While this dimension reduction process was necessary due to the strict adherence to RC Servo standards, we believe that this implementation is beneficial for playful exploration and serendipitous discovery of parameter combinations. In the firmware of the Haptic Servo, a lookup table is used to select a combination of frequency and bin number based on the value sent to the servo.

Expert Users (I2C)

Even for RC servo motors, the limited communication ability of Pulse Width Control poses a problem for expert users. This has led to the development of 'smart' servos, such as the Dynamixel series[11]. These use a 4-wire connection and have a serial bidirectional interface next to the power leads. Similarly, for expert users, the *Haptic Servo* has an I2C port exposed. This enables expert users to set *waveform*, *frequency*, *duration*, *amplitude*, and *number of bins*, as well as request the current sensor value from the servo.

2.4 Evaluation

We validate our design on different levels. As one of the primary technical goals of the Haptic Servo was minimizing system latency, the first evaluation is a technical characterization of system latency. Here we demonstrate that we meet our own technical design goals. The second evaluation explores the experiences which can be achieved with the haptic servo, and is to our knowledge the first study showing that a fixed signal creation algorithm can lead to qualitatively distinct experiences, based on input modality. Finally, in our third evaluation, we explore if the Haptic Servo does indeed support designers.

2.4.1 System Latency

For the technical characterization, we focused on minimizing system latency.

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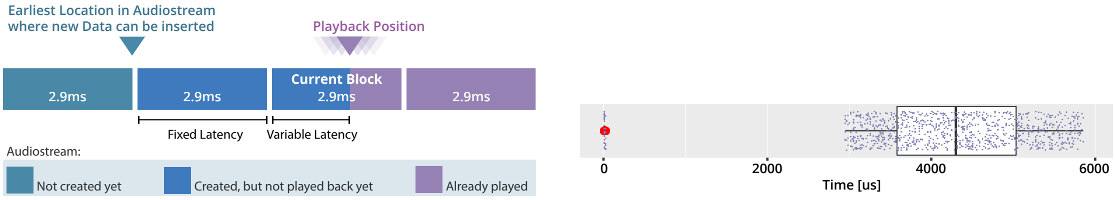
[11] http://www.dynamixel.com/



(**a**) *Example State of Audiostream with a Pulse.* (**b**) *System latency measures (n=1000).*

Figure 2.6: *The audio library processes information in chunks of 128 bytes, or 2.9 ms. When a bin change occurs, the playback position of the current block in the audio buffer could be at any position with equal probability, causing the variable part of the latency (Figure 2.6a). The following block is already being calculated in preparation for writing to the buffer. This causes the fixed part of the latency. As the block duration is 2.9 ms, the average latency is 4.35 ms and the frequency at which the highest possible latency oscillates is the inverse of a block duration, so 344.8 Hz. We measured the system latency (n=1000), i.e. sensor input reading to digital-to-analog converter output, where each point represents a single measurement with the automated setup (Figure 2.6b) supporting the above explanation. The red point indicates outliers.*

Overall Latency

To establish the overall latency, we collected a set of 1000 measurements with an automated setup. A Teensy 4.1 (running at 600 MHz) was used to measure the time between a signal-change at the analog input of the Haptic Servo and the resulting response in the control signal generated by the Haptic Servo (powered by a Teensy 3.5 running at 120 MHz). Measurements were separated by a random amount of time to mitigate aliasing effects.

We found the delay times to be evenly distributed between 2.95 and 5.85 ms, with a mean of 4.35 ms and a standard deviation of 0.86 ms. Figure 2.6 shows a box plot of all measures, with jitter applied to better show the distribution. The raw results of these measurements are shared in our GitHub repository[12]. This result shows that the Haptic Servo's temporal properties are well below the 10 ms we established as our upper bounds. It should be highlighted, that this is not the overall system latency, but just those parts of the latency which we have influence over. In addition to the latency reported here, we must also consider that the actuator also has a rise time (time taken for the actuator to achieve its maximum output in response to a given input signal), which is in turn influenced by how the actuator is mechanically integrated with the rest of the prototype. For example, attached to an object that weighs 100g, the actuators we use require an additional 6ms to reach 10% of transient acceleration[13].

Code Execution Times

To better understand where the latency occurs, we analyzed code execution times. We found that these were negligible, summing up all code blocks to only 8.08 microseconds (μs) on average, with a standard deviation of 2.373 μs over 1000 measurements. The bulk of both the time and variability was introduced by the analogRead() function,

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[12] `https://github.com/sensint/Servo_Haptics`

[13] `http://tactilelabs.com/wp-content/uploads/2020/11/HapCoil_One_datasheet.pdf`

which required 7.55 μs to execute. This highlights that the code executions times are negligible, compared to overall latency.

Towards Optimizing Latency

The current version of the Haptic Servo uses the Teensy Audio Library to generate control signals. In standard settings, the library uses a DMA channel with 256 samples, which is written to in blocks of 128 samples[14].

At any time, there is one 128-sample block which is currently being written to the I2S audio port, and one block which is currently being processed by the audio library. At a sampling rate of 44.1 kHz, each block is approximately 2.9 ms long. The delay time and variability we measured is consistent with a new pulse starting at the beginning of the following block. Theoretically we would then expect the delay times to be at a minimum of 2.9 ms (128 samples) and 5.8 ms (256 samples) at a maximum, with an average delay time of 4.35 ms and a standard deviation of 0.86 ms which exactly matches our measured values.

The first step towards optimizing the latency might be to write a library which bypasses the DMA, potentially writing directly to the I2S port, or implementing a ringbuffer. If required, further optimization might then be achieved by improving code execution times, in particular by directly reading and writing directly to the ADC registers, rather than using the AnalogRead() function provided by the Arduino environment[15].

2.4.2 Qualitative Experience Evaluation

As Haptic Servos' primary purpose is to create novel experiences, we conducted a qualitative study to explore how these experiences were perceived. We focus on the following questions:

- *Can a general purpose device for creating material experiences function across different implementations?* To understand if Haptic Servos can be used as the general purpose device they are intended to be, we analyze the experience of using a haptic servo with set parameters using three different types of human action as input.
- *How do isometric actions and isotonic actions differ when augmented with a Haptic Servo?* We provide additional experiential data by comparing isotonic (slider, knob) input to isometric input (pressure button).
- *How does the experience of action-coupled vibrations produced by the Haptic Servo unfold differently from the experience of continuous vibration?* Finally, to better understand the perceptual mechanism which Haptic Servos make use of, we compare interactions using Haptic Servos to interactions with continuously vibrating objects.

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[14] see also: https://github.com/PaulStoffregen/cores/blob/master/teensy3/AudioStream.h

[15] Pedro Villanueva provides examples on GitHub`https://github.com/pedvide/ADC`

To address these open themes, we chose to conduct micro-phenom-enology inspired elicitation interviews. These have previously been used to identify structures in experiences (Petitmengin-Peugeot, 1999) in general, as well as the exploration of haptic illusions (Valenzuela Moguillansky et al., 2013), and the experience of vibration (Obrist et al., 2013).

Experiment Setup

For this study, we used a Tangible UI (TUI) setup further outlined in Section 2.5.1. The TUIs use either pressure-buttons, sliders, or rotary knobs as interactive elements (Figure 2.7). These elements lead the user to perform different actions: rotation and displacement for the knobs and sliders respectively, and push on the pressure-buttons. This also enables a comparison between isotonic (sliders, knobs) and isometric (pressure button) actions. Each TUI element is connected to a Haptic Servo. To ensure that the difference between elements is purely the type of action that the user performs, the Haptic Servos were set up identically for each task (100 Hz, 50 bins). The continuous comparison signal was a 100 Hz sine wave generated by a Teensy 3.5.

Participants

We invited six HCI researchers (3 male, 3 female – aged 24 to 30, M = 27.5, SD = 2.26) to participate in a study that explored the experiences created by Haptic Servos. The participants were of a variety of nationalities (Turkey, India, Colombia, Italy, Germany, and the UK) but were all residing in nearby cities. Three participants were expert hapticians, while the other three were HCI graduate students.

Task

Each participant was provided with two of the three devices (Figure 2.7). For each device, participants were first asked to interact with a non-actuated TUI element. Then they interacted with an element which was vibrating continuously at a constant frequency as a control condition. At this point, the first micro-phenomenological interview was conducted. As the test condition, participants were then asked to interact with a Haptic Servo generating motion-coupled vibration, followed by a second micro-phenomenological interview. After a 5-minute break, this process was then repeated with the second device, for a total of four interviews. This was followed by a short semi-structured interview in which participants were encouraged to speculate about causation of the experiences and make comparisons to other experiences they have had. The entire process took approximately one hour per participant and was audio-video recorded for later transcription.

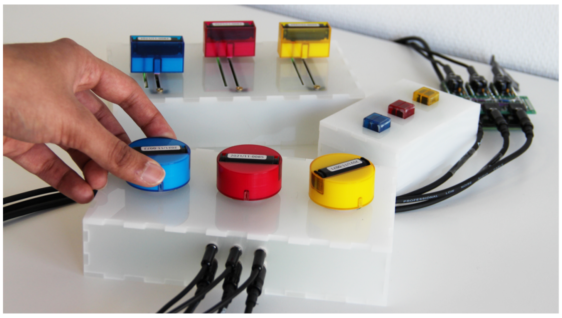

Figure 2.7: *Three forms of tangible user interfaces (rotary knob, sliders, buttons) that are augmented with vibrotactile feedback. A user is interacting with the rotary knobs.*

Interviews

As the interactions with the tactile feedback occurs quickly, many details are overlooked at the time of experience (Claire Petitmengin, 2006). To gather fine-grained pre-reflective detail of how the experience unfolds, we used a method inspired by micro-phenom-enological interviews (C. Petitmengin, 2021)[16] to bring the participants back into an evocation of a specific moment of the experience and guide them through each step as it occurs. In effect, this slows down the experience and allows the participant to examine aspects of their interactions as they occurred in the moment of experience. From the interview, we then extracted the diachronic (chronological events during the experience) and synchronic (dimensions of experience and sensorimotor perception during a particular moment) aspects of the participants' experiences (Claire Petitmengin et al., 2018).

Analysis

The interviews were transcribed at the level of utterances and experiential structures were analyzed (Valenzuela-Moguillansky et al., 2019). First, question and answer pairs were numbered and any satellite dimensions – that is, recollections which deviate away from the specific evoked experience – were identified to be ignored in analysis. Then the structures of the experiences and commonalities between the experiences were identified. Finally, C. Reed and N. Sabnis collaboratively conducted an inductive, reflexive thematic analysis (Braun et al., 2019) of the entire interview to determine salient connections between participants' perceptions and interactions (Braun et al., 2006; Braun et al., 2012).

2.4.3 Findings of Micro-Phenomenological Analysis

We found that the experiences unfolded systematically and involved two key phases: *exploration* followed either by *dissociation* of vibration and action for continuous vibration or *integration* of vibration and action when using the Haptic Servo. This was con-

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[16] The interview was led by C. Reed, who has completed micro-phenomenology interview training and is in the process of being certified in the discipline

stant within interactions done by the same participant and across participants. Figure 2.8 presents a selection of initial interactions with each of the devices. These show the diachronic temporal structure of the interaction, together with the synchronic perceptual dimensions of the experiences. Here, we show the structure of P2's interaction with sliders and buttons in each vibration condition as they relate to P4's interactions with the knobs, as a representative sample of all interviews.

Interacting with Continuous Vibration

The experiences described start with the initial perception of the vibration; here, users note the quality of the vibration. In continuous vibration interactions, this leads to a sense of dissociation between the vibration and TUI element: The user tests various motions and tries to identify the interaction. Because there is no connection between the user and the vibration of the device, this can lead to a mismatch or confusion. P2 describes that there is a contrast between the smoothness of the device and the "buzzing" of the vibration. Generally, interactions with the continuous vibration devices are short and participants disengage quickly. Participants describe the vibration as coming from the device itself. The final understanding of the interaction generally consists of the user perceiving that the element is vibrating, but not doing anything else.

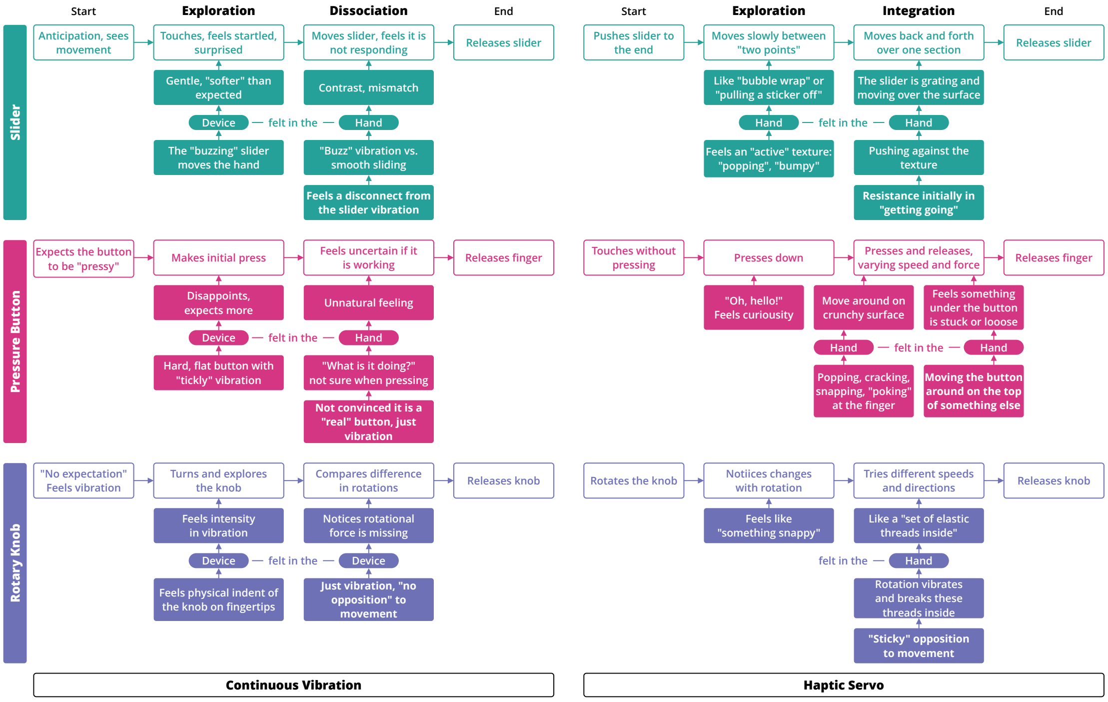

Figure 2.8: *The phases of exploration and identification (either as dissociation or integration) during interaction with sliders (teal), buttons (magenta), and knobs (purple), revealed through micro-phenomenological interviews. These phases are consistent through experiences with the different sensor elements and among different participants.*

Interacting with Haptic Servos

After a short exploratory action, which typically leads to an “Aha!” moment, a connection between vibrotactile experience and the action is made. This results in an integrated experience combining both the tactile and motor elements. The participants were then able to identify the quality of the perceived “pulse” (a “crunchy” or “snapping” sensation). This was followed by lengthier and more repetitive action: participants move over two pulses, varying their speed or their pressure, and run to the extremes of the device’s range to determine where these pulses are placed. With the Haptic Servo-controlled button, P2 experiences a sensation of something being loose underneath. They feel the button moving around on top of whatever this is, resulting in a crunchy or sticky feeling. For P4, the Haptic Servo-controlled knob felt like there was a set of elastic threads underneath. Their rotation caused the threads to catch and then break, resulting in an opposition to their movement. They also described this as being a “sticky” texture. The feedback is experienced as a result of movement of the hand or finger, rather than the device itself, and is associated to moving over or against an object or texture, usually felt as being under the device or inside the box housing the devices.

Reflections on Micro-Phenomenological Analysis

These experiences demonstrate that Haptic Servos are able to provide consistent experiences across individual users and TUI elements. Although each user will experience nuances unique to their own perception, interaction with the vibrotactile feedback is structured similarly. Continuous vibrations provide an experience of information separate from human input, potentially making them useful for passive interaction (e.g., system alerts). Action-coupled vibrations provide an experience of relationship and connection between user and ui-action. This is potentially useful in conveying a sensation of control, and dialogue with the system in return (e.g., tuning parameters). More in depth study in relation to how continuous and action-coupled vibrations are used to design tactile symbols is explained in Chapter 5. The phases of each interaction type followed the same general structure, even for different modalities (i.e.: isotonic and isometric) demonstrating how the Haptic Servo functions as a general purpose device for different implementations. *Haptic Servos* based implementation for isotonic and isometric modalities for foot-based interactions is investigated rigorously in Chapter 3.

2.4.4 Findings of Thematic Analysis

The thematic analysis supports the observations from the micro-phenomenology inspired interviews. We use four main themes to describe participants’ perceptual experience during the interaction: Interaction Phases, Mapping Perception, Feature Perception, and Sensory Perception (Table 2.1).

Table 2.1: *The four main themes of participants' perceptual experience during the interaction with the Haptic Servos.*

	Theme	General Description
Interaction Phases	**Expectation**	Based on previous experience or the characteristics of the element (shape, visible vibration, etc.), participants form expectations for the interaction.
	Exploration & Repetition	Expectation drives initial contact with the element: participants explore the elements with different speeds, pressures, and other input to uncover the interaction.
	Connection & Mapping	Some interactions yield connections and participants are able to make mappings between their actions and the resulting tactile feedback. These are typically directional or functional connections.
	Confusion & Mismatch	Other interactions lead to confusion: participants are sometimes unable to perceive a relationship between their action and the feedback.
Mapping Perception	**Association of Interaction**	Participants associate the interaction as they perceive it with other experiences, including to material properties and textures, different triggers, other devices and objects, and other sensory experiences.
	Perceived Functionality	Participants often directly are able to understand the functionality of the interaction and correctly identify the Haptic Servo implementation.
	Emotion & Reaction	The interaction is often paired with an emotional response: confusion occurs with mismatched input and output and intrigue with mappings and connections.
Feature Perception	**Comparison of Feedback**	Assessments are made in comparing elements and feedback types. Participants are able to connect different elements and make interaction judgements for one element based on the context of another.
	Feedback Type	Participants divide their perception into two large categories: vibrations and pulses. These are distinct perceptually and have different qualities.
	Feedback Parameters	Participants perceive several features which make up the feedback. These features include strength, frequency, proximity, friction, timing, force, texture, and activeness.
Sensory Perception	**Multi-Modal Interaction**	Participants understand their interactions through a multi-modal sensory-based interaction. This is done through visual, auditory, and kinesthetic images and perceptions.
	Feedback from Elements	Participants identify that the feedback is caused by and comes from the element itself. The element moves independently of the user's body and may cause movements or reactions for the user.
	Feedback from the Body	Participants also identify cases where the feedback is generated by the body or its movement. The element moves in response to movement or the user feels they are moving the element over a surface.

Interaction Phases

Participants' experiences occur in a structure as described through the micro- phenomenological interviews: participants first describe their expectation based on the visual look of the elements and their initial approach to explore them. We again see the two major phases of exploration through repetition of particular behaviors to determine interaction and connections to their action. Participants are successful in mapping aspects of their gesture to the haptic feedback with motion-coupled vibration. Otherwise, there is often a mismatch, which results in confusion. Perception of an input-output path is missing: *"[With this vibration] there's something wrong with the button, or something wrong in the way I'm holding it. So I was confused whether that is an actual feedback. Or I am probably not doing it correctly"* (P3). These Interaction Phases are determined and experienced through Mapping, Feature, and Sensorimotor experience, which help to establish a connection between movement and action:

Mapping Perception

This analysis also revealed several additional details about the perception of the interaction from a reflective standpoint. Participants were able to perceive mappings clearly when they existed, referring to physical objects, textures, and other haptic feedback from their day-to-day life to describe them. For instance, there were associations of "a slightly loose key on your keyboard" (P2) or tracing across a "wavy surface" (P6). When a mapping was present, participants commented that the interactions were "intriguing" (P2) and "pleasant," (P4) as the feedback encouraged exploration of movement. For continuous vibration and control elements where there was no feedback, participants initially worried that they were not interacting with the device correctly or that it was not on, before ultimately concluding that the vibration must either be inactive or non-present.

Feature Perception

Participants associated a number of relevant features with the feedback they experienced, including specific parameters of the signal (frequency, timing) and other more subjective features such as activeness, strength, and force. For instance, P5 describes noticing low frequency *"bass"* vibrations coupled to motion as feeling *"like you're dragging on the thing [slider]"*. Textures and friction were associated with the action coupled vibrations, yielding consistent feelings of friction and of "sticky" or "crunchy" elements. Overall, participants referred to continuous actuation as "vibration"; for action-coupled interaction, participants exclusively referred to the feedback as a pulse, trigger, or texture element (e.g., P6 describes "bumps"), rather than vibration.

Sensorimotor Experience

Together, these subjective analyses reiterate that users perceive feedback differently depending on how it is coupled to their motion. We find that this experience is consistent when using Haptic Servos, regardless of their implementation element. In continuous vibration, users perceive vibration and independent elements which are situated away from the body in a distal experience: the element itself was understood to be vibrating and acting independently of the body. In motion-coupled vibration provided by Haptic Servos, users perceive a proximal interaction wherein the element itself does not vibrate, but rather responds as the user moves it over a surface or against something resistant. This feedback is instead seen as a result of the body, caused by movement, and not the element itself. The perception of the vibration is so closely linked with movement, that it can even be experienced as happening within the body itself. P6 describes this as feeling *"it was kind of as if it was my joints, feeling that it was very local,"* while P1 describes feeling as if the vibration was internal, *"touching in my tendons."* Both forms of feedback provide different and unique cues to users; however, with Haptic Servo implementations, we determine that the overall quality and structure of experience is consistent among different sensor implementations used in interaction.

Reflections on Thematic Analysis

The thematic analysis therefore supports the findings of the micro-phenomenological inspired analysis. We demonstrate here that the stages of interaction, and how the users perceive their action's effect on the feedback, shape experience. As well, associations with lived experience and the different parameters set within the Haptic Servo's rendering help to shape the interaction. The implementation of the Haptic Servo in different form factors (knobs, sliders, buttons) shows its versatility in creating unique isotonic and isometric interactions; participants are subject to the same kind of signal in relation to the body, but the feedback feels more like a compliance and reduction in counter-force when pressing into the isometric buttons (e.g., a loose keyboard key or something crunchy) and more of a texture or addition of counter-force when using the isotonic slider (e.g., bumps and waves).

Returning to our research questions outlined in Section 2.4.2, this evaluation demonstrates how the Haptic Servo is able to convey distinct interactions through isotonic and isometric actions using continuous and action-coupled feedback. Exploration of the initial vibration perception demonstrates the distinct phases in participants' interaction experiences, understanding, and connection to the devices. Although the interaction with different elements have slightly different connotations and expectations for interaction behavior, the Haptic Servo is able to render a consistent feedback experience.

This exploration showed that, generally speaking, Haptic Servos can be deployed using arbitrary sensor to vibration mappings, with the resulting experience being interpreted as reminiscent of material properties. However, the specifics of the sensing mechanism and human action influence the qualities of the experience. This is most obvious when comparing isotonic and isometric actions. For isotonic actions, the Haptic Servo appears to *add force*. This might be explained as friction, texture, or obstacles, but can usually be reduced to a description of additional counterforce. For isometric actions, the Haptic Servo appears to *remove force*. In the button example, even though the button is static, participants reported the experience of movement, or reduced counterforce, when interacting with it. Finally, we found that when looking at all the different experiences we observed, the consistent difference between the continuous actuation and the experiences caused by the Haptic Servos was that for the Haptic Servos, vibration and action were experienced as one. This meant that – if made consciously taking note of the vibration – the effects of the haptic servo were described as being caused by their action. This also meant that in many cases participants did not think of these experiences as vibration at all, as the coupling to action transformed the vibration into something qualitatively different.

2.4.5 Workshop: Prototyping with Haptic Servos

We believe that haptic design research benefits from shared platforms and standards. For this reason, we intend to not only publish our *Haptic Servo* design, but also actively work towards the adoption of our platform by other research groups and designers. To investigate if *Haptic Servos* can be used for rapid prototyping of material experiences, we conducted a workshop-style study, which is one of the commonly used approaches for evaluating toolkits and prototyping platforms (Ledo et al., 2018). While the previous exploration was designed to address specific theoretical questions we had about how *Haptic Servos* servos mediate experience, this workshop was primarily motivated as a sanity check, to see if and how others would use our system.

There were five participants in the workshop, three of whom are currently pursuing their PhD in Haptic Feedback design, and two their PhD in HCI for VR. None of the participants work with low-level electronics in their day-to-day research, instead focus on developing for platforms such as Ultrahaptics or Generic VR controllers. The workshop was video-recorded for our own reference. Participants all came from the same research group. This research group was selected as members of the group had

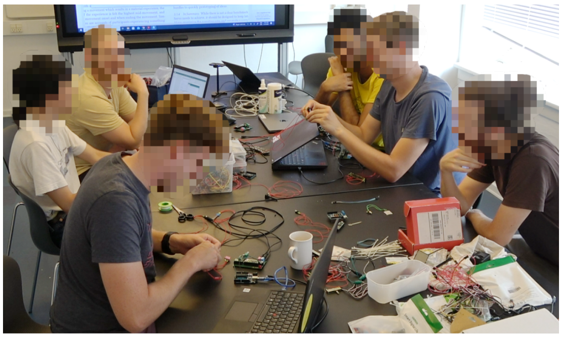

Figure 2.9: *Frame from the video recorded during the workshop*

expressed interest in such technology.

- **P1:** PhD student in VR and HCI, basic Arduino knowledge, no haptic feedback experience.
- **P2:** PhD student in VR and HCI, psychology background, basic Arduino knowledge, no haptic feedback experience
- **P3:** 3rd year PhD in Haptics for HCI, experience with Bela and Beagleboard, but not in low level control of haptics.
- **P4:** 1st year PhD in Haptics for HCI, basic Arduino knowledge
- **P5:** 3rd year PhD in Haptics for HCI, experience with electronics prototyping, but not in low level control of haptics.

Participants were instructed to set up basic haptic feedback systems, to evaluate whether Haptic Servos would be useful in their own research, and to assess if the design was intuitive for a new user. Participants received a brief explanation of the system using Figure 2.4 and Figure 2.3 of this paper for visual explanation. They were then each handed a Haptic Servo as well as a sensor of their choice. We provided rotary and linear potentiometers, force sensitive resistors, and flex sensors for the participants to explore. All participants were able to set up a basic system in 8 to 12 minutes, including instructions. Participants were then asked to adjust the parameters of the Haptic Servo using an additional Arduino and the servo library. Here, participants who already had Arduino installed required ~10 minutes, while those who had to first install Arduino took ~20 minutes. This shows evidence, that a new user can rapidly create prototypes using Haptic Servos.

Regarding customization of feedback parameters, P1 commented that *"oh cool, the different values feel ... distinctly distinct"*. However, workshop participants were not particularly worried about specific mapping of servo values to parameters, it was enough that they could tweak the experience. Instead, they were more interested in experimenting with different sensors and how they affected the resulting experience. Participants also spent time exploring how the sensation changed with different sensors and with ways of interacting with the sensors, for example attaching a flex sensor to the body, as compared to using the flex-sensor as a type of whisker. This highlighted that Haptic Servos do indeed support playful exploration, as we intended.

Generally, the Haptic Servos performed as expected, and participants found them useful. For example, P4 stated that *"This would be helpful for setting up a quick prototype for trying out an idea"*. A simple improvement suggested by participants was adding an LED to indicate if the Servo had sufficient power. A problem area identified was that the debounce algorithm used in the version of the firmware used for the workshop performed well for some sensors and less well for others, leading to glitches. This suggests that future versions of the firmware will require more careful signal conditioning. This might be implemented with a calibration procedure on startup, or after connecting a sensor.

After concluding the workshop, two of the Haptic Servos were given to P4, as they intend to use them for an upcoming research project.

Retrospective Insights & Limitations

We had many internal discussions about the design of the pulse-controlled protocol and how this abstracted away the parameter selection process. We anticipated this as a potential friction point, expecting to update the system based on user feedback. In practice though, none of the participants expressed further curiosity on the specifics of the parameter mappings. We believe this had two reasons. First, it did indeed support the type of playful exploration we were aiming at. Second – and this highlights a potential limitation of the system – participants assumed that they would only use *Haptic Servos* for prototyping, but not for a final design.

A second potential limitation is highlighted by the strong effect of sensors on the experience. As reported, participants were particularly interested in exploring the experience with different sensors. This is because each sensor had its unique output response curve, some linear, some exponential, some arbitrary. This highlights that the sensor choice when using *Haptic Servos* is not neutral, but an important part of the design process. Participants enjoyed this, during our session, however it highlights that *Haptic Servos* might benefit from additional signal-conditioning. This might be designed to work in harmony with a future calibration procedure at startup.

2.5 Haptic Servos in Use

To better explain how a Haptic Servo operates, and to showcase some opportunities they provide, we designed three demo applications as shown in Figure 2.1. Please also refer to our video-figure. Our video shows these in action, together with a sonification of the tactile feedback. We also mention our follow-up research where haptic servos were used for tactile augmentation.

2.5.1 Tangible UIs

Experts working with digital image, video, and audio editing tools often use additional tangible control devices. These are particularly useful when, for example, editing more than one parameter at once. However, depending on the specific application or menu currently in focus, the physical controller might switch its function. Using Haptic Servos, the device can easily be set so that each function has a fixed material experience, so that the user immediately feels what part of the program they are interacting with. We implemented three tangible controllers, each using a different sensor and input modality but all controllers use the HapCoil-One[17] (a wide-bandwidth LRA by TactileLabs)

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[17] The HapCoil-One is also known as Haptuator Mark II-D (`http://tactilelabs.com/products/haptics/haptuator-mark-ii-v2/`)

to provide vibrotactile feedback (see Figure 2.7 and Figure 2.1 B). We used these devices for our qualitative study (see Section 2.4.2). In a rapid prototyping context, such a setup could easily be implemented using an off-the-shelf servo-shield for Arduino for setting up power and communication leads using the Pulse Control port. A designer could then set the different experiences using the Arduino servo library.

2.5.2 Body Feedback

The second example highlights that not only the experience of other materials can be modified, but also the experience of one's own body. Here, we applied a thin film flex-sensor to the finger as well as a haptic actuator (Taptic Engine). Connecting both to a Haptic Servo adds additional cues to the finger movement. Such mechanisms could in the future be used to enhance one's proprioceptive experience, for learning fine motor skills or for bio-feedback and self-regulation. Unconscious actions such as breathing could be made more accessible Reed et al., 2021; Tsaknaki et al., 2021 or even shareable between people Frey et al., 2018; Haynes et al., 2022. Here we chose to use a Taptic Engine as the actuator, due to its small form factor, which also highlights the general purpose nature of the Haptic Servo (see Figure 2.1 C).

2.5.3 Industrial Design

Synthesizers and digital instruments are controlled with a MIDI controller. As this device creates no sound of its own, the primary considerations when assessing the quality of such a device is the tactile behavior of its keys. In our third example, we show how a budget MIDI controller can be augmented by a Haptic Servo to convey a more pleasing tactile experience. This augmentation provides opportunity to design learning applications which use altered material properties as an additional communication channel. Similarly, the tactile experience can be designed to provide additional feedback on key-travel, pressure or aftertouch (see Figure 2.1 D).

2.6 Discussion

Re-framing motion-coupled vibrotactile feedback, designed as a servomechanism, opens up a number of doors. Haptic Servos encapsulate many of the more complex aspects of creating vibrotactile material experiences, which allows both expert and novice haptic designers to focus on the actual design task, rather than implementation details. Modeling the interface closely after regular RC servos further supports this, as off-the-shelf hardware and software can be used. This is not only beneficial in easily sourcing parts, but also enables novices to find documentation and instructions faster, as tutorials and instructions on interfacing with regular servo motors largely apply to Haptic Servos as well. Finally, Haptic Servos might easily be integrated in existing ecosystems for supporting rapid prototyping, such as (Günther et al., 2021; Y.-W. Lin et al., 2017).

Haptic Servos not only make the process easier, but also provide new design opportunities due to their scalability. As our applications highlight, Haptic Servos can be a valuable industrial design tool, for making products such as MIDI keyboards feel more pleasing, as well as an interaction design tool for making multipurpose input devices more intuitive.

2.6.1 Experiences Created with Haptic Servos

Not only do we present a new device for supporting vibrotactile feedback design, our evaluations of *Haptic Servos* also provide new insight into tactile experiences:

Proximal vs Distal

Our qualitative analysis of the resulting experiences reflects the distinction made between proximal and distal vibrotactile perception. Continuous vibration is experienced as originating from the device, which mirrors how we described distal vibrotactile perception. Once synchronization between action and vibration is achieved and understood by the user, the perceptual mode switches. Users speak of the vibration being in the hand or caused by the hand. This matches how we think of proximal vibrotactile experiences. It should be highlighted that this switch is not a matter of degree. Much like a bi-stable image (such as the rabbit and duck illusion[18]) is experienced as either one or the other mode, but never both concurrently, so does the perception of the vibration switch between the distal and proximal mode.

Body Based Feedback

As the tactile actuation by a Haptic Servo is perceived as integrated with the movement, rather than external, this opens up interesting opportunities for movement augmentation from a motor control perspective (c.f. (Schmidt et al., 2018)). In motor control, researchers typically distinguish, feedback provided by trainers or technologies (*augmented feedback*) and feedback provided by one's own body (*intrinsic feedback*). As the feedback provided by Haptic Servos is experienced as originating from one's own body and actions, there is an opportunity to provide augmented feedback which is experienced as proximal, intrinsic feedback with Haptic Servos. This opens up exciting new applications for learning and motor control technologies.

Perceptual Mechanisms

Our analysis showed that, to a large extent, the experiences resulting from interaction with Haptic Servos are dictated by the specific implementation and what type of coupling between action and tactile stimulation this creates. However, while the experiences created by interacting with Haptic Servos can vary based on the specific implementation, in our analysis we found that the structure of the experience is consistent.

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[18] `https://en.wikipedia.org/wiki/Rabbit-duck_illusion`

This highlights that the experiences created share the same perceptual mechanisms, which are addressed by the Haptic Servo.

The specific structure of the experience – the initial exploratory phase followed by an integrated perception of action and vibrotactile actuation – does also highlight an experiential limitation of our current implementation. While the Haptic Servo creates an interaction which is *like* a material experience and the resulting experience has the resemblance of a material experience, it remains an imitation. Participants require an initial exploratory action, before the experience of action and the vibrotactile actuation are integrated. After the initial action and before the integration phase, we observed that the participants experienced something like an *"Aha moment"* which enables the perception to switch from the distal to the proximal mode. We find this observation fascinating, and hope to explore it in more detail in the future. It is currently not clear if this is a general perceptual mechanism or a limitation of Haptic Servos.

2.6.2 Implications for Design

As we highlighted starting out, the tactile properties of an object are often amongst the first cues we use to judge the quality of an engineered object. For example, the tactile response of a keyboard or the feeling of a laptop hinge are important factors in assessing the quality of their industrial design.

Haptic Servos enable new ways of exploring such tactile features: Similarly, to how a 3D render might be created using different colors, now a physical prototype can be implemented and designers can explore different material properties post-hoc. For example, one might 3D print a generic object, and then explore how it is experienced with various material properties.

Haptic Servos also change how we can think about the materials our design consists of. As both sensor-behavior and user actions influence the resulting experience, the sensor choice becomes an important design decision. The designer can experiment with sensors that have different response curves, as a further dimension of signal design. This means, the sensor, quite literally, becomes a design material, as do the actions that the device affords.

2.6.3 Limitations and Future Work

Hardware

The main limitations of the current implementation of Haptic Servos is that it does not yet have the desired form-factor we are aiming for, as the current iteration of the Haptic Servo is a proof-of-concept device. It is implemented as a Teensy shield for convenience. However, the Teensy has many features which a Haptic Servo does not need and is the most expensive component (~ 47 Euros) in the haptic servo (~ 63 Euros). Once we are satisfied with the feature set of the Haptic Servo, we intend to search for a cost-efficient alternative, on which we can optimally implement the required features with a minimal footprint. This will allow us to design a device which – like a servo-motor – is not significantly more bulky than the actuator alone. Once such a device is implemented, it will also become obvious that to integrate multiple sources of vibration, one would simply use multiple haptic servos.

Software

There are also limitations on the software side. The current implementation uses the Teensy Audio Library, again for sake of convenience. This library enabled us to experiment with initial implementations, and will allow others to easily build on our work (for example, by experimenting with alternative waveforms, or with the ADSR object provided by the library). A drawback of the library is that the latency and jitter with regard to synchronization of pulses to analog signal changes is higher than necessary. In the future, we intend to provide either a branch of the audio library or a new library optimized for tactile feedback.

Knowledge Transfer

With regards to usability, our workshop highlighted that researchers perceived Haptic Servos as a tool for early prototyping, but not for building complete systems. This highlights that we need to further work on making Haptic Servos more accessible and their features more transparent. Currently, we use Haptic Servos as the core of multiple systems and experiments in our research group. Further non-technical improvements on the usability and accessibility will be required for others to adopt Haptic Servos in the same way. However, through open sourcing our work and engaging in dialogue by means of workshops, demos, and publications we intend to facilitate the necessary involvement of others to collaboratively achieve this goal.

2.7 Conclusion

In this paper, we highlight that haptic rendering systems can be thought of as servomechanisms. We implemented such a servomechanism for creating vibrotactile material experiences called Haptic Servo. Our implementation is designed to easily integrate with off-the-shelf prototyping systems, as it adheres closely to the standard interface of RC servos. This enables expert hapticians, designers, practitioners and novices easier access to designing vibrotactile material experiences. As Haptic Servos are self-contained and can create a signal automatically – that is, without continuous monitoring of a control device or user intervention – they can be rapidly deployed in versatile applications. We demonstrated this by using Haptic Servos in a tangible UI, an on-body feedback mechanism, and an augmented keyboard. Using the tangible UI, we conducted a qualitative study, which revealed that, from a perspective of subjective experience, the general purpose of Haptic Servo performs as desired. We also highlight that the type of action that is augmented by the Haptic Servo influences the resulting design: isotonic actions are experienced as having added counter-force, while isometric actions are experienced with reduced counter-force. Finally, the workshop with five researchers demonstrated that users new to haptic servos were able to set up a basic rendering system within 10 minutes.

This opens up new doors for thinking about tactile design. Using Haptic Servos, designers can experiment with different material properties, similarly to how designers might render a design in different colors. Our work points towards a new direction for vibrotactile material design, but there is much more to explore. To support others in building on our work, all code and circuits are open source, and we look forward to supporting others in branching, remixing and copying our designs.

3 Foot Pedal Control: The Role of Vibrotactile Feedback in Performance and Perceived Control

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Motion-Coupled Vibration (MCV) offers a robust method for evoking virtual material experiences perceived through the sense of touch. Across this dissertation, I investigate how such vibrotactile signals create embodied tactile experiences – sensations that feel as though they originate from one's own action (moving our hand through sand or crumbing a piece of paper) rather than from an external device (think of mobile phone vibrating on the table or someone hammering a nail on the wall you are resting on). The previous chapter (Chapter 2) established the technical and conceptual foundation for this inquiry by introducing Haptic Servos which induce virtual material experiences, capable of shaping users' experience. The chapter further demonstrated that MCV can generate realistic, self-caused sensations perceptually distinct from continuous vibration. These findings along with established research (Strohmeier, 2019; Mun et al., 2025) suggest that the feedback being perceived as embodied may arise not only from the content of the tactile signal, but also its *temporal and relational structure:* vibrations that are tightly synchronized with the user's movement are experienced as

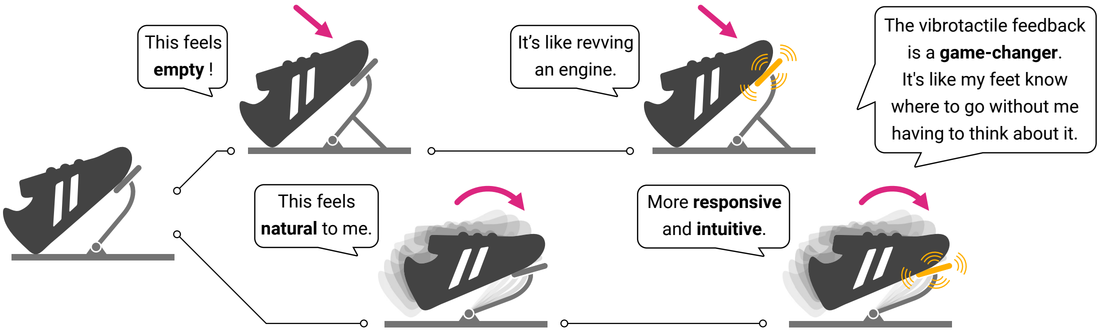

Figure 3.1: *We built a pedal that can either move (bottom row) or is locked (top row). Further, we attached an actuator to augment the interaction with vibrotactile feedback (right). Each mode elicits certain qualities of experiences and perceived control of the pedal.*

part of the action itself.

These observations raise a deeper question on the lines of Section 1.3.2: ***why does coupling vibration with user action feel embodied?”*** This and the following chapter, address these questions by examining how two established perceptual mechanisms: a) Sense of Agency (SoA); b) Sensory Attenuation (SA), contribute to induce material experiences which feel self-generated and embodied.

In this chapter, we go from small-scale interactions predominantly using the hand as the interaction modality to foot operated functional interface: a foot pedal. Foot pedals were chosen due to an industrial collaboration with Bosch that highlighted its potential for real-world translation. Moreover, pedals are interfaces which involve continuous sensory-motor control that unfolds through both, isotonic and isometric actions. Unlike handheld or hand-operated interfaces, foot-based interaction is visually occluded and proprioceptively dominant, making it an appropriate context for exploring how motion-coupled vibrotactile feedback shapes the control/ experience of acting. Finally, pedals are mechanical systems that offer clear physical affordances like compliance, travel, and resistance that are used by the users to gauge their control.

MCV can generate convincing material experiences without requiring physical compliance or complex mechanical assemblies. By coupling vibrotactile pulses to applied force, systems can simulate virtual compliance, making rigid pedals feel as though they yield under pressure. Conversely, coupling vibrations to user movement can evoke sensations of friction or texture as the pedal moves. Rendering these affordances through vibration, rather than through physical mechanisms, raises an important line of inquiry: *if we are able to produce convincing virtual material experiences, how do these material experiences perform? Do they afford benefits for control? In terms of performance, does it matter whether a user presses into a virtual compliant pedal or an actual compliant one?* For material rendering, the same algorithmic structure introduced in the Chapter 2, detecting changes in user input and mapping those changes into discrete vibrotactile pulses, is used.

Through psychophysics and a VR ecological driving tasks, four pedal configurations (rigid vs. compliant, with vs. without MCV) were used to understand the effects of virtual material rendering on objective performance and perceived control. The results reveal a clear dissociation: MCV increases users’ perceived control despite leaving objective performance largely unchanged. This gap between being in control and feeling in control offers an important insight that MCV is experienced as self-generated and hence feels embodied.

3.1 Introduction

The evolution of control mechanisms has continuously adapted to technological advancements. One notable shift is the transition from the early foot tools that applied both power and control – such as the foot pedal of treadle sewing machines – to modern pedals that predominantly serve as input devices for control (Pearson et al., 1986). Modern pedals are typically used as input devices to control aspects such as the acceleration of a car, the speed of a sewing machine, or to pan and zoom computer interfaces (McIlroy et al., 2016; Göbel et al., 2013; Mark Mulder et al., 2004). While pedals are used for a wide range of applications, a predominant use case of pedals is controlling the throttle and brakes of cars. Different feedback strategies, including force and vibrotactile feedback, have been used to improve the user's control on gas pedals (Mark Mulder et al., 2004; Brookhuis et al., 2009; Driel et al., 2007; Tijerina et al., 2000; Kurihara et al., 2013). However, this feedback is often symbolic in nature and needs to be interpreted by the user. This interpretation can be error-prone (Mark Mulder et al., 2010; S.-H. Kim et al., 2009) and can compromise driver safety (Gaffary et al., 2018). One way to make vibrotactile feedback easier to interpret is by rendering material experiences, such as friction (Strohmeier et al., 2017; Sabnis et al., 2023a). This can be achieved using motion-coupled vibrotactile feedback (Sabnis et al., 2023b).

Past research in HCI has primarily focused on motion-coupled vibrotactile feedback to render virtual compliance (Kildal, 2010) and virtual textures (Strohmeier et al., 2017), but also touched on a broader range of material experiences (Heo et al., 2019; Strohmeier et al., 2016; Sabnis et al., 2023a). The underlying perceptual mechanism between virtual compliance and virtual texture share a common foundation: vibrotactile pulses synchronized with the measured human action generate material experiences. Specifically, vibrotactile feedback coupled to applied pressure induces an experience of virtual compliance while vibrotactile feedback coupled to user movement induces an experience of virtual textures (Sabnis et al., 2023a). Therefore, the type of user action plays a crucial role in creating these material experiences. In this research, we implement virtual compliance by coupling vibration feedback with user applied pressure on a rigid pedal configuration. Further, for rendering virtual textures, vibrotactile feedback is coupled with the user movement on a compliant pedal configuration. Thus, compliance illusion can be rendered over a rigid pedal configuration to make it feel as if the pedal can be pushed. On the other hand, virtual textures can be rendered over the compliant pedal configuration so that the user has an experience of the pedal moving over a texture. Doing so presents us with an interesting set of questions: 'If a rigid pedal can be made to feel compliant using vibrotactile augmentation, would the user interact with it as though it were rigid or compliant?', 'Does this augmentation help the user achieve finer motor control, potentially improving task performance?', 'How does the user's subjective perception of control align with their objective performance when vibrotactile feedback is applied?'

The above questions highlight an important aspect, namely, the objective control over an interface might be different from the subjective control the user feels while operating the system. Research highlights the differences between objective and subjective measures; however, they usually focus on the methods of evaluation or usability of the interface (Ferreira et al., 2019; Altin Gumussoy et al., 2022) rather than on performance or control. This experience of being in control is related to the 'sense of agency' (SoA) ("The Experience of Agency: Feelings, Judgments, and Responsibility" 2009) and is a crucial aspect in developing novel interfaces (Shneiderman et al., 2010; Coyle et al., 2012; Didion et al., 2024). Past work has hinted at the similarities and differences between objective control and SoA; however, these have not been explicitly investigated (Strohmeier et al., 2016; Kasahara et al., 2019), hence our interest to understand the relationship between the user's perceived control (SoA) and their objective performance with the four pedal configurations.

In this research, we evaluate the user's perceived control and objective performance on an abstract line-following task and an ecological task in VR by conducting a within-subjects study with 12 participants. We compare objective performance and perceived controllability using four pedal configurations: ***Compliant and Non-augmented*** (***CN***)***;*** ***Compliant and Augmented*** (***CA***)***;*** ***Rigid and Non-augmented*** (***RN***)***;*** ***Rigid and Augmented*** (***RA***), as shown in Figure 3.1. As pedals in cars are a familiar interface for general users, we conduct an ecological driving study in VR as an additional measure of performance. We use qualitative interviews to understand the users' subjective experience of control. Our results show that embodied vibrotactile feedback improves the users' perceived control, despite their objective performance remaining the same for the four pedal configurations. The quotes by the participants for each condition during the study are shown in Figure 3.1. Hence, an increase in perceived control (SoA) is not consequential to an improvement in performance.

This paper makes three contributions:

- It proposes a novel perspective on foot pedals as interactive devices, integrating vibrotactile feedback methods to enrich user interactions.
- It provides insights from a user study evaluating motion-coupled vibrotactile feedback for foot pedals, improving our understanding of the links between feedback and user-action through objective and subjective measures.
- It demonstrates that rigid pedals can perform as well as compliant pedals, and vibrotactile augmentation can improve perceived control while not affecting the performance.

3.2 Related Work

Pedals have been used as control interfaces to manipulate devices ranging from potter wheels to automobiles. This section summarizes the research on pedals as controlled input devices, as well as haptic feedback on pedals. We also summarize the literature on motion-coupled vibration to provide embodied vibrotactile feedback and how augmentations affect the user's sense of agency.

3.2.1 Pedals for Controlled Input

In the field of HCI, pedals have been designed, optimized, and used as a control interface for many years (Pearson et al., 1986; Trombley, 1966; Barnes et al., 1942; Keoemer, 1971). Pedals historically served as basic single-parameter control interfaces, initially functioning as binary switches for transcription with momentary or latched states, offering continuous kinesthetic feedback to users for maintaining active states (Sellen et al., 1992). Today, pedals are primarily used for controlling continuous parameters where the mapping of the pedal position to the parameter being controlled is crucial. For instance, Balakrishnan et al. (1999b) and Göbel et al. (2013) used pedals that mapped the position to the parameter being controlled, whereas Saito et al. (2017) and Kim et al. (S.-H. Kim et al., 2009) preferred pedals that mapped the input to the rate of the parameter being controlled. However, Van Veelen et al. (2003) mentioned that whatever the type of mappings, pedals are not fully controllable and suffer from a lack of feedback.

Input devices like the mouse and the joystick have been studied in regard to control with isotonic and isometric actions (Poulton, 1974). Isometric actions involve muscle contractions without joint movement through either force or torque, like pushing a wall. Isotonic actions encompass joint movement along with muscle contractions (Zhai, 1996), such as the elbow moving when an object is picked up. There are two primary types of transfer functions based on the type of mappings of input devices, namely, position and rate control (Poulton, 1974). Position control, referred to as zero order control, is a linear mapping of the user input to the controlled artifact displacement, for example, when using a computer mouse to move a cursor. The cursor's displacement on the screen is directly proportional to the movement of the mouse. Rate control, on the other hand, maps the user's input to the derivative of the controlled artifact movement, i.e. velocity, which is used, for example, when controlling a drone's speed with a throttle stick. Research has shown position control to be better with isotonic devices, whereas rate control is better with isometric or elastic devices (Zhai et al., 1993b; Zhai et al., 1993a; Zhai, 1996). Moreover, performance was better when isometric sensing was combined with rate control and isotonic sensing with position control (Zhai et al., 1994; Zhai et al., 1997).

Although multi-functional foot-based interfaces with movement and pressure have been studied (Taeyong Kim et al., 2018; Kurihara et al., 2013), to our knowledge, controllability of pedals with isotonic and isometric movements is yet to be investigated. This study focuses on investigating the control of pedals with isometric (rigid) and isotonic (compliant) pedal configurations, with and without embodied vibrotactile feedback.

3.2.2 Haptic Feedback on Pedals

Feedback for pedal input has been provided using audio cues such as modulating the signal in guitar pedals (Lang, 2018) and audio-visual cues such as increasing the speed of a sewing machine pedal as we press into the pedal. However, for situations where the audio and visual modalities are overloaded, haptic feedback can serve as an additional non-intrusive feedback channel. One feature of haptic feedback systems is that the part of the body that receives the information can be the same one that manipulates the interface, thus opening possibilities to couple the user's action with haptic feedback. The most common type of haptic feedback is force feedback, where the pedal provides forces to the user's foot (Mark Mulder et al., 2004). Force feedback has been used in the development of modern haptic pedals, which exert variable counter-forces depending on the vehicle dynamics, surrounding traffic or controlling speed (Brookhuis et al., 2009; Driel et al., 2007; Adell et al., 2008). Force feedback methods are also presented for simulating or enhancing classical pedal feeling in regenerative breaking (Caliskan et al., 2018) or break by wire systems (Abeysiriwardhana et al., 2014). While force feedback on the gas pedal is effective for car-following, it can be insufficient when quick corrective control actions need to be taken to prevent collision (Max Mulder et al., 2008).

Another way of providing feedback is using vibrotactile feedback. For instance, warning signals in the form of vibrotactile pulses have been used in pedals to compel braking events and in speed or collision warnings (Martens et al., 2001; Tijerina et al., 2000). It is crucial to have a high stimulus-response compatibility with the action to be performed (Tijerina et al., 2000). Therefore, the stimulus must be felt on the body part that needs to react (Suzuki et al., 2003; De Rosario et al., 2010). Vibration as a feedback strategy on gas pedals has also been shown to support economical driving (Birrell et al., 2013; McIlroy et al., 2016; McIlroy et al., 2017) and elicit a positive eco-friendly driving experience (Ruiter et al., 2019). Rosario et al. also found vibrotactile stimuli to improve the efficacy of the feedback and elicit differences in user perception (De Rosario et al., 2010).

However, if haptic feedback is abstract, it needs to be interpreted by the user, which can increase their cognitive load (Culbertson et al., 2018). In the context of driving, this leads to a delay in the user's response and compromises driver safety (Gaffary et al., 2018). We are interested in coupling vibrotactile feedback with user actions to elicit embodied and, hence, less cognitively demanding feedback for the user (Sabnis et al., 2023a). We focus on the use of pedals in the context of driving, as this is a commonly understood setting.

3.2.3 Embodied Vibrotactile Feedback

Vibrotactile feedback, when coupled with user action, can create embodied material experiences (Sabnis et al., 2023a; Sabnis et al., 2023b). Research has demonstrated that vibration coupled with the force applied by the user can simulate virtual compliance (Kildal, 2010; Kildal, 2012). Subsequent studies explored virtual compliance further, including creating the illusion of compliance through vibrations coupled with tangential forces (Heo et al., 2016; Heo et al., 2017). This method of coupling vibrations with user actions has been shown to alter the perceived interaction with objects. For example, Strohmeier et al. (2016) induced the sensation of bending a smartphone, and Heo et al. (2019) expanded this to include experiences like stretching, bending, and twisting of a rigid object. Additionally, Vega et al. (2024) demonstrated that virtual compliance could be felt by providing vibrations at a different location than the body part exploring the object. Motion-coupled vibrations have also been used to make hard surfaces feel softer by providing vibrotactile feedback to the user's feet (Strohmeier et al., 2020; Wittchen et al., 2023).

Vibration coupled with the movement of a user-held object can create the sensation of moving over a textured surface with virtual friction. Romano and Kuchenbecker replicated the experience of moving over textures by recording probe movements and playing back these signals as vibrations on a smooth surface (Joseph M Romano et al., 2011; Culbertson et al., 2012). Moreover, texture experiences can be generated on a smooth slider by coupling vibrations with user movement on the slider (Strohmeier et al., 2017; Sabnis et al., 2023a). Furthermore, Ding et al. (2024) showed that vibration pulses coupled to user force can create an illusion of movement for the user, even when there is none. This shows that the same coupling of vibrotactile feedback with user action can generate virtual compliance and virtual textures based on the user action of pressing a surface and moving over a surface, respectively. However, to our knowledge, using vibrotactile augmentation on the same input device (pedal) for creating virtual compliance and virtual friction has not been studied. In this research, we implement these two established methods of vibrotactile augmentation and evaluate user control.

3.2.4 Sense of Agency: Overview and Evaluation

The sense of agency (SoA) describes the experience of controlling one's own actions, and through them, the events in the external world ("The Experience of Agency: Feelings, Judgments, and Responsibility" 2009). It is crucial to note that the SoA is a measure of the user's perceived control (Tapal et al., 2017) and is different from the factual control of a task measured using Fitts' Law, Following Tasks, etc. In HCI, the user's SoA is an important consideration when designing new interfaces (James W. Moore, 2016). It has been described in Shneiderman's Eight Golden Rules of Interface Design, which states that designers should create interfaces that "support an internal locus of control" (Shneiderman et al., 2010). This is based on the idea that users "strongly desire the sense that they are in charge of the system and that the system responds to their actions" (Shneiderman et al., 2010). Experiencing a sense of agency during human-computer interaction is important, as it can benefit the overall user experience (Limerick et al., 2014) and the feeling of responsibility (Moretto et al., 2011).

Building on theories and methods from psychology, early studies on the sense of agency in HCI focused on details of interactions such as input modalities (Coyle et al., 2012; Limerick et al., 2015), latencies (Berberian et al., 2013), level of automation/computer assistance (Coyle et al., 2012; Berberian et al., 2012), and how they affect the user's SoA. More recent work also looked at augmentation of the action or feedback. Feedback influences the sense of control we receive for our actions and is important to avoid sensory-motor conflicts that may disrupt the experience of the user (Faivre et al., 2020; Kumar, 2023). Kasahara et al. used electrical muscle stimulation to actuate the human body to improve the reaction speed during different tasks while maintaining the SoA (Kasahara et al., 2019; Kasahara et al., 2021). Further, vibrotactile feedback indicated that the sense of agency in quite minimal interactions could be manipulated with haptic feedback (Strohmeier et al., 2017; Strohmeier et al., 2016). Recent work on haptic feedback and agency for virtual avatar co-embodiment showed that the SoA decreased with haptic feedback compared to without haptic feedback for VR reaching tasks (Venkatraj et al., 2024).

In the literature, there is a distinction between an implicit sense and an explicit judgement of agency (Synofzik et al., 2008). The unconscious sense of agency happens pre-reflectively, while we feel in control over the action currently being performed and the outcome(s) it causes. Previous research has shown that the two ways to look at the sense of agency do not always show the same results (Didion et al., 2024; Dewey et al., 2014), but the implicit feeling seems to have an influence on the explicit judgement (Nishida et al., 2019). While the evaluation of the judgement of agency is quite straight forward, measuring the implicit feeling is more difficult because as soon as we ask participants about it, it becomes a conscious judgement. The literature currently describes two ways of implicitly measuring this feeling of agency: intentional binding (James W. Moore et al., 2012) and sensory attenuation (H. Brown et al., 2013; Pyasik et al., 2021). The intentional binding measure is designed for a setting where the action and the outcome happen within a few milliseconds and at discrete points in time (James W. Moore et al., 2012). The sensory attenuation measure requires an outcome stimulus with a measurable intensity, such as the volume of a sound or the amount of pressure applied (Kiepe et al., 2021; Palmer et al., 2016). In our study, we focus on explicit judgements of control, as the action and the outcome are continuous, and we do not measure changes in perceived stimulus. Hence, we evaluate the post-reflective judgement of agency by conducting a semi-structured interview with the participants about their subjective performance and control. Our work adds a dimension to this line of exploration by highlighting that the subjectively measured and the objective judgement of control can differ.

3.3 Design Rationale

In the year 2022, we had a discussion with an automotive manufacturer who mentioned that the mechanical pedals, although robust, are very expensive due to the multiple moving parts in the system. With the existing research on virtual textures and virtual compliance, we were curious to investigate how vibrotactile material rendering affects user experience and performance with rigid and compliant pedal configurations.

3.3.1 Rendering Materials and Virtual Affordances

Vibration feedback is a common method for eliciting touch sensations by rendering high frequency tactile effects. Typically, vibrations are used to convey abstract information that needs to be interpreted by the user (Lorna Margaret Brown, 2007; Culbertson et al., 2018; Stephen A Brewster et al., 2004a). For example, a phone might vibrate to indicate that new information is available. Another way of conveying information using vibrotactile feedback is by designing vibrations that are embodied and feel natural to the user (Sabnis et al., 2023b). For example, vibration can be coupled to voluntary actions such as a limb movement or by applying pressure on a surface, similar to how the home button (iPhone) or virtual keyboard touches on some smartphones are coupled to vibration feedback. Hence, vibrations that are coupled to user actions can simulate physical control entities like buttons and sliders, offering alternative design approaches for such control hardware. These design approaches can include augmenting the existing control hardware with additional material sensations. For example, a slider that is controlling a speaker can be programmed to feel like it is resisting the user's command towards increasing the volume too much. Or a scroll wheel can have textured clicks for precise control, while switching to a smooth glide allows for larger adjustments.

Adding vibrotactile feedback can have a variety of benefits such as simplifying the design, fabrication, or maintenance of the interface or providing more available space for additional interactive hardware. Moreover, the simulation of control entities can enable completely replacing the conventional control hardware. For example, the iPhone home button is not necessarily more effective in terms of button control, but it creates additional advantages such as more screen space, water resistance, and ease of manufacturing. As for pedals, like we discussed with the automotive manufacturer, research shows that pedals, although robust, are very expensive due to the multiple moving parts in the system (Horiue et al., 2012). Further, the manufacturing of pedals is very complex, and they also need regular servicing. This affords the investigation of whether the current pedal limitations can be overcome by integrating embodied vibrotactile feedback, which has been robustly shown to render virtual textures and virtual compliance.

However, such crucial design decisions must be preceded by a careful assessment of the gained interaction opportunities and performance metrics. To evaluate the novel ways of interaction, we need to measure both objective performance and subjective experience of control (Sense of Agency). In this work, we investigate the effect of motion- and pressure-coupled vibration feedback on the users' pedal control. We compare four pedal configurations, with and without vibrotactile feedback, in rigid and compliant configurations.

3.3.2 Pedal Configurations

Most users are familiar with pedals in the context of the car driving experience. These automobile pedals have been studied extensively as input devices but are now being studied as I/O interfaces. The shortcomings of current pedals, based on the discussion with the automotive manufacturer, and the opportunities of creating material experiences with embodied vibrotactile feedback, raise an interesting question: *Can we incorporate embodied vibrotactile augmentation into gas pedals to improve the user's perceived control of the interaction without affecting performance?* We can relate getting rid of the movable pedal to getting rid of the button on iPhones. Our research seeks to answer the question of whether we need to rethink feedback strategies for foot pedals.

Embodied vibrotactile feedback can be elicited by providing pulses of vibration coupled with user movements. In the context of pedals, by providing vibrations based on the pressure applied by the user for rigid pedals, we expect the user to feel that they are pressing into a (slightly) compliant/ soft pedal. On the other hand, when the vibration pulses are provided with the physical travel of the pedal, we expect that the user experiences the movement of the pedal over virtual textures. Such pedals with embodied vibrotactile feedback would be mechanically simpler, cheaper to manufacture, easier to maintain, and would last longer; however, it is unclear if users would want to use such a pedal, and if it can provide a similar level of control as compliant pedals.

To test the aforementioned unconventional approaches, we evaluate the effect of having compliant vs. rigid and augmented vs. non-augmented pedals. This comparison gives us four pedal configurations, as shown in Figure 2.2 (Left):

- **Compliant and non-augmented (CN):** This refers to the conventional pedal approach. The pedal movement is not constrained, and there is no vibrotactile augmentation.
- **Compliant and augmented (CA):** The pedal movement is not constrained, and there is vibration feedback. This configuration can induce friction illusion.
- **Rigid and non-augmented (RN):** The pedal movement is constrained, and there is no vibration feedback. This configuration provides no proprioception or vibration feedback. The user can only feel the reaction force from the pedal and receive visual feedback from the GUI.
- **Rigid and augmented (RA):** The pedal movement is constrained, and there is vibration feedback. This configuration can induce compliance illusion.

Using these pedal configurations as the independent variables for our research, we investigate the performance of users and their perceived control. Our research questions are: (1) "How does vibrotactile augmentation affect the performance and perceived control of the users?" and (2) "How are subjective and objective performance correlated for the four pedal configurations?"

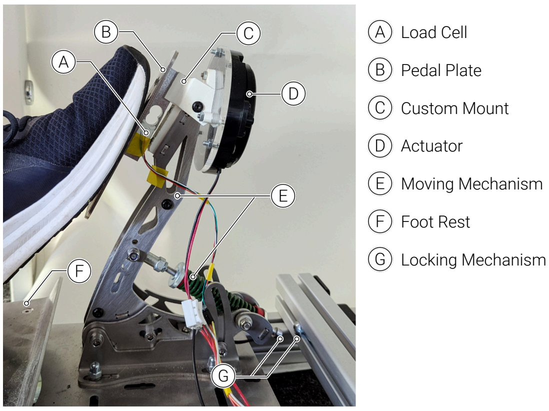

Figure 3.2: *Modified off-the-shelf gaming pedal. We designed a custom part (C) to mount the load cell (A) and an vibrotactile actuator (D) on the top of the pedal. We mounted the pedal on a custom rack including a foot rest (F). A locking mechanism (G) was used to fixate the pedal's moving mechanism (E).*

3.4 Implementation

In this section, we describe the hardware and firmware implementation of augmenting a single pedal to have multiple configurations. We also describe the algorithm used to provide motion-coupled vibration.

3.4.1 Hardware

Our hardware design consists of an augmented, commercially available gaming throttle pedal[1] with a force sensor (strain gauge) and a vibration actuator, as shown in the Figure 3.2. High-end commercial gaming pedals use an additional spring and load cell coupling for measuring the movement of the pedal. Since our rigid pedal scenario requires us to block the movement of the pedal, we moved the load cell directly behind the pedal plate. We connected the lower screw terminals of the load cell to the pedal plate and the upper screw terminals to the pedal are through a mounting unit. Thereby, the foot pressure on the pedal can be sensed by the load cell in both compliant and stiff cases. The mounting unit is also used for connecting the vibration actuator, Dayton Audio TT25-16 Tactile Transducer[2], on the pedal arm. The vibration actuator was controlled with a 40 W amplifier. The whole structure was connected to a large sigma profile base that rested on rubber dampeners, such that the propagation of the vibration to the surroundings was limited. To switch between the rigid and compliant pedal scenarios quickly during the experiments, we designed a blocking mechanism that can slide along the aluminum profile to constrain or release the pedal movement. The travel length of the pedal was 25mm, which was shown to be suitable (Zhou et al., 2016).

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[1] KRE Win Pv3 sim racing pedals: `https://www.kre-sim.eu/kre-win-pv3-sim-racing-pedals/`; accessed October 26, 2024

[2] Dayton Audio TT25-16 Tactile Transducer: `https://www.daytonaudio.com/product/1037/tt25-16-puck-tactile-transducer-mini-bass-shaker-4-pk`; accessed October 26, 2024

We used haptic servos (Sabnis et al., 2023a) to couple the vibration with user-applied forces. Haptic servos helped to keep the delay between the sensor value and vibration onset below *5ms*, which is important, as delay diminishes the SoA by inducing a temporal discrepancy between an action and its effect (Wen, 2019). The signal chain consists of the user input of force sensed by the force sensor (20 kilogram strain gauge), which is converted to an analog signal using an HX711 breakout board that functions like a 24-bit Analog to Digital signal Converter. This signal is read by Teensy 4.1 microcontroller, which maps the input signal to the output vibration based on the binning algorithm (Figure 3.3, Right). The output signal is then converted to an analog signal using a PT2811 shield before finally amplifying and feeding it to the actuator. The load cell values are sent to the computer via real-time serial communication.

3.4.2 Firmware

To render vibrotactile feedback based on the applied force by the user, we divided the sensor range between the resting value of force (global minimum) and maximum force applied on rigid and compliant pedals into a number of discrete bins. When a sampled sensor value enters a new bin, an AC pulse (i.e., audio signal) is generated, as shown in Figure 3.3-Right. Based on the changes in the measured signal, pulses are generated, i.e., if the signal changes fast, pulses are generated rapidly, whereas if the signal changes slowly, the pulses are generated proportionally slowly. The relevant variables required for generating the signal are the number of bins, which corresponds to the overall density of pulses (in the sensor range), a.k.a. granularity. The vibration specification of each pulse is determined by the type of waveform used as well as by the duration, amplitude, and frequency of that waveform. The duration was derived from frequency to minimize clipping artifacts. We found that both a full period and a half period of the waveform work well. The amplitude, frequency, and number of bins/grains were set based on the pilot studies within authors (Section 3.5.1). This leaves the frequency and number of bins as the primary parameters to consider when designing a vibrotactile material experience. The algorithm with the calibration code, the trajectories used, and processing UI used in the experiment are open source[3].

3.5 Evaluation

We evaluate the interaction between the objective performance of the user and their perceived control on an abstract task as well as an ecological driving task.

3.5.1 Pilot: Psychophysics study for parameter selection

We conducted a psychophysics study within 4 of the authors to ensure the use of correct parameters of the motion-coupled vibration, namely frequency and grains, for augmenting the pedals. The objective of this pilot study was to understand the effect of

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[3] GitHub repository: `https://github.com/sensint/HapticGasPedal`

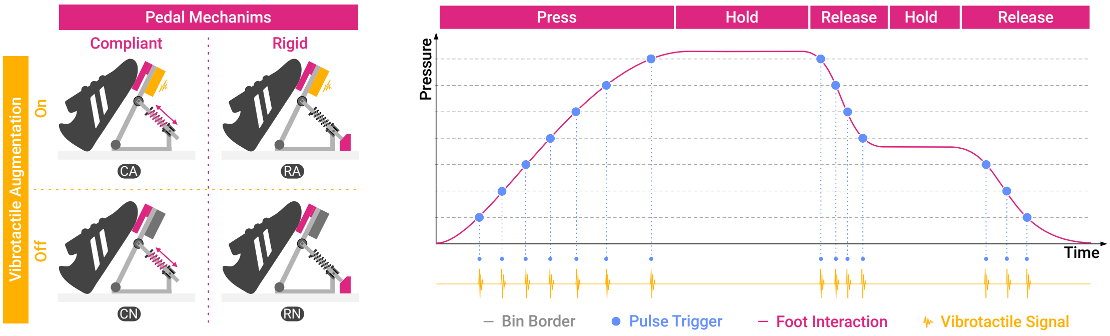

Figure 3.3: *We designed four conditions based on two factors, i.e. pedal mechanism and vibrotactile augmentation, with two levels each (left). In the two conditions with activated vibrotactile feedback, we utilized the grain-based augmentation algorithm (Section 2.3.3), which renders vibration pulses (grains) at certain levels of applied pressure, i.e. motion-coupled augmentation (right).*

parameters of the vibrotactile augmentation that elicit an experience of softness and controllability.

Experiment Design

Frequency was selected as one of the independent variables since the used actuator's preferred operating range of frequency is between 20 and 80Hz for rendering haptics, whereas a frequency of 220Hz is best perceived by the meissner corpuscles. Moreover, the number of grains (pulses of vibration based on user input) has been shown to affect the user's sense of control (Heo et al., 2019). Hence, the independent variables were the frequency of the vibration (20, 40, 60, 80, 220 Hz) and the number of grains (12, 24, 36). The amplitude and waveform of the vibration was kept constant throughout the study. The number of grains were mapped linearly throughout the sensor range, which was calibrated per participant (author). Only the rigid pedal with vibrotactile augmentation was used for the psychophysics study, as we were interested in the distribution of vibrotactile augmentation that would elicit an experience of softness (ability to push the pedal and not push into the pedal) and controllability. Each participant rated (on a free scale) the softness and controllability for the 15 possible combinations of the frequency and number of grains as well as for a rigid pedal with no augmentation, which was considered the ground truth. During the study, the participants wore noise-cancelling headphones playing white noise in order to mask the audio cues.

Pilot: Results

The results of the psychophysics study show that granularity relates to perceived control. Participants associated higher granularity (higher number of grains) with an increase in the sense of agency and vice versa. Two participants unknowingly tested a number of grains over 36 as well, but they reported that the vibrotactile feedback felt very noisy. Anecdotally, it appeared that frequency and grain count interacted, but we did not find a clear pattern. The results showed that frequency was related to the perceived softness. The 220Hz condition was rated to be least perceivable. We decided to choose the number of grains to be 36 as it seemed to provide good control and a frequency of 80Hz, which, in combination, seemed to elicit an experience of virtual compliance. The participants described the feeling of pushing the pedal as squeaky, crunchy, and crispy.

3.5.2 Study Design

We evaluated the objective performance of the participants using all four pedal configurations with an abstract line-following task and a driving task for testing the ecological validity. For the subjective performance evaluation, we conducted qualitative interviews with all participants.

Study Rationale

The first task was focused on evaluating the control with the different pedal configurations on a simplified one-dimension following task. The second experiment evaluated the controllability of driving a car in a Virtual Environment. Before both experiments, training was conducted to familiarize the participants with the tasks and different pedal configurations. Finally, we concluded the study by interviewing the participants to understand their perceived control and customized design of vibrotactile augmentation with pedals.

Trajectory Design: The easy level was designed using three types of segments in terms of the position-time graph: (1) Holding the position constant (corresponds to pushing the pedal with a constant force), (2) a sine connector (for slow approach and release), and (3) a line connector (for constant approach and release). Using these as the ground rules, trajectories were randomly designed with 3 second holds at 20, 40, 60, and 80% of the trajectory amplitude. The easy difficulty level had one hold each at every amplitude level , while medium and hard levels ran the same trajectories at 1.5 times and 2 times the frequency, respectively. Figure 3.3-Right shows a sample trajectory along with the algorithm used for rendering vibrotactile pulses coupled to user action.

Procedure

The study consisted of the calibration phase followed by training, a line-following task, a driving task, and finally, qualitative interviews. The total study time was 1.5 hours.

Calibration: Calibration was done for the maximum force applied by every participant for the rigid and the compliant pedal configurations. Moreover, the global minimum force (for both pedals), when the participant rests their foot on the pedal, was calibrated to reduce fatigue and accidental activation, similar to (L Barnett, 2009). These ranges of the applied force on the pedals enabled us to have an individualized task and vibrotactile augmentation for every participant. The grains were played with respect to the calibrated sensor range. We also calibrated the amplitude of vibration where the participant was able to feel the vibration without hearing it.

Training: Post calibration, there was a training phase before each task. The pedal order was generated for every participant using a balanced Latin square approach to mitigate any ordering effects, and was fixed throughout the study for each individual participant. Training was done to familiarize participants with the tasks, the pedal configurations, and the mappings between the force applied and the visual feedback they received. Training for the driving task made sure the participants were comfortable with the headset and the virtual reality environment and would not experience motion-sickness. The training phase was 30 seconds per pedal configuration for both the tasks and was done at the beginning of each task. Participants were allowed to repeat the training as many times as they wanted, provided they did it for all the pedal configurations.

Visualization: **Processing** version 3.5.4 was used to create a one degree of freedom following task. We used a multiscreen layout to enter the participant ID, followed by the code of the pedal selected for the trial, and a countdown timer to indicate the start of the task. The task screen, which can be seen in Figure 3.4-B, consisted of two rectangles on a white background. The movement of the target rectangle (red) was based on the predefined generated trajectory, while the movement of the other rectangle (blue) was mapped based on the pedal position, which was controlled by the user. There was no explicit information provided to the user in terms of the distance between the target and the user-controlled rectangle, besides the visual information on how far the two rectangles were, in order to avoid any distractions. Next steps, which included the next trials before going to the next pedal configuration, were displayed sequentially as the trials were completed.

Unity was used to create the ecological driving task showed in Figure 3.4-C. The cars were restricted to moving along a straight road. Natural artifacts such as trees, ponds, and rocks were placed around the road to augment optic flow in the peripheral vision of the participant to improve their sense of motion. As an indicator of performance, we considered adding a slider for informing the participant about their current distance in seconds from the leading car. Time-headway (THW) is generally used to indicate safe following distance at any speed. However, we omitted using an additional indicator for this, since it would introduce a higher cognitive load and would not be natural.

Participants

We recruited 12 participants (7 identified as male, 5 as female), aged 23 to 33, with normal or corrected-to-normal hearing and vision. 9 out of the 12 participants had a full driving license and a median driving experience of 7 years. All the participants wore shoes during the study, which, despite leading to changes in the perception of the vibrotactile cues, was our conscious decision to match the usual way of interacting with gas pedals. Participants were seated during the entire duration of the study. They were first briefed about the study, and their demographic information was recorded.

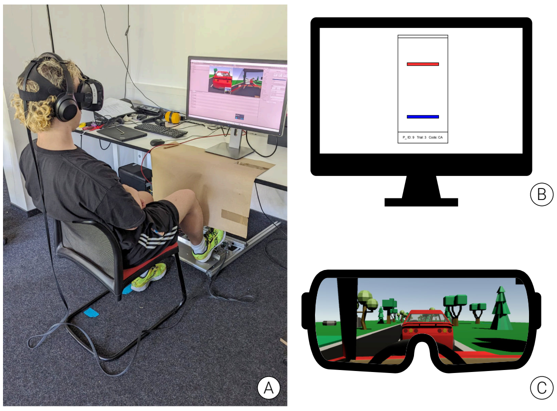

Figure 3.4: *Participants sat at a table with the pedal rack underneath and a visual barrier attached to the table (A). In the line-following task, we presented them a simple GUI on a monitor, which showed two colored blocks representing the target (moves automatically) in red, and the follower (controlled by participants) in blue (B). In the Driving task, participants wore a VR headset (C).*

To avoid any influence from fatigue, we instructed the participants to take breaks as needed before starting the subsequent trial. Participants wore noise-cancelling earphones playing white noise during the trials. The participants received a financial compensation of 18 Euros for their participation.

3.5.3 Task 1 - Line-Following

In this task, the participants were instructed to control the movement of a horizontal line (rectangle) for a one dimensional vertical movement to follow a target line, with the goal of maintaining the minimum distance between them (Figure 3.4-B). The position of the follower line was linearly mapped (positional mapping) based on the applied force on the pedal by the user for all the pedal configurations. Pushing the pedal with maximum calibrated force would position the line at the top of the area, while resting or removing the foot would cause the line to fall back down to the bottom. The task consisted of 3 difficulty levels for each pedal-easy, medium, and hard. Each pedal configuration had three trials of 30 seconds, each corresponding to the three difficulty levels. The order of the within pedal trial was always from the easiest to the hardest level of the designed trajectories. There was a 3-second countdown before the start of each trial. We analyzed the performance of all the participants using a three-way repeated measures ANOVA with the rigid/compliant; augmented/non-augmented and trial difficulty as the three within-subject factors. Normality of the data was assumed. Outliers within the data were retained to ensure that the analysis accounted for the full range of variability in the participants' performance. We evaluated the following metrics:

- *Root mean square error (RMSE):* The participants' mapped pedal positions were compared with the positions of the targets for the entire trial.
- *Pedal Adjustment Speed (PAS):* The differences between the participants' mapped pedal positions and the target positions, computed through cross correlation.

- *Overshoot Behavior (OB):* ratio of the differences between the maximum overshoot and the minimum overshoot during the hold phases of the trajectory. (Lower is better)

3.5.4 Task 2 - Driving task

To explore the pedals in a setting with higher ecological validity, we designed a second task. In this task, participants controlled a car in Virtual Reality (VR) to follow another car on a straight road (Figure 3.4-C). The participants could only control the car using the accelerator (gas) pedal. The driving task was in a straight line, and, hence, a steering wheel was not necessary. Applying force on the pedal accelerated the car forward, and wind drag and road friction forces worked in the backward direction, decelerating the car, meaning it would slow down until coming to a halt if not enough force was provided by the pedal input. The task consisted of two difficulty levels - easy and hard. In the hard level, the leading car ran the same trajectory as in the easy level, but at twice the frequency. The trial duration for each trajectory was 100 seconds. This duration was deliberately chosen to be longer than for the first task, as we were interested in how participants adapt to a car driving simulation and their control with different pedal conditions over a longer time period. The same trajectories were used for all the four pedal configurations in this experiment. This was intentional, as it allowed a direct comparison between the different pedal configurations. We analyzed the objective user performance in terms of the following parameters:

- *Root mean square error (RMSE) of vehicle velocity:* The following vehicle's velocity compared to the velocity of the leading vehicle for the entire trajectory.
- *Pedal Adjustment Speed (PAS):* The time difference between the velocities of the leading vehicle and following vehicle, computed through cross correlation for the entire trajectory.
- *Time headway (THW):* Safe following distance metric calculated by dividing the distance between two consecutive vehicles by the velocity of the following vehicle. Time headway is consistent for individual drivers for a large variety of speeds but could differ between drivers (WINSUM et al., 1996). Insufficient THW is usually the cause of rear-end collisions.

We did not consider the overshoot behavior for the VR study as a metric due to lesser hold situations to imitate real-world driving. The analysis was done similarly to the first task. We used CSV files to save the data during both the tasks. MATLAB and R were used for data analysis.

3.5.5 Qualitative Evaluation

A semi-structured qualitative interview was conducted to understand primarily three aspects of the participants' experience with the four pedal configurations:

- Subjective performance and control

- Overall and task-based pedal preferences
- Designing pedals with vibrotactile augmentation

Moreover, we were interested to know how participants experienced the differences between virtual compliance elicited using RA and the physical compliance using CN pedals. We also wanted to understand whether they could associate vibrotactile feedback with any experiences, emotions, or objects from their daily life. The questions in the interview were as follows: 'How do the different pedal configurations affect your performance?'; 'How well are you able to control using the different pedal configurations, and why?'; 'What pedal configuration is preferred and why?'; 'How can vibrotactile augmentation be used for pedal interaction?' and 'What are the associations from real-life to the experience of vibrotactile augmentation?'. Depending on the participants' responses and interest, we were able to delve deeper into their experiences of control and designing of vibrotactile augmentation.

All the interviews were audio and video recorded with the consent of the participants. We transcribed the interviews and performed a qualitative content analysis following flexible coding approaches (Muehlhaus et al., 2023). These approaches build on Grounded Theory to code data, but allow more flexible analysis. We analyzed the data using the questions asked to the participants. OtterAI was used for transcribing the data and taguette was used for coding. Coding of the interviews was done by one author, who approached the transcripts based on their dialogues with the participants during the study. The themes were constructed around the perceived performance, subjective experience of control, and designing with vibrotactile augmentation.

3.6 Results

We investigated the objective performance and subjective perception of control for two tasks using four different pedal configurations: compliant, rigid; with and without vibrotactile augmentation (Figure 3.3-Left).

3.6.1 Objective Performance Results

We provide a summary of the main results at the beginning of each subsection, followed by detailed statistics. To test for sphericity, Mauchly's test was used and then Greenhouse-Geisser correction was applied when the assumption of sphericity was violated, and, hence, no correction was applied to the reported p-values.

Following Task

We conducted a 3-Way Repeated Measures ANOVA (augmentation, pedal, difficulty) to analyze the effects of augmentation (augmented or non-augmented), pedal type (rigid or compliant), and trajectory difficulty (easy, medium, hard) on performance metrics (RMSE, PAS, OB) for the following task. Figure 3.5 shows the mean and confidence interval along with the box-plots to represent the effects of the independent variables on each of the performance metrics.

Root Mean Square Error (RMSE): We found no significant main effects of augmentation or pedal type on RMSE, see Figure 3.5-Left. Specifically, the effects of augmentation: $F(1, 144) = 1.464$, $p = 0.2283$ and pedal type: $F(1,144) = 1.955$, $p = 0.1642$ were not significant, suggesting that performance on a targetting task is not affected by the pedal configuration. However, the trajectory difficulty had a statistically significant effect on RMSE: $F(2,144) = 3.454$, $p < 0.05$, $\eta^2 = 0.021$. The RMSE increase, with an increase in the difficulty level, serves as a validation of the setup and analysis. It further implies that as the task became more challenging, users tended to deviate more from the target trajectory. Finally, no significant interaction effects were observed between augmentation, pedal type, and difficulty on RMSE.

Pedal Adjustment Speed (PAS): Similar to RMSE, for PAS, neither augmentation: $F(1,11) = 3.208$, $p = 0.101$ nor pedal type: $F(1,11) = 2.279$, $p = 0.159$ had significant effects on performance, see Figure 3.5-Right. Hence, pedal configuration did not play a role in objectively improving the pedal adjustment speed or the latency between the target and their mapped pedal position. However, the main effect of difficulty was statistically significant, $F(2,22) = 22.199$, $p < 0.05$, $\eta^2 = 0.152$, indicating that an increase in trajectory difficulty resulted in slower pedal adjustment speed. None of the interaction effects were significant. This result supports the idea that task difficulty naturally modulates user response times, independent of augmentation or pedal compliance.

Overshoot Behavior (OB): In contrast to RMSE and PAS, vibrotactile augmentation played a significant role in reducing the overshoot behavior, $F(1,11) = 76.291$, $p < 0.05$, $\eta^2 = 0.468$, see Figure 3.5-Bottom. The significant effect of augmentation on OB suggests that vibrotactile feedback helped users limit their tendency to overshoot, giving them a stronger sense of control over the task. Pedal type and trajectory difficulty did not have significant effects on OB, $F(1,11) = 0.057$, $p = 0.815$ and $F(1.36,14.94) = 1.088$, $p = 0.337$, respectively. There was a significant interaction between augmentation and pedal type, $F(1,11) = 21.153$, $p < 0.05$, $\eta^2 = 0.074$, indicating that the vibration feedback's effectiveness in minimizing overshoot might have varied, depending on whether the pedal was rigid or compliant. This provides a potential area for further exploration on optimizing haptic feedback. No significant interaction effects were found between other combinations of the independent variables.

VR driving task

The participants' performance in the VR study was measured by their performance in tracking the leading virtual vehicle. Similar to the following task, we performed a

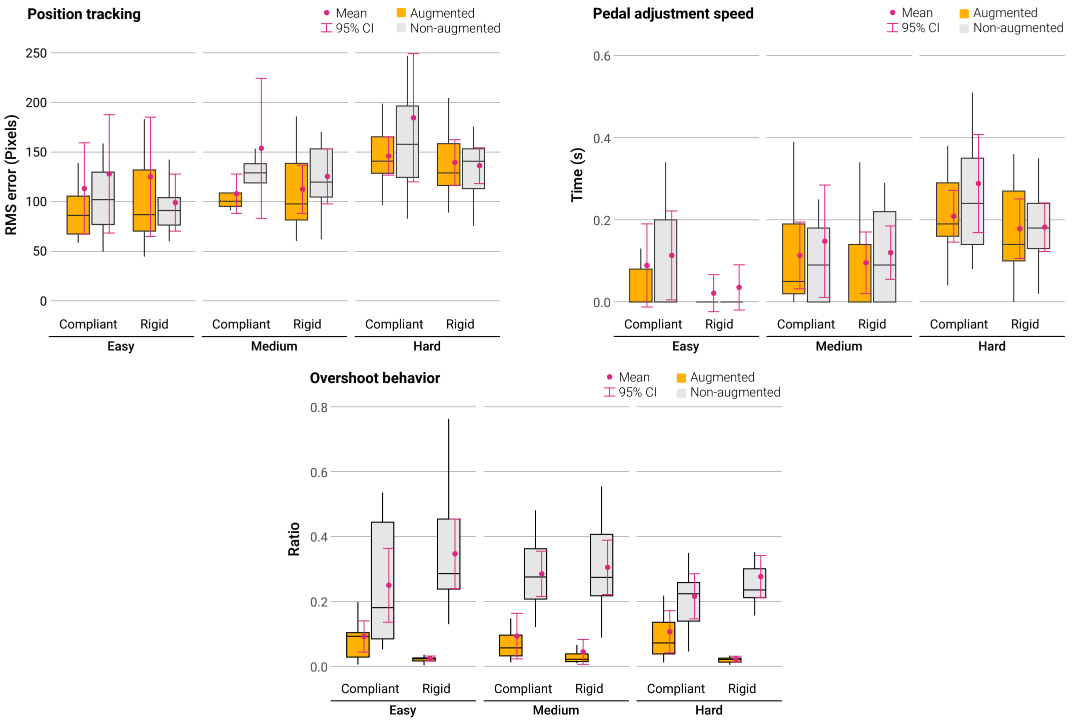

Figure 3.5: *Line-following task results: The left plot describes the RMSE for the three levels of difficulty. The right plot shows the pedal adjustment speed. The bottom plot shows the overshoot behavior with respect to the independent variables of pedal type, augmentation, and trajectory difficulty. Each plot shows the box plots for each pedal configuration and the mean and confidence intervals.*

3-Way Repeated Measures ANOVA on performance metrics of velocity tracking performance computed (RMSE), pedal adjustment speed (PAS), and time-headway (THW), see Figure 3.6.

Root Mean Square Error (RMSE): The participants performed significantly better in velocity tracking computed through RMS error during the easy trajectory compared to the hard trajectory, F(1,10) = 35.8, $p < 0.05$, $\eta^2 = 0.174$, see Figure 3.6-Left. In the easy scenario, in two trials, we observed instances of crashing into the leading car. In the hard scenario, more than half of the cases had at least one instance of crashing into the leading car, and most of these instances slightly touched the leading car. We did not find any significant difference between the participant performances with respect to augmentation: F(1,10) = 1.72, p = 0.219 or pedal type: F(1,10) = 4.05e-5, p = 0.995. None of the interaction effects were significant.

Pedal Adjustment Speed (PAS): The pedal adjustment speed between the pedal input and the tracking, calculated using cross correlation, showed no significant difference in terms of pedal type: F(1,10) = 2.93, p = 0.117; augmentation: F(1,10) = 3.17, p = 0.105; or difficulty: F(1,10) = 4.80, $p \approx 0.05$, $\eta^2 = 0.10$. The interaction effects were not significant. It is interesting to note that the trends of RMSE and PAS were similar for both tasks.

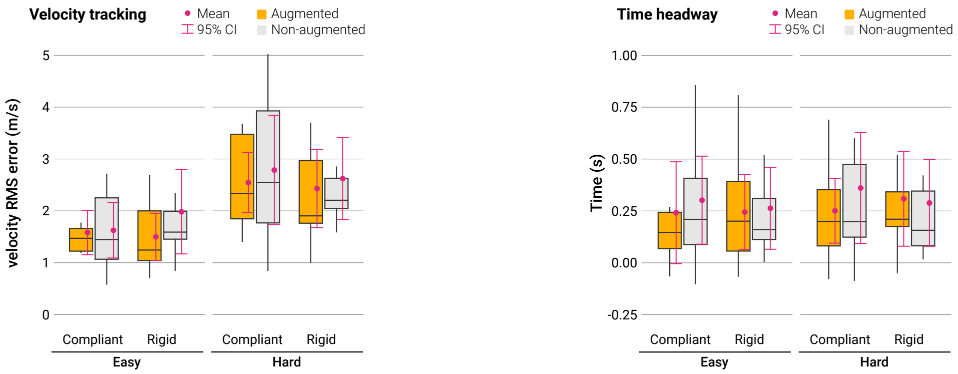

Figure 3.6: *Left: root-mean-square (RMS) velocity tracking error for easy and hard cases; Right: Time headway (THW) over all pedal configurations. Each plot shows the boxplots for each pedal configuration and the mean and confidence intervals.*

Time headway (THW): The mean values of THW throughout did not show a significant difference in terms of pedal type: F(1,10) = 0.234, p = 0.639; augmentation: F(1,10) = 4.52, p=0.060; or difficulty: F(1,10) = 0.828, p = 0.384; see Figure 3.6-Right. None of the interaction effects were significant. This means that participants similarly consistently controlled their speed and distance to the leading car for all pedal configurations.

3.6.2 Subjective Control: Qualitative Content Analysis

Participants in the study expressed their preferences for specific pedal configurations and provided insights into their reasons for these choices. The favored pedal configuration across various tasks, such as line-following and car driving simulations, was the "soft pedal with vibration feedback." Participants found this configuration to be the most intuitive and controllable. Participant 2 highlighted this preference, stating, "Soft, with the vibration feedback for the following task" emphasizing the value of the compliant pedal combined with vibrotactile feedback.

Vibrotactile Augmentation increases the perceived Sense of Agency: The primary reason behind the preference for the "soft pedal with vibration feedback" was its perceived intuitiveness and the enhanced sense of control it offered. Participants found that this configuration allowed them to finely modulate their actions, particularly in tasks requiring precise control, such as line-following. P5 noted, "Soft [compliant] with vibration makes it easier to control the movements; it's intuitive." And P8 mentioned that the vibration feedback was perceived to be corrective, thus helping to make more precise movements. They said, "The vibrotactile feedback is a game-changer. It's like my feet know where to go without me having to think about it." Further, P1 said that the vibrotactile augmentation makes the pedal "more responsive", and P7 mentioned, "It enhances the overall performance". Moreover, P6 mentioned, "I like knowing exactly where each pedal is. It gives me confidence and reduces my mistakes." The tactile feedback provided an extra layer of information that complemented their actions, leading to a sense of mastery and comfort.

With respect to the kinesthetic cues, the compliant pedal was perceived to be easier to control. P1 mentioned, "The [compliant] pedal setup felt natural to me, which made it easier to control the vehicle. When the pedals were arranged differently [rigid], I felt less confident and in control." And P9 added, "Using pedals that I was already used to make a big difference. I didn't have to think about how to use them, which kept my focus on the task."

Vibrotactile Augmentation improves the perceived Performance The perceived performance varied significantly depending on the pedal configuration and the nature of the task, whether it was VR-based or a line-following task. Participants generally felt that their performance improved when the pedal setup provided clear vibrotactile feedback. P2 stated, "In VR, when the pedals are intuitive, I can focus more on the virtual task rather than worrying about my foot placement." The line-following task, on the other hand, required precise movements, and participants noted that compliant pedal configurations made it easier to follow the line accurately. P5 commented, "With the right [compliant] pedal setup, I can follow the line much more precisely. It feels more natural, and my performance definitely improves." Participants also pointed out that motion-coupled vibrotactile feedback played a critical role in enhancing their performance by providing immediate and intuitive cues about their actions. Participant 9 elaborated, "The vibration feedback tells me instantly if I'm doing something right or wrong. It's like having an extra sense that boosts my performance."

Balancing information and non-intrusiveness with vibrotactile feedback: Participants also mentioned that while compliant pedals were preferred, the addition of vibration feedback struck a balance between comfort and control. It enhanced the pedal's usability without causing discomfort or fatigue. This finding highlights the importance of providing users with tactile cues that amplify their sense of control without overwhelming them. P3 mentioned, "I like soft pedals, and the vibration makes it just right; not too hard, not too soft." On the other hand, P6 and P8 mentioned, "The vibration could be more subtle." and "the timing of the feedback needs adjustment." Participants identified the potential of vibrotactile feedback to enhance the overall user experience when interacting with pedals. They emphasized the importance of providing feedback on factors such as speed, pressure, and precision. P7 noted, "Vibration could help me understand how fast I'm pressing or if I'm applying too much pressure," highlighting the role of vibrotactile feedback in aiding a user's understanding of their actions.

Customizable and Context-Aware Design: Participants also emphasized the need for customizable vibrotactile feedback settings to cater to individual preferences and task-specific requirements. They suggested that users should have the flexibility to adjust the vibration intensity and patterns. Additionally, participants discussed the importance of context-aware feedback, where vibration cues adapt to different situations. P4 mentioned, "Customizable settings would be great, and it should change based on the task. In some situations, I may want more feedback than others." They stressed the need to prioritize safety and non-distracting feedback in real-world applications.

Associations Between Real-Life Experiences and Vibrotactile Augmentation: Participants in the study frequently drew connections between their real-life experiences and the sensations they encountered through vibrotactile augmentation. For instance, participants compared these tactile sensations to a sewing machine. P2 remarked, “It feels a little bit like the sewing machine. I can gauge the speed and force based on the vibration frequency.” Moreover, some participants associated it with everyday safety alerts, such as phone vibrations for a call or notification. They emphasized that vibrotactile feedback should not be distracting or overwhelming, particularly in scenarios like car driving. P9 remarked, “In a car, the feedback should be subtle enough not to divert attention but still provide information about pedal usage.” This connection emphasized the potential of vibrotactile feedback as a safety or warning mechanism in pedal-based interactions. Additionally, participants related the experience to the learning process in real-life scenarios, analogous to acquiring new skills or adapting to unfamiliar tasks, where feedback helps to learn. P7 described it like this, “It’s like learning to ride a bike. You get the hang of it by feeling the subtle changes in vibration.” These associations highlight the role of vibrotactile feedback, encompassing safety and control, and how motion-coupled vibration provided the participants with a tangible reference point for understanding the vibrations and how they related to their actions. Participants used these tactile cues to interpret their interactions with pedals. For instance, rapid vibrations were equated with high-speed movements, as illustrated by P8: ”The vibration pattern tells me how fast I’m going. It’s like revving an engine.” This correlation between real-world actions and vibrotactile feedback highlights the potential for intuitive pedal interactions.

3.7 Discussion

“The horseman’s stirrup, the farmer’s hay fork and shovel, the pipe organist’s bellows and foot keys, and the potter’s kick wheel, are all pre-Industrial-Revolution examples of foot against tool, transmitting both power and control. As mankind captured in turn the power of falling water, burning hydrocarbons, and splitting atoms, rotary motion and electricity became commonplace, and human muscle was first multiplied and then significantly supplanted by machinery. Consequently, the function of newer foot-tools is no longer to apply both power and control, but chiefly control alone” (Pearson et al., 1986). But control in its essence has a subjective and an objective aspect to it, and, as shown by our results, at least in the case of foot pedals, they do not necessarily go hand-in-hand. Next, we discuss our findings and reflect on this consistency between objective (performance) control and subjective (perceived) control.

Our results show that the objective performance of subjects for the line following as well as the ecological driving task in VR did not vary significantly over the four pedal configurations, except for the overshoot behavior, where augmentation had a significant effect. This result differs from the studies done by Zhai et al., who found rate control to be better with isometric devices and position control to be better with isotonic devices (Zhai et al., 1994; Zhai et al., 1997). This difference might be due to the difference in interaction devices, type of interaction, or due to the task. One reason for the overshoot behavior being less for the augmented pedal configurations can be due to the vibrotactile feedback that notifies the user as soon as they apply different pressure or move. One of the participants also hinted at this in the qualitative interview, mentioning that the vibrotactile feedback helped them to understand how fast and how much pressure they were applying. For position as well as velocity *RMSE* and *PAS*, however, we believe that the participants relied on how they modulated their foot pressure and position according to the visual feedback from the line or the car they controlled rather than the vibration feedback. The findings of the objective performance metrics suggest that while vibrotactile feedback does not improve raw performance metrics such as tracking error and pedal adjustment speed, it positively impacts the user's behavioral control by reducing overshoot. Having no measurable differences in the performance of the different pedal configurations provides opportunities for the designer to fully focus on practical considerations and user experience, without worrying about performance. *THW* showed differences between subjects based on their driving style, but was constant over different pedal configurations. The THW metric evaluates the safe tracking distance, which is generally consistent at different speed levels but can differ from one driver to another (WINSUM et al., 1996). The finding of significant differences between users in terms of average THW values over all pedal types implies that users were able to impose their unique driving styles despite the changes in pedal type.

In contrast, the qualitative content analysis of the interviews indicated that vibrotactile feedback increased the participants' perceived control as well as perceived task performance. Most participants preferred the compliant pedal configuration with vibrotactile feedback, which creates a virtual texture. The compliant configuration was preferred since the participants appreciated configurations that mirrored real-life experiences or provided a familiar interface; it helped them feel more in command, which is similar to the principles from past research (Shneiderman et al., 2010). Based on participant quotes, the embodied vibrotactile feedback assists in intuitively understanding the position of the pedal, providing an additional mode of feedback without increasing the cognitive load, as already observed by Sabnis et al. (2023b) in the context of symbol design. Furthermore, the embodied vibrotactile feedback provides additional sensory information that aligns with the user's actions, thereby enhancing user experience. The associations the participants were able to make due to motion-coupled vibrations emphasize the importance of designing systems that align with the user's existing sensory references and real-life experiences. Designers can use these associations to enhance the usability and intuitiveness of such systems, making them more effective tools for pedal-based interactions. Additionally, the design space of embodied vibrotactile feedback offers opportunities for the designers to create customized and real-life inspired experiences with vibrotactile augmentation on the gas pedal, prioritizing user needs and usability, without compromising performance.

Finally, the most interesting finding from our study is that the objective performance and the perceived control do not necessarily correlate. This mismatch between performance and perceived control highlights an interesting research opportunity. It appears that not only the successful completion of a task influences the user's experience of control, but also other factors, such as the feedback they receive while performing the task. In the present study, while the visual feedback remained the same, providing more levels of vibrotactile feedback increased participants' *judgment of control* during the tasks. One key factor might be that the vibrotactile feedback provides immediate sensory cues that make users feel more actively engaged with the task. Moreover, the pedal augmentation allowed our participants to get a clearer picture of their movement's impact on the pedal, which increased the pedal's perceived intuitiveness and ease of use of the pedal, increasing the overall confidence participants had when using the pedal. This can create an increased sense of control over the pedal's movement and position, which then transfers onto the visual outcomes of the pedal's movements, the position of the line, and the car. The increased intuitiveness and confidence using the pedal is likely to have caused the increase in perceived performance as well as the participants' feeling that they were able to communicate their intentions to the system more easily. Additionally, vibrotactile feedback provided using motion-coupled vibrations simulates a responsive interaction which might help users feel more attuned to the system's state. This might make the task feel more manageable and give an impression of improved control that does not correspond to actual performance metrics. However, this is only speculation, and further research is needed to provide a detailed explanation for this phenomenon. The results show a connection between people's perceived control and performance, highlighting that, especially in the design of haptics, one must consider subjective and objective controls separately, as some optimization might improve subjective experience without producing measurable improvement in performance. This does not mean that these optimizations are useless – on the contrary, they profoundly shape the user experience.

3.7.1 Application Scenarios

Among the many potential application scenarios, here we discuss three scenarios from different fields.

Fuel Efficient Driving: For fuel-efficient driving, the pedal should encourage smooth and gradual acceleration to promote economical driving habits. A compliant pedal with integrated vibrotactile feedback can serve this purpose by providing immediate feedback to the driver when excessive pressure is applied, thereby discouraging rapid acceleration. The feedback should mimic a resistance or a gentle pulse that intensifies with pressure, reminding the driver to ease off the pedal. This configuration might enhance the driver's sense of control while fostering a driving style that maximizes fuel efficiency. A version of this has already been prototyped[4].

Sewing Machine: In the context of a sewing machine, the pedal must enable fine control over the speed of the needle, allowing for both rapid stitching and precise, slow movements. A rigid pedal with augmented vibrotactile feedback would work well here. The vibrotactile feedback should be designed to provide a clear tactile response that increases with pedal pressure, giving the user immediate and intuitive feedback about the speed of the needle. This would help the user maintain a steady pace and make precise adjustments as needed, improving both control and confidence.

Pottery: For pottery, the foot pedal should provide smooth and precise control over the wheel's speed to accommodate the nuanced and gradual adjustments the potter needs to shape their work. A compliant pedal with vibrotactile feedback would be ideal, as it can simulate the feeling of the wheel's resistance, enhancing the potter's sense of connection with the material. The vibrotactile feedback should be subtle and proportional to the wheel's speed, providing an intuitive sense of how much pressure is being applied, thereby allowing for delicate adjustments without visual distraction.

3.7.2 Limitations and Future Work

The users relied on visual feedback for the tasks, and hence the differences in the task performance between the different pedal configurations was not significant. This can be investigated in future research about how the user performs on the given task with different kinds of haptic feedback only. Although we simplified the gas pedals in our study compared to their real-world application, it needs to be pointed out that controlling an automobile with a gas pedal is a safety-critical application, and augmenting such pedals should take into account the phenomenon of 'riding the pedal' (L Barnett, 2009). Our results should not be taken as a proposal to replace existing gas pedals, but as a recommendation to think about embodied vibrotactile feedback as a control mechanism, which can increase perceived control and provide customizable designs and real-world associations on pedal interfaces. This study was driven by curiosity about pedals as an interesting I/O device to investigate the subtle intricacies of perceived and factual control, but our future work will explore whether the results hold for joysticks, sliders, knobs, and other interactive devices.

For future work on pedals, an interesting area to explore is the design space of the parameters of motion-coupled vibrotactile feedback on pedals, which could add realism to the different modes in an automobile (sports, eco, city, cruise, etc.). Moreover, future work could also investigate other modalities, such as auditory or visual cues, to determine whether the enhancement in perceived control is unique to vibrotactile feedback or generalizable across sensory modalities. Additionally, studying the long-term effects of embodied vibrotactile feedback on user learning and adaptation may

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[4] The Bosch active gas pedal: `https://www.bosch-press.nl/pressportal/nl/en/press-release-585.html`

reveal that extended exposure leads to improvements in actual performance, potentially bridging the gap between perceived and objective control. Lastly, these findings potentially inform the design of other simulated control systems, where enhanced perceived control through feedback could improve user experience and satisfaction in applications such as surgical training, movement guidance, virtual interfaces or remote-controlled systems, without requiring hardware modifications.

3.8 Conclusion

This study explored the relationship between objective performance and perceived control in the use of foot pedals with varying configurations. Despite the lack of significant differences in objective performance metrics across the four pedal configurations—rigid and compliant pedals, with and without motion-coupled vibrotactile feedback—the qualitative data gathered from participant interviews revealed a notable increase in perceived control when vibrotactile feedback was present. This finding underscores the importance of considering both objective and subjective measures when evaluating user interfaces for dynamic control systems. The enhanced perceived control with vibrotactile feedback suggests potential benefits in user experience and satisfaction without detriment to performance. Consequently, this research paves the way for designing customized pedal feedback mechanisms that enhance user perception and interaction, thereby contributing to the development of more intuitive and effective control interfaces. Future work should balance objective and subjective evaluations to fully capture the nuances of user interaction with emerging technologies.

4 Motion-Coupled Asymmetric Vibration

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The previous chapter demonstrated a striking dissociation: although vibrotactile augmentation on a foot-pedal did not measurably improve task performance, it reliably increased users' perceived control. This finding suggests that when vibration is synchronized with the user's own movement, it is no longer perceived as an external disturbance but as something self-generated. In other words, Motion-Coupled Vibration (MCV) may enhance the user's sense of agency, but the pedal study provided no quantifiable or objective means to understand if the vibration pulses are indeed perceived as self-generated.

To understand why Motion-Coupled Vibration (MCV) feel embodied and self- generated, this chapter examines a fundamental phenomenon in human perception: sensory attenuation. Sensory attenuation refers to the well-established phenomenon in which sensations produced by one's own actions are perceived as weaker, less salient, and less disruptive than identical sensations generated externally. It explains everyday experiences such as why the soft motion of a T-shirt against the skin fades from awareness, or why a colleague's typing seems louder than your own.

Taking inspiration from daily life, the soft-movement of a T-shirt on the skin while wearing it is noticed, but we stop noticing its presence on our body within a few seconds. Similarly, touching fabric or pressing into a sponge produces vibrations that feel

Figure 4.1: *We investigate perceptual properties and potential applications of motion-coupled Asymmetric Vibration (AV) that elicit force sensations while minimizing vibration. Perceptual properties of force and vibration are examined in a psychophysics study in which participants move their hand along a line while pulses of AV are rendered (holding actuators in fingers) corresponding to their movement Ⓐ. We apply the same rendering approach in a bow-and-arrow VR game, where the AV pulses mimic the bow's string tension while stretching the bow Ⓑ. The higher tension is reflected by rending more AV pulses, as depicted in Ⓒ.*

intrinsically tied to our own motion; whereas the buzz of a phone in a pocket is feels disruptive and external. Sensory attenuation is tightly linked with the Sense of Agency: when the brain successfully predicts the sensory consequences of an action, the resulting sensation is attenuated and experienced as part of the action itself (Garrido-Vásquez et al., 2020).

Sensory attenuation offers a compelling explanation for why Motion-Coupled Vibration, despite being physically identical to ordinary vibration, can yield such different perceptual outcomes. When vibration pulses are caused by a user's movement, the sensorimotor system may treat them as self-generated, thereby reducing their salience as "vibration" and allowing users to instead perceive material qualities such as resistance or compliance.

To investigate this hypothesis, we focus on the pseudo force illusion where asymmetric vibrations have shown to induce a sensation of force (Tomohiro Amemiya et al., 2008). However, one of the pressing problems in rendering pseudo forces is that vibration is inherently linked to the induced pseudo force effect. Thus, to increase pseudo force, vibration amplitude needs to be proportionally increased, where the increase in vibration intensity is perceived as distracting and annoying (E. Kim et al., 2020). Furthermore, in my personal experience when trying different prototypes which render pseudo forces, I felt that the vibration aspect draws attention, interferes with the force perception and disrupts the realism of the pseudo force experience.

As an alternative to the traditional method of rendering pseudo forces and to investigate the sensory attenuation hypothesis, we present a novel method of rendering pseudo forces: Motion-Coupled Asymmetric Vibration (MCAV) where the asymmetric vibration pulses are coupled with user motion[1]. The underlying principle for rendering MCAV remains the same as in previous chapters: changes in user action are detected and mapped to vibrotactile grains. What changes here is the waveform, which allows us to connect motion-coupled haptics to the broader literature on pseudo-forces and movement guidance while isolating the role of sensory attenuation. This reframing leads to a foundational perceptual question: Can the qualia of "vibration" be attenuated while that of "force" remains the same based on whether the stimulus is self-generated or externally delivered?

The remainder of this chapter introduces the conceptual motivation for studying the role of sensory attenuation in the perception of Motion-Coupled Vibration, describes the proposed pseudo-force rendering method, presents psychophysics and Virtual Reality studies evaluating perceived vibration and force, and discusses implications for Motion-Coupled Vibration perception and rendering. Ultimately, this chapter contributes to the thesis by providing the first empirical evidence that motion-coupled asymmetric vibrations recruit sensory attenuation, offering a perceptual explanation for why motion-coupled vibrotactile feedback feels embodied.

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[1] Motion-Coupled Asymmetric Vibration teaser video: `https://youtu.be/alqkHEZyNWg`

4.1 Introduction

Virtual Reality (VR) enables us to create immersive experiences where the addition of haptic feedback enhances already compelling audio-visual stimuli. However, one crucial element remains challenging, namely creating force sensations. Due to the importance of force rendering (Provancher, 2014), grounded force-feedback devices have been proposed (Endo et al., 2010; Massie et al., 1994). However, such haptic interfaces are bulky, mechanically complex, expensive, and have limited workspaces. Alternatively, VR haptics research has proposed custom hand-held controllers (Jaeyeon Lee et al., 2019; Benko et al., 2016), pneumatic systems (Delazio et al., 2018; Günther et al., 2019), or wearable interfaces (I. Choi et al., 2017; Fang et al., 2020; Lopes et al., 2017a). While these methods can create immersive tactile experiences, they are difficult to scale, as they are either invasive (EMS), optimized for special use cases (custom hand controllers), or mechanically complex. Due to these constraints in implementation, vibrotactile feedback remains the dominant method.

Besides the ease of implementation and scalability, there are also strong reasons in perceptual theory to support the use of vibrotactile feedback. Research shows that a significant part of our tactile experience is mediated by cells sensitive to vibration (Johansson et al., 2009). This has led to sophisticated algorithms that simulate material properties of texture (Strohmeier et al., 2017), movement (Ding et al., 2024; Heo et al., 2019), and compliance (Kildal, 2010; Vega et al., 2024). These material properties are induced by providing discrete, symmetric vibration pulses that are synchronized with user motion (Sabnis et al., 2023a). Beyond simulating textures, carefully designed vibrations have also been shown to convey force sensations (I. Choi et al., 2017; Yudai Tanaka et al., 2020; Culbertson et al., 2017b; Tanabe et al., 2020; Sabnis, 2021). These forces, known as “pseudo forces” can be elicited using asymmetric vibrations, typically generated by unequally accelerating a mass in opposite directions (Tomohiro Amemiya et al., 2005; Culbertson et al., 2017b). Pseudo forces have been used to simulate weight, force, and inertia in VR (I. Choi et al., 2017; H. Kim et al., 2018; Yudai Tanaka et al., 2020). However, one limitation remains: **force sensations elicited using asymmetric vibrations are inherently linked with the experience of vibration**. Therefore, it is not possible with current approaches to induce a force experience or increase its intensity without the user also experiencing an increased vibration, which has been shown to be distracting (Vasseur et al., 2024), annoying, and aggressive (Seifi et al., 2015; Strohmeier et al., 2018; Sabnis et al., 2023a; Sabnis et al., 2023b; O. S. Schneider et al., 2015; E. Kim et al., 2020).

We present **motion-coupled asymmetric vibration**, a novel algorithm that renders discrete asymmetric vibration pulses synchronized with user motion, generating pseudo forces that maximize the perceived force while minimizing the perceived vibration (Figure 4.1-C). Our algorithm leverages two mechanisms established in sensory attenuation literature: (a) the diminished perception of stimuli that correlate with our sensorimotor activity, i.e., self-generated stimuli are perceived to be less intense compared to externally generated stimuli (Kiepe et al., 2021; Bays et al., 2006; Voss et al., 2008), and (b) the reduced perception of vibration during movement (Bays et al., 2005; Blakemore et al., 1998; Kilteni et al., 2022). To evaluate our algorithm, we perform two studies. First, in a controlled task, we explore the differences in the perceived intensity of vibration and force compared to traditional asymmetrical vibration (Tomohiro Amemiya et al., 2005). Following a standard psychophysics magnitude estimation protocol (George A Gescheider, 1988), we identify the relative contributions of *continuity*, user *motion*, and *coupling* to movement on the resulting vibration and force experiences (Figure 4.1-A). Second, in a free-form exploration, we evaluate how our algorithm could be employed in VR. Compared to continuous asymmetric vibrations from previous work and symmetric vibrations in off-the-shelf VR controllers, our algorithm improves realism in action-dependent force scenarios, such as pulling a bow (Figure 4.1-B). The interviews revealed that continuous asymmetric vibrations obscure the perceived force, while motion-coupled asymmetric vibrations can enhance the user's experience in the absence of visual feedback.

> **Contribution Statement.** Our contribution is threefold: We contribute a novel algorithm based on sensory attenuation principles to render strong pseudo forces while reducing the perceived vibration. Next, empirical insights from our psychophysics study show that coupling asymmetric vibration to user motion attenuates vibration equivalent to a 30% reduction in amplitude. Finally, we demonstrate that our algorithm enhances the realism in VR applications.

4.2 Related Work

Research highlights several approaches to render forces, including the construction of novel haptic interfaces and vibrotactile rendering techniques. We contribute to the latter, building on algorithms established in the literature and adapting them based on established perceptual phenomena. We organize the related work into two parts: force rendering in VR with vibration design and perceptual mechanisms informing our algorithm design.

4.2.1 Force Rendering in VR and Beyond

Force Rendering Approaches for VR

Force rendering in VR was initially explored using grounded haptic interfaces, which provide accurate sensations (Massie et al., 1994; Endo et al., 2010), but are bulky and expensive. An approach that avoids these limitations is augmenting commodity VR controllers to provide forces; for example, Stellmacher et al. (2022) augmented a VR controller's trigger button. Dynamic and continuous resistance during interaction with virtual objects, generates counter-forces that simulate different levels of virtual weights.

This experience can be enhanced even further by introducing visual discrepancies when lifting virtual objects (Stellmacher et al., 2023). Such visual augmentations provide convincing impressions of counterforce or weight, even in the absence of physical feedback (Lecuyer et al., 2000; Speicher et al., 2019).

Then there are custom-built hand-held haptic devices; for example, *Thor's Hammer* generates force feedback through six propeller motors integrated into an ungrounded device (Heo et al., 2018). Similarly, *AirRacket* provides directional force feedback using pneumatic actuators to simulate virtual racket sports (Tsai et al., 2022). Moreover, ungrounded graspable interfaces directly stimulate the user's fingertips or palm during grasping interactions, for example, *NormalTouch*, where an extruded and tiltable platform provides force feedback (Benko et al., 2016). The *CLAW* device uses a force impedance approach to provide force feedback with actuated movement to the user's index finger to simulate grasping, touching, and triggering actions (I. Choi et al., 2018), while the *CapstanCrunch* device provides adjustable friction to render haptic compliance in response to grasping (Sinclair et al., 2019). Alternatively, dynamic passive haptic feedback uses repositioning or reconfiguration of the controller to generate weights and forces through physical properties (Zenner et al., 2017; Zenner et al., 2019a). However, to provide sufficient forces, body-grounded haptic interfaces use kinesthetic links affixed to the user's body (Nisar et al., 2019). Here, braking mechanisms render spring-like forces (Burdea et al., 1992). Wearable solutions using EMS can also simulate forces by directly stimulating the user's muscles (Lopes et al., 2017a; Lopes et al., 2017b; Lopes et al., 2018) to simulate virtual weights (Faltaous et al., 2022) or physical boundaries (Lopes et al., 2015), but user acceptance remains low (Knibbe et al., 2018). Furthermore, recent skin stretch devices like *QuadStretcher* (Taejun Kim et al., 2024) and *ArmDeformation* (Y. Lin et al., 2024) provide directional force cues and have been shown to enhance body ownership and realism in VR. *Springlets* are epidermal skin stretch devices that provide directional cues among other tactile primitives (Hamdan et al., 2019). Despite their potential, such methods rarely find their way into commodity VR, mainly due to a lack in generalizability beyond the envisioned use case, which might be due to the limited expressive range they are able to apply (Zenner et al., 2021).

Vibration Algorithms to Render Material and Force Experiences

The potential of vibration in shaping tactile experiences is shown by how our tactile receptors respond to different vibration frequencies (Johansson et al., 2009) and how vibration can help us distinguish between materials (Bensmaïa et al., 2005a). Providing discrete vibration pulses coupled with user motion elicits material experiences of stretching, bending, and twisting on a rigid rod (Heo et al., 2019). Similarly, providing vibration pulses at fixed intervals of user movement successfully simulates texture experiences in air and on smooth sliders (Strohmeier et al., 2017; Strohmeier et al., 2018; Sabnis et al., 2023a). Vibrotactile cues, coupled to changes in exerted pressure by the user, are sufficient for compliance (and deformation) experiences to emerge (Kildal, 2010; Wittchen et al., 2023; Vega et al., 2024). Furthermore, Ding et al. (2024) showed that discrete vibration pulses coupled to user force can create an illusion of movement for the user, even when there is no motion. Sabnis et al. (2025a) showed that motion-coupled vibrations give users the feeling of being in control, despite their objective performance remaining the same.

On the other hand, asymmetric vibrations are used to create a sensation of force (Tomohiro Amemiya et al., 2008; Culbertson et al., 2017b; Sabnis, 2021). This is achieved by accelerating a mass unequally in two opposite directions such that the user perceives a pulling sensation in the direction of the higher acceleration. Early implementations used a slider-crank mechanism to induce a "virtual force vector" (Tomohiro Amemiya et al., 2005; T. Amemiya et al., 2005). Tomohiro Amemiya et al. (2008) showed that weight perception can be altered by aligning the device in the direction of gravity. Recently, researchers have used vibrotactile actuators such as voice coils (Culbertson et al., 2018; Culbertson et al., 2017b) and linear resonant actuators (Rekimoto, 2014) to produce asymmetric vibration with compact devices. Research on actuator modeling and finger pad interaction identified an optimal signal frequency of 40Hz to elicit compelling pseudo forces (Rekimoto, 2014; Culbertson et al., 2016).

In VR, I. Choi et al. (2017) developed *Grabity*, a haptic device designed to simulate grip contact forces, weight and inertia in pinch grasp configuration using pseudo forces. Further, they demonstrated that the magnitude of the generated pseudo forces can be adjusted by changing the amplitude of the asymmetric input signal. H. Kim et al. (2018) developed *HapCube*, a miniaturized device to provide pseudo forces using asymmetric vibrations. Asymmetric vibrations have also been used in VR to demonstrate a fishing experience (Takamuku et al., 2016) and kinesthetic forces arising from moving masses (Yudai Tanaka et al., 2020). Research into the perception of pseudo force sensation shows that the perceived strength of the pulling sensation increases with the motion of the hand holding the actuator (Tomohiro Amemiya et al., 2016), which might be due to the phenomenon of tactile suppression, where the vibration is suppressed when the user moves. Recently, Tanabe et al. (2020) have shown a method of generating stronger pseudo forces using vibrations asymmetric in time rather than in amplitude. Tanabe et al. (2024) has also shown that providing pseudo forces in the direction of movement can decrease the user's sense of agency, indicating that the illusion contributes to the sensation of the hand being moved.

The drawback of pseudo forces induced by continuous asymmetric vibrations is that the pseudo forces and vibrations are intricately linked. Thus, to increase the pseudo force, one needs to increase the vibration intensity. However, strong vibrations are perceived as distracting, annoying, and aggressive (O. S. Schneider et al., 2015; Strohmeier et al., 2018; E. Kim et al., 2020; Sabnis et al., 2023a; Vasseur et al., 2024). Also, continuous vibration is perceived by the user as being external (Sabnis et al., 2023b), which might distract the user from the intended pseudo force sensation. Our contribution focuses on asymmetric vibration, typically perceived as external, coupled with user movements, which elicits a self-generated sensation of force and thereby attenuates the perceived vibration.

4.2.2 Perceptual Phenomena

Habituation is a form of learning that allows organisms to gradually reduce their response to repeated inconsequential stimuli (Thompson et al., 1966). This process helps conserve cognitive resources by diminishing the attention to stimuli that lack biological significance. According to the Sokolov model (Sokolov, 1963), the nervous system builds a stimulus model after repeated exposure. As this model becomes more accurate, the response diminishes, leading to habituation.

Sensory Attenuation (SA) through Prediction

SA is a form of Habituation where self-generated sensory signals are perceived less intensely compared to externally generated signals of similar intensity, particularly during voluntary movements (Kiepe et al., 2021). The attenuation is believed to stem from the brain's predictive mechanisms, where an efference copy of the motor command generates a prediction of the sensory consequences, which is then compared against the actual sensory feedback (Kilteni et al., 2022). If the prediction matches the feedback, the sensory signal is attenuated (Wolpert et al., 1995). For example, tickling yourself is almost impossible as the predicted sensation closely matches the actual sensory feedback, leading to a cancellation of the tickling sensation. In contrast, when someone else tickles you, there is no efference copy to predict the incoming sensory signal, and, thus, the tickling is perceived more intensely (Blakemore et al., 1998).

One of the primary functions of SA is to differentiate between self-generated and externally generated stimuli that are less predictable (Wolpert et al., 1995). For example, the brain attenuates sensory feedback from self-induced touch while remaining sensitive to similar external stimuli (Kilteni et al., 2022). This selective filtering is essential not only for efficient sensory processing, but also for the attribution of agency, whereby movements perceived as self-generated are subject to attenuation while externally caused movements are not (Desantis et al., 2012; Blakemore et al., 1998). Thus, SA is closely linked with the sense of agency – the feeling of being in control of one's actions (Garrido-Vásquez et al., 2020). When there is a match between the predicted and actual sensory outcomes of a movement, sensory attenuation occurs, reinforcing the sense of agency and making the user feel that the observed movement has been internally generated (James W Moore et al., 2009; Kilteni et al., 2017) and vice versa.

We speculate that vibrotactile texture rendering approaches (Sabnis et al., 2023a; Strohmeier et al., 2017) inducing texture experiences despite providing vibrations is partly due to such attenuation processes. In this research, our focus is to understand whether sensory attenuation can attenuate the perceived vibration while preserving the pseudo force when the asymmetric vibration pulses are coupled to user motion.

Sensory Attenuation through Movement

We look at two neural processes that contribute to sensory attenuation of stimuli during movement. The first, called tactile suppression, refers to the reduction in sensitivity to touch stimuli during self-generated movements (Blakemore et al., 1998; Bays et al., 2005; Kilteni et al., 2017). This phenomenon is thought to arise from the brain's predictive mechanisms, which estimate the sensory consequences of one's own movements. Research has shown that when these predictions are precise, the reliance on tactile feedback decreases, leading to reduced tactile sensitivity (Bays et al., 2006; Chapman et al., 2006). For example, during activities like typing on a keyboard, tactile suppression minimizes the perception of key presses generated by one's own fingers, allowing the user to focus on the outcome of the typing, such as the words on the screen. This reduction in tactile sensitivity helps prevent sensory overload, which could otherwise result from the continuous processing of self-generated tactile feedback. Tactile suppression has been extensively studied in the context of sensory attenuation, where externally generated stimuli are perceived as less intense during voluntary movement compared to when the individual is stationary (Chapman et al., 1987; Fraser et al., 2018; Voudouris et al., 2021).

The second process, known as tactile gating, prioritizes certain tactile inputs over others based on factors such as attention, intention, and relevance, effectively filtering sensory information to ensure that the most relevant touch sensations reach conscious awareness or are processed more efficiently (Colino et al., 2014). This goes beyond merely reducing sensation during movement (tactile suppression) by selectively processing specific tactile information. For example, in a VR scenario where a user interacts with virtual objects, tactile gating can help amplify the perception of the object's surface texture while attenuating the sensation of the user's own hand movements, making the virtual environment feel more tangible and believable. The difference between tactile suppression and tactile gating is as follows: tactile suppression specifically involves the reduction of sensitivity to self-generated touches during voluntary movement, while tactile gating refers to the selective filtering of external tactile inputs during those same movements (Kilteni et al., 2022).

Our algorithm uses these two principles by coupling user motion to asymmetric vibration, such that it provides a stimulus only when the user moves. Thus, we expect tactile suppression of the vibration to take place while the tactile gating process allows the user to focus their attention on the elicited pseudo force.

4.3 Motion-Coupled Asymmetric Vibration

Careful consideration of our somatosensory experiences shows that the same physical stimulus can lead to different perceptual experiences depending on the context. For example, the same sound at 60 decibels seems loud in a library, while it might go unnoticed in a bustling café. Similarly, when you sit, you initially feel the pressure of the chair against your body, but shortly after, you stop noticing the pressure, unless you move or shift your position. In the same way, we investigated whether it is possible to render asymmetric vibration stimuli in a way that elicits levels of pseudo forces similar to traditional methods while reducing the perceived asymmetric vibration. Symmetrical vibrations, whether motion-coupled or continuous, do not elicit pseudo-forces (Sabnis, 2021; Strohmeier et al., 2018). This was further informed by preliminary tests we conducted, which showed that neither motion-coupled nor continuous symmetric vibrations induce a force sensation.

Focusing on asymmetric vibrations, this research addresses the drawback of rendering forces using continuous asymmetric vibration: increasing the pseudo force is linked with an increase in the amount of vibration. This is not ideal, as research has shown vibration is often described as aggressive (Strohmeier et al., 2018; E. Kim et al., 2020; Sabnis et al., 2023a), annoying (O. S. Schneider et al., 2015; Sabnis et al., 2023b), agitating, or a combination of all of them (Seifi et al., 2015). People often have negative associations with continuous vibrations (Sabnis et al., 2023b), and these can be perceptually misleading, such that the desired effects are not communicated. The ability to render perceptually pure forces, that is, forces that are not accompanied by an experience of vibration, is crucial for a general purpose tactile display.

4.3.1 Designing Motion-Coupled Asymmetric Vibration based on Sensory Attenuation

Motion-Coupled Asymmetric Vibration (**MCAV**) is a novel approach that aims to minimize the perceived intensity of asymmetric vibrations while preserving the perceived pseudo forces elicited by those vibrations. This design leverages two sensory attenuation mechanisms. The first mechanism is based on sensory attenuation through prediction, where self-generated stimuli are perceived weaker than the same stimuli generated externally (Kiepe et al., 2021). The second mechanism is the reduction in sensitivity to touch stimuli during active self-generated movement (Kilteni et al., 2017).

In applying these principles, we designed vibrations that are generated in direct response to user motion, known as motion-coupled vibrations (Sabnis et al., 2023a) or grain-based vibrations (Heo et al., 2019). Since the vibrations are generated based on the signal measured from human motion, they are caused by the user, enabling the user to develop a predictive model. In consequence, they are perceived as self-generated, reducing the intensity with which the vibrations are perceived (Sabnis et al., 2023b). This coupling of vibration pulses with user action takes advantage of the body's natural ability to filter out self-induced stimuli, reducing discomfort usually associated with external vibrations (Seifi et al., 2015). Thus, we expect that MCAV would attenuate the vibration aspect, in turn increasing the pseudo force.

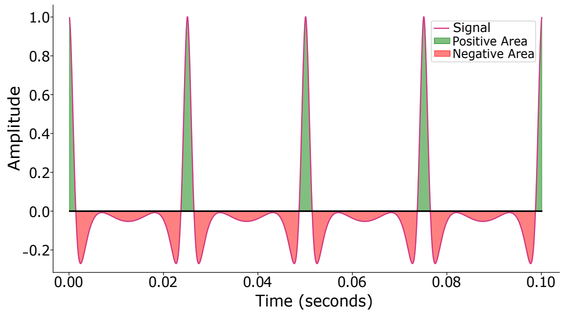

Figure 4.2: *Asymmetric vibration signal at 40Hz (cf. (Tomohiro Amemiya et al., 2009)). The positive and negative area of each cycle is equal (i.e., net force is zero).*

4.3.2 Implementation of Motion-coupled asymmetric vibration

Rendering Motion-Coupled Asymmetric Vibration requires: (a) a method for sensing human movement (b) a controller for transforming human movement to a control signal and (c) an actuator for rendering vibrations. Moreover, sensory attenuation is highly sensitive to the timing and contingency between the action and the sensory feedback, so even a slight delay between the action and the resulting feedback significantly weakens the attenuation effect (Blakemore et al., 1998; Rushton et al., 1981; Kilteni et al., 2019). Thus, good quality rendering of MCAV requires tracking precision during sensing, latency considerations and broadband vibrotactile actuation (Yao et al., 2010; Culbertson et al., 2016).

Different sensing methods can be used to sample user action. For distance sensing, the entire sensor range in which the user moves is divided into a discrete number of bins, Figure 4.3-Ⓐ. The bin distribution over the sensor range can be any desired function. If the user movement changes the sensor value and enters a new bin, an asymmetric vibration pulse is generated, as shown in Figure 4.3-Ⓑ. When the user moves fast, bins change fast, and the asymmetric vibration pulses are generated rapidly. When the bins change slowly, the pulses are generated proportionally more slowly, thus creating a dynamic effect of force: assisting or resisting the user based on the direction of the asymmetric vibration. Any suitable haptic actuator can be used to generate vibrations from the audio signal.

Referring to Figure 4.2, asymmetric vibrations are generated by accelerating a mass with unequal velocities in two opposite directions. One cycle of an asymmetric vibration consists of a large acceleration peak for a short duration (green) in one direction, followed by a small acceleration peak for a long duration in the opposite direction (red). Humans only perceive the larger acceleration, and if such asymmetric vibrations are provided in succession, they create a sensation of force in the direction of the larger acceleration. The asymmetric vibrations are generated by double differentiating the displacement x of the moving mass described in (Tomohiro Amemiya et al., 2009) with an amplitude factor A as a pre-multiplier:

$$x = A \cdot [(r \cos \omega t + \mu(d - r \cos \omega t) + \sqrt{l_2^2 - \{r(\mu - 1) \sin \omega t\}^2})] \tag{4.1}$$

where

$$\mu = \frac{l_1}{\sqrt{r^2 + d^2 - 2rd\cos\omega t}}, \quad \omega = 2\pi f \tag{4.2}$$

To render MCAV, one pulse of asymmetric vibration was triggered for every bin change, Figure 4.3-Ⓒ. We used the frequency of 40Hz for the best experience of pseudo force (Culbertson et al., 2016; Rekimoto, 2014; Sabnis, 2021). This fixed the duration of a single pulse to 25 milliseconds to have a full period, thus minimizing clipping artifacts. In the current implementation, if the bin is changed, i.e. the next pulse is triggered while the current pulse is being played, the algorithm stops the current pulse and plays the next one. Triggering two or more pulses was experimented with, but having a pulse of 50 milliseconds or more goes beyond the perceptual threshold (Vogels, 2004), compromising the experience of self-generated vibrations. Thus, the variables required for generating the signal are the number of bins, which corresponds to the overall density of pulses (in the sensor range) and to how the bins are distributed in the sensor range. We have adapted an established system in research, Haptic Servos (Sabnis et al., 2023a), which is able to produce the desired signal in under *5ms*. Like Haptic Servos, we use a Teensy 4.1 microcontroller with a PT8211 DAC. However, we use the Visaton 2.2 voltage amplifier rather than the D-class amplifier (PAM8403) that is integrated in Haptic Servos. This is because the D-class amplifier removes the high-frequency components while amplifying the audio signal, and, hence, it filters the short-duration-high-peak of the asymmetric vibration responsible for inducing force sensations. The technical evaluation shows that the driving signal and the measured acceleration of the actuators match the desired asymmetric waveform. Details of the technical evaluation can be found in Section B.1.

Ergonomic Gripping We explored multiple configurations for integrating the actuators to render high quality pseudo forces. These include attaching the actuators to a handle like Tanabe et al. (2023), tying the actuators to a finger like Culbertson et al. (2017b), and using the pinch configuration (I. Choi et al., 2017). The rendered MCAV did not elicit pseudo forces when the actuator was attached to a handle, but was able to elicit forces when attached to the finger and worked best with the pinch configuration. In our experience, the sensitivity of perceived pseudo forces on the body for MCAV is similar to continuous asymmetric vibration perception. We used the pinch configuration because it gave the strongest pseudo force sensation, due to the higher density of direction sensitive Meissner corpuscles on the fingertips (Johansson et al., 1979; Morioka et al., 2008; Corniani et al., 2020). Finally, the pinch configuration offers flexibility to change actuator orientations while holding the VR controllers (Figure 4.8).

4.3.3 Study Rationale

Our algorithm is based on the literature that describes foundational principles of human perception. In this paper, we confirm the observations from the literature and further advance the state-of-the-art by providing empirical data to better understand

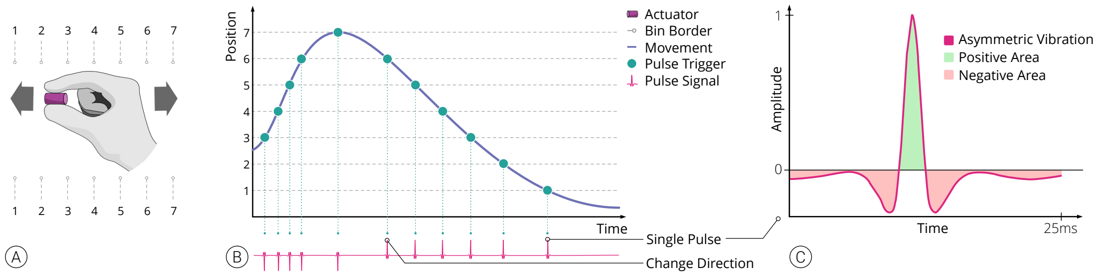

Figure 4.3: *Motion-coupled asymmetric vibration algorithm: we sample the user movement Ⓐ and render vibrotactile pulses at predefined sensor thresholds Ⓑ. Depending on the dynamics of the movement, this results in a varying density of pulses that are timely synchronized with the movement (i.e., motion-coupled), as shown in Ⓑ. Each pulse is rendered as an asymmetric vibration Ⓒ that provides assistive or resistive forces depending on the direction of movement (see Ⓑ pulse signal).*

what might cause the effect. We have conducted two studies: First, a controlled psychophysics study compares motion-coupled asymmetric vibration with traditional continuous asymmetric vibration. Using magnitude estimation, we aim to understand the overall effect of *coupling* asymmetric vibration to motion as well as the relative contributions of *continuity*, human *motion*. Magnitude estimation is an established method in psychophysics to obtain quantitative judgments of the perceived magnitudes of stimuli (Kingdom et al., 2016; George A Gescheider, 1988) which is commonly used in investigations of haptic and visuo-haptic perception, both in- and outside VR (Vega et al., 2024; Ding et al., 2024; Degraen et al., 2021; Jingu et al., 2024; Zenner et al., 2017; Zenner et al., 2019a; Zenner et al., 2021). In a follow-up study, we situate these results in real-world applications, in which users explore three interactive scenarios in VR. These explorations compare two state-of-the-art approaches (off-the-shelf vibrotactile haptics and continuous asymmetric vibration) with motion-coupled asymmetric vibration to provide insights about the type of interaction MCAV is best suited for. Study 1 presents primarily quantitative results, supplemented by semi-structured interviews, while study 2 provides primarily qualitative insights, supplemented with magnitude estimation scores.

4.4 Study 1: Sensory Attenuation of Vibration & Pseudo Force

The goal of this study was to quantify the perceived intensity of vibration and force to compare motion-coupled asymmetric vibration with the state-of-the-art in a controlled task. Our investigation focuses on asymmetric vibration, which shows two qualities: vibration and pseudo force. Our research question is: *Can the perceived vibration be attenuated while preserving the perceptual quality of force?* Therefore, we compare motion-coupled asymmetric vibrations to continuous asymmetric vibrations. To better understand *what might specifically cause attenuation*, we investigate the relative contribution of *continuity*, human *motion*, and *coupling* to motion.

4.4.1 Study Design

We conducted a single-blind within-subject psychophysics study to compare motion-coupled asymmetric vibration and continuous asymmetric vibration. A direct comparison is meant to provide information on which algorithm performs better; however, because there are multiple differences between them, it does not explain what specifically caused this difference. These are three main differences between the two algorithms (**independent variables**): (1) The *continuity* of vibration: Usually, asymmetric vibration is provided continuously. Motion-coupled asymmetric vibration is provided based on user movement. (2) The user *motion*: Continuous asymmetric vibration can be provided whether the user is moving or not. Motion-coupled asymmetric vibration can only be experienced during movement. (3) *Coupling* of vibration to user motion: For motion-coupled asymmetric vibration, the occurrence of pulses is proportional to the speed of user motion. However, a signal with the same variability, but decoupled from human movement, can be created. We designed four vibrotactile signals to individually assess the effect of these differences on the perceived vibration (*VibrationIntensity*) and perceived pseudo force (*PseudoForceIntensity*), which are the **dependent variables**:

(A) **Motion-coupled asymmetric vibration (*MotionCoupled*):** These vibrations are rendered as pulses of asymmetric vibration coupled with the user's motion.
(B) **Motion-decoupled asymmetric vibration (*MotionDecoupled*):** Based on the vibrations triggered for condition *MotionCoupled*, the asymmetric vibration pulses are replayed in reverse, thus decoupling vibration from user movement.
(C) **Continuous asymmetric vibration when user is moving (*ContinousMoving*):** The asymmetric vibration is played continuously while the user moves for a certain duration.
(D) **Continuous asymmetric vibration when user is stationary (*ContinuousStationary*):** The asymmetric vibration is played continuously while the user is stationary for a certain duration.

We took care to make the signals equivalent in all other ways. The signal in *ContinousMoving* and *ContinuousStationary* has the same number of pulses as *MotionCoupled*, but stitched together as a continuous signal. Due to this stitching, the signal duration per trial in conditions *ContinousMoving* and *ContinuousStationary* is less than in *MotionCoupled* and *MotionDecoupled*. The signals *ContinousMoving* and *ContinuousStationary* have the same average power as *MotionCoupled*. Each signal was presented to the user at three different intensity levels: 40%, 70%, and 100% of maximum amplitude. A schematic representation of the signals, including the comparisons made, is shown in Figure 4.4. We provide the measured output acceleration in Section B.1 as well as a recorded movement profile of a participant for the four conditions, including pulse triggers, in Section B.2, Figure B.4.

Hypotheses: The comparison between *MotionCoupled* and *ContinuousStationary* con-

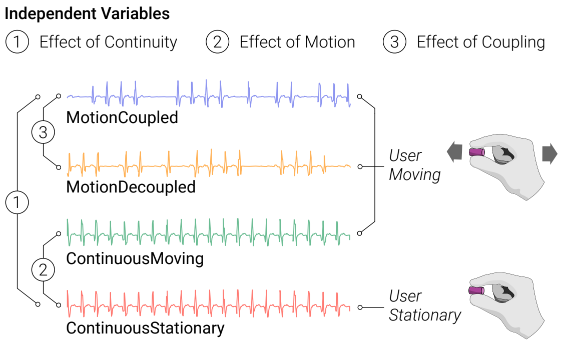

Figure 4.4: *The signals generated with the four algorithms (vibration stimuli) described in Section 4.4.1 with the respective user states (moving/ stationary) and the independent variables of the comparisons made.*

Table 4.1: *Hypotheses Tested for the Psychophysics Study*

Effects of	Perceived Vibration is ...	Perceived Force is ...
Continuity	**weaker** for MotionCoupled than ContinuousStationary – **H1a**	**weaker** for MotionCoupled than ContinuousStationary – **H2a**
Motion	**weaker** for ContinuousMoving than ContinuousStationary – **H1b**	**stronger** for ContinuousMoving than ContinuousStationary – **H2b**
Coupling	**weaker** for MotionCoupled than MotionDecoupled – **H1c**	**stronger** for MotionCoupled than MotionDecoupled – **H2c**

ditions tests our algorithm against the state-of-the-art, while comparing sensory attenuation during self generated (*MotionCoupled*) and external (*ContinuousStationary*) asymmetric vibrations. We hypothesize that *MotionCoupled* condition will result in weaker perceived vibration (H1a) and pseudo forces (H2a) compared to the *ContinuousStationary* condition (Table 4.1).

The *ContinousMoving* versus *ContinuousStationary* comparison focuses on the impact of user movement on sensory attenuation. We expect that vibration will be perceived as weaker in the *ContinousMoving* condition (H1b), but based on the findings of Tomohiro Amemiya et al. (2016), we anticipate that the pseudo forces will feel stronger (H2b) when users are moving.

Finally, the comparison between *MotionCoupled* and *MotionDecoupled* examines how synchronizing vibrations with user movement affects sensory attenuation. We hypothesize that the *MotionCoupled* condition will lead to attenuated vibration (H1c) and stronger perceived pseudo forces (H2c), due to this alignment of stimuli with user movement.

4.4.2 Apparatus

The study setup is shown in Figure 4.5. For constraining participant movements, an area was laser cut with markings spaced 10cm apart and was enclosed on three sides to assure that participants move primarily in a single dimension. Time of flight (ToF)

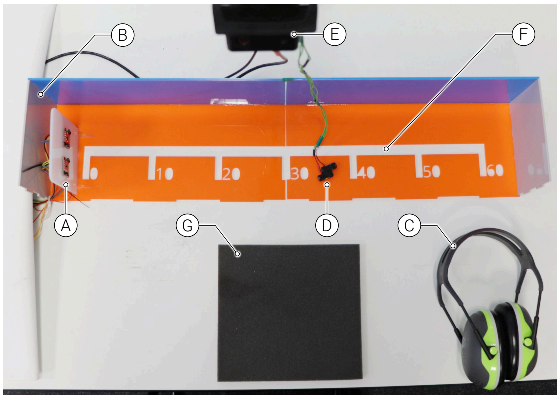

Figure 4.5: *The study setup with the Time of Flight sensors Ⓐ, the semi-closed box in which participants moved Ⓑ, ear protection gear Ⓒ, the system of actuators Ⓓ, the wires (slack) to connect the actuators Ⓔ, 1-D trajectory for guiding participants' movements Ⓕ, and elbow pad to rest their elbow between conditions Ⓖ.*

– VL53L4CD sensors[2], with a sampling frequency of 100Hz, were used to measure users' movements along a straight line and were placed on the left end of the box. We chose midair movements to prevent the influence of other forces on the participants' movements. Two ToFs were used post-calibration to increase the sensing accuracy, which was crucial for generating motion-coupled asymmetric vibration. Further, we low-pass filtered the values received from the ToF sensors and used a jitter threshold to mitigate the noise of the sensors. The sensed data (users' hand motion) was measured by ToF sensors and sent to a microcontroller (Teensy 4.1). Based on the algorithm, the actuation pipeline (modified from Haptic Servos (Sabnis et al., 2023a)) consisted of a Teensy, which was converted to an analog signal using a 16-bit digital-to-analog (pt8211 DAC) converter, and then amplified using a Visaton 2.2 voltage amplifier before feeding it to the low frequency DRAKE TacHammer[3], which converted the signal to vibrations. We used two TacHammers connected to each other to provide a stronger pseudo force sensation and enable ergonomic gripping. Sand-paper tape was attached to the actuators to provide better grip and avoid slipping between the fingers, which is important for pseudo force perception (Culbertson et al., 2017b). The two actuators do not provide torque since they are in the same direction, and they minimally affect each other's system dynamics. The signal provided to them is split using a wire-splitter. Further, the measured accelerations during the technical evaluation of the combined actuators did not show any significant differences compared to the driving signal, refer to Section B.1, Figure B.2. For all practical purposes, the actuators can be considered as a single unit, without phase difference between the two actuators. The actuator wires were soft, flexible, and had minimal tension to not create any force or interfere with the movements of the participants. The maximum intensity was set using the Visaton amplifier. Individual adjustments were then done by modifying the strength of the

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[2] SparkFun Distance Sensor, VL53L4CD: https://www.sparkfun.com/products/18993; accessed September 11, 2024

[3] TITAN Haptics DRAKE TacHammer (LF): https://titanhaptics.com/product/drake-haptic-actuator-kit-12-pack/; accessed September 11, 2024

output signal in the firmware. Vibrations were stopped using a velocity threshold to prohibit the vibrations participants might feel when they momentarily stop at either end of the play area. The asymmetric vibration pulses were provided such that there is a force towards the ToF sensors. The code with algorithms used in the study can be found in the online repository[4].

4.4.3 Procedure

Before starting, we informed participants about the purpose of the study. They were asked to sign a consent form and complete a demographic questionnaire. Our study consisted of three phases:

Orientation Phase: During the orientation phase, participants were asked to hold the vibrotactile actuators between their index finger and thumb (Figure 4.8-A), move the device over the marked area, and provide scores using absolute magnitude estimation. The experimenter informed them that no vibration and no pseudo force would have a score of zero and should be used as a baseline to assign scores to the vibrotactile stimuli. Asymmetric vibration stimuli were provided alternately– towards and away from the ToF sensors for a duration of 3 seconds with a 500ms gap in between and repeated three times. They were told that they might feel a "directional cue" or "force" in either direction, which the experimenters called pseudo forces. All participants felt pseudo forces in both directions. Furthermore, they were asked to perform 4 to 7 movements from 5cm to 55cm and back, in a straight line within 15 seconds, to ensure that no participant moves too slowly or too fast during the study.

Study Phase: During the study phase, participants evaluated different algorithms of rendering pseudo forces by rating the perceived vibration and perceived force. To do so, we presented them with each condition at three intensity levels (40%, 70%, and 100% of maximum amplitude), resulting in 12 unique conditions per trial. Using a balanced Latin-square design, we created 12 trial combinations. Each participant completed two trials for both maximum perceived intensity of vibration and maximum perceived pseudo force. The two trials were combined to form a sequence with 24 conditions. The sequence was kept the same for both vibration and pseudo force, but half of the participants rated the vibration they perceived first, while the other half rated the pseudo force they perceived first. The condition *MotionCoupled* was played before *MotionDecoupled*, *ContinousMoving*, and *ContinuousStationary* as the latter were dependent on the condition *MotionCoupled*. Between the trials for rating pseudo forces and vibration, the participants took part in a game of ball-in-basket with 5 throws. This was done to reduce the fatigue of the participants and to add a fun element.

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[4] GitHub: `https://github.com/sensint/Motion-Coupled-Asymmetric-Vibration`

Task: Participants moved their hand in 1-D over a 50 cm distance 4 to 7 times based on the orientation phase (see Figure 4.5, Figure 4.1-A) within 15 seconds and assigned scores to the maximum perceived vibration and pseudo force for each stimulus, using absolute magnitude estimation. The participants were free to choose the scores on an arbitrary scale, and these were recorded manually. The stronger the maximum perceived intensity of vibration/ pseudo force elicited by the condition, the higher the score. Before *ContinuousStationary* condition, participants were patted on the shoulder to signal them to stay stationary for this condition.

Qualitative Interviews: We collected qualitative feedback on the elicited sensation for each condition by conducting a semi-structured interview. Prior work has shown that evaluating subjective experience has proven to be an effective method to investigate “what the haptic experience feels like”, which is difficult to capture with other evaluation methods (Strohmeier et al., 2018; Jingu et al., 2024). Each condition was presented at 100% intensity level. The participants were asked to describe their experience of vibration, forces, and overall experience. They were asked to reflect on their experience and qualitative associations only if the participants hinted at them.

Participants:

We recruited 12 healthy participants (7 identified as male, 5 as female; 10 were right-handed) aged 19 to 33 years ($M = 26.2; SD = 3.7$). Seven participants had no experience in vibrotactile haptics, and the remaining five participants worked in haptics for 4 to 36 months and had experienced pseudo forces generated using continuous asymmetric vibration before. During the study, participants wore ear protection gear (NRR: 37dB) to cancel out audio cues generated by the vibrotactile actuators. The duration of the study was one hour and all participants received a financial compensation of 12 Euros for participating.

Measurements and Data Processing:

The estimates of perceived vibration and pseudo force were collected using absolute magnitude estimation with two separate user-dependent numerical scales (Kingdom et al., 2016; George A Gescheider, 1988). The raw estimates of the maximum perceived intensity of vibration (*VibrationIntensity*) and the maximum perceived pseudo force (*PseudoForceIntensity*) were individually standardized (z-score normalization) by subtracting the grand mean of each participant’s estimates from all individual estimates and dividing the resulting value by the standard deviation of the participant’s grand mean. After standardization, the mean estimate over all conditions for each participant is zero, with larger and smaller estimates represented as positive and negative values, respectively. This type of normalization ensures that even though participants were allowed to choose the values they used for estimates freely, statistics are performed on data with a common scale. To assess significance, we calculate ~95% confidence intervals for differences between estimates. If the interval includes zero, there is no significant difference; otherwise, the difference is statistically significant.

Interviews were audio recorded, transcribed and themes were extracted. Coding of the interviews was done by one author, who approached the transcripts based on their dialogues with the participants during the study.

4.4.4 Absolute Magnitude Estimation Results

We conducted two RM-ANOVAs to understand the effects of the different vibration algorithms and intensity levels on vibration and pseudo force estimates. To address our hypotheses (Table 4.1), we conducted three post-hoc comparisons for each RM-ANOVA. We compared *MotionCoupled* and *ContinuousStationary* to gain insights on the effect of the *continuity* of the signal and how our algorithm compared to the state-of-the-art, see Figure 4.6, Figure 4.7. To understand the effects of *movement*, we compared *ContinuousMoving* to *ContinuousStationary*. Finally, to understand the effects of *coupling*, we compared *MotionCoupled* and *MotionDecoupled*. We preregistered our intention to make these comparisons on OSF[5].

Effects on Perceived Vibration

MotionCoupled received the lowest vibration estimates with M = -0.51 and SD = 0.25, while *ContinuousStationary* vibration received the highest vibration estimates with M = 0.56 and SD = 0.25 – more than a standard deviation apart. *MotionDecoupled* (M = -0.23, SD = 0.21) and *ContinuousMoving* (M = 0.19, SD = 0.12) were between, (Figure 4.6-Ⓐ). As expected, higher amplitude levels lead to higher perceived vibration, (Figure 4.6-Ⓑ).

The RM-ANOVA showed that the main effect of the *algorithm on perceived vibration* was statistically significant, $F(3, 33) = 44.48, p < .001$, with a generalized eta squared (η^2_G) of 0.644. Similarly, we found a statistically significant main effect of *intensity level on perceived vibration*, $F(2, 22) = 238.72, p < .001$, with, $\eta^2_G = 0.860$. The interaction between *algorithm* and *intensity level* was also statistically significant, $F(6, 66) = 6.35, p < .001$, with $\eta^2_G = 0.134$, however, with a smaller effect size.

Bonferroni corrected post-hoc comparisons revealed a significant difference for all three preplanned comparisons, suggesting that *continuity*, *movement*, and *coupling* all contributed to the attenuation of perceived vibration, as shown in Figure 4.7 (left).

Effects on Perceived Pseudo Force

Results show that the algorithms lead to a similar estimate (*MotionCoupled*: M = 0.22, SD = 0.25; *ContinuousMoving*: M = 0.44, SD = 0.20; *ContinuousStationary*: M = 0.13, SD = 0.50), except for *MotionDecoupled*, which was much lower with a mean of -0.79 and SD of 0.34, (Figure 4.6-Ⓒ). We found that higher amplitude leads to stronger pseudo

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[5] OSF preregistration link (Sabnis et al., 2024): `https://osf.io/rfw36`

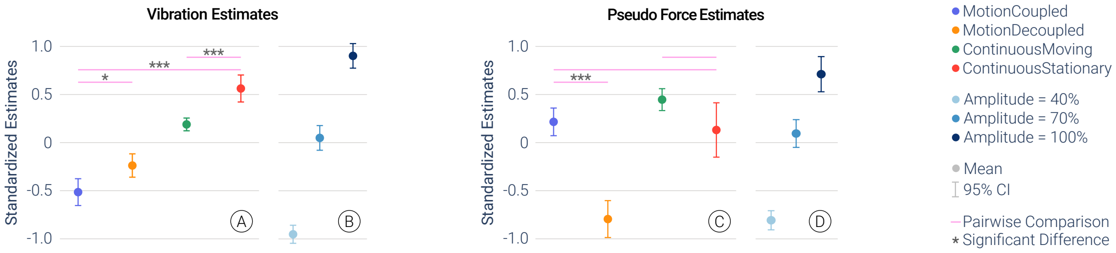
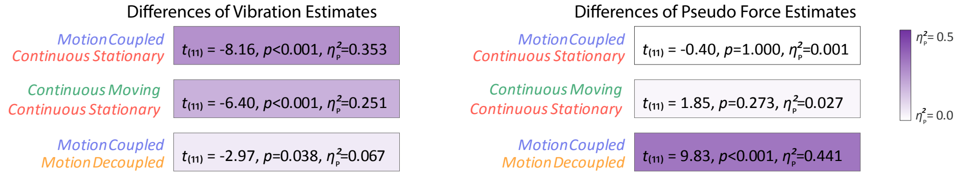


Figure 4.6: *Results of study 1. Left figure shows the vibration estimates for each algorithm,* Ⓐ *along with the averaged vibration scores over all stimuli for each intensity* Ⓑ*. Right figure shows the pseudo force estimates for each stimulus* Ⓒ *along with the averaged pseudo force scores over all stimuli for each intensity* Ⓓ*. Plots depict mean and 95% confidence interval for comparing effects of algorithm and amplitude. The y-axes in all the figures show standardized scores (z-score normalization). We mark the statistical significance (if observed) for the six comparisons of interest* ($*: p < .05$; $**: p < .01$; $***: p < .001$).



Differences of Vibration Estimates

MotionCoupled *Continuous Stationary*	$t_{(11)} = -8.16$, $p<0.001$, $\eta_p^2=0.353$
Continuous Moving *Continuous Stationary*	$t_{(11)} = -6.40$, $p<0.001$, $\eta_p^2=0.251$
MotionCoupled *MotionDecoupled*	$t_{(11)} = -2.97$, $p=0.038$, $\eta_p^2=0.067$

Differences of Pseudo Force Estimates

MotionCoupled *Continuous Stationary*	$t_{(11)} = -0.40$, $p=1.000$, $\eta_p^2=0.001$
Continuous Moving *Continuous Stationary*	$t_{(11)} = 1.85$, $p=0.273$, $\eta_p^2=0.027$
MotionCoupled *MotionDecoupled*	$t_{(11)} = 9.83$, $p<0.001$, $\eta_p^2=0.441$

Figure 4.7: *t-statistics, significance levels and partial eta squared* (η_p^2) *of post-hoc comparisons. Colors correspond to effect sizes.*

force estimates; however, the difference between medium and high amplitude was less pronounced than for vibration estimates, (Figure 4.6-Ⓓ).

The main effect of *the algorithm on perceived pseudo force* was statistically significant, $F(3,33) = 22.88, p < .001$, with $\eta_G^2 = 0.520$. The main effect of *amplitude on perceived pseudo force* was also significant, $F(2,22) = 71.74, p < .001$, with $\eta_G^2 = 0.653$. The interaction between *algorithm* and *amplitude* was statistically significant, $F(6,66) = 8.78, p < .001$, with $\eta_G^2 = 0.133$. However, the effect size for the interaction was comparably small.

Bonferroni corrected post-hoc comparisons revealed that *coupling* had a significant effect: the *MotionDecoupled* condition was significantly lower than for *MotionCoupled*. Changes in participant *movement* and in *continuity* of the signal did not significantly impact the pseudo force estimates as seen in Figure 4.7 (right).

Comparison and Discussion of Statistical Results

The goal of motion-coupled asymmetric vibration was to reduce the perceived vibration while maintaining pseudo force. Comparing *MotionCoupled* with *ContinuousStationary* (Figure 4.7, top), vibration estimates were significantly lower, showing the largest effect on perceived vibration. Perceived pseudo force, however, showed no measurable difference, confirming that motion coupling reduces vibration without affecting pseudo force. *We, therefore, accept H1a and reject H2a.* This highlights that our design goal behind motion coupled asymmetric vibration is achieved: The perceived vibration can be reduced significantly without measurable change in the perceived pseudo force. The magnitude of the attenuation in the perceived vibration between *MotionCoupled* and *ContinuousStationary* is comparable to reducing the amplitude by ~30%, see Figure 4.6-Ⓑ.

To understand the role of *movement*, we compared *ContinuousMoving* and *ContinuousStationary* (Figure 4.7, mid). Movement significantly reduced perceived vibration but did not significantly affect pseudo force, despite slightly higher average estimates. *We accept H1b and reject H2b.* Finally, to understand the effect of *coupling*, we compare *MotionCoupled* with *MotionDecoupled* (Figure 4.7, bottom). Vibration was unaffected, but pseudo force was significantly reduced without coupling. *We accept H1c and H2c.*

In summary, the results highlight that motion-coupled asymmetric vibration is preferable over continuous asymmetric vibration, as it reduces the perceived vibration. We see that *continuity*, *motion*, and *coupling* all contribute to this reduced vibration perception. However, for perceived force, it appears that only *coupling* is required, as both continuous and motion-coupled asymmetric vibrations induced robust force sensations[6].

4.4.5 Qualitative Interview Themes

Asymmetric Vibration Obscures the Perceived Force: Participants often found it challenging to distinguish between the perceived vibration and pseudo forces with *ContinuousStationary* and *ContinuousMoving*, with sensations often blending together and complicating the perception of distinct pseudo forces. The confusion was indicated by P1 stating, “My confusion here is the vibration and the force that you’re talking... like the vibration. I can feel them vibrate. What’s the force that we’re talking about?” and P9 indicating for *ContinuousStationary* that “I feel sometimes the vibration also overpowers. ... it feels like if my mind is thinking about vibration then I feel the vibration but then if I try not to focus on the vibration... then I start feeling a bit of a pseudo force.” Moreover, P5 mentioned for *ContinuousStationary* and *ContinuousMoving*, “It’s hard to just extract the vibration out of it... sometimes it... screws up”.

Participants preferred motion-coupled asymmetric vibration for pseudo force rendering because they perceived the vibrations less intensely. For *MotionCoupled*, P12 stated, “I like the ones that have the more like subtle ticks. Yeah, the subtle ones *pull* nicely actually.”, and, “Sometimes I feel more of the force, but it’s just that the vibration is weaker right?”. Furthermore, P9 stated, “The force is more intense than the vibration... if the force is intense then it’s clear, and then you understand direction [of pull].” Moreover, P11 mentioned, “The drag with the more subtle ones [*MotionCoupled*] felt more natural... the continuous sensations sometimes felt overwhelming.”

Onset Behavior and Response to Pseudo Forces: Participants highlighted the onset behavior of pseudo forces, noting the time it took to detect and respond to these forces

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[6] We provide a visual overview of the estimates for each algorithm and intensity level in Section B.3, Figure B.5

during the study. For some, the forces were apparent from the beginning, while others required multiple interactions to recognize them. The clarity and timing of these forces depended on both the stimuli and the participants' movements. P3 mentioned that the fastest onset behavior was when they were moving in the *ContinuousMoving* case, "It wasn't apparent from the very first instant, but then as you move, you are able to perceive it fairly clearly." P7 noted that they quickly understood the direction for the *MotionCoupled* case stating "It feels like inertia for this condition [*MotionCoupled*], when I move faster the pull becomes stronger". However, P9 mentioned "At first I can feel really strong force... but as the thing [actuator] keeps going [vibrating] I can't feel it", and P11 said "This was strong in the beginning... after a second it got down", showing that the perceived force decreased for the continuous case over time.

Qualitative Associations and Real-World Analogies: Participants associate sensations elicited during different vibration conditions in the study with their real-world experiences. For instance, for the continuous asymmetric vibration condition, P4 mentioned "it's sort of like a magnet. So I definitely feel more attraction when I move to the left." P6 said that for *ContinuousStationary*, "my dog is trying to run away", whereas for *MotionCoupled*, the pseudo forces felt like "the dog is trying to sniff at different flowers". Moreover, rotating the actuators by 90 degrees, P3 mentioned that the *MotionCoupled* clearly gave them a feeling of pull which was equal to "holding a (electronic) tablet in the vertical direction, against gravity". Participants also referred to the feeling of force by many names while trying to describe the experience like, "Pull" (P2, P8, P12), "Tug and Nudge" (P7), and "Drag" (P3, P11). P5 also stated that the pseudo force elicited using motion-coupled asymmetric vibration, "reminds me of plucking my guitar string". P4 was excited to have these effects of pseudo forces on a cane for blind people (similar to Tanabe et al. (2023)).

4.5 Study 2: Exploration of Pseudo Force Rendering Approaches for Virtual Reality

This study investigated the effectiveness of the motion-coupled asymmetric vibration algorithm in providing realistic sensations, compared to the two common approaches representing state-of-the-art in product (controller vibrations) and research (continuous asymmetric vibration). Here we are primarily concerned with the resulting realism and less concerned with the magnitude of vibration or force. In this study, magnitude is tangential to our primary objective, similar to how the brightness of a display is only tangentially related to the realism of the image it depicts.

4.5.1 Study Design

To understand the effectiveness of motion-coupled asymmetric vibration in creating realistic experiences in VR, we compared the perceived realism with widely available

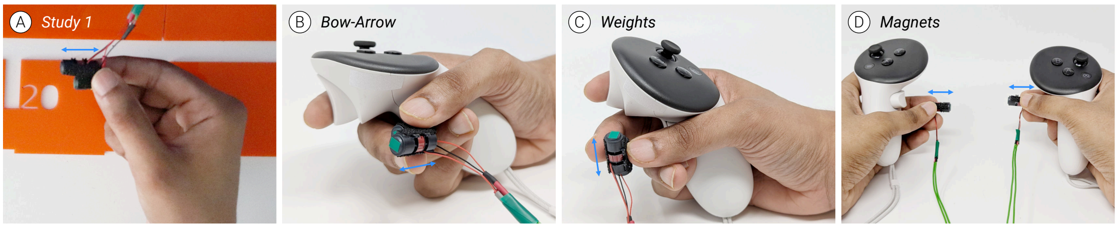

Figure 4.8: Ⓐ *shows how the participants held the combined actuator system in the psychophysics study. The other images show how the participants held the actuators with the hand-controller for bow-arrow* Ⓑ*, weights* Ⓒ *and magnets* Ⓓ *scenes, respectively, during the VR study. The actuators are held horizontally for the bow-arrow and vertically for weights to provide forces in the respective directions, indicated by blue arrows. One actuator is held in each hand for the magnets scene.*

systems, preserving their unique vibration characteristics. We use the built-in controller of the Meta Quest 3 (*Controller*) with continuous symmetric vibration, as an example of consumer products, and we use continuous asymmetric vibrations (*Continuous*) to represent the state-of-the-art in research, to compare with motion-coupled asymmetric vibrations (*MotionCoupled*). Moreover, we rendered continuous vibrations for the controller condition to optimize for realism using a physics-based approach and previous work where vibration intensity is used to display the force and weight of the object (Lim et al., 2021). We designed three application scenarios, Figure 4.9-Left:

- Bow and Arrow (Scene-B): This application evaluates the linear increase in tension. (Amplitude is linearly modulated between 40% and 100%)
- Lifting Weights (Scene-W): This application evaluates weight rendering with different sizes of boxes.
- Haptic Magnets (Scene-M): This bimanual application evaluates force changes cubically (cubic mapping of amplitude) based on the distance between magnets.

4.5.2 Apparatus

We used a Meta Quest 3 headset for displaying the virtual scenes. The hand controllers were used to render vibrotactile feedback for the scenes as control condition. Further, for rendering the continuous as well as motion-coupled asymmetric vibrations, we used the TacHammer DRAKE (LF) with the same actuation pipeline from study 1, where two actuators were used together for the bow-and-arrow and weight rendering scenes. For the magnet scene, however, we used two separate actuators, one in each hand. The hand controllers have a lower intensity of vibration compared to the TacHammers (Figure B.3). Rendering of the virtual environment was done in Unity (2022.3.34f1), with Oculus link transmitting the data to the headset using a USB-C cable. A unidirectional communication protocol was used to communicate the message from Unity to the microcontroller over serial. The amount of bow pulled and the distance between the magnets was used to modulate the amplitude of the pseudo forces linearly for the bow and cubically for the magnets. A mobile phone with automatic transcription feature was used to audio record the interviews. The scenes, algorithms, and communication protocol can be found in the repository[7].

4.5.3 Procedure

We used the method of open design exploration to assess the type of preferred vibration feedback for representing forces and weights in virtual reality in three scenarios. Participants were informed about the study and were asked to give their consent. Next, participants were introduced to the VR system with the headset, hand controllers, and vibrotactile actuators. They were also instructed on how to hold the actuator while holding the controller. For the bow-arrow and weights, two actuators (similar to study 1) were given in a single hand (Figure 4.8-Ⓑ, Ⓒ) with horizontal and vertical configurations, respectively, whereas for the magnets, one actuator was given in each hand (Figure 4.8-Ⓓ). The trigger key on each of the hand-controllers was used to grab objects in the scenes. Pressing the trigger once attached the object to the controller in VR, and, to release the object, they had to press the trigger again.

All tasks were performed while seated. The chair for the participants was calibrated using the Quest's calibration procedure. The scenes and vibration conditions were randomized between the participants. To familiarize themselves with the scene, participants explored the scenes with the hand controllers, while holding the actuators, but without vibration feedback.

Participants then performed the study with 3 scenes (B, M, W) × 3 vibration conditions (*Controller, Continuous, MotionCoupled*). After exploring all the vibration conditions for a particular scene, participants set aside their VR headset, hand controllers, and actuators and were asked to mark their experience of vibration, force, and realism on a paper-based semantic differential scale, and a semi-structured qualitative interview was conducted.

After all the scenes were completed, participants were asked to select their favorite scene to perform the task partially with visual and partially without visual feedback, sequentially for each vibration condition. Finally, they were asked to describe and differentiate between their overall experience of the scene with and without visual feedback. This comparison aimed to capture the effect of pseudo forces elicited by MCAV with and without the presence of visual feedback, as well as the presence of potential pseudo forces generated by the visual dominance effect (Lecuyer et al., 2000; Speicher et al., 2019). Furthermore, this approach enabled us to uncover the contribution of visual and haptic stimuli on subjective force perception, similar to related work in visuo-haptic perception in VR (Degraen et al., 2019; Zenner et al., 2017; Zenner et al., 2019a).

Task

There were particular tasks for every scene to not have the participants focus on the vibration. Every scene lasted as long as the duration needed to complete the task or 1

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[7] GitHub: `https://github.com/sensint/Motion-Coupled-Asymmetric-Vibration`

minute of exploration, whichever finished first. For scene B, participants had to shoot at least 5 arrows; for scene M, they had to do 2 attractions and 2 repulsions, with their hands significantly apart for each repetition; for the weights, they were asked to lift the brown boxes once and then place each blue box of a particular size (big, medium, small) on the corresponding sizes of the brown boxes. During the final phase of with and without visual feedback, participants were asked to perform the same task partially, for example, shooting two arrows with visual feedback and then two arrows without visual feedback.

Participants

Eight healthy participants (6 male, 2 female) aged 24 to 32 years ($M = 27.6$; $SD = 2.9$) took part in the study. Four participants had taken part in the first study, two of them not working in the field of haptics. The other four were new participants, only one of them working in the field of haptics. The other three new participants had never experienced pseudo forces, and one had never experienced VR before. The duration of the study was on average one hour, and all participants received a financial compensation of 12 Euros for their participation. Participants were not told anything about pseudo forces. The vibration conditions were referred to as *Controller*, *Buzz* and *Tick* for controller vibration, *Continuous* asymmetric vibration and *MotionCoupled* asymmetric vibration, respectively. White noise was played through the headset to mask audio-cues.

Measurements and Analysis

To understand participants' perceptions and experiences of vibration, forces, and realism, we applied a mixed-method approach and collected the following data:

Semantic Differential: After experiencing all the conditions for a single scene, participants were asked to mark each of the conditions with respect to the other on a scale on paper. The realism scale was inspired by realism studies of VR experience (Jung et al., 2021) and was marked from "unreal" to "real" to rate the overall experience. We also collected the perceived force and vibration data, which is reported in Section B.3.

Qualitative Interview: After experiencing all the conditions for a single scene, a short semi-structured qualitative interview was conducted. The questions for the qualitative interview were:

- Which type of vibration feedback (*Controller, Buzz, Tick*) do you prefer and why?
- Can you describe how the experience of forces (if any) and vibration feedback affected your experience?

After the exploration with and without visual feedback, participants were asked to describe the effects of visual feedback on the overall experience of the scene they explored. Based on the participant's responses, additional questions were asked.

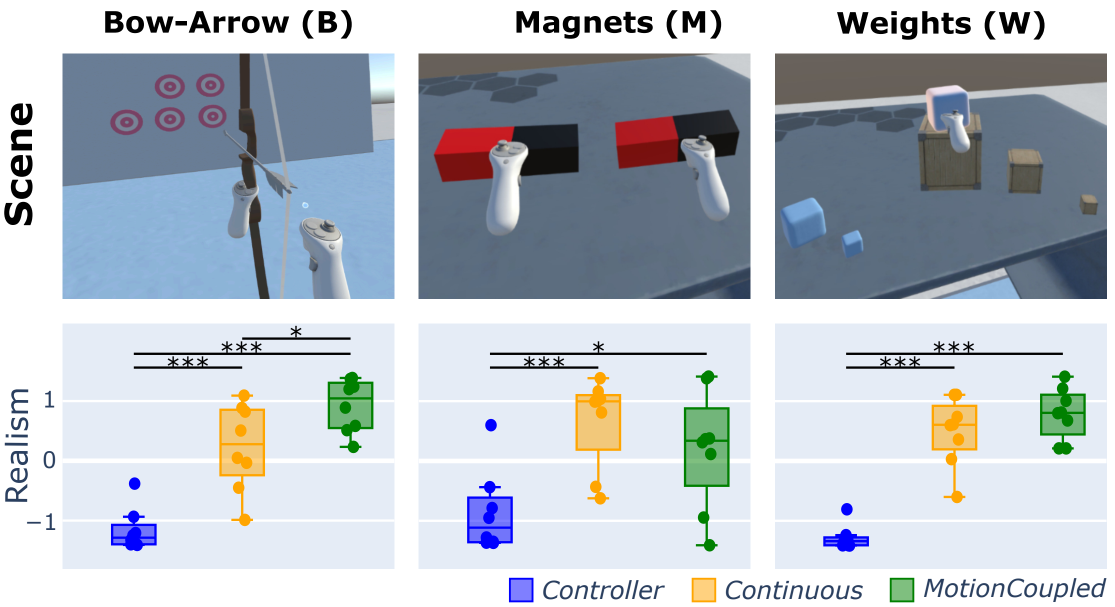

Figure 4.9: *The top row shows the three scenes explored in the VR study. The bottom row shows the standardized realism scores for the scenes for the three vibration conditions: Controller, Continuous, MotionCoupled. Each point is a user estimate. The y-axis for realism represents the standardized scores, and each box-plot represents the median and the interquartile range.* ($* : p < .05$; $** : p < .01$; $*** : p < .001$)

Analysis: The qualitative analysis was done similar to study 1. For the semantic differential, post-standardization, RM-ANOVA was performed for each dependent variable, followed by pairwise t-tests using Bonferroni correction.

4.5.4 Results

Semantic Differential

Figure 4.9 shows that the vibration conditions had a statistically significant effect on the perceived realism for all the scenes, (Bow-Arrow: $F(2, 14) = 21.63, p < 0.05, \eta^2 = 0.75$; Weights: $F(2, 14) = 36.72, p < 0.05, \eta^2 = 0.84$); Magnets: $F(2, 14) = 4.91, p < 0.05, \eta^2 = 0.41$. Pairwise comparisons showed that the *MotionCoupled* and *Continuous* conditions significantly improved the realism compared to the *Controller* condition for bow-arrow (*Continuous* and *Controller*: $t(7) = 3.77, p < 0.05$; *MotionCoupled* and *Controller*: $t(7) = 17.61, p < 0.05$) and weights scene (*Continuous* and *Controller*: $t(7) = 6.81, p < 0.05$; *MotionCoupled* and *Controller*: $t(7) = 16.50, p < 0.05$). In none of the scenes were the realism ratings different for *Continuous* and *MotionCoupled* conditions. Detailed results of perceived vibration and pseudo forces are in Section B.3.

Qualitative Interviews

Vibrotactile Feedback Preferences for Perceived Realism *MotionCoupled* was preferred for its pseudo force experience and responsiveness, particularly during tasks involving motion such as pulling a bowstring. Participants (P1,P2, P4, P5, P7) found this condition aligned well with the sensation of exerting force (tension) and weight, which enhanced realism. P4 mentioned, “I preferred *Tick* because it was not just pure vibration like previous two (*Controller, Buzz*). It felt more like a force.” P2 added, “When pulling the string, *Tick* felt like it matched the resistance I was expecting. It gave me a sense of force.” *Continuous* was often described as providing a strong and continuous sensation that contributed more to the feeling of weight or a continuous force. P3 noted, “The *buzz* had a strong, clear feedback that made it easy to tell the size of the box,” which hints at vibration helping the lifting of weights, and P6 said, “*Buzz* had more force, especially for smaller actions like moving a magnet.” However, some found the continuous nature of *Continuous* “too intense” (P3), “a bit too much” (P4), and “*Buzz* felt too constant, like it didn’t match the force needed” (P5). The *Controller* was often seen as less immersive compared to other conditions, with many participants stating that it contributed “too little,” “spoke a different language” (P2), “felt like background vibration” (P3), and “couldn’t tell if what I was doing matched the vibration at all—it didn’t feel connected to the action” (P7).

Impact of Visual and Vibrotactile Feedback on Experience: Out of 8, 6 participants chose bow-arrow as their favorite scene, with 5 participants choosing the *MotionCoupled* condition as their favorite. The other two participants preferred the magnets scene with the *Continuous* condition. Without visual feedback (lights-out), participants relied more heavily on the vibration feedback to gauge their actions, particularly noting that *MotionCoupled* helped compensate for the lack of visual information. P1 mentioned, “Without the lights, *Tick* really helped me know how much I was pulling the bow,” and P6 said, “Without visual feedback, the *Controller* vibrations didn’t help much—it was hard to tell what I was doing.” Participants perceived more clearly that the *MotionCoupled* and *Buzz* conditions had a force aspect. P1 mentioned, “second (*Continuous*) felt like first (*Controller*), but with force,” and P2 said, “I felt more force with eyes closed compared to eyes open in second (*MotionCoupled*) and third condition (*Continuous*).”

4.6 Discussion

The goal of designing motion-coupled asymmetric vibration was to separate the experience of vibration from the experience of force. The qualitative results of study 1 underscore how important this separation is:

The interviews (Section 4.4.5) indicate that continuous asymmetric vibrations distracted participants from perceiving pseudo forces clearly, with P5 saying, “It’s hard to just extract the vibration out of it... sometimes it... screws up” and P9 adding that the perception of forces depends on where they were focusing attention. Conversely, interviews showed that motion-coupled asymmetric vibrations provides much clearer directional cues, with P9 stating that “you understand direction” and P3 feeling a force in the vertical direction after orienting the actuators vertically. Another insight from the qualitative interview was that the pseudo force elicited using continuous vibration decreased after constant exposure, which can be linked with sensory habituation (Thompson et al., 1966). However, motion-coupled asymmetric vibration did not show this effect in our studies, likely due to the dynamic nature of the signal. These results highlight both the need and benefit of minimizing the experience of vibration while providing force sensations.

4.6.1 Sensory Attenuation as Design Resource

Literature mentions that vibration has led to confusion in perceiving forces elicited by continuous asymmetric vibrations, mainly for opposite directions in the same dimension (Culbertson et al., 2017b) and for two actuators being close and vibrating opposite each other (Maeda et al., 2024). This is simply considered as a limitation of this type of vibrotactile feedback.

Our work, however, suggests that one reason for being confused with the continuous asymmetric vibration might be the experience of vibration itself, which is perceived as originating from an external source and therefore is not attenuated by our perception. Katz calls this a distal stimulus (Katz, 1989). In contrast, motion-coupled asymmetric vibration is perceived "less in vibrations" (P7) and "more natural" (P11). As these vibrations are generated based on human motion, we assume they are experienced as self-caused, or proximal (Katz, 1989) stimuli, leading to sensory attenuation (Synofzik et al., 2008). This highlights how motion-coupled asymmetric vibration, perceived as self-caused, leverages sensory attenuation to address the limitations of traditional vibrotactile feedback.

Building on the attenuation of perceived vibration while preserving the sensation of force through motion-coupled asymmetric vibrations, we hypothesize that a similar sensory attenuation occurs with symmetrical vibration pulses coupled to user motion. This attenuation could potentially explain how diverse material experiences—such as virtual texture (Strohmeier et al., 2017; Sabnis et al., 2023a), compliance (Vega et al., 2024), movement (Ding et al., 2024), and deformation (e.g., stretching or bending) (Heo et al., 2019)—are induced while masking the underlying vibrations. Moreover, this attenuation of perceived vibration might also be the reason why Sabnis et al. (2025a) found motion-coupled vibration to improve the sense of agency. However, future research needs to experimentally confirm the attenuation phenomenon associated with symmetrical vibrations and its role in shaping tactile experiences.

4.6.2 Perceived Vibration and Force in Rendering Motion-Coupled Asymmetric Vibrations

The first part of this paper investigated perceived vibrations and pseudo forces. The key to understanding our results lies in the differentiation between stimuli and qualia (e.g. (Strohmeier et al., 2020)): A stimulus is a physical phenomenon, for example, asymmetric vibration. Although the vibration itself is purely mechanical, how the user interprets it (whether as a sense of force or annoying vibration) depends on the interaction between the stimulus and their sensory processing. We explored this distinction by comparing different algorithms for rendering asymmetric vibrations (stimuli) to elicit pseudo forces (qualia). Therefore, we asked: *Can the same basic stimulus be perceived differently depending on the algorithm used to control it, effectively shaping the resulting qualia?*

Comparing our contribution to baseline:

We first compared motion-coupled asymmetric vibration and baseline continuous asymmetric vibration. Referring to Figure 4.6-Ⓒ, there is no significant difference between the magnitude of the perceived force. The difference in perceived vibration, however, is both large and statistically significant (Figure 4.6-Ⓐ). For context, this reduction in perceived vibration with motion-coupled asymmetric vibration to generate the same level of pseudo forces as continuous asymmetric vibration is equal to a 30% reduction in the intensity of vibration, see Figure 4.6-Ⓑ. Our results showed that motion-coupled asymmetric vibration successfully attenuates vibration, in line with literature on sensory attenuation, and can be thought of as self-generated. However, our comparison does not explain why this occurs, as there are multiple differences between these two experiences.

Effect of movement:

The obvious difference between our algorithm and state-of-the-art is that users move when experiencing motion-coupled vibration, while the state-of-the-art measures are typically experienced without movement. However, since movement attenuates external stimuli (Bays et al., 2005; Kilteni et al., 2017), it is possible that the difference in perceived vibration is due to movement. To examine this effect, we compared *ContinuousStationary* (Figure 4.6-red) and *ContinuousMoving* (Figure 4.6-green). We confirmed that movement reduces the perceived vibration similar to sensory attenuation literature (Bays et al., 2005; Kilteni et al., 2022); however, the average rating of pseudo force was not significantly higher with movement, differing from the literature (Tomohiro Amemiya et al., 2016). We believe that this might be due to the differences in the setup and evaluation methods, as in our study, participants were allowed to rate the force on a free scale. However, this observation is not enough to fully explain the strong attenuation of perceived vibration for motion-coupled asymmetric vibration.

Effect of Coupling:

To understand the effects of motion-coupling, we compared *live* motion-coupled signal to *replayed* motion-coupled signal while participants were moving. The only difference being the exact correspondence to movements for the live motion-coupled signal and a non-correspondence for the replay condition. We found that the replayed signal also displayed strong attenuation, larger in magnitude than the attenuation by movement alone. However, the pseudo-force was no longer perceived. The higher attenuation for a replayed signal compared to continuous vibrations shows that the latter are perceived stronger than the same number of individually spaced pulses in time, concurring to previous findings in the vibrotactile perception literature (Sabnis et al., 2023a; Sabnis et al., 2023b).

In summary, there are three differences between our suggested algorithm and the state-of-the-art: (1) continuity of vibration, (2) user motion, and (3) coupling of vibration to user motion. We found that movement leads to slight attenuation of vibration, but likely contributes to the success of preserving forces with motion-coupled asymmetric vibration. We also found that the replayed signal attenuates vibration but destroys the force illusion. This leads us to believe that the tight coupling of pulse occurrence to a user's motion is key to optimizing the pseudo-force illusion.

These findings are relevant because stimuli induced by self-generated actions are attenuated and leading to higher levels of Sense of Agency (SoA) (H. Brown et al., 2013; Sabnis et al., 2025a). Moreover, Tanabe et al. (2024) show that pseudo forces can decrease the SoA of the user, leading to the user's feeling that pseudo forces cause the movement, with continuous asymmetric vibration stimuli. In contrast, we can increase the SoA by using motion-coupled asymmetric vibration, thus giving the user an experience of *self-caused* forces.

4.6.3 Motion-Coupled Asymmetric Vibration in the Presence of Visual Information

Using vibrations to render perceptually pure forces has practical implications for designing more immersive and intuitive haptic feedback systems in VR. Results showed that motion-coupled asymmetric vibration was preferred for dynamic tasks like shooting arrows or lifting weights. One reason for the increase in realism for dynamic tasks using motion-coupled asymmetric vibration might be because, in the absence of visual feedback, motion-coupled vibration helped users understand the intermediate states of the action they were performing, for example, "how far the bow is stretched" (P1). Despite the controllers being ergonomically optimized, and the other conditions were "holding a motor in fingers", asymmetric vibration still performed better for the application scenarios. Reasons could be that controller vibrations "spoke a different language" (P2) or "felt like background vibration" (P3), but it might also be due to the controller vibrations being symmetric. Interestingly, continuous asymmetric vibrations were preferred in the bimanual handling of haptic magnets, with participants expressing, "I can clearly feel the attraction and repulsion" (P3) and "there is nothing to improve" (P6), which might be due to the fact that magnetic force is an external force for the user. In contrast, pulling a bow or lifting a weight is based on the user's applied force, which makes motion-coupled asymmetric vibration the preferred choice.

It should be noted though that the controller is a fully integrated and ergonomically optimized, whereas the TacHammer system used for rendering motion-coupled asymmetric vibration is a simplified device optimized for output. Future work should investigate the integration of MCAV with commercial devices, which might require ergonomic modifications (e.g. to have a pinch-grip), which is beyond the scope of this paper. Here, we wanted to demonstrate that our rendering approach can be beneficial in VR environments.

4.6.4 Limitations and Future Work

One of the primary limitations of motion-coupled asymmetric vibration is that force experiences cannot be provided when the user is stationary. Similar to pseudo forces rendered by continuous asymmetric vibrations, the pseudo forces elicited by MCAV are limited to body locations with a higher density of Meissner corpuscles, such as fingertips and lips. Further research should investigate different body locations for MCAV along with integrating it with other devices (Tanabe et al., 2023). Moreover, coupling user motion with asymmetric vibrations in time rather than amplitude might offer opportunities to provide stronger pseudo force sensations (Tanabe et al., 2020). Similar to continuous asymmetric vibrations, motion-coupled asymmetric vibrations can induce pseudo forces with a wide array of systems (Martín-Rodríguez et al., 2024). The psychophysics study was conducted in a non-naturalistic setting, where participants performed a controlled task. The results for vibration perception are more robust and less dependent on the actuator type compared to the pseudo force perception, while the effect sizes of amplitude are larger for vibration than for pseudo force, which highlights that pseudo force is less amplitude dependent. Although there were no noticeable phase differences in the actuators, future research should investigate this, along with how holding the actuators and movement affect the output accelerations. While our qualitative interviews hinted at the onset behavior of perceiving pseudo forces, more in-depth study is needed to understand the intricacies of what happens on a perceptual level while perceiving pseudo forces. The VR study was conducted with fewer participants, so the statistical power was low. We were interested in comparing how different devices contribute to the sense of realism in VR. Hence, we did not account for the differences in the strength of vibration between the hand controllers and TacHammers. Although rendering continuous symmetric vibration using hand controllers in VR did not induce force sensations, controller-based motion-coupled symmetric vibrations should be investigated to assess the individual effects of motion-coupling and the type of vibration on attenuation of vibration in commercial devices.

We presented motion-coupled asymmetric vibrations based on fundamental principles of sensory attenuation. Our method provides seemingly continuous pseudo forces to induce a feeling of force by sampling the user movement fast enough. The sampled movement to output vibration has multiple possibilities: from encoding pseudo forces as vectors in 3D VR-environments to real-environments with force fields. Future research should systematically explore whether the perceptual mechanism of sensory attenuation contributes to reducing perceived vibration when using motion-coupled symmetric vibrations, as suggested by anecdotal evidence in (Strohmeier et al., 2018).

Although we looked at linear, constant, and cubic mappings, the design space and modulations of the algorithm to generate uni-directional and multi-directional force effects need to be explored systematically. With appropriate sensing, motion-coupled asymmetric vibration can generate a range of experiences in VR, ranging from linear and torsional springs to damping and viscous elements for single-handed and bimanual applications with appropriate adaptations of the algorithm. Finally, integrating MCAV with other material experiences rendered using vibrotactile feedback can contribute towards generic tactile displays.

4.7 Conclusion

We present motion-coupled asymmetric vibration, a novel algorithm based on sensory attenuation mechanisms that provides asymmetric vibration pulses coupled with dynamic changes in user movement. To evaluate our algorithm, we compared to continuous asymmetric vibrations and conducted a psychophysics study that evaluated perceived vibration and force. Our findings showed that motion-coupled asymmetric vibrations were able to reduce perceived vibration by 30%, while maintaining the force sensations. In VR scenarios like shooting arrows and lifting weights, participants preferred motion-coupled asymmetric vibrations, highlighting the algorithm's potential for enhancing realism. Motion-coupled asymmetric vibration offers a wide range of force effects in VR and a potential to facilitate the creation of versatile, immersive tactile displays in both virtual and real environments.

4.8 Applications of Pseudo Forces

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Hyung Il Yi, Kun-Woo Song, **Nihar Sabnis**, Andrea Bianchi, Sang Ho Yoon. *InvisiBow: Finger-Held Device for Bimanual Haptic Illusions during Virtual Archery*, Proceedings of the 2025 ACM International Symposium on Wearable Computers, 2025. (Yi et al., 2025)

This chapter focused on how motion-coupled asymmetric vibrations are able to induce a similar sense of pseudo force but reduce the perceived vibration as compared to continuous asymmetric vibrations. However continuous asymmetric vibrations are more applicable in situations where the pseudo force needs to be continuous and independent of sensing. In this section, I briefly describe the work done in collaboration with researchers from Korean Advanced Institute for Science and Technology (KAIST) where we used continuous asymmetric vibrations along with tendon-based vibrations to replicate the feeling of drawing an arrow with one hand while holding the virtual bow in the other.

Invisibow (Yi et al., 2025) presents an initial step in exploring the design space of multi-illusion, bimanual haptics using bow and arrow as an example application. We investigated how multiple complementary illusions, which exploit different physiological pathways (asymmetric vibrations are based on asymmetric skin stretch (Culbertson et al., 2016) and tendon vibrations essentially provide vibrations on the muscle spindles to create the illusion of muscle being lengthened (Goodwin et al., 1972)) can be integrated into a single interaction to create convincing, force sensations during complex two-handed tasks. More specifically, Finger Tendon Vibration (FTV) is an illusion in which high-frequency vibration applied to a muscle tendon produces a compelling sense of involuntary finger motion while pseudo forces induced using asymmetric vibration use unbalanced acceleration profiles to induce a directional force percept. By placing these two illusions on different hands, the device simulates the asymmetric nature of archery: FTV on the thumb evokes the sensation of the bow pushing forward, while asymmetric vibration on the other hand produces the tension of pulling the bowstring. Importantly, the pseudo-force actuation pipeline reuses haptic servos (Chapter 2) highlighting how audio based rendering architecture can render multiple illusions.

The evaluation shows that combining these illusions produces markedly higher realism, immersion, and enjoyment than commercial handheld VR controllers and either illusion used in isolation. Participants also reported interesting cross-illusion perceptual interactions: increasing the amplitude of pseudo-force vibrations on the right hand heightened the perceived intensity of tendon vibration on the left hand. This suggests the presence of bimanual coupling effects, where sensory stimulation on one hand modulates perception in the other, and potential interactions with tactile suppression, where the brain attenuates self-generated or movement-related sensations. Such findings underscore the value of studying haptic illusions not merely in isolation but as components of coordinated, bimanual interaction which was one of the reason to investigate bimanual haptics (see Chapter 6).

5 Tactile Symbol Design with Continuous and Motion-Coupled Vibration

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Nihar Sabnis, Dennis Wittchen, Gabriela Vega, Courtney N. Reed, Paul Strohmeier. *Tactile Symbols with Continuous and Motion-Coupled Vibration: An Exploration of using Embodied Experiences for Hermeneutic Design.* In Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems.

The previous chapters established a central claim of my thesis: Motion-Coupled Vibration (MCV) feels strikingly embodied, even though the underlying stimulus is mechanically identical to ordinary vibration. This observation highlights that the same physical vibration is able to render different perceptual effects. When vibration is shaped by the dynamics of user's own movements, the sensorimotor system integrates the vibration stimuli with action, attenuating its salience and allowing users to experience material properties such as friction, texture or compliance, without perceiving the stimulus as "vibration" per se. Iterating on **RQ3** (Section 1.3.3), these findings raise a question about haptic design: *if Motion-Coupled Vibration can evoke familiar, material-like experiences that feel more embodied, how can we use it for designing tactile symbols which are typically symbolic, abstract and Hermeneutic?*

In this chapter, I bring together two ends of the haptic mediation spectrum: Embodied mediation, where meaning emerges pre-reflectively through action; and Hermeneutic mediation, where users must interpret symbolic vibrotactile patterns such as tactons, alerts, or notifications.

Most digital interfaces like mobile phones and smartwatches rely almost exclusively on hermeneutic vibrations: short rhythmic patterns that must be recognized and learned. These cues rarely resemble natural tactile interaction and often feel perceptually detached from the body. In contrast, MCV rendered using the same grain-based approach of previous chapters induce virtual material sensations, that are understood pre-reflectively through the user's action. Although HCI literature often treats these two forms of mediation as distinct or incompatible, many everyday interactions naturally blend them—for example, the rumble strips that signal lane boundaries, the detents of a rotary dial that structure interaction while carrying symbolic meaning, or sliders whose friction intentionally "nudges" action. These examples illustrate that symbolic meaning and embodied feel are not opposites but co-existing dimensions of tactile communication.

This chapter explores that intersection by investigating how haptic designers design tactile symbols using MCV which induced embodied experiences and continuous

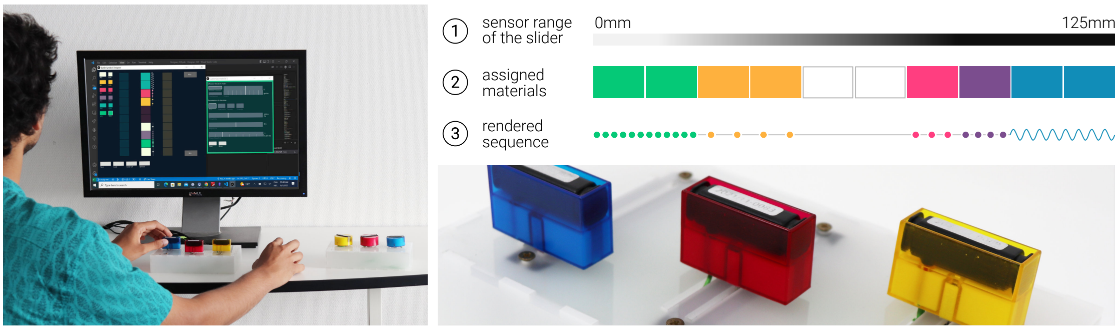

Figure 5.1: *Users create vibrotactile effects using a custom application. These effects are rendered to Tangible User Interface (TUI) to explore the symbols throughout the design process (left). A TUI consists of three sensors, each coupled with a dedicated haptic actuator (bottom right). A symbol is designed in a sensor range (1) by assigning vibrotactile effects to certain sensor regions (2). These effects are created as motion-coupled vibration (consisting of discrete grains, denoted as dots) or a continuous vibration for the specified sensor range (denoted as sine waveform). The rendered sequences can be a single symbol or multiple symbols separated by a non-augmented sensor range (3).*

vibration, which need to be interpreted and are hermeneutic in nature. The designers designed symbols using a Graphical User Interface and could feel their designs using Tangible User Interface[1].

We asked, 'how can we design tactile symbols which do not need to be interpreted but rather we can associate to material experiences which we are familiar with?' 'And if we are able to generate such tactile symbols, how would designers use this new method of designing embodied tactile symbols with the existing method of designing hermeneutic tactile symbols?' The findings of the study revealed that haptic designers draw heavily on embodied metaphors even when creating symbols intended to be interpreted hermeneutically. Motion-Coupled Vibration in particular, was consistently associated with gentle, low-arousal, positive-valence meanings, while continuous vibration was favored for urgent and disruptive cues. With the option of using embodied vibrotactile feedback for designing tactile symbols, designers also treated tactile symbols not as isolated alerts but as experiences that unfold within a broader tactile context: gradients, transitions, spatial neighborhoods, and "pre-warnings" became integral parts of the symbol itself. Finally, the study showed that embodied vibrations can enrich the expressive palette of tactile symbols, offering a way to design not only abstract notifications but tactile experiences grounded in familiar material interaction.

By examining how haptic experts negotiate the boundary between embodied and hermeneutic mediation, this chapter broadens the foundation by introducing a mixed approach of conveying information using vibrotactile patterns. It contributes to the thesis by demonstrating that motion-coupled vibration is not only a tool for simulating material qualities but also a resource for designing tactile symbols that feel intuitive, affectively grounded and experientially meaningful. I conclude this chapter by discussing how this hybrid perspective may support future haptic design practices. Finally, this chapter extends the overarching thesis argument that motion-coupled vibra-

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[1] Teaser video of the design process: `https://www.youtube.com/watch?v=KrsCr11Z68k`

tion not only helps in rendering virtual material experiences but can also be integrated into the design of tactile symbols.

5.1 Introduction

Tactile symbols communicate information through the sense of touch. These symbols typically use vibrotactile patterns to convey information, alerts, or task-based cues. Such symbols can be given additional expressivity by fine-tuning the vibration parameters (such as frequency, amplitude, rhythm, or envelope) to ease their interpretation or memorability (Stephen A. Brewster et al., 2004b). However, compared to the complex interactions we have with the physical world and with one another through the sense of touch, their expressivity is relatively poor. Thus, providing meaningful and realistic sensations in computer mediated interactions remains a major challenge in the field of haptics (Nunez et al., 2020; Erp et al., 2015). In this chapter, we suggest that as an alternative to diving deeper into details of vibrotactile signal parameters, we might instead expand the design space of tactile symbols, by incorporating embodied experiences in their design.

Generally speaking, vibrotactile stimuli in HCI are used in two different ways. The first is as *symbol*. For example, a phone might vibrate to acknowledge user input, or indicate that new information is available. Here, vibration is used in an abstract way to represent information which the user must consciously interpret. The second is as *simulation*, that is the vibration is not used as representation, but is designed to feel like the object of interest. For example, vibration can be used to simulate the experience of friction or compliance or other material properties. In this case, vibration is used to create an experience that the user is familiar with from their day-to-day life. The user need not attend the stimulus to interpret it; rather, there is a pre-reflective understanding based on lived experience of the world.

According to Don Ihde, we can classify these two ways of using vibrotactile feedback according to how they mediate information. The first case, where vibration is used as a symbol representing something else, might be called *hermeneutic mediation* while the second case, where vibration is used to encode the target experience itself, might be thought of as *embodied mediation*. In HCI applications, we typically encounter vibration used for only one type of mediation, but seldom a combination of both approaches. In fact, it is often implicitly assumed that they are at odds with one another. In this paper, we therefore present an exploration demonstrating how these design approaches might be combined, showing that embodied haptic feedback can be used as a tool for hermeneutic mediation.

Here, we explore how embodied experiences can be used as design elements for hermeneutic mediation. More specifically, we explore how tactile symbols or tactons might benefit from integrating embodied experiences in their design. To do so, we created a design tool which supports two different modes of generating vibrotactile signals (from here on referred to simply as GUI). The two modes are designed to correspond to hermeneutic and embodied mediation. The first mode corresponds to hermeneutic mediation and provides tools to modify parameters of *continuous vibration*. This supports designers to shape the experience of the buzzing sensations we are familiar with from tactile symbols used in phones; for example, to alert a user that a text message is received. The second mode corresponds to embodied mediation and provides tools to modify parameters of *motion-coupled vibration*. Here the designer is given control over parameters of vibration, where the pulse frequency is coupled to the dynamics of a user motion. This enables creating the day-to-day experiences people are familiar with in the material world; for example, properties such as friction, compliance, texture, bending, or torsion. In addition to the GUI, we designed two tangible user interfaces (TUIs). Once a symbol is designed in the GUI, these symbols can be deployed in the TUI, where designers can experience them and compare and contrast design variations.

In a case study with five haptic design experts, we show how embodied experiences can be used in the design of tactile symbols. Experts were invited to design tactile symbols with the option to incorporate embodied experiences in their design. We instructed them to create four symbols which were chosen in such a way that they combined both positive and negative valence and high and low arousal, similar to a 2x2 factorial design. We then interviewed each expert to understand their design approach and the specific symbols they created. The thematic analysis of the interviews revealed insights on how haptic experts design tactile symbols. Four underlying themes were uncovered. In particular, highlighting how vibration was associated to previous lived experiences, both in designing and reflecting on symbols. Additionally, we found that experts had clear affective associations with the symbols and that these associations introduced consistency in the designs. Designs also appeared shaped around the idea of symbols which actively communicate information, as opposed to symbols which are passive and require the user to discover them. Finally, experts typically created symbols which considered the context in which they were experienced, including what users perceived prior to or after experiencing the symbol, as part of their designs.

We found that symbols created using continuous vibration were preferred for symbols with high arousal or negative valence (for example, warnings), while embodied experiences created using motion-coupled vibration were preferred for designing symbols with low arousal and positive valence (for example, reassurance). Finally, we also present a set of designs which were provided by the experts when they were given the opportunity to freely create new designs, after the main study was completed. Hence, we introduce the idea of using motion-coupled and continuous vibration to design tactile symbols, thus expanding the tactile vocabulary. We also reflect on the design process used by the experts to implement motion-coupled and continuous vibration based on the design context.

5.2 Context and Related Work

The work presented here applies directly to the design of tactile symbols; however, in doing so, also explores more fundamental themes around the design of tactile interactions, and information representation in general. Therefore, this section starts with a broad overview of touch and experience in general, to better position our work within this larger discourse. This is followed by presenting related work of the specific example we are using for this exploration, that is tactile symbol design and vibrotactile rendering of material properties. We conclude by providing an overview of how vibrotactile designs are commonly evaluated, justifying our own evaluation choice.

5.2.1 Ways of Touching

Intuitively, most people will agree that there is a qualitative difference between the vibration of a phone, and a material's texture. This is remarkable, as both are mediated by vibration. What exactly this difference is, however, is difficult to grasp. In this and the following section, we discuss ways in which these stimuli might differ.

In the literature, there are a number of ways of distinguishing between different ways of touching. For example, a common distinction made in haptics is that touch can be either **active** or **passive**. The general idea is that experiencing a material property, requires action. To feel a texture, one must scan it with one's finger, to experience the softness of an object, one must apply force to it. This is considered *active touch*, possibly first used by Katz (Katz et al., 2013) in the context of texture exploration, and later popularized by Gibson, who describes a breadth of exploratory actions we use to understand the world (Gibson, 1962). Naturally, it is not always we who touch things, sometimes other things touch us. If another object touches us, this is considered *passive touch*. While we are able to infer information about objects through passive touch, studies have shown that our acuity in interpreting such information is substantially lower than for active touch (Heller, 1984).

Returning to the qualitative distinction between a vibrating phone and a material texture, active and passive touch might be useful terms. The vibration of the phone is clearly related to passive touch, as the vibration we experience is indifferent of our actions. However, we can also passively experience a texture; for example, when someone pulls a piece of paper from underneath our fingers. So while active and passive touch are related to the qualitative difference between the vibrating phone and a material texture, it does not fully explain the qualitative difference we care about.

Another set of terms commonly used for when distinguishing between types of vibrotactile stimuli is **proximal** and **distal**. Katz (Katz et al., 2013) suggests that there are multiple ways in which tactile information can be experienced. He suggests that, with respect to a sensory organ, stimuli can be *proximal* or *distal* (Katz et al., 2013). He suggests that the ears and eyes, for example, allow us to perceive distal stimuli; to hear thunder from miles away, or even see stars in the sky. The tongue, on the other hand, is responsive to proximal stimuli. To taste the flavor of a drink, the tongue must be in contact with that drink. Tactile perception, according to Katz, is capable of both. When scanning a texture, it acts as a proximal sense. When we feel the rumbling of a far-away avalanche, or the vibration of the spin-cycle of a washing machine, it acts as a distal sense.

The distinction between proximal and distal already is closer to this qualitative difference we are searching to describe. For instance, we consider the vibration of a phone a distal stimulus, while the vibrations through which we feel a material texture are proximal. However, this still does not fully capture the way in which a material experience and the phone's vibration are different. For example, when we probe a sheet of ice with a stick, vibrations travelling through the stick help us understand the material properties of the ice. These vibrations are distal, yet intuitively the resulting experience is more like touching a texture than feeling a vibrating phone.

It appears that the qualitative difference we care about lies not in how we touch, nor in the properties of the stimulus. Instead, we need to look at the experience itself.

5.2.2 Ways of Experiencing

Here we find it useful to draw on the vocabulary suggested by Ihde (Ihde, 1990) as it does not focus on the specifics of the stimulus, nor the methods of how we acquire it, but instead describes the ways in which we make sense of it. Ihde's taxonomy, often presented through the lens of Verbeek (Verbeek, 2005) describes different ways in which technology shapes our experience of the world. This taxonomy has found use in the Human Computer Interaction community, where it has been expanded upon (Hauser et al., 2018; Verbeek, 2008).

To describe the difference between vibration caused by a buzzing phone and touching a material texture, we need to concern ourselves with mediation. We experience the world through mediation whenever we access the world *through* a technology or medium; for example, when seeing through spectacles, or experiencing information encoded in vibration. Verbeek and Ihde distinguish between two types of mediation, *Hermeneutic* and *Embodied*. To Verbeek, a hermeneutic mediation occurs when information requires an interpretive step to understand, for example presenting the following numbers (255,0,0) to represent the color red. Alternatively, we might also directly display the color, which need not be interpreted for us to understand the redness in a pre-reflective manner. Verbeek refers to this as embodied mediation.

Looking towards the tactile domain, we find many ways in which vibration acts as a medium for **embodied mediation**. For example, when we touch different textures, the frequency spectrum of the resulting vibrotactile signals provide the primary cue which enables us to identify materials (BensmaÏa et al., 2003). This occurs pre-reflectively; we are not consciously aware of the role vibration has in this understanding, and we do not even think of vibration. Instead, we directly understand what the texture feels like and make pre-reflective judgments such as ”this must be a brick” or ”this fabric feels a little bit like satin". The haptics research community has found many ways of using vibrotactile feedback for creating such embodied mediation systems, providing users with pre-reflective understanding of material consistency (Strohmeier et al., 2016), texture (Joseph M Romano et al., 2011), compliance (Kildal, 2010), torsion (Heo et al., 2019), and force (Heo et al., 2017). The shared mechanism in all these natural and digital vibrotactile mediation mechanisms is that the frequency at which tactile cues are provided to the user is proportional to the dynamics of the exploratory movement the user performs — we call this motion-coupled vibration. We learn to interpret these cues as babies and have perfected this skill throughout our sensory development.

Tactile symbols behave very differently. Their very purpose is for **hermeneutic mediation**; they are iconic placeholders which refer to some other concept. Users need to perform an interpretive step after perceiving them to understand what they represent. That is, the meaning of a tactile symbol only reveals itself upon reflection. It is this difference between embodied, pre-reflective sensemaking and hermeneutic interpretive sensemaking of the vibrotactile signal which best captures the distinction between the buzzing phone and the experience of the material texture we care about.

5.2.3 Hermeneutic Mediation: Tactile Symbols

Tactile symbols can be defined as the vibrational cues provided to the tactile modality of the user, with the aim of conveying a familiar idea, experience or construct in a predefined context (Stephen A. Brewster et al., 2004b). The creation of tactile symbols to encode information has revolved around identifying, modulating and combining physical parameters of vibration such as frequency, duration, amplitude, waveform, body location, rhythmic patterns, and spatio-temporal patterns (Hoggan et al., 2007; Lorna M. Brown et al., 2005; Stephen A Brewster et al., 2004a). Researchers have attempted to optimize these parameters to create tactile symbols which maximize the rate of information transfer; for example, by studying how parameter dimensions relate to human perception (Ferguson et al., 2018) or by providing vibrotactile signals designed as metaphors of real world experiences (Chan et al., 2008). Another approach to design tactile symbols is inspired from the principles of icon and earcon design (Blattner et al., 1989; Lorna M. Brown et al., 2006b; E. Freeman et al., 2017).

Tactile symbols have been investigated unidimensionally (Stephen A Brewster et al., 2004a), multidimensionally (modulating more than one vibrotactile parameter simultaneously to convey more complex information) (Lorna M. Brown et al., 2005; Azadi et al., 2014), and in cross-modal contexts in combination with audio feedback (Hoggan et al., 2007; Hoggan et al., 2010). These approaches of creating and evaluating tactile symbols have been fundamental to optimize the tactile symbols. However, intuitively designing for the user's perceptions of the vibrotactile symbol to the information it represents is still a challenge, and mismatches often lead to confusion in the interpretations of tactile symbols (Ferguson et al., 2018). Also, the mapping from sensation to meaning is often abstract, and hence users need to learn the meanings, identify and interpret the tactile symbols which may cause delay in the user's response (Culbertson et al., 2018). Moreover, tactile symbol design sometimes leads to unstructured vibrotactile patterns without any clear salience (Chan et al., 2008).

In this research, we explore how the design space of tactile symbols might be expanded by integrating embodied experiences in the symbolic design. By means of a qualitative study, we wish to address if doing so might address some of the shortcomings of existing vibrotactile symbol design.

5.2.4 Embodied Mediation: Material Experiences

An orthogonal research direction to tactile symbol design, is work that attempts to better understand how experiences unfold when we touch objects in the physical world. Here the elementary role of action on experiences cannot be understated: Touching an object can give an impression of temperature or reveal shape features if they are prominent enough to distort the skin, but, to experience the texture, one must move relative to the object one is touching (Katz et al., 2013). This relative movement of the finger over a surface produces vibration, which is used to infer properties of the material (BensmaÏa et al., 2005; BensmaÏa et al., 2003; Lederman, 1974). There has been growing interest in coupling vibration with user movement to generate an experience of texture and other material properties. This vibration has been provided in research using three popular actuation methods, namely: vibrotactile, electrostatic and ultrasonic (Basdogan et al., 2020).

Focusing on vibrotactile actuation, Romano and Kuchenbecker coupled the movement of a probe, which acted as a texture recording device, to an actuated stylus. The stylus is then vibrated as it moves over a flat and smooth surface, providing users a sensation of moving the device over recorded materials (Joseph M Romano et al., 2011). This idea of coupling vibration with motion has also been explored by Kildal to provide an experience of compliance based on the pressure applied by the users (Kildal, 2010). Strohmeier et al. presented a flexible device which couples pulse frequency to the amount by which the device is bent, resulting in an experience of changing material composition (Strohmeier et al., 2016). Moreover, Heo et al. coupled changes in force and torque applied to a device by the user to generate the experiences of bending, twisting, and stretching of the device (Heo et al., 2019) and also created a haptic illusion of compliance based on tangential force provided by the user (Heo et al., 2017). Furthermore, Ahmaniemi described a method to create dynamic virtual textures by using vibration coupled to user's hand movements driven based on wavetable synthesis (Ahmaniemi et al., 2010).

The underlying principle of all these research is: when coupling vibrotactile feedback with user action, the vibration and action are perceptually combined, leading to a holistic experience of a dynamic system rather than a vibrating actuator (cf., (Strohmeier et al., 2017; Sabnis et al., 2023a)). Although extensive research has been conducted in the use of motion-coupled vibration to generate material experiences, to our best knowledge, this is the first study that explores using such vibration for designing tactile symbols.

5.2.5 Evaluating the Tactile Symbol Design Process

The evaluation of tactile symbols primarily focuses on the dimensions for their design, investigation of the parameter space, information transfer rate, and the effectiveness of designed symbols to communicate the desired information (Hoggan et al., 2007; Azadi et al., 2014; Stephen A. Brewster et al., 2004b). Understanding these factors provides limited value in the overall understanding of this design process from a human-centered design perspective. Instead, behavioral studies that investigate how tactile symbols can be used to convey data efficiently are preferred (Ferguson et al., 2018; Lorna M. Brown et al., 2006a). However, these studies do not provide insight and reasoning about the design approach and resultant symbols.

When research does report on the subjective experience of user interactions with haptic systems, it is often done briefly or as a collection of responses to questionnaires (Lorna M. Brown et al., 2007; Strohmeier et al., 2016). Notable exceptions include an interview study done by Obrist et al. (Obrist et al., 2013), which presented in-depth interviews comparing haptic feedback designed to target either Meissner or Pacinian corpuscles, structured interviews done by Schneider et al. (O. Schneider et al., 2017) to understand what hapticians do and the challenges they face when working with haptics, and interviews used by Strohmeier et al. (Strohmeier et al., 2018) to elicit descriptions of introspective, subjective experiences. Since we are interested in the design approach and reasoning behind the design of tactile symbols, we also focused on qualitative methodology in this research.

5.3 Study Rationale

Both in the literature (Verbeek, 2005) and casual discourse, hermeneutic and embodied mediation are often presented as opposites, almost incommensurable. We wish to highlight how these concepts can be blurred. We wish to understand *if and how embodied material experiences might be used as a design element to create a hermeneutic, tactile symbol*. For the same, we use motion-coupled vibration capable of creating embodied material experiences and traditionally used continuous vibration, to design hermeneutic tactile symbols.

We conducted in depth interviews with expert haptic designers, who were provided with a system that allows them to combine continuous vibration and motion-coupled vibration for designing haptic symbols. We chose to work with experts, as we wish to minimize reactions due to the novelty effects of designing haptic systems in the first place, and instead focus on how material experiences might be used within the context of traditional tactile symbol design. We intentionally do not explore symbols related to materiality (for example, we do not ask participants to design experiences

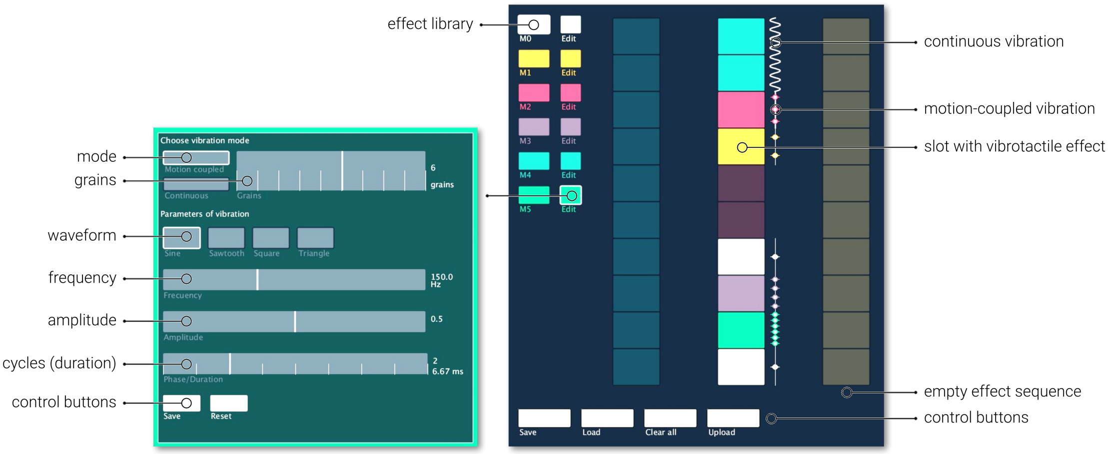

Figure 5.2: *The GUI used for this study has two windows – one to parameterize vibrotactile effects: Effect Designer (left), and another to create sequences of these effects: Effect Sequencer (right).*

such as *roughness* or *concrete-like*) but instead observe tasks which might require the designers to use the experience of *roughness* or *concrete-like* as a part of a symbol that refers to something immaterial, abstract.

Other studies present how one might create material experiences through vibration. Our study therefore does not aim to assess the quality of a particular tactile rendering approach or vibrotactile material experience, rather, we explore how such material experiences might be used for symbolic design.

After concluding our study, we intend to report *if* experts were able to use embodied experiences in hermeneutic design. Through analysis of the resulting designs, we wish to talk about *how* this was done in practice. Based on our interviews, we report on *why* this was done. Finally, based on all data we collect, we intend to highlight potential *benefits* this blurring of mediation types has for future design.

5.4 Implementation

The study uses two systems, a GUI for designing tactile symbols (Figure 5.2) and TUI for experiencing them (Figure 5.3). Tactile symbols designed in the GUI are rendered on the TUI, where the user can experience their design in real time with two basic interactions: a linear motion using a slider and a rotary motion using a knob. Since the vibration is motion-coupled, the user can explore their tactile symbols at varying movement speeds within a designated region, which might change the experience.

5.4.1 Graphical User Interface

A multi-window GUI was developed using Processing (v4.0) and run on a laptop (Lenovo ThinkPad - AMD Ryzen 7 PRO, Windows 10) throughout the study (Figure 5.2). Participants used the first window of the GUI to design a sequence of vibrotactile effects – *Effect Sequencer*. The other window of the GUI – the *Effect Designer*

– provided control over a set of vibration parameters (Table 5.1).

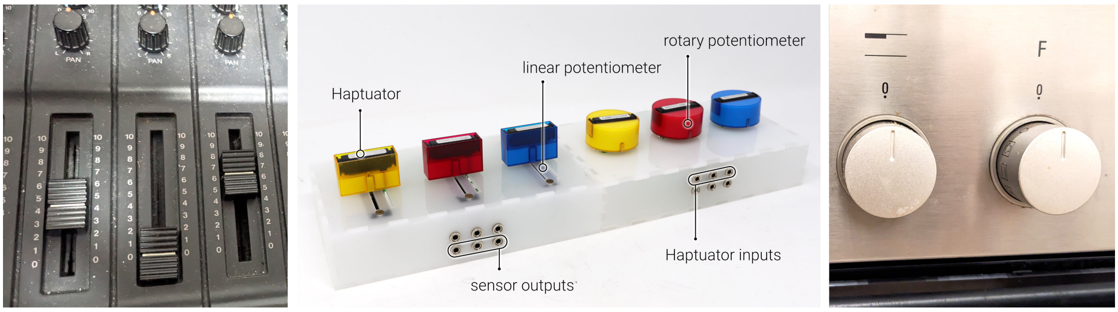

Figure 5.3: *Middle: Participants explored their rendered vibrotactile effects with two types of physical elements: sliders (left) and knobs (right). Sides: similar UI elements found "in the wild".*

The design parameters were chosen for the GUI screen in a way that would help designers to understand and assist them in designing motion-coupled as well as continuous vibrations effectively. The selection was initially inspired by work which explored such parameters (Strohmeier et al., 2020; Kildal, 2010) and then optimized for the experiment. Parameters which we implemented but excluded for sake of simplicity in the GUI include an envelope (attack, decay, sustain, release) a filter (cutoff frequencies) and the ability to add noise.

Once the user creates their vibrotactile effects, they can switch to the *Effect Sequencer* to assign these effects to slot(s) in the sequences (Figure 5.2, left). Each sequence represents the sensor range of a physical element (e.g., a slider). The *Effect Sequencer* allows for the designing of three sequences simultaneously, where each sequence refers to one of the physical elements (Figure 5.2, right). These are connected through the central controller to the PC. When a tactile sequence design is ready to be experienced, the user uploads the design to the corresponding physical element and can explore the experience. Sequences, as well as the vibrotactile effects, can be edited at any time and re-uploaded to the TUI. Users can also export their designs as JSON files and load them later into the GUI. This enables users to expand their design beyond the three TUI slots, create fast design iterations, and share their designs with collaborators in co-located or remote setups.

5.4.2 Physical Elements

Two types of physical interfaces were used for experiencing the designs rendered by participants – linear sliders and rotary knobs (Figure 5.3). These two devices were selected after a pilot study, and were selected to support the scenarios we wished to explore. Moreover, linear sliders and rotary knobs nicely demo some of the hand motions often used to interact with tools and gadgets in the physical space/world. Their counterparts in the digital world are also known and commonly used in GUIs. For our purposes, functionally and in terms of haptic experiences, they are sufficiently similar to be interchangeable. The first interface consisted of a set of three 200k ohm slider potentiometers, the second a set of three 100k rotary knob potentiometers. The change in the resistance of the physical elements indicates the physical angular and linear movement made by the user on the knobs and sliders, respectively. The system is agnostic to potentiometers of any physical size, as all the calculations are done based on the sensor range. Each physical element is connected to one peripheral microcontroller (Figure 5.4). Based on the position of the physical element (sensor value) and the vibrotactile effect designed at the corresponding location using the GUI, the designated vibrotactile effect is played. The tactile signal generation is based on customized implementation of Haptic Servos (Chapter 2). The signal is generated using the Teensy Audio Library[2] and then converted to an analog signal using a PT8211 DAC shield. This analog signal is amplified using a Visaton 2.2LN amplifier and then fed into a Haptuator Mark 2D (Actronika). The Haptuators were placed in custom-made housings over the knobs and sliders. The housings were made to suppress the audio cues and constrain the propagation of the vibration along the length of the Haptuator. This GUI implementation and TUI housing designs are all open-source[3] and accessible for use with other TUI setups.

5.4.3 System Setup and Communication

The system consists of a cascade of physically connected hardware (Figure 5.4). The GUI, running on a PC, is connected via USB-serial with the TUIs central control unit – a Teensy 3.5 (Figure 5.4). This unit receives messages from the GUI via a serial interface and forwards them via an I2C-interface to the peripheral devices. These messages are ASCII strings, including control-messages to modify the system's state and data-messages to transfer the vibrotactile effects and effect sequences to the corresponding physical elements (Figure 5.4, bottom). Both message types include the I2C-address, which enables sending messages to a single device or all devices (unicast or broadcast, respectively). The peripheral devices (three Teensy 3.5s) receive the messages and update their state accordingly. To augment the physical elements, the peripheral devices read analog values from the sensors (slider or knob) and render vibrotactile pulses according to the selected effect sequence and parameters that were assigned for the current sensor position or region.

5.4.4 Design Justification

For this study to be valid, the motion coupled vibration must indeed be experienced as embodied mediation. We therefore base our design on previous work: It is well understood that vibration, when coupled in frequency to pressure changes (Kildal, 2010; Strohmeier et al., 2020; S. Kim et al., 2013; Heo et al., 2017) or movement speed (Strohmeier et al., 2017; Joseph M Romano et al., 2011; Culbertson et al., 2017a; Culbertson et al., 2014) creates material experiences.

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[2] `https://www.pjrc.com/teensy/td_libs_Audio.html`

[3] `https://github.com/sensint/Haptic_Material_Designer`

Vibration Parameter		Description	Value / Range
Type	**Mode**	Refers to the types of vibration discussed in Section 5.2.	motion-coupled, continuous
	Grains	The number of grains (pulses) spread across a single effect slot (motion-coupled only).	1 to 10
Waveform Parameters	**Waveform**	The waveform of the vibration/pulse	sine, sawtooth, square, triangle
	Frequency	The frequency of the vibration/pulse	10 to 400 Hz
	Amplitude	The amplitude of the vibration/pulse	0.0 to 1.0
	Cycles	The number of cycles (periods) of the vibration/pulse. (motion-coupled only).	1 to 8

Table 5.1: *The controllable vibration parameters in the Effect Designer by the haptic users. These include vibration type (mode and number of grains) and waveform parameters (waveform, frequency, amplitude, and cycles).*

This study was implemented based on *Haptic Servos*, an open source vibrotactile rendering system, capable of implementing the above described experiences (Sabnis et al., 2023a). In a previous study, we tested if signals created with Haptic Servos lead to embodied mediation: Six participants were provided with either motion-coupled or continuous vibration and asked to describe their experience.

We found that the *continuous vibration* was often experienced as somewhat startling, or confusing. Often participants wondered if there might be a problem with the system, as the continuous vibration stood out from the other experiences. The *motion coupled vibration* on the other hand elicit curiosity and made the UI elements feel more interactive. Participants described their experience in terms of material metaphors, such as *"like moving it over a rough surface"* or *"Like peeling a sticker off"*. These experiences appeared to work equally well for both linear sliders and rotary knobs, and the difference of motion type did not appear to have any systematic effect on how the stimuli were experienced (Sabnis et al., 2023a).

We therefore concluded that our system performs as desired and that we can use the tangible UI elements interchangeably.

5.5 Study: Design of Tactile Symbols

This section describes the participants and their background in haptics who designed the tactile symbols, the experiment design and the analysis methodology used to analyze the results of the study.

5.5.1 Participants

The inclusion criteria required that the participants have a minimal experience of 4 years and are active researchers contributing to the field of vibrotactile haptics in HCI. Five haptic experts (4 male, 1 female) were recruited through our research networks in

Germany to participate in our study (referred as participants or designers). The participant group represented four countries and had between 4 and 7 years of experience in haptic design. Each participant received financial compensation for their time. The following are each participant's years of experience in the field of haptics and current research areas:

P1: 7 years; Vibrotactile feedback in virtual reality to design haptic experiences.
P2: 7 years; Designing for haptic interaction, tactile displays and wearable technology.
P3: 5 years; On skin interfaces and vibrotactile feedback in wearable technology.
P4: 4 years; Fabrication and designing of novel vibrotactile feedback devices.
P5: 6 years; Designing haptic feedback for communicating emotion, soft robotics.

To demonstrate that one can use material experiences to support traditional haptic symbol design, one does not need a large sample. A single example would have been sufficient. However, we chose to add additional participants, so that we can make claims beyond the mere fact that it is possible, and can also report on patterns we found in observing experts designing symbols which included such material properties. We stopped conducting interviews, once we felt that observed themes started repeating. Any further claims, especially those aimed at generalization, will require follow-up studies, beyond the scope of this paper.

5.5.2 Experiment Design

As soon as the participants arrived, they were introduced to the apparatus and given a tutorial on the design process and the GUI/TUI setup so that they could render their desired effect sequence with the vibrotactile effects they want. This tutorial is provided in the Supplementary Material. After the initial exploration with the tutorial, the experiment was explained to them. The experiment involved three phases: a context-defined tactile symbol design phase, a forced choice selection of pre-designed tactile symbols for both knobs and sliders, and an optional creative exploration phase (sliders only). The tactile symbol design and the creative exploration phases were followed by a semi-structured interview in order to understand the design approach of the participants, their reasoning behind the symbols they designed, and the qualitative experiences they associated their designed symbol with. Interviews lasted 30-50 minutes per participant. Interviews with the participants were audio-video recorded with consent for later analysis.

Tactile Symbol Design

The haptic experts were asked to design symbols for warning, reassurance, ecstasy, and disengagement. To ensure that the symbols are different from one another, in multiple dimensions, we reference Russell's Circumplex Model of Affect, which maps emotions to a two-dimensional space according to the arousal (high or low energy) and valence (pleasure or displeasure) of an affective state Russell, 1980. The model is expressed as a two-dimensional space, with the horizontal axis as *valence*, and the vertical as *arousal*. The tactile symbols to be designed were chosen based on their positions in the valence-arousal space, as follows: 1) warning - negative valence, high arousal; 2) reassurance - positive valence, low arousal; 3) ecstasy - positive valence, high arousal; 4) disengagement - negative valence, low arousal. The tasks were designed in order to design symbols covering the valence-arousal space, however, the words valence and arousal were not conveyed to the participants at any point.

For the knobs, the task was to design tactile symbols for *warning* and *reassurance*. The context for the knobs was that the steering wheel has been replaced by a knob in a futuristic car. The participants needed to design a tactile symbol for *warning*, which indicated the driver should stay out of a lane where an accident has occurred. They also needed to design a symbol for *reassurance* to assure the driver that it is safe to switch to another lane. We selected these tactile symbols to be designed for the knobs. Here, the knob acts as a metaphor of a steering wheel of a car.

For the sliders, the designers were asked to design a feedback system for a fictional mood jockey (someone who sets the mood for an event, as a DJ would control the music for an event) which indicates the mood of the event. The task was to design tactile symbols for *ecstasy*, to indicate that everyone is enjoying the event, and *disengagement* to indicate that people are not enjoying the event. The important distinction between the two tasks was that there was no urgent call to action for the slider task. This distinction was made in order to keep the symbol design space versatile and fit into different contexts. For this task, we chose to use the sliders, as they are reminiscent of the UI elements a traditional DJ or audio-engineer uses for controlling music. Each tactile symbol was a pattern spanning 1 to 4 slots in the event sequencer. Participants were asked to narrate aloud their thought process as they designed the tactile symbols. The design prompts as given to the participants can be found in the Supplemental Material.

Forced Choice Selection

Following each design task, participants completed a forced-choice evaluation in which they had to select the suitable out of two presented symbols to better indicate warning, reassurance, ecstasy and disengagement. These presented symbols were preset and loaded using the GUI and presented to the designers using the same physical knobs and sliders. For each symbol, four comparisons were made. The comparison was always between a continuous and motion-coupled vibration The tactile symbols were preset and presented to the designers using the same physical knobs and sliders.

Creative Exploration

Finally, the participants were provided with time for creative exploration, to go back and try any other designs they wished to render without being constrained. Again, participants were asked to narrate their design process aloud.

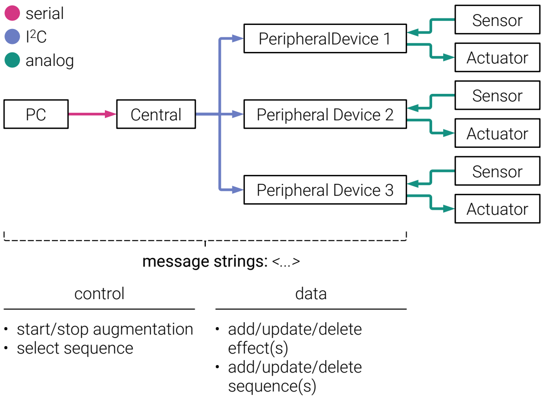


Figure 5.4: *The PC and the central controller uni-directionally communicate via USB-serial. Each peripheral device is connected to the master using an I2C, and the communication is uni-directional from the central device to the peripheral devices. USB-serial and I2C communication is done with formatted message strings. The messages are used to modify the system's state (e.g., start/stop augmentation) and transfer data to the peripheral devices (e.g., send effects and effect sequences).*

5.5.3 Analysis

We used a qualitative approach to focus on this group of haptic experts. We conducted a reflexive inductive thematic analysis Clarke et al., 2021 of the interviews with the designers to provide a narrative of the preference over the type of vibration used, design decisions, approach to design each tactile symbol, and reasoning for the final designs of the symbols. The initial coding of the interviews was done by N. Sabnis. Further coding and theme organization was completed jointly by N. Sabnis and C. Reed, who approached the data through their own design experience and dialogue with the designers during the study. We use an inductive approach to ground these themes within the design context while applying the design experience of the researchers doing the analysis. N. Sabnis and C. Reed first familiarized themselves over a two-week period with the data during transcription and highlighting an initial code set of salient points relating to the design choices made and described in the interviews. N. Sabnis and C. Reed then coded together while recursively reviewing the interviews and the objective, parameterized aspects of the vibrations themselves. We also determined the design approach for each of the symbols based on the parameters used in the context-oriented design phase and forced choice evaluation. After reviewing the symbols and their designed parameters, we constructed and then iteratively refined a series of themes. The themes were constructed around the designers' perspectives and choices of vibration for the provided contexts, focusing how each symbol matched the designers' expectations and priorities in the design.

5.6 Results

In this section, we describe the process of the participants to design tactile symbols using both types of vibration. Furthermore, we elaborate on the spanning of the type of vibration in the valence-arousal space as well as the qualitative associations of the type of vibration and their parameters. We present the results of the reflexive thematic analysis in which we explored four themes pertaining to the haptic experts' symbol designs, through which we investigate the use of continuous and motion-coupled vibration in the design of tactile symbols. Finally, we depict the free-form designs made by the participants during the creative exploration task.

5.6.1 Tactile Symbol Design Process

Participants followed a five-step process for designing Tactile Symbols. Below, we summarize the participants' thought process as they were designing the symbols thus highlight the commonalities and differences in their approach of designing the symbols.

Exploration of both types of vibration

After explaining the task to the participants, they first explored both types of vibrations. This exploration was done within the capabilities and constraints of the system in order to determine the parameters available for manipulation. P1 first wanted to 'get a feel for the material properties'. P5 described the initial interaction with motion coupled vibration to be 'just ticks' rather than a material experience, whereas P2 described motion-coupled vibration as 'something which feels easier to overcome and which wants me to be at a spot'. P3 described continuous vibration to be 'more expressive' than the motion-coupled vibration in their exploration phase. The participants also explored the vibration parameters for both types of vibration. The exploration phase helped the participants understand the potential design space for both types of vibration.

Association of the types of vibration to qualities conveyed using the symbol

Exploration phase was followed by association of both vibration types to the properties which need to conveyed using the tactile symbol. Overall, continuous vibration was associated with urgent, actionable and extreme symbols. P1 and P4 associated continuous vibration to raise awareness and convey different warning and disengagement levels. P1 and P3 also associated continuous vibration with high energy and high levels of ecstasy in the mood jockey task. On the other hand, all the participants associated the motion-coupled vibration to encouragement in the car turning task. While designing for disengagement, P1 and P3 associated motion-coupled vibration with low grains with higher disengagement. Hence, associations made by the participants with the type of vibration while designing the symbol were based on the context of the symbol.

Creating a pattern of multiple blocks to generate a symbol

After qualitative associations for both types of vibration in the given context, the participants designed a symbol iteratively, by combining multiple blocks in a pattern. P1 switched from motion-coupled vibration to continuous vibration to convey an increase in the level of warning. Moreover, in their pattern, P3 switched from motion-coupled to continuous vibration to indicate higher intensity of the emotion to be conveyed. The participants got creative and also designed a less intese state leading up to a final burst of the emotion to be conveyed. For instance, in their pattern, P1 indicated pre-warning as the user would approach the final warning state. No standard patterns amongst participants were observed but, patterns between a single participant were noticeable. For example, less number of grains throughout the pattern is associated to an ecstatic state by P5, whereas P2 increased the number of grains to indicate an increase in the level of ecstasy. P4 in their pattern made a gradient by increasing the number of grains for high levels of reassurance.

Fine-tuning the parameters of the symbol

The next step of designing the symbol was the fine-tuning of the selected vibration type. For instance, P5 noticed that they did not perceive the higher frequency vibration as an instance in the symbol for warning. Moreover, P1 increased the amplitude and reduced the frequency of the continuous vibration as the intensity of warning increased in their designed symbol. Moreover, they further optimized their design by using a square wave as it felt more assertive to indicate a strong warning. P4 described triangle waves to be more assertive and sine waves to be smoother compared to other waveforms. After playing around in the parameter space for motion-coupled vibration, they finalized on using a square wave with high amplitude and frequency. The fine-tuning was done by exploring the parameter space till the participants found parameters to suit their concept of how the symbol should feel.

Evaluating the symbol in the context

Finally, the participants evaluated their designed symbol in the context of the task which was given to them. This evaluation was done by experiencing the symbol on the TUI. After experiencing their symbol, P1 commented, ‘the continuous increase in the parameters for warning will make the driver aware of pre-warning, and different stages of the warning symbol’. P5 evaluated their symbol for ecstasy by moving the slider over the designed symbol and feeling if the movement over the symbol is able to experience ecstasy. Similarly, the reassurance symbol was evaluated by P1 and P4 by imagining themselves in the place of the automobile driver and how rotating the knobs with vibration coupled to their rotation feels like they are being encouraged to turn in that direction. Thus, after iteratively designing the tactile symbol, it was evaluated by experts in the context of its intended use.

Vibration			Qualitative Associations
Type	**Vibration Type**	Continuous	Non-enticing (P4), Expressive (P2), Obstructive (P1), Urgent (P5) Recognizable (P2), Annoying (P1),
		Motion-Coupled	Exploratory (P4), Guiding (P4), Subtle (P2, P3), Soft (P5), Encouraging (P5), Nudging (P2, P4, P5), Sticky (P5), Resistive (P5)
	No. of Grains	High (>5)	Intense (P4), Strong (P4), Intrusive (P3), Ecstatic (P2)
		Low (<5)	Comforting (P1), Encouraging (P5), Low Information-Dense (P4, P5)
Vibration Parameters	**Waveform**	Sine	Smooth (P4), Soft (P4)
		Sawtooth	Hard (P4), Funky (P1), Disengaging (P5), Strong (P4)
		Square	Harsh (P4)
		Triangle	Aggressive (P4), Strong (P4) Noticeable (P4)
	Frequency	High (>200)	Urgent (P1), Ecstatic (P2), Enjoyable (P5), Alarming (P5), Intense (P5), Annoying (P4)
		Low (<200)	Low-Energy (P2, P5), Comforting (P1), Alarming (P1), Sad (P2), Unsafe (P1)
	Amplitude	High (>0.5)	Alarming (P1), Pronounced (P2), Engaging (P3), Enjoyable (P5), Harsh (P4), Unsafe (P1, P2, P3, P4)
		Low (<0.5)	Subtle (P1), Comforting (P1), Quiet (P4), Low-Energy (P2, P5), Negative (P1)
	Duration	Long (>4 cycles)	Ecstatic (P2)
		Short (<4 cycles)	Harsh (P4)

Table 5.2: *Vibration types and parameters mapped to qualitative associations by the haptic experts.*

5.6.2 Mapping Vibration to Affective Qualities

The tasks for which the participants designed symbols for, namely - warning (negative valence, high arousal), disengagement (negative valence, low arousal), reassurance (positive valence, low arousal), ecstasy (positive valence, high arousal), were based on the Circumplex Model of Affect. Without any knowledge about the selection of tasks as well as the qualities for which the symbols were designed, there was a pattern in how motion-coupled and continuous vibration spanned the valence arousal space in the participant designs. Moreover, the associations made by the experts of vibration type and properties to subjective qualities is depicted in Table 5.2.

Valence

A trend of using continuous vibration to indicate negative valence whereas using motion-coupled vibration for positive valence was observed in the designed symbols. Negative valence was usually associated with irritation, annoyance or sadness. Continuous vibration with increasing amplitude, and frequency was preferred to design symbols in order to convey these qualities. Moreover, sawtooth, square and triangle waveforms were associated with negative valence. In contrast, positive valence is indicative of qualities like comfort, gentleness and encouragement. Motion-coupled vibration was associated with these qualities. For instance, P3 who used motion-coupled vibration to indicate positive valence qualities mentions, "for ecstasy, I'm thinking in terms of visceral experience, as it needs to be something comfortable." Sine waveform was perceived to be pleasant and gentle, thus associating it with positive valence. Figure 5.5a demonstrates P2's design of the symbols for reassurance (positive valence) using motion-coupled, whereas warning (negative valence) using continuous vibration.

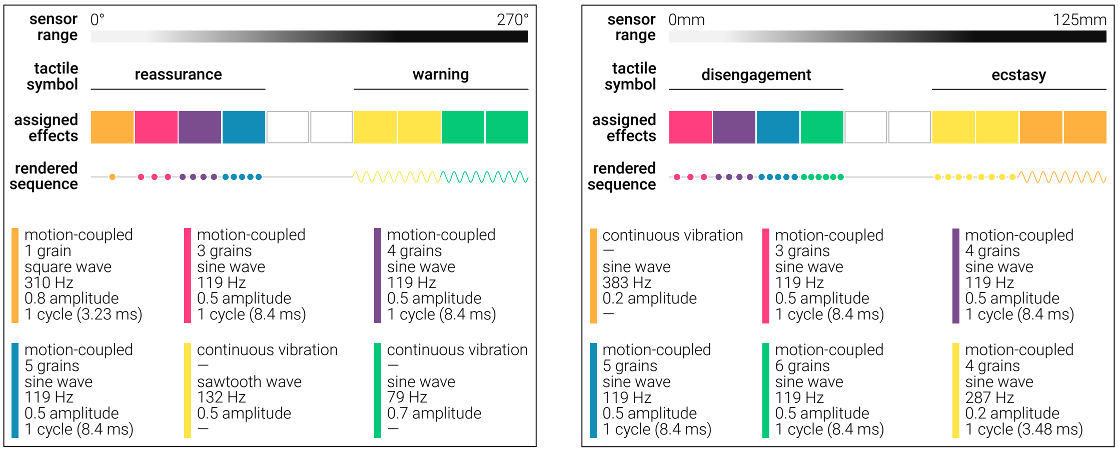
Arousal

Experts preferred to use continuous vibration for indicating high level of arousal. High arousal was associated with strong, rough, and energetic, thus making continuous vibration a preferred choice. P5 used continuous vibration for designing the symbol for ecstasy and mentions, "continuous vibration indicate high energy and a vibrant mood." On the other hand, motion-coupled vibration is preferred to indicate low level of arousal. Low level of arousal is associated with qualities like soft, subtle and gentle. These qualities were similar to what the experts observed when rendering symbols using motion-coupled vibration. Figure 5.5b demonstrates how P1 designed the symbol for disengagement (low arousal) and ecstasy (high arousal), starting with motion-coupled vibration for low arousal and shifting towards continuous vibration for high levels of arousal.

Summarizing, as the valence shifted from negative to positive, experts preferred using motion-coupled vibration over continuous vibration. And, as the level of arousal increases, experts preferred the use of continuous vibration to design the symbol. Thus, if we were to map continuous and motion-coupled vibration to the circumplex model, with increasing in arousal, continuous vibration is preferred whereas with increase in positivity of valence, motion-coupled vibration is preferred. Hence, a clear distinction of preferred type of vibration is seen with the high arousal, negative valence quadrant represented by warning, and low arousal, positive valence quadrant represented by reassurance, where, continuous and motion-coupled vibration has been preferred for the two quadrants respectively. On the other hand, for high arousal, positive valence represented by ecstasy, and low arousal, negative valence, represented by disengagement, no clear trend in the preferred type of vibration within the participant's design was found. These findings are concurrent with the results of the two alternative forced choice test described below.

Two Alternative Forced Choice

The results of the 2 alternative forced choice test show that the 4 out of 5 participants in our study preferred continuous vibration to motion-coupled vibration to indicate *warning*. On the other hand, motion-coupled vibration was preferred over continuous vibration to indicate *reassurance*. However, for *ecstasy* and *disengagement*, no particular vibration type preference was noticed. Note that we do not endeavor to prove any statistical significance in these results, but rather to examine this particular group of designers and speculate the reasoning for the correlation between the type of vibration and the emotion to be conveyed.



(a) *P2's reassurance and warning symbols (knob).*

(b) *P1's disengagement and ecstasy symbols (slider).*

Figure 5.5: *Example tactile symbols designed by two participants are shown with the rendered sequence and the parameter values for each vibrotactile effects in those rendered sequences.*

5.6.3 Thematic Analysis

The participants' design process can be outlined through four themes, presented in Table 5.3. These themes provide insights on how designers connect both types of vibration to their lived experiences, and how the vibration is selected based on the information which needs to be conveyed with the symbol. Then the designers define the affective qualities of the symbols, which are innately mapped to valence and arousal characteristics and designed around a reference state designated by the context or by the designer themselves.

All Vibration is Associated with Lived Experiences

We claim that the difference between embodied experiences and hermeneutic experiences is that embodied stimuli reveal their meaning in a pre-reflective manner, while hermeneutic stimuli require conscious reflection to interpret them. However, when approaching a design task, or when reflecting on a design, both hermeneutic and embodied experiences are discussed in the context of participants' lived experiences. Participants also reference familiar stimuli from other modalities to make sure that the symbol will be understandable and consistent with what the user already knows.

Participants suggested that symbols should be designed around experiences that users are familiar with from their day-to-day life, rather than requiring them to learn new mappings: safety especially can be maintained if "There are like standard symbols, not new generated ones, otherwise people first ignore them." (P4) For example, road warnings such as painted lines and rumble strips were associated with motion-coupled vibration and referenced when deciding to convey haptic pre-warnings in a futuristic car. P2 intends to "have like something equivalent to the [road] stripes, and then you actually enter the danger zone." P1 references the shock and negativity they feel with

Theme	**Description**
Vibration is Associated with Lived Experiences	Both motion-coupled and continuous signals are used in reference to lived experiences which provide a frame of reference for the designs: *"The strips on the side of the road [are] painted in a way that when you go with your car, you feel it"* (P5)
Symbols have Affective Qualities	Participants agreed on affictive qualities of symbols such as valence and arousal. This supports creating consistant designs, both with respect to lived experiences referenced, vibration type, and vibration parameters: *"With less energy you would show it with less number of grains, lower frequency, and lower amplitude"* (P2)
Symbols can be Active or Passive	Continuous vibration was preferred to evoke immediate action (e.g., warnings), while motion-coupled vibration was preferred for passive background information (e.g., reassurance): *"A warning should be recognizable and you should feel it right away so continuous vibration makes more sense"* (P1)
Context is Part of the Symbol	Participants did not only design the target symbol (e.g., "Danger") but also the context of that symbol. Here the context is what the user experiences before or after the primary symbol, or gradients between symbols: *"We're going from engaged to disengaged. We show this by reducing the haptic feedback"* (P2)

Table 5.3: *Four themes which emerged during the design process. These show how designers used vibration types and parameters when creating tactile symbols.*

alerts on their phone, which inspires them to use continuous vibration: "My phone for example does continuous vibrations... whatever is annoying on my phone, I have experienced it there. I tried to deal with the warning this way." In iterating their design using continuous vibration, P4 is pleased when "It actually sounds like those warning beeps on some devices, and I think a lot of people might associate it with that."

The ability to use motion-coupled and continuous vibration enabled designing haptic equivalents of alerts in other modalities. For example, motion-coupled vibration when rotating a knob was associated with "the indicator (beeper) in the automobile while turning" (P2), whereas continuous vibration is connected creating shock or annoyance. Thus, the expert intends that the user will not have to think very hard about what they experience. In the disengagement case, P2 reflects on auditory stimuli they know from paragliding, which "uses an audio system that gives beeps when you dip, that beeps for your vertical velocity" to notify and encourage the glider to pull upwards. These beeps are similar to going over bumps created by the motion-coupled vibration, where each bump corresponds to a higher level of disengagement. Thus, *designing and reflecting on symbols and signal parameters with both motion-coupled and continuous vibration is done within the context of one's lived experiences.*

Symbols have Affective Qualities

Symbols were not only designed within the context of previous experiences, but also in reference to symbols affective properties. Without mentioning valence and arousal, designers had an intuitive understanding of the symbols' affective qualities. This was expressed through qualitative descriptors, which consistently place the symbols in an affective space. Symbols for warning (designated negative valence, high arousal by us) were designed to be "aggressive" and "stressful" (P4) while reassurances (positive valence, low arousal) were "comfortable" (P3) and "pleasant" (P1). Symbols for ecstasy (positive valence, high arousal) were intended to be "energetic" (P1) and "vibrant” (P5), while disengagement (negative valence, low arousal) was “depressed” and “unhappy” (P4).

This, in turn, led to consistency in the use of vibrotactile patterns. For example, P4 stated “I’m thinking in terms of visceral experience, as it needs to be something comfortable.” when designing with motion coupled vibration and P5 describes that “my initial thought for the ecstatic [symbol] is like the vibration is umph-umph-umph full of energy.” P5 then designed a signal based on continuous vibration structured in the same way, providing an energetic beat and resembling the experience of a lively club environment. Our analysis showed that these choices were not only made based on real-world experiences, but that the experiences were also chosen to align with the affective qualities of the symbol. These *affective qualities provide guidance in selecting vibration parameters*.

Symbols can be Active or Passive

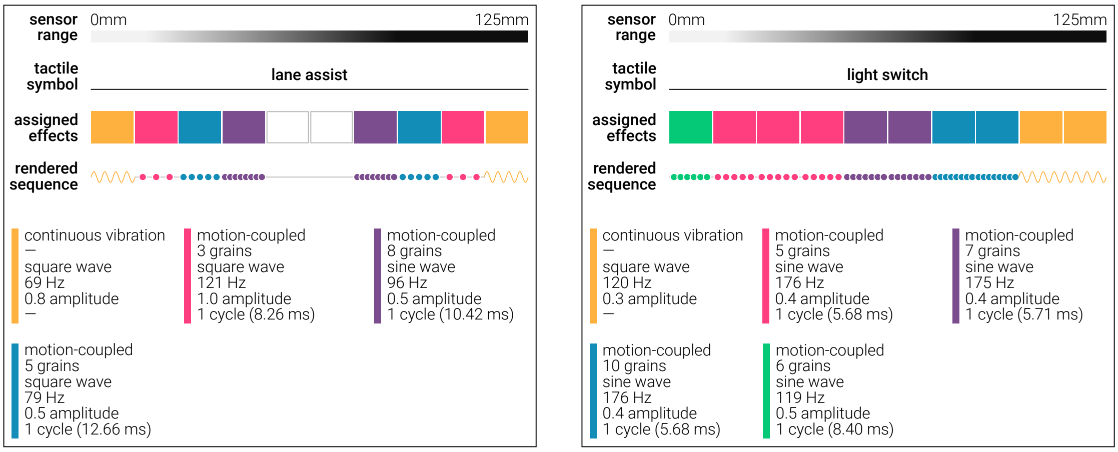
The designers decide on the use of motion-coupled or continuous vibration based on how urgently a user may need to take action and potential repercussions of the situation. Here, P1 and P4 explicitly differentiated between *Active Symbols* which the user can experience even if they do not move the TUI element or *Passive Symbols* which the user would only feel when moving the TUI element. In practice, this means active always is designed with continuous vibration, while passive refers to symbols using only motion coupled vibration. Using an active symbol, the user might be informed to not explore beyond a certain point. For instance, in the case of futuristic driving, the information that there has been an accident in the adjacent lane needs to be provided actively to the user and hence the experts preferred to use continuous vibration. The information and potential repercussions conveyed by the vibration should act as a barrier to discourage the user: “It immediately needs to be continuous [vibration], because it wants you to go back.” (P1) “The driver needs to be alert as lives can depend on it.” (P3) The expert’s intention is to convey this information in an urgent fashion, without the driver needing to seek it out. To convey active symbols, high urgency and disruptive qualities are prioritized: “I would use continuous vibration... to actually alert the person not to turn. You don’t want people to explore that region.” (P4) It should be a “more noticeable, louder” (P2) and “stronger” vibration (P3). Thus, for conveying information actively, experts tend to use continuous vibration.

On the other hand, the information that it is safe to switch lanes can be provided as the driver turns; because there is no danger, it can be given as the driver moves into the space. Experts used motion-coupled vibration to convey passive symbols, because - “It was important to encourage the drivers gently that they are doing the right thing.” (P2), “... as you are turning more, you get an indication like yup, it’s okay, it’s okay” (P5) wherein each grain of the motion-coupled vibration feels like, “there’s this sort of nudge” (P1). Motion-coupled vibration might also be used for exploration, where the information is passively provided in case the user needs it; for instance, the mood jockey must seek out the emotional state, which is only provided if they move into the corresponding region on the slider: “What I imagine is that the mood jockey is playing around with the sliders... the urgency is low.” Motion-coupled vibration was used to convey gentle feedback where the user needs to fetch passive information: “Grains make me feel that I can notice the vibration, but it doesn’t appear too strong to me. I won’t get too intrusive signals, but I will still know that I’m on the right way.” (P3) As these systems are in constant use, continuous vibration is not used to convey the system state: “You do not want the vibration to be distracting or be vibrating even when you don’t need it.” (P5) For passive symbols, vibration is often intended to be slower, shorter and qualities like softness, gentleness and being non-disruptive are prioritized: “[I] just want to give you a notification in a gentle way.” (P3). Thus, motion-coupled vibration was preferred for conveying information passively. *The designation of active or passive information in the designer’s intention conveyed using continuous and motion-coupled vibration, respectively, makes subjective qualities of the symbol clearer.*

Context is part of the Symbol

Typically, a symbol is something binary: A warning that it is not safe to change lanes is either provided to the user or not provided to the user. However, in our study, experts embedded such symbols in a continuous context. Here, the active warning symbol, designed using continuous vibration, is embedded within a larger passive symbol. This way, feedback might be given as a driver begins to approach a zone of danger. Once it is reached, the designers indicate this by switching from motion-coupled vibration to continuous. This contextual part would gradually fade in, for instance “the closer you get, the amplitude is more,” (P5) and “three increasing incremental feeling designs [so] that the further you go, the more it warns you” (P1). This approach was taken by four out of five participants in designing the warning: they indicated a “pre-warning” stage with a softer vibration leading up to the strongest vibration, the final warning symbol.

In other cases, the active element of the symbol was not well-defined. The designer wanted to designate an end point; here, motion-coupled vibration was used to design the approach as well as indicate the end point. For instance, “for the reassurance you kind of had a pattern but then had a virtual stopping point, which indicated that you actually changed lanes... the shift was from many grains to one grain that gives them [a] click. So you have a definite endpoint” (P2). This is like creating a “barrier” (P1) which tells the user they have received all the information. In the case of ecstasy and disengagement, designers view them as emotional states and approach from either side with motion-coupled vibration. The surrounding vibrations describe “a gradient where you go down in levels” to finally reach that key piece of information (disengagement), in this case described by P5. P2 describes their design made with motion-coupled vibration like a ratchet when designing the reassurance symbol to let the driver know they had gone far enough into the next lane: “the idea is that if you are



(**a**) *P4's design of a lane assist.* (**b**) *P4's design of a light switch.*

Figure 5.6: *Example tactile symbols created by participants during the free-form design task (both rendered on a slider).*

in the end position, you don't keep on doing it [turning]" (P2). *Provided with the ability to add motion-coupled vibration to the design of tactile symbols, designers started considering the context of the symbol, what users would feel before or after, as part of the design.*

5.6.4 Free-form Designs

The following are two of the designs of the creative exploration task, which was performed by four out of the five participants. Without constraints of the design space, the participants used a combination of motion-coupled and continuous vibration to render vibrotactile effects, for four out of the six designs. All the free-form designs were only done on the sliders to investigate how participants use the design space (provided by the system) of a single TUI, rather than comparing their approaches between different TUIs. In this section, we depict a visual representation of two free-form design they explored and describe their thought process in brief:

Lane Assist: Participant 4 designed a lane assist using one of the slider as shown in Figure 5.6a. The idea of the participant behind this design was that - "The user needs to find this sweet spot. How can we inform them where the sweet spot is. This sweet spot can be a lane assist or something to stay in the same lane while driving" For the same, a symmetric pattern of a combination of continuous and motion-coupled vibration was used. The continuous vibrations at the end are made rough to avoid the user from going there, whereas the motion-coupled vibrations are rendered in a way that the user gets encouraged to move in the direction of more grains if they are in the region which has fewer grains. The center region has no vibration and is the lane where the user is encouraged to be in.

Light Switch: 2 Participants (by co-incidence) designed a light switch with haptic feedback. The design by participant 4 is shown in Figure 5.6b. The switch is designed as a combination of continuous and motion-coupled vibration, where the number of increasing number of grains indicate the increase of light intensity. Excerpt from the participant - "I am trying to use a considerably lower frequency and lower amplitude because you don't want to hear the light switch. Plus, lower frequencies and amplitudes are less distracting when using the light switch. The reason of choosing a sawtooth signal was to have distinct clicks and a gentle continuous vibration was used at the end to indicate the maximum light intensity" (P4).

The design of a light switch by P1 can be found in the Figure C.3c. Other designs include typewriter's key press effect by P1 in Figure C.3a, the design of virtual hill and valley by P5 in Figure C.3b, and the design of alternating roughness and softness regions described by P2 as 'hiccups' in Figure C.3d.

5.7 Discussion

Our results demonstrate that haptic experts are able to explore the design space using motion-coupled and continuous vibration effectively to design tactile symbols. Combining continuous and motion-coupled vibrotactile cues was done effortlessly. For participants, the two types of vibrotactile signal simply became part of the repertoire they had at their availability to create symbols.

We did not instruct participants on how they might use motion-coupled vibration or continuous vibration, there was no explicit requirement to use one or the other, or to combine them. However, for almost all symbols, participants opted to use both types of vibration. Generally, while symbols typically used both types of vibration, motion-coupled vibration was used more often than continuous vibration; often continuous vibration was used to highlight a certain element of a larger motion-coupled symbol. For example, participants often used motion-coupled vibration as a feed-forward mechanism, which users would experience before they were exposed to the main part of the symbol. In our analysis, we describe this as designers considering not only the symbol itself, but the context of the symbol as part of the design. However, one might also frame this within the context of feedback and feedforward mechanisms (cf., (D. Freeman et al., 2009)). Here the continuous vibration elements can be seen as a mechanism for feedback, whereas motion-coupled vibration as a tool for feed-forward, as a way to communicate the intention of the message to be conveyed prior to the actual message conveyance. The way in which designers in our study expanded the scope of the symbols was remarkable to us, as we had hosted previous studies and workshops on tactile symbol design using continuous vibration only (Wittchen et al., 2022; Wittchen et al., 2021), where such topics never came up, nor are we familiar with this being observed in other studies of symbol design (Ziakas et al., 2014; Jaebong Lee et al., 2009; Chan et al., 2008).

We found that participants actively adapted their design based on the type of information it represented, for example, information which did not require immediate attention from the user was often represented using motion-coupled vibration, so as not to disrupt the activity of the user, but allowing them to attend to the information as they chose to. On the other hand, information which required immediate attention, such as warnings, was represented using continuous vibration, to nudge people to take direct action. Participants spoke of these as *active* or *passive* symbols. This distinction between actively and passively providing information was one of the first considerations people made when designing a symbol. Here, again, adding embodied experiences to the design space made participants reflect on the symbols in new ways, resulting in more diverse designs. It should be noted here that active and passive refers to the symbols, not to the user. Compared to discussion of active and passive touch (Lederman, 1981; MacLean, 2000; Velázquez et al., 2019), subject and object are switched. Active symbols have an affinity to passive touch; they can be perceived even when the hand is just resting on the TUI element. Passive symbols have an affinity with active touch, they typically require the user to actively engage with the TUI element to experience them.

We also found that participants tended to present symbols with a positive valence using motion coupled vibration, and in a negative valence using continuous vibration – possibly a consequence of information requiring immediate action more likely having negative valence and vice versa. Consequently, motion-coupled vibration and continuous vibration appear on opposite sides of Russel's Circumplex Model, continuous being related to negative valence and high arousal, and motion coupled related to positive valence and low arousal. This highlights that adding embodied experiences to symbol design broadens the range of affect which might be designed into the experience of a tactile symbol. These results are also interesting within the context of shape-change in relation to emotion (Pedersen et al., 2014).

Generally speaking, our study highlights, that combining embodied and hermeneutic experiences – here represented with continuous and motion-coupled vibration – works effortlessly in symbol design. The resulting designs are more varied than they would be without both types of stimuli. Providing designers with both types of stimuli, however, not only lead to more varied designs, it also prompted designers to think about symbols differently. Without being prompted to do so, designers integrated feed-forward mechanisms into their design and adapted their design based on the type of response they hoped to elicit from the user. Finally, it appears that combining embodied, and hermeneutic experiences might expand the range of effects, designers are able to represent in their symbols.

5.8 Limitations & Future Work

It should be noted that all symbols were created on a dynamic interface. While we believe that this type of symbol has ecological validity, typically when designing tactile symbols, they are deployed in a more static context. Some of the observations we make here might also be due to the user movement, rather than symbol parameters. However, as by our very definition of embodied experience dynamic input from the user is required, it is difficult to separate the final symbols from human movement.

While we have observed anecdotal associations between parameters types and symbol properties, further studies are needed to reveal if there are more underlying conceptual associations involved in the design and use of haptic symbols and perhaps where these associations originate through culture, design craft, and other lived experience. Also, there are ways of combining motion-coupled and continuous vibration other than used in our rather dichotomous approach: An interesting recommendation which came out of the interviews of haptic experts was the ability of stacking motion-coupled vibrations on top of continuous vibrations, which the current system doesn't allow. This would also allow combining different vibration types to render more realistic effects, as well as to superimpose multiple vibrotactile illusions to create more robust experiences.

Finally, it is important to restate that the intent of our study is not to present a "how-to" of designing haptic symbols. Rather, we demonstrate the strategies and qualities associated with different vibration parameters by the haptic experts we worked with. This is true also for the preferences expressed during the creative explorations. It will be important to work with larger groups of designers in a cross-cultural study to gather more general design behaviors and material associations. The symbols designed by the haptic experts here would also benefit from additional evaluation by end-users. The observations we present here might act as inspiration for other design tools, or concrete designs, and provide an initial hypothesis for further quantitative studies to see if any of the observations we make generalize. However, the data we collected for this study does not allow us to make any claims of generalization. While we believe that both vibrations can be used to generate tactile symbols, demonstrating the standardization and translation to real world applications of the symbols, is up to future work.

5.9 Conclusion

We investigated the use of continuous and motion-coupled vibration in the design of tactile symbols to explore how embodied mediation might be used in hermeneutic design. We conducted a study with five haptic experts who were asked to design symbols using both types of vibration and were later interviewed to understand their approach and final designs. Thematic analysis of the interviews revealed that experts were able to associate both vibration types with lived experiences, and that the symbols they designed have affective qualities. Moreover, symbols can be active or passive based on the type of vibration and that experts integrate the context as a part of the symbol.

On a high level, our results show that embodied experiences can indeed be used for hermeneutic design. Resulting designs were more varied than they would be without both types of stimuli. In addition to more varied designs, this approach also shaped thinking about design: designers integrated feedforward mechanisms into their design and adapted active or passive symbols based on urgency. Overall, we showed that combining embodied, and hermeneutic experiences extends symbol design opportunities in useful ways.

6 Bimanual Motion-Coupled Vibration with Crosstalk

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The previous chapters of this thesis focused on how Motion-Coupled Vibration (MCV) can generate compelling unimanual material experiences such as virtual compliance, texture, and pseudo-force. Yet in everyday life, our engagement with material properties is rarely confined to a single hand. Many of the fundamental mechanical qualities we perceive—flexibility, stretchability, torsion—are discovered through bimanual exploration, where both hands move in coordination.

Whether stretching fabric, bending a plastic strip, twisting open a jar, playing a guitar, or drawing a bowstring, our two hands work together in complex, often out-of-phase movements. These coordinated motions create relative displacement, differential force, and distributed tactile cues that jointly shape how material properties are perceived. In contrast, most haptic rendering techniques—-especially those using vibration—-have been developed for single-point, single-hand interaction. As a result, they do not capture the inherently relational and distributed nature of bimanual material perception.

This leads us to **RQ4** (Section 1.3.4) which is based on the lines of: ’If motion-coupled vibrations can evoke compelling unimanual material experiences, can they also be used to render bimanual virtual material experiences? And if so, what are the fundamental building blocks and algorithmic strategies required?’

Existing bimanual haptic systems typically rely on specialized, mechanically linked devices or grounded force-feedback systems. These approaches offer powerful capabilities but constrain movement, require complex hardware, and are often inaccessible outside research laboratories. What remains underexplored is whether ungrounded, controller-based, and purely vibrotactile rendering methods like Motion-Coupled Vibration can approximate bimanual material interactions without the need of physical linkages.

This chapter broadens the scope of MCV rendering by presenting an algorithm that measures the relative orientation between the two hands to render the crosstalk-modulated Motion-Coupled Vibration across both hands[1]. We conduct a psychophysics

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[1] Teaser Video of the project: `https://youtu.be/eKU1wixW-Ug`

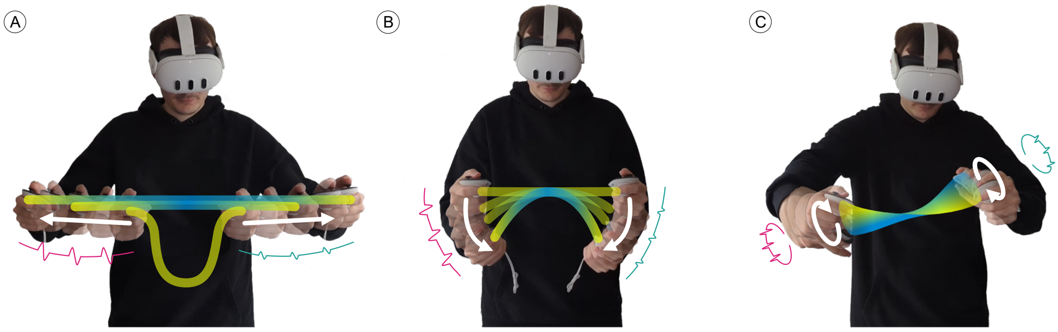

Figure 6.1: *We present a bimanual motion-coupled vibration algorithm capable of creating connected material experiences between two hands. By modulating the parameters of vibrations between the hands, our algorithm can induce material properties of elasticity while stretching* Ⓐ*, flexibility while bending* Ⓑ *and torsion while twisting* Ⓒ*.*

study followed by a qualitative association study. Finally, we present an authoring tool called *Dvihastīya* and collect user impressions on example demonstrations.

By extending Motion-Coupled Vibration into the bimanual domain, this chapter broadens the expressive potential of single-point rendering to multi-point or distributed material rendering. Ultimately, this work offers a first step toward accessible, portable, and intuitive bimanual haptic experiences that reflect the natural ways in which humans physically engage with the world.

6.1 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 (Talvas et al., 2014). 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 (Guiard, 1987). 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 (Plaisier et al., 2012; Squeri et al., 2012). Forces or torques on one hand are transmitted as counter-forces to the other hand, offering richer haptic feedback about the object being manipulated (Talvas et al., 2014). 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 haptic feedback (I. Choi et al., 2018; Zenner et al., 2017; Zenner et al., 2017) to modified commercial VR controllers (Yudai Tanaka et al., 2020; Stellmacher et al., 2022) which aim to simulate the haptic presence and properties of virtual objects which can be probed with *both hands* concurrently. One notable example that refrains from using world-grounded actuation is *PseudoBend* (Heo et al., 2019), demonstrating a design that enables to create bimanual material experiences of stretching, bending, and twisting. Besides *PseudoBend*, only few previous works have tried to address this gap, and the proposed solutions depend on specialized and custom-designed hardware (Ryu et al., 2021; Strasnick et al., 2018), which mechanically connect controllers or use body-grounded force feedback devices restricting accessibility (Pratticò et al., 2022). 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 freehand 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 (S. Choi et al., 2012; Ding et al., 2024). Motion-coupled vibration, a technique where vibrations are synchronized with user action, has shown to induce material sensations like compliance, texture, and deformation (Sabnis et al., 2023a). For instance, vibrations coupled with the pressure applied by a user on rigid objects has shown to induce virtual compliance (Kildal, 2010) and vibrations coupled to users' movement over smooth sliders have shown to generate virtual textures on the slider (Strohmeier et al., 2017; AliAbbasi et al., 2025). Yet, most prior work using motion-coupled vibration to render material experiences has only been limited to a single hand (Jaeyeon Lee et al., 2019; Ding et al., 2024) or even a single finger (Kildal, 2010; Vega et al., 2024; Sabnis et al., 2023a). 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 them 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 properties using both hands, (see Figure 6.1). 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 which 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 influence perceptions of connectedness, material properties, and object structure. Finally, we introduce *Dvihastīya*, an authoring tool for creating immersive bimanual material experiences in VR and collect user impressions, highlighting the expressive potential of our approach for natural, intuitive, and accessible bimanual virtual interactions.

6.2 Related Work

Research on the role of haptic feedback in bimanual interaction dates back to the late 20th century (Gibson, 1962; Guiard, 1987; Kay et al., 1987; Buxton et al., 1986). 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 actions 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.

6.2.1 Bimanual Material Perception

When humans explore materials, they often use bimanual (Guiard, 1987), bi-fingeral or bi-digital gestures (Tajadura-Jiménez et al., 2014) 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 (Guiard, 1987) established how humans use both hands together to explore materials bimanually, and remains a primary framework validated in motor control (Hinckley et al., 1997; Ullrich et al., 2011; Cienfuegos et al., 2024) and applied in haptic interface design (Talvas et al., 2014).

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 (Talvas et al., 2014). Several studies showed that it is easier to follow the relative position between the hands rather than their individual position in 3D space (Balakrishnan et al., 1999a; Veit et al., 2008; Hinckley et al., 1997; Hinckley et al., 1998). This proprioceptive capability proves particularly valuable when visual feedback is absent, inconsistent, or incomplete (Balakrishnan et al., 1999a; Veit et al., 2008). Moreover, bimanual exploration enhances stiffness discrimination compared to unimanual exploration, with the combined percept aligning with optimal cue integration models (Plaisier et al., 2012). Similarly, studies have shown that exploring curvature with two hands can reduce discrimination thresholds relative to one-handed touch (Panday et al., 2013) and symmetric shapes are perceived more accurately with two-handed exploration than with a single hand (Ballesteros et al., 1997). For bimanual feedback, studies have also shown proprioceptive illusions in one arm can induce a measurable motor influence on the other arm (Biggio et al., 2021).

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 (Plaisier et al., 2012). 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.*

6.2.2 Motion Coupled Vibrations to render Material Experiences

Vibration has been shown to contribute to shaping tactile experiences based on how our tactile receptors respond to different vibration frequencies (Johansson et al., 2009). Moreover, vibration can also help us distinguish between material and textural properties due to the differences in their frequency spectrum (Bensmaïa et al., 2005a; Weber et al., 2013). Using this as the foundation, research has presented prototypes which provide vibrotactile pulses synchronized with user action to induce material experiences during the interaction (Sabnis et al., 2023a; Sabnis et al., 2023b). For instance, studies by Joseph M Romano et al. (2011) demonstrated that users experience textures on smooth surfaces by rendering a vibrotactile pulses proportional to users' movement. Providing vibrotactile pulses at fixed intervals of user movement successfully simulates texture experiences in air (Strohmeier et al., 2018) and on smooth sliders (Strohmeier et al., 2017; Sabnis et al., 2023a; AliAbbasi et al., 2025). Similarly, for isometric actions like applying pressure on objects, vibrotactile cues, coupled to changes in exerted pressure by the user, are able to induce experiences of compliance (and deformation) (Kildal, 2010; Wittchen et al., 2023; Vega et al., 2024), even for objects having an inherent base compliance (Mun et al., 2025). Furthermore, Ding et al. (2024) showed that discrete vibration pulses coupled to user force can create an illusion of movement for the user, even when there is no motion. Changes in tangential force applied by the user has also been leveraged to create a haptic illusion of compliance (Heo et al., 2017). Jaeyeon Lee et al. (2019) demonstrated that vibrotactile feedback coupled to holding, squeezing and sliding of fingers can generate experiences of textures and compliance which helps in precisely manipulating objects in virtual reality.

However, most of the motion-coupled vibration methods of creating material experiences are either limited to single-handed interactions (Sabnis et al., 2023a; Strohmeier et al., 2017) or at times even single-finger interactions (Vega et al., 2024). *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.*

6.2.3 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 (Lindeman, 1999; Jeon et al., 2009), from grounded force-feedback devices (Cirio et al., 2011) to prop-based systems (Nilsson et al., 2021; Lindeman, 1999; Strandholt et al., 2020), often combined with visual–haptic illusions such as hand redirection (Azmandian et al., 2016; Kohli, 2013; Zenner et al., 2019b; Gonzalez et al., 2019). 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. (2018) 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 (Zenner et al., 2017) or by constrained ranges of motion (Strasnick et al., 2018).

Overcoming these challenges, Ryu et al. (2021) 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. (2017), used apparent tactile motion illusions to elicit an experience of passing a ball between hands in VR. *Invisibow* by Yi et al. (2025) 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 (Heo et al., 2019). 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 which 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.

As an alternative to existing methods, we address how to render bimanual haptic sensa-

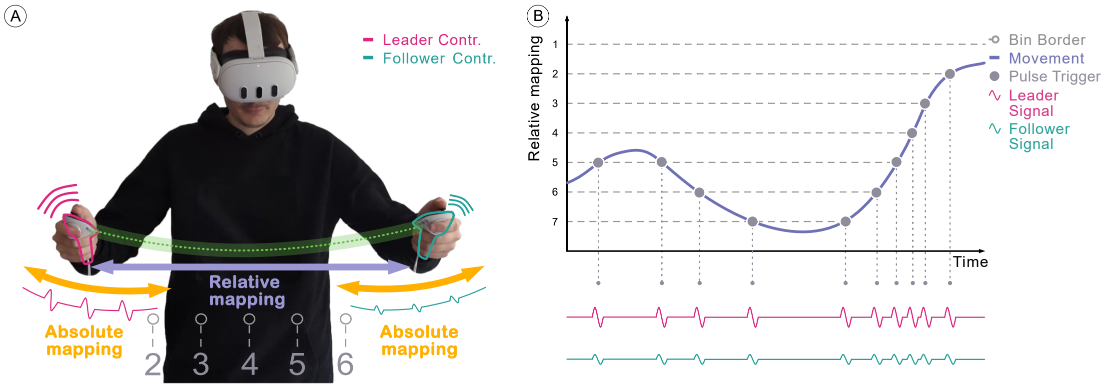

Figure 6.2: *Relative and absolute mapping-Ⓐ: relative mapping triggers vibrotactile pulses synchronously on both hands based on the distance between two controllers, while absolute mapping tracks individual controller and triggers vibrotactile pulses independently on each hand. The bimanual motion-coupled 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.*

tions 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 that brings bimanual material experience rendering closer to real, deployable VR implementations.

6.3 Bimanual Motion-Coupled Vibration

Motion-coupled vibration where vibrations are synchronized with user action have shown to induce material experiences (Kildal, 2010; Joseph M Romano et al., 2011; Heo et al., 2017). 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.

6.3.1 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 (Strohmeier et al., 2020) and the individual parameters of amplitude, frequency, phase and waveform function to design individual grains (Sabnis et al., 2023b). Building on the foundation that the brain naturally binds

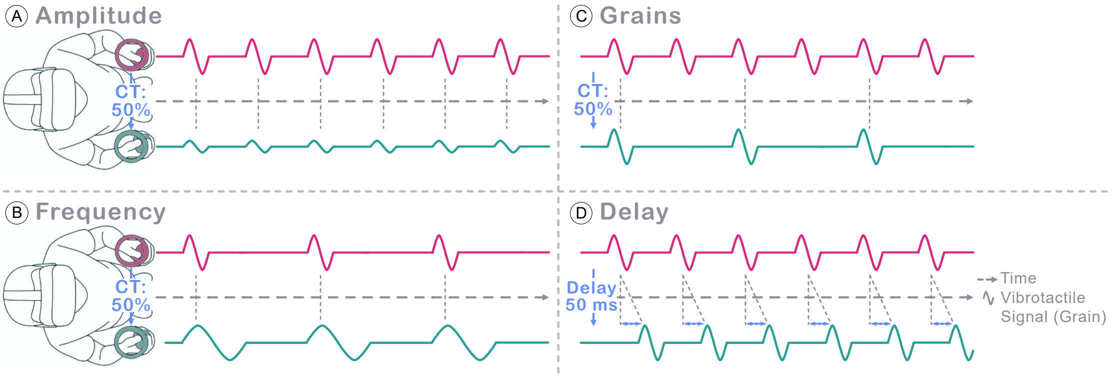

Figure 6.3: *Crosstalk (CT) in amplitude-Ⓐ, frequency-Ⓑ, grains-Ⓒ and delay-Ⓓ is visualized with the vibrotactile pulses (top view of the user is generated using ChatGPT version 5).*

both hands and explicit haptic coupling strengthens this binding (Biggio et al., 2021), 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 6.2 Ⓐ). When both hands move together such that the relative distance is constant, relative mapping produces no pulse, 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 6.3, 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 6.3-Ⓐ).
- *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 6.3-Ⓑ).
- *Grain Crosstalk:* One hand receives a fraction of the vibrotactile pulses (grain) of the other hand, modulating whether the experience feels continuous or discrete (see Figure 6.3-Ⓒ).
- *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 6.3-Ⓓ).

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 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 (Strohmeier et al., 2018; Kildal, 2010; Vogels, 2004)). 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 their ratio; and (c) wideband vibration actuators to render vibrotactile stimuli on both the hands.

6.3.2 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 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 Section D.1 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[2]. 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[3]. VCAs have a stable amplitude response across a

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

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

broad range of frequencies (McMahan et al., 2014) as opposed to Liner Resonant Actuators (LRAs) which are tuned to operate at specific resonant frequencies. Referring to Section D.1, 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 use in our research.

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 6.2 Ⓑ. 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 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.

6.3.3 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* (Heo et al., 2019) (see Figure 6.1-Ⓐ,Ⓑ,Ⓒ). 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 a suitable for understanding perceptual dimensions from different stimuli (Pasquero et al., 2006; Park et al., 2020), 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. Thus, we chose inductive qualitative analysis to capture richness and variability in induced material experiences. Finally, in an authoring tool study, we asked users to design bimanual motion-coupled vibrotactile feedback for immersive VR objects, providing insights into how algorithm parameters shape bimanual material rendering.

6.4 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.

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 (Vega et al., 2024; Jingu et al., 2024). For example, magnitude estimation has been applied to evaluate perceived salience, depth and continuity of motion-coupled vibration (Strohmeier et al., 2020) as well as magnitude and naturalness of induced movement (Ding et al., 2024). 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) (Strohmeier et al., 2020), 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 (George A Gescheider, 1988), 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. (2020) and Ding et al. (2024).

6.4.1 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 Section 6.3.1)
- Mapping Type: relative vs. absolute. (see Section 6.3.1),
- Amplitude Crosstalk Level: 0%, 33%, 66%, 100% crosstalk between the controllers. (see Section 6.3.1)

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 own changes in position, so pulses are generated independently for left and right hand. Absolute mapping is inspired from the motion-coupled vibration rendering methods used for unimanual material rendering (Strohmeier et al., 2017; Sabnis et al., 2023a). 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 or compressing 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 Section 6.3.1, 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 felt connected.
- **[StrengthNaturalness]** (magnitude estimation): how closely the interaction resembled real-world expectations.
- Qualitative Descriptors or Associations (verbal).

For both mappings, the leader hand (or the one which 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. (2019) and Sabnis et al. (2025b) 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 (Wittchen et al., 2023; Vega et al., 2024) and texture (Strohmeier et al., 2018; Sabnis et al., 2023a). Moreover, 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, so that 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 (Makous et al., 1995). Amplitude of 1.0 corresponded to the maximum amplitude from the controllers measured to 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. *We hypothesized 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.*

6.4.2 Procedure

Participants were informed about the study, and they were asked to sign a consent form and complete a demographic questionnaire. They were also explained what does unimanual and bimanual interaction mean in the context of the study. Moreover, they were explained what is meant by connectedness: 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 only 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.

Task

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

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 (6 months) and one actively worked in the field of haptic feedback. The study duration was about 1 hour 30 minutes depending upon the participant responses to each of the conditions as well as the final qualitative interviews. Participants were seated throughout the study and compensated with 18 Euros for their participation. White noise was played through the headset to mask audio-cues of the controller vibrations.

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* (Armstrong, 2017). 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 object, material or experiential qualities to the conditions. These responses were coded and clustered using flexible coding approaches to identify recurring themes, similar to (Sabnis et al., 2025a;

Muehlhaus et al., 2023).

6.4.3 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.

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.

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 6.4 Ⓐ,Ⓑ, and Figure D.2 Ⓐ, Ⓑ (Section D.3) 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 ef-

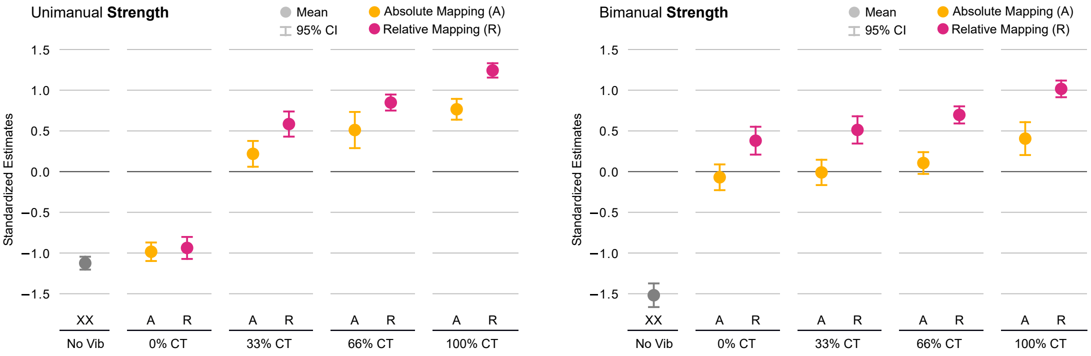

Figure 6.4: *Estimates of connectedness strength for unimanual Ⓐ and bimanual Ⓑ configuration over different amplitude crosstalk levels and relative, absolute mapping type. Each confidence interval bar corresponds to 96 data points (16 participants * 3 actions * 2 repetitions)*

fects 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 6.5 Ⓐ, Ⓑ and Figure D.2 Ⓒ, Ⓓ (Section D.3) 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 ($t(15) = 4.96$, $p < 0.01$, $g = 1.07$).

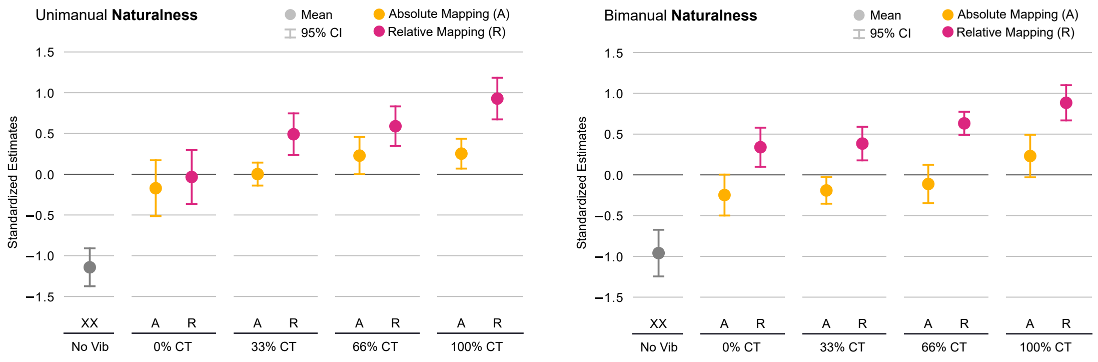

Figure 6.5: *Estimates of StrengthNaturalness for unimanual Ⓐ and bimanual Ⓑ configurations over different amplitude crosstalk levels and relative, absolute mapping type. Each confidence interval bar corresponds to 96 data points (16 participants * 3 actions * 2 repetitions)*

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), "resistance/ exercise bands," (P4, P9, P10) for multiple conditions. Bending also evoked associations such as "rubber band fixed to a fixture" (P2-A66) "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.

6.4.4 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 naturalness of the material experience was independent if 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.

6.5 Study 2: Variable Crosstalk-induced Material Associations

After establishing connectedness during the first study, to understand how do 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 dependent 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 using only crosstalk-based bimanual vibrotactile feedback.

6.5.1 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 as 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 Section 6.3.1) 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); *delay CT*: (D50, D100, D200, D400 ms) For each condition and for each 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?'*.

6.5.2 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 Section 6.4.2. The sequences of conditions were randomized. 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.

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 perceived connection between both hands.

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). With respect to experience in virtual reality, six participants were beginners and one reported being experienced. Participants were compensated with at the hourly rate corresponding to the location where the study was conducted for their participation. During the experiment, white noise from the headset was used to cancel any audio cues from the hand controller vibrations and were blindfolded using the VR headset.

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[4]. Post transcription, all the relevant codes including the material and objects 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 highlighting 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.

6.5.3 Results: Qualitative Analysis

We present themes from the qualitative content analysis done per crosstalk type for different levels and three movement primitives, (Figure 6.6 shows visual overview). For

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

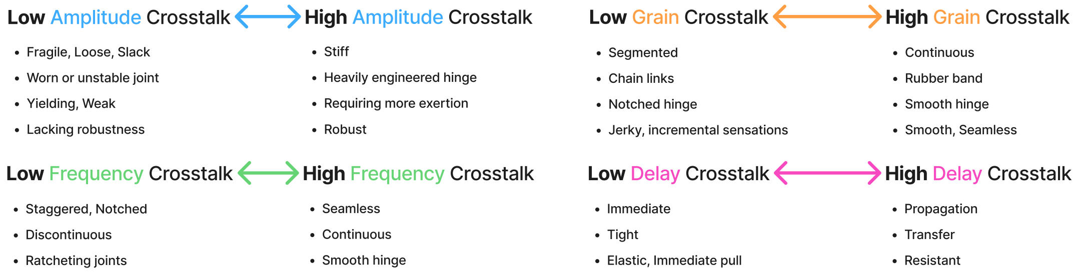


Figure 6.6: *Selected descriptors representative of the qualities associated by participants for different crosstalk types and levels. Refer to Section 6.5.3 for the complete qualitative analysis*

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.

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 to 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.

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, 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 "a small pocket gate... 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 vibrations seemed slower to reach the left hand, evoking springs with multiple coils or jointed 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."

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), 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," 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.

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,", "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, as P1 reflected: "the twist feels like rubber winding up smoothly without stops” and P11 mentioned it felt like ”stirring thick paint”.

6.5.4 Concluding Thoughts

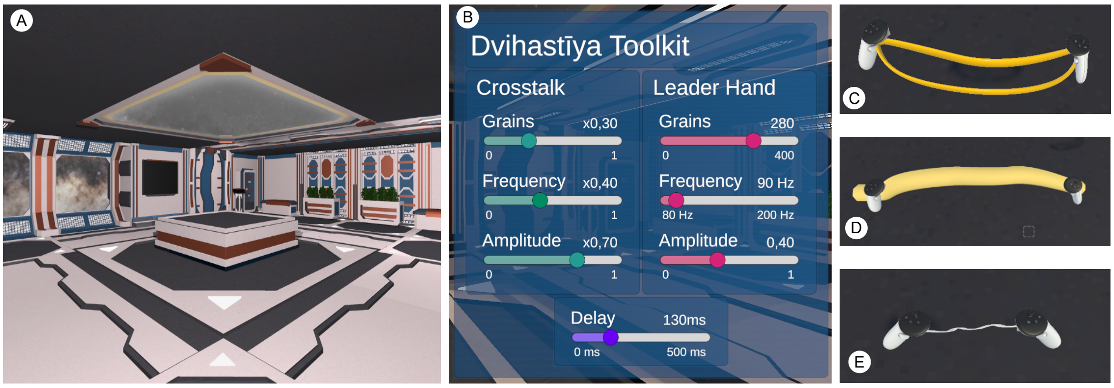
While this study presented a rich overview of the types of experiences users have when engaging with bimanual motion-coupled vibration with crosstalk, there is another interesting observation that can be made in the data. The *amplitude crosstalk* condition provides participants with exactly the same stimulus as was used 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.

6.6 Dvihastīya Authoring Tool: Design and Initial User Impressions

Based on our observations around the importance of multi-modality, our final explorations were conducted in VR. To receive a different type of insight, here we do not provide fixed stimuli to the user, but we instead observe if our approach was robust enough to allow users to independently design their own bimanual experience. The design tool was made to facilitate the users’ to design bimanual experiences for demo applications in VR and not as a results of the previous studies. For this purpose, we designed *Dvihastīya*, an authoring tool that enable users to design bimanual motion-coupled vibrotactile feedback for different demo applications in VR (Figure 6.7-Ⓑ). *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 involve two-hand interaction. Each of the interactive demonstrations change their state from unstretched to stretched, straight to bent and untwisted to twisted.

The focus was on how users utilized 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



Crosstalk: Grains x0,30; Frequency x0,40; Amplitude x0,70

Leader Hand: Grains 280; Frequency 90 Hz; Amplitude 0,40

Delay 130ms

Figure 6.7: *The virtual room used for the exploration Ⓐ, Dvihastīya Authoring Tool Ⓑ and three of four interactive demo objects which were designed for in VR are shown (elastic band-stretching Ⓒ, pool noodle-bending Ⓓ, braided wire-twisting Ⓔ).*

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.

6.6.1 Bimanual Motion-Coupled Vibrotactile Feedback Authoring Tool

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 for 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[5].

6.6.2 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 6.7 Ⓐ). The setup used the hardware described in Section 6.3.2.

Users: We recruited 3 male and 2 female users, aged 25-32 (M=28), to participate in this exploration. The participant'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

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

feedback for movement guidance. U3 worked in the fields of passive haptic feedback, audio-haptic feedback and vibotactile haptics.

Virtual Objects: Participants interacted with four virtual objects: an *elastic band* (Figure 6.7 Ⓒ), a *pool noodle* ((Figure 6.7 Ⓓ), a *braided wire* ((Figure 6.7 Ⓔ), and *table-tennis rackets*. The first three demo applications mapped directly to stretching (elastic band), bending (pool noodle), and twisting (braided wire). All the three demos were suggested by previous study participants (see Section 6.4.3). Objects (except table tennis rackets) were simulated in real time using the Obi Rope[6] (inspired by Games-Bond (Ryu et al., 2021)), with parameter values tuned to reflect their distinct physical properties (Section D.2). 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.

Procedure: At the start, each user was introduced to the central theme of the session: to design bi-manual 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 the relative importance of visual versus haptic cues in shaping their experience of interacting with the object.

6.6.3 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 6.8, amplitude was one of the most 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 felt higher frequency meant flexibility, while P5 saw it as useful for fine-tuning. Delay divided users: U3 preferred a small delay for realism, but U2 and U4 wanted minimal delay for unity, and P5 favored mid-to-high delays for believable flexibility.

Users often adjusted amplitude crosstalk in ways that aligned with their interpreta-

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

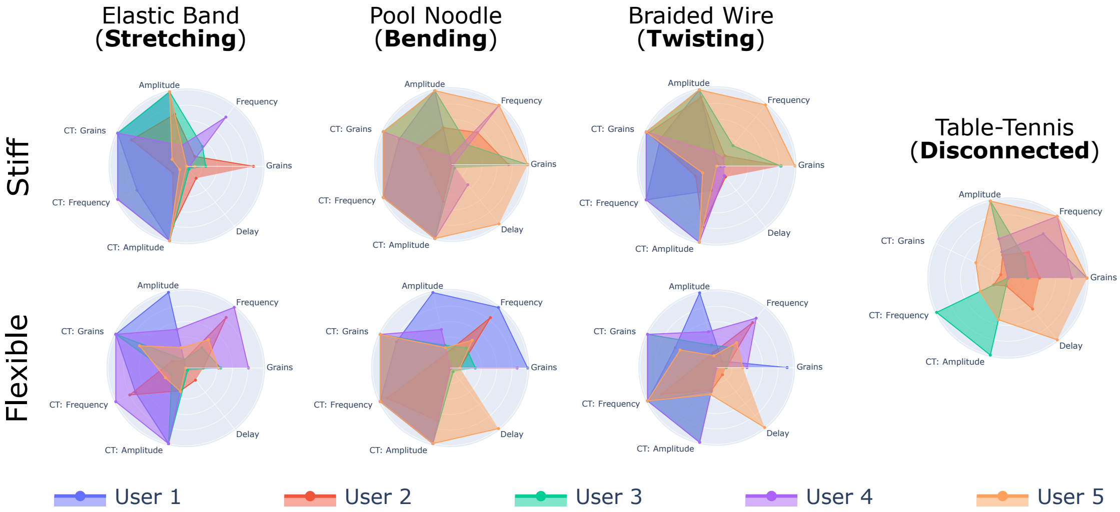

Figure 6.8: *Parameter configurations showing seven haptic designs made by five users using the Dvihastīya authoring tool. Designs for the elastic band, pool noodle, and braided wire were created to fit both flexible and stiff material properties. For the table tennis rackets, the users were instructed 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.*

tion 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), user preferred to tune amplitude to adjust tightness (All users), while grain crosstalk was used to refine continuity of the bend (U1, U2, U4). Overall, 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.

With regard to 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. Together, these impressions highlight that Dvihastīya supports both quick prototyping and fine-tuning. Finally, none of the users noted any visual–haptic mismatch in the cues they received 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 with the interactive VR demonstrations illustrating its real-time usage. Beyond one application for each bimanual movement of stretching, bending, twisting, as well as indpendent bimanual actions, the tool can be used to design a wide range of bimanual interactions such as collaborative object manipulation (e.g.: deforming clay, kneading a 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.

6.7 Discussion

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

6.7.1 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 6.4) and naturalness (Figure 6.5), consistent with Guiard's model, which emphasizes that bimanual actions depend on the relationship between hands rather than their absolute positions (Guiard, 1987), while also closely matching how humans naturally perceive bimanual interactions with strong inter-hand relationships than individual hand positions (Hinckley et al., 1998).

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 (Strohmeier et al., 2018), 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* (Heo et al., 2019), indicating strong need for having a physical prop to provide resistance and opposing force for bending and twisting actions.

Finally, the 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 (Vega et al., 2024; Strohmeier et al., 2017). This finding directly supports the observation by Squeri et al. (2012) 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 (Cirio et al., 2011) or physical connectors between controller (Strasnick et al., 2018), which limit accessibility and natural movement.

6.7.2 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 (Sabnis et al., 2023a; Sabnis et al., 2025b) 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 (Pittera et al., 2017). 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 (Muender et al., 2022; Biswas et al., 2021). The dichotomy of frequency and grain crosstalk suggests that these parameters primarily influence the perceived granularity of material structure rather than other material properties, with frequency affecting material character, as already touched upon in previous research for single-point material rendering with motion coupled vibrations (Strohmeier et al., 2020; Sabnis et al., 2023b). 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 5.5), further highlighted that crosstalk plays an important role in establishing a shared experience in the presence of visual cues as well.

6.7.3 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* (Heo et al., 2019), which focuses on relative deformations between hands, but extends this principle to purely vibrotactile implementations 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 simple design 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.

6.7.4 Limitations and Future Work

While our approach demonstrates the potential of bimanual motion-coupled vibrations, some limitations must be acknowledged. The psychophysics study tested many conditions but had a small participant pool, reducing generalizability. We also only 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* (Ryu et al., 2021) and *PseudoBend* (Heo et al., 2019). 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, 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 lower level parametric design space provided by *Dvihastīya* authoring tool was the reason for diverging designs for similar material properties. The next version of the authoring tool should be based on the relationship between feedback parameters and their material qualities established in the qualitative study (Section 6.5). Such an authoring tool could be evaluated by allowing users to directly modulate material qualities and observing if the designs match their expectations.

Future research could combine our vibrotactile bimanual rendering with mechanically connected haptic devices (Strasnick et al., 2018; Ryu et al., 2021) to strengthen connectedness through both cutaneous and kinesthetic cues. Integrating multimodal feedback, such as audio or audio-haptic cues (Degraen et al., 2021), 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 would be worthwhile and can extend the applicability of our approach.

Future work should examine our qualitative analysis 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 multi-sensory mechanisms underlying perceived material unity. The insights from our application design using the toolkit are of exploratory nature and these should be considered as preliminary patterns for bimanual haptic design rather than generalizable guidelines. 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. Finally, toolkits like *Dvihastīya* could be adapted for application-specific scenarios, including medical training, teleoperation, and collaborative VR.

6.8 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-hand interactions and offer a flexible, accessible approach for designing cohesive bimanual experiences in VR. Finally with *Dvihastīya* authoring tool, we provide user impressions of authoring bimanual vibrotactile experiences. This work opens new opportunities for more immersive, intuitive, and widely deployable bimanual interactions in virtual environments.

7 Haptic Servos to Design Motion-Coupled Vibration Across Contexts

Chapter 2 established Haptic Servos as a platform for rendering motion-coupled vibration, which are action-synchronized tactile pulses, capable of rendering virtual material experiences of compliance, friction and texture. While the mechanism itself is simple, its value lies in how easily it generalizes. Once action-synchronized pulses can be generated with low latency and minimal hardware requirements, they become a ***modular building block*** that other researchers can embed, adapt, and recombine for very different purposes.

The purpose of this chapter is to precisely highlight that. Rather than remaining a one-time system tied to a single study, Haptic Servos are a reusable haptic rendering platform that others could take into new form factors, perceptual questions, and application domains. This chapter presents six published research projects that build on this principle, each demonstrating how the Haptic Servos platform can be repurposed, extended, or transformed to address different interaction contexts, theoretical questions, or application domains. The chapter is organized to reflect these broader contributions:

- **System Contributions** highlight how the principle enabled new haptic devices and interaction modalities.
- **Application Contributions** demonstrate how action-coupled feedback enriches real-world interactions such as walking and sports.
- **Theoretical Contributions** show how the same mechanism can probe deeper perceptual questions or extend to new stimulation modalities.

Collectively, these works show how a single haptic rendering principle-—discrete grains triggered by user action-—can serve as a foundation for new systems, new applications, and new research areas of close coupling of action to feedback can create novel experiences.

7.1 System Contribution

These projects demonstrate how the core Haptic Servos principle can be re-implemented, or extended into new hardware systems and interaction modalities. They show how a single perceptual mechanism can support novel form factors and new classes of haptic devices.

7.1.1 vARitouch: Back-of-the finger system for rendering virtual compliance

vARitouch extends the core idea of motion-coupled vibrotactile rendering into a new form factor: instead of embedding sensors and actuators into objects, it relocates them to the back-of-the-finger, enabling compliance rendering on physical surfaces and objects. The system detects changes in the applied pressure when pressing with a finger by re-purposing a pulse oximetry sensor as a pressure sensing mechanism, and converts these changes into short vibrotactile grains delivered through a nail-mounted actuator. This input-output mapping is based on the core idea introduced in Section 2.3.3. The goal was to preserve the natural tactile qualities of the fingertip to maintain access to real textures, shapes, and temperatures while adding an overlay of virtual softness to otherwise rigid objects. Through psychophysics experiments, we showed that vARitouch can continuously modulate perceived compliance, increasing softness by roughly 30 Shore A levels, and that users systematically interpret grain-based stimulation on the nail as a property of the object being touched.

vARitouch frames a compelling design space for tactile augmented reality: one in which the body itself becomes a site of haptic rendering, enabling interaction with any environment without instrumenting the world. The qualitative evaluation highlights both the desirability and practical potential with users appreciating the rich material experiences vARitouch induced while leaving the fingertip free for exploration. As a system built using motion-coupled vibrations, vARitouch demonstrates how the haptic servos principle can scale beyond held devices toward body-worn, perceptually transparent systems that modify material perception in situ. It illustrates how motion-coupled feedback can serve as a lightweight, mobile, and expressive method for tactile augmentation, expanding interaction possibilities across everyday settings.

Citation: `https://dl.acm.org/doi/10.1145/3613904.3642828`
Gabriela Vega, Valentin Missir, Dennis Wittchen, **Nihar Sabnis**, Audrey Girouard, Karen Anne Cochrane, Paul Strohmeier. *VARitouch: Back of the Finger Device for Adding Variable Compliance to Rigid Objects* In Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems, pp. 1-20. 2024. (Vega et al., 2024)

7.1.2 Motionless Movement: Vibrotactile Kinesthetic Displays for Illusory Motion

This project investigates whether motion-coupled vibrations generated using the haptic servo pipeline can be leveraged not only to shape virtual material properties like texture and compliance, but to generate an embodied sense of movement itself, even when no movement occurs. The motivation for this work begins from the observations of users interacting with the compliance illusion (Strohmeier et al., 2020; Kildal, 2010): to feel that a surface deforms under pressure, users implicitly assume that their own finger is moving, even when the surface itself does not displace. Building on this insight, this project explores whether carefully timed vibrotactile grains, triggered by a user's force-onset but delivered while the hand remains physically stationary, can induce a convincing experience of kinesthesia. Through a series of psychophysics studies, we show how different grain-distribution strategies—-particularly distance-based mapping—-modulate the magnitude, naturalness, and vividness of the resulting movement illusion, and how increasing granularity yields stronger perceived displacement with diminishing returns. We present a prototype kinesthetic display that synchronizes visual feedback with motion-coupled vibrotactile pulses, demonstrating that tactile cues can provide a substantially more embodied sense of movement than vision alone. When combined, the two modalities produce the strongest and most coherent experience of "moving without moving." As an application of the Haptic Servos principle, Motionless Movement illustrates how action-contingent grain rendering can serve not only as a means for simulating material qualities, but also as a mechanism for altering perceived body dynamics.

Citation: `https://dl.acm.org/doi/10.1145/3613904.3642499`
Yuran Ding, **Nihar Sabnis**, Paul Strohmeier. *Motionless Movement: Towards Vibrotactile Kinesthetic Displays* In Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems, pp. 1-16. 2024. (Ding et al., 2024)

7.2 Application Contribution

These works illustrate how motion-coupled vibrotactile feedback can be embedded into real-world interaction contexts, using the core principle of Haptic Servos to augment everyday activities such as walking and sports. By applying the technique in ecologically valid settings, these projects highlight the practical versatility and experiential richness of action-coupled feedback.

7.2.1 Designing Interactive Shoes: A Foot-Based Application of Motion-Coupled Feedback

This project explores how motion-coupled vibrotactile feedback can extend beyond hand-held and body-mounted devices into foot-based interaction. In this project, we combine the physiological, biomechanical and technical design space for augmented footwear and introduce an open-source prototype sandal that integrates multiple pressure sensors (Force Sensitive Resistor (FSR)), Inertial Measurement Unit (IMU), and vibrotactile actuators. Similar to the grain-based input-output mapping algorithm, vibrotactile pulses are triggered whenever the sensed foot dynamics cross predefined thresholds. Through lab-based and real-world explorations, we showed how grain-based vibrations can evoke different compliant experiences while walking along with experiences of walking on different surfaces.

Citation: `https://dl.acm.org/doi/10.1145/3582700.3582728`

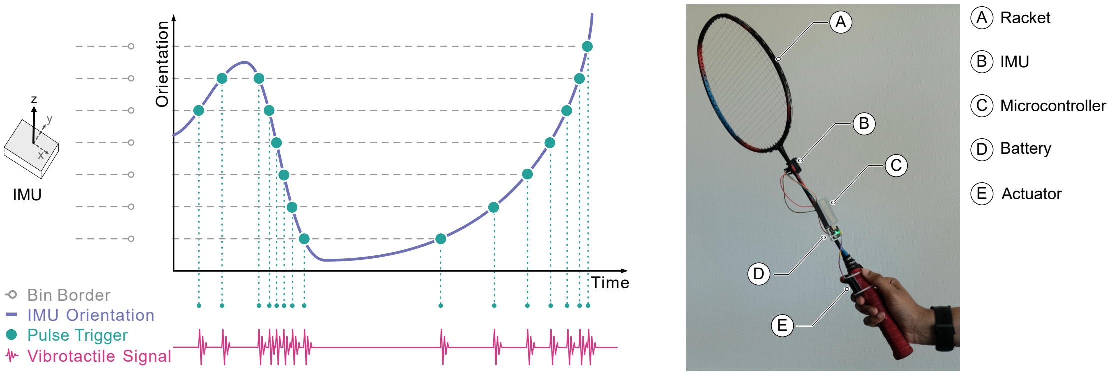

Figure 7.1: *The left figure visualizes the binning algorithm in which the vibrotactile pulses are generated based on the orientation changes of the IMU (pitch: x-axis, yaw: y-axis, roll: z-axis). The right figure shows VibRacket with the IMU sensor and the M5 Atom Echo vibration pipeline.*

Dennis Wittchen, Valentin Martinez-Missir, Sina Mavali, **Nihar Sabnis**, Courtney Reed, Paul Strohmeier. *Designing Interactive Shoes for Tactile Augmented Reality* Proceedings of the Augmented Humans International Conference, pp. 1-14. 2023. (Wittchen et al., 2023)

7.2.2 VibRacket: Designing and Experiencing Embodied Vibrotactile feedback on a Badminton Racket

With *VibRacket*, we wish to extend the core principles of Haptic Servos into the domain of sports, demonstrating how motion-coupled vibrotactile grains can be used to augment strokes used in motor sports using embodied feedback. We presented three versions of embodied vibrotactile feedback on the badminton racket as follows: 1) GUI Interfaced System; 2) Mountable Prototypes; 3) Handle-Integrated System with minimum alteration in the physical characteristics of the racket. We explore a badminton racket-based interface that detects changes in player movement during a swing and renders short vibrotactile pulses in response to the movement (see Figure 7.1). We use an IMU to sample racket movement in air and provide vibrotactile pulses using Haptic Servo inspired pipeline. The GUI is build upon the GUI use for designing tactile symbols with motion-coupled and continuous vibration in Chapter 5. The demo shows that motion-coupled grains can support real-time movement guidance in high-velocity interactions—an area where haptic systems often struggle due to latency or mechanical limitations. With this demo our goal is also to show how different feedback technologies including guidance-based, resistance-based and potentially embodied feedback for motor learning can be experienced using a single system.

Citation: `https://dl.acm.org/doi/10.1145/3749385.3749417`
Nihar Sabnis, Louis Badr, Gabriela Vega, Valentin Martinez-Missir, Paul Strohmeier. *VibRacket: Designing and Experiencing Embodied Vibrotactile Feedback on a Badminton Racket* Proceedings of the First Annual Conference on Human-Computer Interaction and Sports, pp. 1-5. 2025. (Sabnis et al., 2025c)

7.3 Theory Contribution

The following projects show how the underlying principle of close coupling between sensation and action can be used for creating electrotactile compliance as well as to probe fundamental perceptual mechanisms underlying our understanding of how a material percept is formed. Together, the following projects contribute to theory as the following: 1) They generalize the MCV principle beyond vibration, showing that the perceptual mechanism of discrete, action-synchronized pulses extends to electrotactile stimulation. This demonstrates that the illusion of compliance is not tied to a specific actuator technology but to a sensorimotor structure. 2) They expand the theoretical understanding of grain-based haptics from material perception to movement guidance, showing that the same principle that produces virtual deformability can also modulate kinematics.

7.3.1 Shaping Compliance: Electrotactile Grains for Spatially Resolved Material Illusions

This project extends the core idea behind Haptic Servos which is to use motion-coupled grains triggered by changes in user-applied action, to explore a fundamentally different modality: electrotactile stimulation. Whereas classical vibrotactile grains can successfully evoke a sense of pressing into compliant materials, they are mechanically bulky, difficult to localize, and limited when rendering spatially structured haptic information. This work introduces an electrotactile grain-based compliance illusion that divides the force-sensor range into bins and triggers short electrical pulses whenever the user's finger crosses a boundary. By leveraging localized stimulation on a 3×3 electrode array integrated into a thin, flexible, finger-worn device, the system can not only mimic virtual compliance but also render distinct shapes of compliance—such as squares, lines, and triangles—something that vibrotactile interfaces cannot achieve. A controlled study demonstrates that increasing the number of grains and the number of simultaneously active electrodes systematically increases perceived compliance, and that users can reliably perceive the intended shapes.

Beyond experimental validation, the work positions electrotactile grains as a theoretically rich extension of motion-coupled haptic illusions. The approach reveals how the grain principle generalizes across actuation modalities while preserving its perceptual mechanism: discrete, self-generated cues coupled to user action create haptic qualia associated with material deformation. Three application scenarios illustrate this potential—augmenting physical illustrations with touch-sensitive compliant regions, enriching touchscreens with material-like feel during interaction, and enabling shape-specific compliance cues in VR. This paper demonstrates that grain-based rendering is not merely a vibrotactile technique but a broader design paradigm for producing structured material qualities through action-contingent pulses, thus providing a bridge between tactile perception and electrotactile feedback design.

Citation: `https://dl.acm.org/doi/pdf/10.1145/3613904.3641907`
Arata Jingu, **Nihar Sabnis**, Paul Strohmeier, Jürgen Steimle. *Shaping Compliance: Inducing Haptic Illusion of Compliance in Different Shapes with Electrotactile Grains* In Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems, pp. 1-13. 2024. (Jingu et al., 2024)

7.3.2 Haptic Redirection: Modulating Hand Movement Speed via Grain-Based Feedback

This project extends the applicability of motion-coupled vibrotactile feedback typically used to render material experiences into the domain of movement guidance, to investigate whether vibrotactile feedback can subtly modulate hand motion in a way that feels embodied rather than externally imposed. We take inspiration from a simple but powerful observation: when a finger moves across a textured surface, the resulting vibration depends not only on the texture itself, but also on the speed of movement. Rather than using vibration to convey material qualities, as in traditional haptic rendering, in this work we invert the relationship and ask whether systematically altering vibrotactile feedback can change how fast the hand moves. Using a custom-built slider that delivers position-dependent vibration pulses (grains), we conducted three psychophysical studies manipulating grain density and frequency content while tracking hand motion. The results show that grain-based feedback can reliably modulate movement speed, and that when transitions between grain densities occur without participants' awareness, movement speed increases by approximately 20%. Importantly, this modulation emerges not as a symbolic cue but as a natural, embodied adjustment, consistent with the idea that motion-coupled vibrations are processed as self-generated.

Haptic redirection offers a new modality for guiding movement in VR without relying on visually induced illusions or noisy symbolic cues. It leverages sensorimotor contingencies and the embodied integration of motion-coupled vibrotactile feedback to produce subtle, unconscious modulation of action. As such, it expands the design space of haptic augmentation: from shaping perceived materiality to shaping the dynamics of movement, pointing toward future redirection techniques that are more natural, and deeply integrated with users' proprioceptive systems.

Citation: `https://dl.acm.org/doi/10.1145/3743049.3748585`
Easa AliAbbasi, **Nihar Sabnis**, Yuran Ding, Nadine Wagener, Paul Strohmeier. *Haptic Redirection: Modulating Hand Movement Speed with Vibrotactile Feedback* Proceedings of the 2025 Mensch und Computer, pp. 1-6. 2025. (AliAbbasi et al., 2025)

8 Results Overview

> *"If the only tool you have is a hammer, everything may appear as a nail – but using that hammer in different situations, we come to know the world —- and the world, in turn, reshapes the instrument's meaning."*
>
> (Modified Abraham Maslow's Quote)

In this chapter, I summarize the empirical and technical findings presented across the six previous chapters that constitute the core of this dissertation. While the broader implications of these results are discussed in the following chapter (Chapter 9), the present section focuses on the following observations: (1) how *input mappings* structure the interpretability of vibrotactile signals; (2) how specific *output parameters* of Motion-Coupled Vibration (MCV) shape tactile experiences; and (3) how these parameters jointly influence perception and experience. For the input mappings and output parameters I build upon the ones explored by Strohmeier (2019) by reflecting on the observations from the studies in this thesis.

8.1 Input Mappings: How Action Shapes Sensation

Across all studies, one of the clearest findings is that the *mapping between user action and vibrotactile feedback fundamentally determines how the resulting sensation is interpreted*. Even with identical vibration algorithms, changes in the type of input sensing and the corresponding, dimensionality, tactile modality, action type, and order of the input variable transform the resulting material experience.

8.1.1 Single-Input Sensing: Single Sensor, Many Materials

An interesting finding for us during the studies was that the sensing of a single input is far more expressive and contributes significantly (perhaps the most significantly) to elicit material experiences using MCV. Our prototypes from sliders, knobs and buttons to foot-pedals showed that the same algorithm can evoke radically different perceptual qualities depending on how the user interacts with the device. On a slider or a knob, MCV produced roughness or texture (Chapter 2). On a button, MCV produced compliance or "give." On a compliant foot pedal, MCV produced a sensation of mechanical friction or resistance, while on a rigid foot pedal, a sensation of softness and the pedal being pushed inside was elicited (Chapter 3). Moreover the same slider or knob in Chapter 2 could be used to design tactile symbols of warning, reassurance, ecstasy and disengagement in the contexts of futuristic steering and a mood jockey (Chapter 5). This supports one of the central themes of my dissertation: *material experience is co-constructed by the action itself along with biomechanics of the action and the context in which* *the action takes place.*

In other words, MCV does not ”render a texture”, but rather it participates in the sensorimotor loop where the body interprets the feedback in an embodied manner. The material experience is not elicited through the vibrotactile feedback alone, but arises from the interaction context and the movement affordances of the device. The same signal can thus be “rough” when sliding, “soft” when pressing, and “resistant” when rotating—reflecting the flexibility of embodied perception. With Haptic Servos, we wanted to bring this in practice to create a resuable tactile unit which can generate a range of material experiences for different actions with minimal hardware.

8.1.2 How Body and Object Location Shapes Meaning

Motion-Coupled Vibration was applied to a variety of different interactions done by distinct parts of the human body including finger, hands (single-handed and bimanual), feet, and objects which can be considered an extension of the user’s body during the applications. For instance, augmenting the feet or foot interfaces primarily produced feet-based and ground-material interactions experienced through the feet. On the other hand, bimanual interactions induced sensations of coordinated materiality, tension as well as distributed force. Augmenting objects such as the badminton racket (Section 7.2.2) create tool-mediated experiences such as ”moving a heavy racket”, which also points towards a strong sense of embodiment and ownership (Ihde, 1990). These findings contribute to a broader understanding of how embodiment structures tactile interpretation. The same tactile pattern is not universally meaningful; instead, the body part involved shapes the perceptual experience that emerges. This aligns with theories of active perception (O’regan et al., 2001), which base tactile experience not as something which is delivered to the body, but as co-constituted through bodily activity (Noë, 2004; Merleu-Ponty, 1962; Ratcliffe, 2013).

8.1.3 Impact of Action Type on Exploration and Experience

Input actions can be broadly classified into isotonic, isometric and elastic actions (Zhai et al., 1994). These distinctions matter because each action type affords a different form of motor control, and based on it, MCV through which the interaction is shaped. Isometric input can be defined as the application of force without having the corresponding displacement, such as pushing into a rigid foot pedal (Chapter 3) or pressing a button (Chapter 7). On the other hand isotonic input can be defined as the movement with minimal resistance; where the user’s displacement directly controls the system, examples include moving a slider, rotating a knob or pressing a compliant gas-pedal. Finally, elastic input is the deformation caused by the action where resistance increases with displacement. During my experiments, participants consistently explored isotonic actions (sliding, rotating, stretching) by varying speed, amplitude, and direction of the movement often engaging in rhythmic motions to make-sense of the vibrotactile pattern. By contrast, isometric exploration was more ’cautious’ and ’analytic’: participants experimented with micro-adjustments in pressure rather than large-scale movements, often pausing between pulses to decipher the relationship between action and sensation. Elastic actions on the other hand were somewhere in between. For the bow-arrow in Chapter 4 as well Section 4.8, the Exploratory Procedures employed by the participants were somewhere between isometric and isotonic explorations. They started their movements and then at an interesting point during their movement, switched towards the Exploratory Procedures of pausing and understanding the relation between their action and the feedback, before going back to performing the remaining movement.

With Motion-Coupled Vibration, isotonic actions induced experiences of *resistance*, *friction*, or *weight* when interacting with objects whereas isometric actions, made the object feel more *compliant* and *pushable*, in line with findings by Strohmeier (2019). There was no difference between isotonic and isometric actions on the foot pedal for the sense of control and objective performance which suggests that input actions affect the interaction and sense-making of MCV more than the overall performance.

8.1.4 Multi-Input Sensing

While most interaction modalities in my thesis relied on single-point sensing, our exploration of the material properties of the world goes beyond single-handed interaction. Bimanual interaction is one of the most common strategy of material exploration beyond using a single-finger or a single-hand. Bimanual interactions can be classified as asymmetric (think of differentiated bimanual activities such as dealing cards or playing a stringed musical instrument) or symmetric where the two hands play essentially the same role, either in phase (as in rope skipping or weightlifting) or out of phase (as in stretching, bending, twisting) (Guiard, 1987). For the sake of simplicity and inspired from previous literature (Heo et al., 2019), we focused on out of phase symmetric bimanual movements of stretching, bending, twisting. Beyond the interaction possibilities, in Section 4.8 and the second study of Chapter 4, we had bimanual applications of bow-arrow and magnets, where the amplitude of vibration which was based on the relative distance between the two hands showed promising results.

One of the fundamental extension of input space which bimanual interactions make over single-handed interactions is that of the relative movement, as described in Chapter 6. In single-handed interactions, the change in the sampled user movement is in relation to the ground or the minimum and maximum values of the sensor. However, bimanual interaction introduces a qualitatively different class of input mappings, those grounded in the relative differences between the two hands. Instead of treating each hand as an independent source of motion data, bimanual mappings can be defined over the relationship between their positions, orientations, or higher-order quantities such as velocity and acceleration. This relational input structure fundamentally expands the design space. As demonstrated in Chapter 6, mappings based on relative motion consistently outperformed absolute mappings. A key reason for this improvement is that relative mappings inherently synchronize the vibrotactile output across multiple actuators: the rendered pulses emerge from a unified relational signal rather than from two separately sampled streams. In contrast, absolute mappings treat each hand independently, which leads to asynchronous or phase-misaligned actuation, disrupting the coherence of the intended material illusion. Relative mappings, by coupling actuation to inter-hand dynamics, therefore create a more temporally aligned and perceptually integrated haptic experience.

These insights open new avenues of using relative measures between two seemingly disconnected inputs in the research we already conducted. For instance, in the augmented sandals (Section 7.2.1), currently, the feedback comes from local foot-ground interactions to create virtual compliance experiences. However, the augmentation can be based on the distance or the orientation of the different legs during the gait cycle to generate richer material experiences (e.g., virtual shearing forces in the terrain, changes in soil density, or emergent bipedal proprioceptive textures). Similarly, vARitouch (Section 7.1.1), originally developed for single-finger motion-coupled compliance, could be reimagined as a multi-input system where two fingers collaboratively shape a dynamic virtual material, expanding the expressive range beyond what either finger can achieve alone. Multi-input sensing and then the corresponding mappings provide opportunities to move beyond simulating isolated surfaces or button presses, towards distributed material renderings.

8.1.5 Effect of Movement Dimensions

In Chapter 6, when participants were asked to rate the connectedness and naturalness when performing unconstrained bending, stretching and twisting movements, we found that stretching was more stable and interpretable in terms of the induced vibrotactile experiences than actions involving movements over multiple dimensions such as bending and twisting. This in turn can be attributed to one-dimensional movements inducing clearer changes of the input being mapped to render the MCV, thus maintaining a stable experience with motor activity. Bending, in contrast, blends translation and rotation around multiple axes which can create ambiguous mappings that make the feedback rendered by a single actuator harder to interpret. Specifically if the input for triggering pulses for bending is related to position or orientation, it is hard to induce the experience of bending, whereas mapping both of them to the output leads to inconsistent material renderings. Future research should either have independent actuators for mapping multidimensional inputs or map the input of each dimension to independent signal parameters of a single actuator.

8.2 Output Parameters of the Vibrotactile Pulse

When I refer to the feedback parameters, I mean the specific properties of the vibrotactile pulse which is provided as the output of Motion-Coupled Vibration rendering to the user along with the density of grain (vibrotactile pulse) occurrences which I call

Granularity. The properties of the vibrotactile pulse typically include the signal properties of the designed vibration including the shape of the waveform, frequency, phase and other signal parameters (ADSR envelopes etc.). In this section, based on the experiments I conducted, I describe how variations in the different feedback parameters influence the user's resulting tactile experience.

8.2.1 Granularity

Second to input action, one of the most significant parameters of rendering material experiences can most likely be attributed granularity. Conceptually, granularity can be defined as the occurrence of vibrotactile impulses with respect to the amount of movement performed. Granularity also directly interacts with input mappings.

Across multiple interactions and devices ranging from sliders and knobs (Chapter 2) to foot-based gas pedals (Chapter 3) and bimanual stretching/twisting actions (Chapter 6), the empirical trend was remarkably consistent: higher granularity amplifies the intensity of the perceived material quality, while lower granularity diminishes or smoothens it. This modulation held independent of the specific quality being evoked (e.g., roughness, compliance, resistance, friction), suggesting that granularity can be considered as a "gain" parameter for rendering materiality using Motion-Coupled Vibration. For example, in pressure-based interactions such as the pressing of a button and pushing into an augmented pedal, increasing granularity led participants to describe the interaction as *softer, more compliant*, or *more yielding*. In contrast, decreasing granularity made the experience feel firmer, and less interesting closer to a *rigid object* or *stiffer material*. Similarly, for isotonic actions higher granularity is associated with *finer* and *smoother* textures, whereas coarser granularity was associated with *bumpy*, and *less detailed impressions*. These observations are in line with Heo et al. (2019) and Strohmeier et al. (2020).

Generally, higher granularity creates a denser, more continuous tactile stream, which perceptually induces richer material qualities whereas, lower granularity leaves more temporal gaps between pulses, which can reduce the perceptual coherence of the illusion making the feedback feel more mechanical or artificial. Thus, granularity can be considered a design parameter to render a broader spectrum of the same style of virtual material experiences.

8.2.2 Type of Waveform

The type of waveform used to generate vibrotactile pulses has received comparatively limited attention in the Motion-Coupled Vibration literature. Most of MCV research has used a sine wave, either as pure tones (Strohmeier et al., 2020) or a modified version thereof like a multi-cycle sine wave that decays over time (Kildal, 2010; Heo et al., 2019). In contrast, I introduced a method of using *asymmetric vibrotactile pulses* coupled to user action, thereby generating not only material-like sensations but also *self-generated pseudo-forces* that differ qualitatively from experiences produced by symmetric vibrations.

Although continuous asymmetric vibration is established in research as a technique for creating illusory forces (Tomohiro Amemiya et al., 2008; Culbertson et al., 2017b), its use in the form of discrete pulses remained unexplored. We hypothesized that the temporal structure of having a continuous series of pulses contributed more to the experience of force, than the shape of the pulse itself. Previous research did indicate that it is the shape of the pulse by showing that symmetric vibrations do not induce pseudo forces (Tomohiro Amemiya et al., 2008). However, no research explored whether a continuous pulses or series of single pulses with temporal delays which induced force sensations. Hence, during the initial exploration, we were not sure if having the pulses in a temporal succession and coupled to user movement, would generate a pseudo force sensation. Our initial exploration of coupling asymmetric vibration pulses with changes in orientation of IMU could induce pseudo forces, but the granularity became too dense, eliminating the overall induced pseudo force effect. However, when the same pulses were instead mapped to linear motion, the system successfully produced a clear perception of force—results that are described in detail in Chapter 4. These observations suggest that while waveform shape has traditionally been treated as a secondary design parameter, the waveform asymmetry is central to producing compelling directional illusions.

Asymmetric vibration, most perceivable at a frequency of 40Hz, generates asymmetric skin-stretch to stimulate direction sensitive meissner corpuscles, which induce the pseudo forces (Culbertson et al., 2014). Hence, the actuators need to be in direct contact with the skin to induce pseudo forces, which limits the augmentation space to the body which has a high density of meissner corpuscles such as fingertips and lips (Neubarth et al., 2020). In contrast, the advantage of non-direction inducing (symmetric) waveforms is that they typically target the pacinian corpuscles which are not direction sensitive and hence vibrations can be provided through objects or direct body actuation. Thus, although motion-coupled asymmetric vibrations, broaden the space of tactile illusions induced with MCV, they are still one step farther from Universal tactile displays.

8.2.3 Type of Mapping

Although in no part of my thesis, did I experimentally investigate input-output mappings, for Motion-Coupled Asymmetric Vibration, I explored several mappings types which revealed distinct perceptual affordances. Below I describe my experiences. Linear Mapping that coupled movement velocity to vibration amplitude proved particularly compelling: increasing amplitude with velocity produced a strong, immersive sense of pseudo force that peaked convincingly at high speed and decelerated naturally, whereas decreasing amplitude with increasing velocity generated an unusual “pull–release” sensation that may have niche applications such as isometric or resistance-

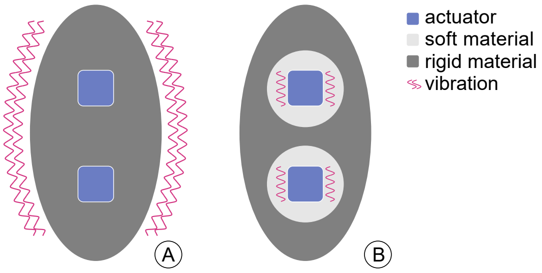

Figure 8.1: *Illustration of multiple actuators embedded in: (A) a rigid objects leading to vibration of the entire object; (B) soft material to provide localized vibrations, taken from (Wittchen et al., 2023).*

training scenarios. Linear Mapping based on user displacement to vibration amplitude were similarly effective, enabling clear impressions of pushing against virtual media (e.g., wind, elastic bands) and producing convincing pseudo force illusions. By contrast, linear mappings from movement velocity or displacement to granularity (bins) were generally less effective: coarse modulation often broke the illusion, while subtle changes were difficult to perceive reliably. Gaussian Mapping introduced more nuanced dynamics; mapping velocity to amplitude yielded smooth, bump-like force envelopes, whereas mapping velocity to bin count produced vivid, yoyo-like sensations during short, rapid movements. Gaussian Mapping based on displacement were mixed where, amplitude-based variants produced convincing "virtual bumps," while bin-based variants felt less coherent. Overall, the clearest and most robust pseudo-force experiences emerged from mappings that modulated amplitude rather than bin count, with linear velocity and displacement mapped to vibration amplitude standing out as the most immersive and intuitively interpretable, suggesting that amplitude-based control offers the most perceptually stable foundation for future motion-coupled pseudo-force rendering.

8.2.4 Actuator Placement and Vibration Localization

Throughout my thesis, I explored augmenting different body-locations and interactive objects. One of the most important observations we made throughout our prototypes and applications is: *the spatial proximity between the site of actuation and the body part performing the exploratory action, is crucial and higher proximity leads to coherent and embodied virtual material experiences*. This observation is in line with tactile physiology where mechanoreceptors exhibit spatially localized receptive fields (Johansson et al., 1979). Further, from a biomechanical standpoint, actuators should ideally avoid bony surfaces and instead be placed on soft-tissue regions like the muscle belly and glaborous skin, where mechanical coupling to the skin is strongest and less dampened by rigid anatomical structures (Rittweger, 2010).

For isotonic actions, the actuator should ideally move with the limb generating the action itself. If multiple parts of the body move, the location of vibrotactile pulses should be the body-part which needs to experience the material sensation. For instance, if the slider needs to feel rough, typically the slider or the fingers should be augmented.

Whereas if the intended sensation was to elicit an experience of the forearm moving through a textured material, the forearm should be the site of augmentation rather than the manipulated object. This distinction was clearly noted when we augmented the badminton racket (Section 7.2.2). Augmenting the racket led to inducing sensations of moving the racket through ”different midair textures” rather than the arm or hand moving through the virtual texture.

Another important observation concerns *vibration localization*. The vibrations should be localized to the body part which is performing the action. Propagation of vibration across the body or object, diminishes the specificity of the rendered material experience. Especially in foot-based interaction, where mechanoreceptor density and the overall sensitivity is low, vibration localization becomes crucial (Nurse et al., 1999; Strzalkowski et al., 2015). Hence there is a tradeoff between using strong enough vibration and isolating the vibration. Based on these observations, we enclosed actuators in silicon casts to localize the vibrations in the augmented shoes (Section 7.2.1) as shown in Figure 8.1, as well as in the design of the actuator mounting mechanism for foot-pedals (Chapter 3). We also used the same principle for Section 7.1.1 where the actuator was enclosed in a soft-silicon finger-cap. These enclosures improved localization while perceptually increasing the *crispness* of the vibrotactile pulse.

8.2.5 Single-Point and Multi-Point Actuation

Single-point actuation is a term I use to refer to providing MCV with a single actuator on a specific point on the body or the object with which the user interacts. Upto Chapter 6 most projects and applications focused on single-point actuation. These explorations revealed limitations of single-site stimulation for creating distributed material experiences. We asked, *how multiple actuators might jointly contribute to a coherent tactile percept?*

I use the term multi-point actuation to denote configurations in which Motion-Coupled Vibration – generated either from shared input data (sampling of user action) or from independent sensors – are delivered at more than one bodily or object-based locations. Although we did explore multi-point actuation in the VR applications of Chapter 4 as well as for Invisibow (Section 4.8), the actuators functioned independently of each other. We did not consider the idea of exploring the possibilities of multi-point actuation to coordinate temporal, spatial or relational behavior of the actuation to induce material experiences beyond those elicited by single-point actuation. While with CollabJam (Wittchen et al., 2025), we introduced a multi-point actuation platform, its goal was to observe collaborative pattern creation rather than to render unified material sensations and hence, the vibrations were not motion-coupled.

But, in Chapter 6, we found a way to design bimanual material experiences with multi-point vibrotactile actuation which opened up abundant opportunities to design the feedback. A key observation in our exploration of bimanual vibrotactile feedback systems was that distributed material experiences are strongly shaped by the temporal structure of vibrotactile output: synchronizing the onset of pulses across actuators produces a coherent, unified percept, whereas temporal misalignment disrupts the shared material experience.

One way in which we explored the relationship between multiple actuators using motion-coupled vibrotactile stimuli is using crosstalk. Crosstalk can be defined as the partial or complete transmission and modulation of vibrotactile signals from one hand to the other hand. Referring to Figure 6.6, we observed that increasing the amount of crosstalk amplified the perceived material quality similar to granularity for single-point actuation, while decreasing the crosstalk mitigated the perceived material quality (Section 8.2.1). Thus similar to *granularity* can be considered the “gain” parameter for single-point actuation, crosstalk can be considered as the “gain” parameter for multi-point actuation.

Another important consideration with multiple actuators is the relation between the actuators. We introduced a *leader–follower* coupling strategy, in which the actuator contributing the larger magnitude of movement served as the leader, receiving full-strength MCV pulses, while the follower received crosstalk-modulated feedback. Determining the leader and follower can be based on the overall movement, predefined or by comparing the rate of change of sampled action in either of the sensors. Our experience showed that predefining leader and follower breaks the illusion; instead, it must be computed dynamically based on velocity, acceleration, or rate of change of sensed movement. However, future work should look into strategies for different bimanual actions described in Section 8.1.4.

To evaluate the quality of the overall material percept induced with bimanual or multi-point actuation, we assert the evaluation of connectedness as a primary metric. Without connectedness the material experience is no longer homogeneous and can be separated into discrete experiences, undermining the opportunities of multi-point actuation. Collectively, these insights can position multi-point actuation as a promising next step for motion-coupled vibrotactile rendering.

8.3 Perceptual and Experiential Effects of MCV

Along with conducting experiments, I demonstrated our prototypes in multiple workshops, social events as well as unofficial demo presentations along with official ones done most recently at Eurohaptics 2024 and Sports HCI in November 2025. Below, I outline the repeated observations across the studies and free-form explorations of this type of rendering that shed light on why Motion-Coupled Vibration (MCV) feels embodied as well as what factors affect the elicited material experiences.

Objective and Subjective Control

Participants in the psychophysics following task as well as VR-ecological study for our pedal study did not have any objective benefit on the controllability of the interface withe motion-coupled vibrations (Chapter 3). However there was a clear preference within the participants for the pedal interface with vibrotactile augmentation, and they believed it led them to improved performance, which was not the case. A similar trade-off between performance and control with material experiences was noted previously by Strohmeier et al. (2016). Thus, it seems that altering the material experience gives users the impression of having greater control over the interaction. Yet, because the mechanical interaction remains unchanged, this effect is subjective and does not lead to measurable performance gains.

Sense of Agency (SoA)

With Motion-Coupled Vibration, participants often perceived the vibration stimulus as self-generated rather than an external stimulus. Moreover, participants mentioned that with MCV, the prototypes feel satisfying to use. Whereas without vibrotactile augmentation the same interaction feels dull and empty. Moreover, participants mentioned that they receive more information of their movement with their movement with the vibrotactile feedback, especially when it is an isotonic movement such as moving the slider (Chapter 2) or exploring with the badminton racket (Section 7.2.2). Finally, with the foot pedal studies, we clearly observed that the augmentation improved the perceived control and participants described the pedal as “more predictable” or “more responsive”. Thus, SoA becomes a key resource in the design of haptic interfaces to make the tactile interactions feel embodied, intuitive and satisfying for the users.

Emergence of Experience

One of the most striking questions which we get when people are exploring our prototypes is, “What is the prototype supposed to do?” or “What is vibration telling me?”. However as soon as we guide them to interact or think about the vibration experience, they have their ”Aha!” moment. This emergence of material-like experiences can be understood as a phenomenological progression: users first touch the device, feel the vibration pulses, begin to explore it in motion, and eventually experience a continuous material quality, as summarized in Figure 2.8. Part of this shift in experience might stem from the limited fidelity of vibration rendering and because people cannot instantly make sense of temporally distributed sequence of vibrations. These observations show that MCV is not just a technical approach of rendering thoughtful vibrations but also is a perceptual strategy integrated with our sensorimotor loops.

Cultural and Lived Experiences

As observed in the thematic analysis of Chapter 5, the designed tactile symbol was usually associated with lived experience. I was fortunate to demonstrate my prototypes in India along with the studies being conducted in Germany. An important aspect emerged when prototypes were shown in diverse contexts: similar vibrotactile patterns evoked different metaphors and interpretations depending on the user’s cultural background and lived experience. For example the same tactile symbols for warning and reassurance Figure 5.5a, the experience was associated with driving a car on the Autobahn [1] with lane-assist, whereas few school students in India expressed it as *resting their hand on the table of a flour mill.*

8.4 Conclusion

In this chapter, I presented the empirical and conceptual insights that emerged across the studies of my dissertation. I outlined how input mappings – including the dimensionality of user action, the body parts involved, the distinction between isotonic and isometric exploration, and the transition from absolute to relational (bimanual) sensing – fundamentally shape how motion-coupled vibrotactile feedback is interpreted. I then describe how output parameters such as granularity, waveform asymmetry, actuator placement, and multi-point actuation contribute to induce virtual material experiences.

Together, these parameters not only shape how an object is perceived but also how the interaction is understood: Motion-Coupled Vibration enhances subjective control, agency, and embodied engagement, even when performance does not objectively improve. Thus, input mappings and output parameters together provide insights into designing tactile experiences that feel meaningful, self-generated, and experientially rich, a key aspect of embodied interaction.

In the following chapters, I discuss the broader implications of my research in Chapter 9 and directions for future work in Chapter 10.

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[1] Autobahn are high speed expressways in Germany

9 Implications

Recently, the top scientists in the field of haptics were interviewed about the grand challenges and future directions that the field of haptics should dedicate itself. The following are the points which came out of the interviews and also to which my thesis contributes. Referring to the summarized article of the interviews (Colgate et al., 2025), I quote:

- ”Developing models of the cognitive systems involved in decoding and processing tactile information so that these could be used to inform the design of devices.”
- ”The importance of understanding and simulating physical interactions.”
- ”The need to develop more sophisticated tactile communication systems for consumer products that go beyond the delivery of simple vibrations.”

In this section, I reflect on these points in the light of the research I conducted during my Ph.D. period. Section 9.1 and Section 9.2 relate to the cognitive systems involved and how they can inform the design of devices. Section 9.3 looks at understanding and simulating haptic interactions from a phenomenological perspective. Finally Section 9.4 presents Motion-Coupled Vibration as a commercially viable option for providing more expressive haptic feedback in consumer products.

9.1 Sensory Attenuation as a measure of Embodiment

In Section 8.3, we looked at the perceptual and experiential underpinnings of MCV. However, one of the most important findings of my thesis was that MCV feels intuitive and embodied. This can be associated to the principle of Sensory Attenuation (SA), as seen in Chapter 4 where we show how Sensory Attenuation can be used as a design resource (Section 4.6.1). Here I further extend the applicability of sensory attenuation combined with Magnitude Estimation as an objective measure for quantifying embodiment.

Embodiment is a multi-layered phenomenon discussed in many fields including phenomenology, cognitive science, philosophy of technology, and contemporary HCI (Merleau-Ponty et al., 2013; Ihde, 2002; Verbeek, 2005; Hornbæk et al., 2019). At its core, embodiment concerns the extent to which a tool, interface, or technological artifact becomes integrated into the user’s body schema -— the pre-reflective structure through which we organize perception and action (Marshall et al., 2013). Merleau-Ponty describes embodiment as the moment when an external object “withdraws” from consciousness as an object of attention and becomes an extension of the body (Merleau-Ponty et al., 2013). Recent research has explored the framing of embodiment in terms of sensorimotor contingencies: when an artifact affords reliable, reciprocal couplings between action and sensory feedback, it becomes experientially transparent and integrated with the user's interaction (Hay et al., 2018). For example, when writing with a pen, our attention shifts from holding the pen to feeling the interaction between the pen's tip and the page, and because the sensory feedback matches your movements, the pen temporarily becomes an extension of your body. Referring to Chapter 5, embodiment contrasts with hermeneutic mediation: hermeneutic relations require interpretive effort, whereas embodied relations enable the user to act through the technology rather than on it.

Embodiment has many experiential properties like fluency, transparency, pre-reflective integration, sensorimotor predictability, and a sense of agency over the resulting action. Despite its importance in interaction design, the field currently lacks a robust, objective metric for quantifying embodiment in a manner suitable for empirical HCI research (Strohmeier, 2019). Most studies rely on subjective questionnaires, behavioral proxies, or indirect measures of agency, which —- while valuable —- do not capture the full dynamics of how perception changes when an external tool becomes an extension of the body.

Sensory Attenuation (SA) offers a promising entry point to this measurement problem. SA refers to the perceptual phenomenon in which sensations resulting from one's own actions are experienced as weaker or less salient than externally generated sensations. This reduction is thought to arise from internal forward models in the sensorimotor system: when the brain predicts the sensory consequences of an action, it attenuates the incoming sensory signal (Bays et al., 2006; Kilteni et al., 2022). When a device or interface becomes embodied, the user feels that the sensory feedback is intrinsic or self-generated; consequently, feedback generated through voluntary movement should exhibit reduced perceived intensity relative to identical feedback delivered externally or without contingency.

In this sense, SA provides insight into at least one essential dimension of embodiment: sensorimotor integration. If the user's action produces a vibrotactile event that is tightly coupled, predictable, and experientially "owned," then the perceptual system treats that feedback as self-generated and attenuates it. Conversely, when feedback feels externally imposed, or not aligned with one's action, attenuation decreases and sensations appear more intrusive or vivid. The strength of SA therefore provides a quantifiable window into how deeply the tool has been integrated into the body schema. This perspective positions sensory attenuation as a candidate for an objective measurement of embodiment.

This was observed particularly in Chapter 4 where with Motion-Coupled Vibration, the vibration feels attenuated compared to the same intensity vibrations generated as continuous vibrations, while the material sensation induced by MCV was maintained.

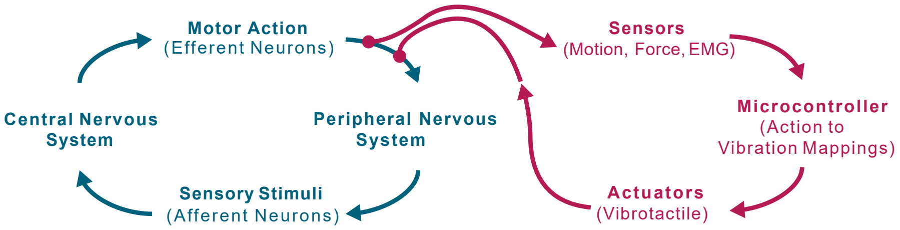

Figure 9.1: *Blue: Sensorimotor system. When performing a controlled movement, motor action and sensory feedback form a closed loop system which enables the planned movement execution. Pink: Motion-Coupled Vibration is provided while performing the motor action which is perceived to be intrinsic and augments the closed loop sensorimotor system.* (*Originally created by Dr. Paul Strohmeier and used in his ERC Grant: Kinesthetic Displays: Creating Embodied Experiences of Movement Using Vibrotactile Feedback.*)

9.2 Tactile Perception: A Closed-Loop Perceptual Process

Another useful lens through which we can think about Motion-Coupled Vibration is the distinction between open and closed-loop theories of perception. Traditional literature on tactile perception assumes it to be an open-loop process: sensory information flows from the environment, through the sense organs, to the brain, where it is interpreted into percepts (Connor et al., 1992). In this view, perception is a largely passive, serial process where bodily movement introduces noise that must later be corrected or filtered out (Noë, 2004). However, this process struggles to explain why perception often unfolds over extended temporal durations, why Exploratory Procedures (e.g., rubbing a surface, tapping, squeezing, modulating pressure) are crucial for tactile judgment, and why material perception remains stable despite large variations in movement speed or direction.

In contrast, closed-loop models of perception treat perception as an active, convergent process (Gibson, 1962; Ahissar et al., 2016). In this model, the brain generates motor commands which move sense organs. These movements alter the incoming sensory stream, which is then fed back into the nervous system, driving further motor adjustments. In this framework, perception is not a one-way process; instead, perception emerges when the sensorimotor loop converges toward a steady-state with the environment and movement is not a confound to be compensated for, but a necessary part of how perceptual content arises.

Tactile perception being a closed-loop process aligns with the empirical findings of my dissertation. Motion-coupled vibrotactile feedback is, by definition, closed-loop: the user's movement generates the vibration, which in turn shapes further movement and interpretation, as seen in Figure 9.1[1]. Whether in bimanual movements of stretching, pushing into pedals, or rotating a knob, participants associated meaning from the coupling of action and feedback. The difficulty many users had in understanding the prototypes until they "played" with them is better explained under a closed-loop

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[1] European Research Council Grant- Kinesthetic Displays: `https://cordis.europa.eu/project/id/101165100`

model than an open-loop one.

More broadly, closed-loop perception provides conceptual grounding for why motion-coupling is effective for rendering virtual material experiences. When the feedback is directly derived from a user's action, the system becomes part of their sensorimotor loop, enabling a perceptual convergence similar to how we make sense of real materials. Thus, motion-coupled haptics succeeds not because it perfectly simulates real-world forces or textures, but because it engages the sensorimotor system responsible for making sense of touch in the first place.

Developing models based on the closed-loop perception will allow us to design haptic interfaces that work with the natural dynamics of human perception. Such models can specify when and how tactile cues should be delivered, how they should relate to the user's motion, and how the brain's expectations might shape the resulting percept, enabling feedback that feel more intuitive and embodied.

9.3 Haptics as Calm Technology/ Mediation theory

Beyond augmenting the interaction, Motion-Coupled Vibration (MCV) also shapes the experience of interaction as the interaction unfolds. The systems and algorithms developed in this thesis including Haptic Servos, augmented foot pedals, crosstalk-based MCV for bimanual material experiences, highlight that haptic feedback is more useful when it operates not as interruptive feedback but as a subtle, embodied, and continuously available feedback coupled to user action. This finding positions MCV within the broader discourse of Calm Technology, where digital information recedes into the periphery of attention until it becomes relevant (Weiser et al., 1997). Unlike traditional haptic notifications that demand focus through discrete alerts, MCV are coupled to user action and induce meaning only through user engagement, while fading into the background when not acted upon. This tight sensorimotor contingency allows MCV to remain "calm" because the user's own movement governs when, how, and why the signal becomes salient. Thus MCV can be used to minimize the perceptible invasiveness of digital interactions, especially those mediated through touch, in everyday life.

Calm technology can be linked with technological mediation, especially background mediation, where a tool goes into the background and only comes to our attention when it for instance, stops working (air-conditioner in the room). Referring to Verbeek (2005) technologies can mediate information in at least three modes: *embodied mediation*, in which the tool a tool becomes transparent and extends the user's bodily capabilities (a walking cane or a stylus in use); *hermeneutic mediation*, in which the tool provides symbolic information requiring interpretation (as with thermometers or dashboards), and *background mediation*. Motion-Coupled Vibration belong to the first category of embodied mediation of information.

In my research and in our everyday experience, much of the continuous vibration patterns like those given by our digital devices, need to be interpreted by the user and are primarily hermeneutic. In contrast, when exploring a surface or crushing a

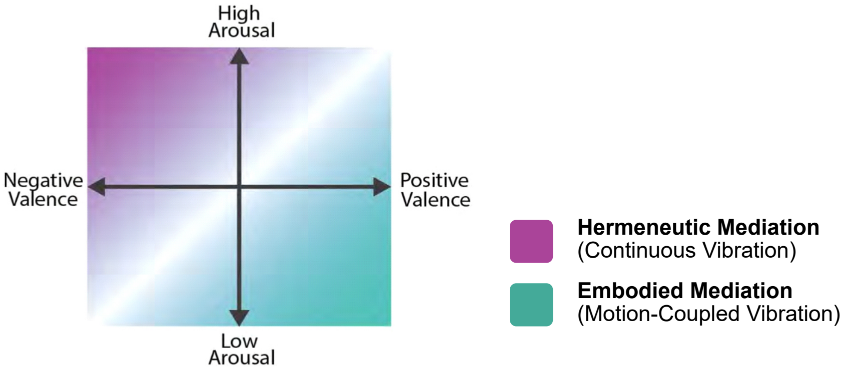

Figure 9.2: *Patterns of Designed Tactile Symbols in Chapter 5 with Continuous and Motion-coupled vibration mapped to Russel's circumplex model (Russell, 1980). This figure is originally made by Dr. Paul Strohmeier.*

piece of paper, the vibrations are generated through our actions (MCV) and induce a material experience which is embodied. Designing tactile symbols (Chapter 5) using continuous and Motion-Coupled Vibration demonstrate that continuous vibrations are preferable for action-independent, urgent, negative-valence, high-arousal states such as warnings; while MCV can be used for positive-valence, low-arousal symbols such as reassurance or disengagement, refer Figure 9.2. However these distinctions cannot be thought of as *black and white* as seen by the designed tactile symbols by haptic experts where the symbols ranged over a spectrum from embodied to hermeneutic mediation to indicate an increase in the warning levels. Thus, different forms of mediation can be combined, contrasted and transitioned to design a tactile symbol. This observation contributes to post-phenomenology by showing how vibrotactile feedback can traverse the mediation modes depending on the intended application.

Another way to think about tactile interaction is based on the work by Katz et al. (2013) on proximal and distal interaction (refer Chapter 2). During proximal interactions, such as experiencing the feel or temperature of a material requires direct contact with the object. In contrast, for distal interactions, direct contact is not required. Examples include feeling the vibration of a food-processor or a train passing by. MCV communicates information through proximal interaction, where the tactile information is received through the user's action rather than being imposed on the user. Yet as seen in the designed tactile symbols (Chapter 5), vibrotactile patterns can also serve distal communicative functions when decoupled from movement and imbued with semantic meaning. Therefore, proximal and distal modes of interaction can coexist within the same haptic channel, depending on how feedback is temporally and semantically structured.

Importantly, these distinctions between embodied and hermeneutic, proximal and distal are not binaries. Instead, *the value lies in understanding this continuum along which haptic mediation operates, and designing for it.* Our findings reinforce this continuum: the more tightly a vibration is coupled to bodily movement, the more proximal and embodied it becomes; the more abstract, detached, or symbolically encoded it is, the more distal and hermeneutic it becomes. This also explains why the same vibration can feel “material-like” in one context yet “message-like” in another, thus highlighting that the source of its meaning is not the signal itself but its relationship to bodily action.

With these findings, we can go back to the theme of 'the importance of understanding and simulating physical interactions' especially in haptics and Human-Computer Interaction. By designing technologies that work with rather than against the sensorimotor system while leveraging embodied mediation and proximal interaction, interfaces can become more intuitive, more meaningful, and deeply integrated into action. Motion-Coupled Vibration can serve as a foundation for calm interfaces which mediate information in an embodied manner. Along with replicating physical sensations, future tactile interfaces should also mediate information, based on our knowledge of how the body experiences, interprets, and engages with information in ways that feel natural, meaningful, and experientially rich.

9.4 Going beyond "Buzz" Vibrations in Consumer Haptics

In the current consumer electronic devices, vibrotactile feedback is one of the most commonly used forms of haptic feedback. This vibrotactile feedback is often limited to simple, generic vibration patterns, like the familiar "buzz" indicating a notification, button press, incoming message, making a payment or change in direction on the map. These vibrations observed in smartphones, smartwatches, game controllers, touchpads and other consumer devices, are rendered using basic vibration motors such as Eccentric Rotating Mass and Linear Resonant Actuators. Companies have started developing more complex and expressive form of haptics, such as the vibrations coupled to capacitive pressure sensing on iPhones giving an illusion of a button[2], tactile sensations that simulate recoil of a weapon or a jolt of a collision[3], touchscreen augmentation (Gordon et al., 2019), and even feedback on gas pedals to make them feel active[4]. However, this still is a narrow fraction of what vibrotactile technology is capable of.

Over the course of my dissertation, I transition from developing custom hardware, software prototypes including Haptic Servos, Tangible User Interface, Graphical User Interface to modifying industrial hardware (augmenting pedals and algorithms for rendering pseudo forces) towards finally developing motion-coupled vibrotactile algorithms that, in principle, use commercially available hand-controllers to render material experiences. The experiments conducted with the augmented foot-pedal (Chapter 3) showed how by adding minimal hardware, and by coupling the user's pedal actions with vibrotactile output, one can render a richer sense of resistance, compliance, and material experiences with more “relatable feel,” rather than a mere buzz. Similarly with the crosstalk-based motion-coupled vibrotactile feedback (Chapter 6)

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[2] https://tinyurl.com/titan-haptics-technology

[3] https://www.amorserv.com/insights/applications-of-haptic-feedback

[4] https://www.bosch-press.nl/pressportal/nl/en/press-release-585.html

we showed the same hardware which is commercially used to create buzz sensations to indicate lifting, grabbing or colliding an object can be further extended to render material experiences of stretching, bending and twisting.

Through this dissertation I aim to contribute towards closing the gap between academic haptic research and industrial / consumer deployment. I demonstrate that with relatively minimal hardware (a small actuator, basic sensing) but carefully designed input–output mappings and vibrotactile rendering strategies, one can generate perceptually rich and functionally meaningful tactile experiences. Thus, we can move from haptics being only a notification channel to one where we are able to convey texture, compliance, resistance and even force sensations, thus enriching how digital systems mediate our interactions with the world.

9.5 Conclusion

To summarize, in this section, I connect my research with some prominent challenges identified for the future of haptic technology (Colgate et al., 2025). By thinking about sensory attenuation to quantify embodiment, and Motion-Coupled Vibration through the lens of closed-loop perception, this section contributes to models of how tactile information is decoded and integrated within the sensorimotor system. I further situate these findings within theories of technological mediation and calm technology highlighting how tactile feedback can be designed to shift between embodied and hermeneutic modes, supporting different types of mediating information. Finally, I connect how the projects described in this dissertation can be extended to consumer haptic feedback helping it move from the current ”buzz” notifications towards richer, more expressive vibrotactile feedback.

10 Future Research Directions

Beyond the grand challenges relevant to my thesis mentioned in Chapter 9, the 20 years report by Colgate et al. (2025) also mentioned future directions which the field of haptics should dedicate itself to, which I quote:

- ”Having a better understanding of human sensorimotor capabilities so that haptic effects can assist in motor skill learning.”
- ”The need for generalized and reconfigurable haptic displays that can be applied in multiple use cases.”

Although this was always my vision, the report from top scientists in the field of haptics, helps in reinforcing my vision. As next steps for investigating the applicability of motion-coupled vibrations, in this chapter, I elaborate on two concrete research directions: (1) Embodied Vibrotactile Feedback (EVF) to Enhance Motor Learning; (2) Towards Universal tactile displays.

10.1 Embodied Vibrotactile Feedback for Motor Learning

I have been playing badminton semi-professionally for more than 15 years now. In parallel, I am enthusiastic in understanding how people learn. How people learn movements with and without haptic feedback has always been of interest to me. In my master thesis, I showed that pseudo forces induced through asymmetric vibrations can be used as an external feedback mechanism for providing movement guidance (Sabnis, 2021). Although movement guidance provides real-time assistance or feedback to shape a movement as it is being performed, it does not necessarily produce long-term skill improvement.

Whether serving in tennis, practicing yoga, playing the piano, or regaining balance after injury, *motor skills* are fundamental to humans and require coordinated, purposeful movements. Motor Learning is the process by which movements are acquired, refined, and retained over time with repeated practice (Magill et al., 2010). Central to motor learning is *feedback* that helps learners understand what went well, what did not and how to improve their intended motor action. Feedback is typically classified as *intrinsic*, arising naturally from the body’s sensory systems during movement, or *augmented*, delivered through external cues using different sensory modalities such as vision, audio, proprioception and touch (Sigrist et al., 2013). Among these modalities, the tactile modality is unique as it simultaneously senses and shapes movement, and covers the whole body (Van Breda et al., 2017). Tactile cues are typically provided using skin-mounted vibrotactile actuators or body-worn wearables, which provide real-time, spatially encoded signals. Research has shown that vibrotactile feedback assists

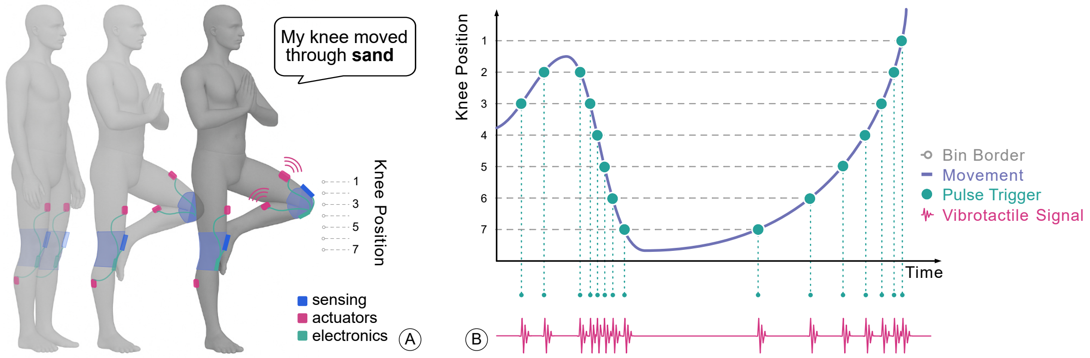

Figure 10.1: *EVF for Single Leg Balance Training. (A) Placement of sensing, actuator and electronics on the body with the knee position being sampled (using on-body sensors or motion-capture technology). (B) Algorithm generating vibrotactile pulses when the knee position crosses a bin, thus dynamically coupling the pulse sequence to the knee motion giving the user an experience of moving the knee through virtual material.*

motor learning by accelerating learning rate, improving target-motion accuracy and quicker responsiveness (Lieberman et al., 2007; Spelmezan et al., 2009). More recent work done by Rokhmanova et al. (2025) use vibration pulses to provide movement guidance in real-time. However, current vibrotactile feedback approaches risk sensory overload (Van Breda et al., 2017) and lack intuitiveness and realism (Culbertson et al., 2018), making the feedback feel extrinsic and disruptive to motor learning. Research suggests that effective motor learning requires vibrotactile feedback that is meaningful, metaphor-based, or elicits realistic sensations (Spelmezan et al., 2009; Jansen et al., 2004). **Yet, no known literature explores how to design meaningful[1] and realistic[2] vibrotactile feedback for motor learning.**

In contrast, when balancing in yoga or re-learning to walk we receive subtle tactile feedback from muscles, tendons, and foot contact providing essential cues that the body uses to evaluate and adjust its actions, thus changing our movement (Bensmaïa et al., 2005a). *In daily life, we naturally adapt our walking pattern depending on whether we are on ice, clay, or dry grass—highlighting how material properties directly shape movement. This raises a key question: if materials can alter how we move, can we deliberately design tactile stimuli that augment, guide movements to enhance motor learning?*

Throughout my thesis, I show that vibrations coupled to user actions elicit virtual material experiences, where vibrations are not perceived as vibrations, but rather as intrinsic and natural properties of the interaction. When vibrotactile feedback is optimally synchronized with the measured user action such that it consistently correlates with the motor activity, the feedback feels intrinsic and integrated with the sensorimotor loop. I refer to this feedback as Embodied Vibrotactile Feedback (EVF) and it can augment, or shape movement perception and reinforce motor learning while remaining non-disruptive and intrinsic as shown in Chapter 2, Chapter 4 and Chapter 5. The

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[1] intuitive, task-relevant information that clearly guides the learner's actions

[2] sensory information that closely mimics natural bodily sensations or environmental interactions

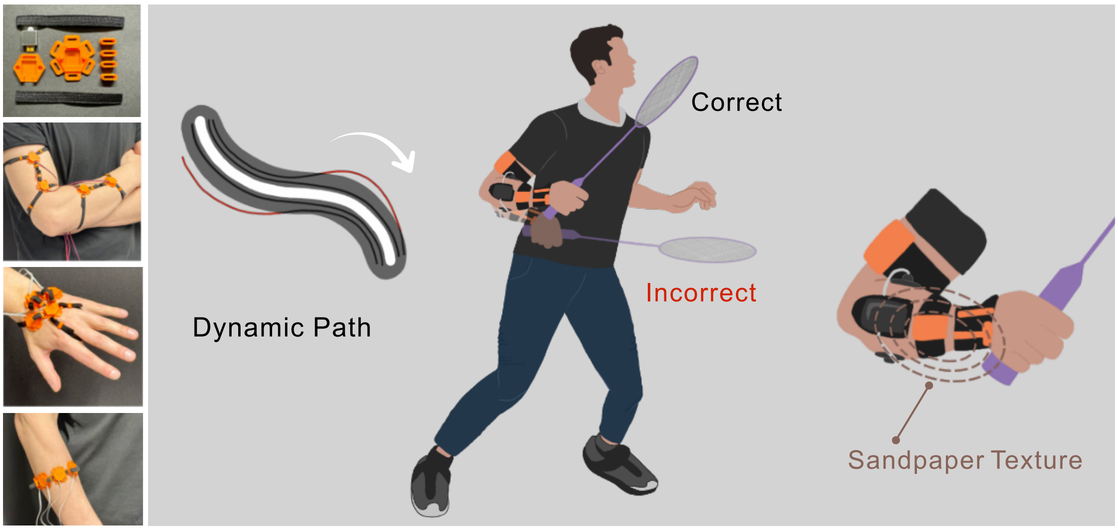

Figure 10.2: *Concept of EVF provided to correct the wrist position while preparing for a badminton smash. The left column shows different position options for placing vibrotactile actuators on the user's body using the Wittchen et al. (2025) platform. The zoomed in view of the arm shows the placement of actuators (in orange) which are rendering a sandpaper texture to resist the incorrect movement.*

findings of rendering MCV closely align with key requirements of effective feedback for motor learning: temporally precise, embodied, movement-contingent information that augments proprioceptive awareness without disrupting the movement to be performed. However, most of the interactions using Motion-Coupled Vibration have been evaluated as one-time interaction, and hence if the modified behavior due to augmentation is able to generate any lasting effects needs to be evaluated. Key questions include whether skills learned under MCV generalize to unaugmented conditions, how the learning of movements becomes faster, and enable transfer of motor skills over different contexts.

I believe Embodied Vibrotactile Feedback will pave the way of providing more natural and embodied feedback for motor skill learning, acquisition and transfer. Future work should investigate how MCV can be used to shape movement execution during skill acquisition by continuously modulating the felt dynamics of an action. For example, increasing granularity could exaggerate perceived resistance during incorrect movement trajectories, while smoother, lower-granularity feedback could reinforce efficient motor patterns. Similarly, asymmetric MCV could be used to introduce directional force illusions that bias motion toward desired trajectories without explicit instruction. Such approaches would allow errors to be corrected not through cognitive interpretation of feedback ("you were too slow" or "you overshot"), but through direct changes in how the movement itself feels, similar to how the knee movement for balance training feels like moving the knee through sand, rather than "you moved too fast", see Figure 10.1.

Moreover, research should look at designing MCV for distinct phases of the movement, rather than treating the motion as a single homogeneous event. The movements can be classified into at least three phases:

1. ***Preparation***, where posture, grip, and pre-tension are established;
2. ***Acceleration***, where force generation and coordination dominate;
3. ***Follow-through***, where dissipation of momentum and stability become critical.

MCV can be differentially mapped to each phase. During preparation, vibrotactile cues could reinforce optimal joint alignment, grip force, or stance stability through low-granularity, low-amplitude signals. Acceleration phases are typically Ballistic Movements which are characterized by rapid execution and a strong dependence on feedforward motor planning. Providing Motion-Coupled Vibration for ballistic movements presents challenges of rendering vibrotactile stimuli and perceiving the temporally distributed stimuli within an extremely short temporal interval while the movement is typically large. Hence, motion-coupled vibrotactile feedback can be aligned with the follow-through phases of the action by encoding movement quality into tactile signals that accompany and follow the signal. For instance, exaggerated vibrotactile resistance during improper swing trajectories, or directional pseudo-forces aligned with optimal motion paths, could reinforce correct feedforward motor plans over repeated trials. Thus, movement phase-specific mappings would allow MCV to act not as a generic augmentation, but as a temporally structured learning signal embedded within the natural kinematics of movement. Figure 10.2 shows a concept application of Embodied Vibrotactile Feedback to improve the wrist posture for the preparation phase during a badminton movement and VibRacket (Section 7.2.2) can be the first step in that direction.

10.2 Towards Universal Tactile Displays

The work presented in this dissertation points towards the vision of Universal tactile displays: *systems capable of rendering a broad spectrum of vibrotactile sensations, ranging from symbolic notifications to embodied material qualities including force cues.* Just as screens function as general-purpose visual displays capable of showing text, images, and videos with a single display, Universal tactile displays would function as a general-purpose *tactile channel*, capable of rendering a variety of material properties including textures, compliance, resistance, motion cues and abstract tactile symbols.

As mentioned in Section 9.4, current vibrotactile displays in consumer technology still rely on simple vibrotactile buzz patterns rendered with a single actuator, occasionally refined into richer but still narrow experiences (e.g., simulated button clicks, weapon recoil, or basic surface textures). Even advanced research prototypes often render particular tactile effects or illusions (e.g., texture, pseudo-force, or skin-stretch), implemented through elaborate and customized hardware (O. Schneider et al., 2022) and advanced signal processing. By contrast, the findings of my thesis indicate that a broad range of material-like sensations can be induced with relatively simple hardware – low-cost actuators and sensors – when combined with carefully designed Motion-Coupled Vibration. Using this as the basis for Universal tactile displays, we propose a more universal tactile system that prioritizes sensorimotor principles over mechanical complexity. While this thesis does not claim to realize such a display, the findings provide several concrete directions for how this vision may be approached through future work based on motion-coupled vibrotactile feedback.

10.2.1 Hardware Scalability and Algorithmic Generalization

One of the crucial implications of Chapter 6 is the importance of distributed and multi-point motion-coupled vibration for rendering spatially extended material experiences. While most of the systems explored here relied on single-point actuation, rendering bimanual haptic experiences demonstrates that coherent material percepts emerge when vibrotactile stimulation is rendered across multiple contact points and coupled through relative motion. This suggests that Universal tactile displays will require multi-point actuation across fingers, hands, limbs, or even larger regions of the body. Future work must therefore investigate scalable hardware architectures that allow motion-coupled vibrotactile feedback to be delivered at multiple locations simultaneously, while maintaining temporal synchronization, controllable crosstalk, and spatial localization (based on findings of Chapter 8). Importantly, such systems should move beyond independent multi-actuator stimulation towards coordinated, relational actuation strategies that reflect material exploration with the body.

Moreover, the mappings explored in this thesis remain tightly coupled to specific tasks, devices and movements. Future work should abstract these into device- independent mapping frameworks that operate on higher-level sensorimotor descriptors such as relative motion, shear, strain, and compliance. Such frameworks would allow the same material percepts to be rendered across different form factors (e.g., handheld objects, shoes and other wearables).

10.2.2 Beyond Vibration: Multimodal Tactile Output

Although vibrotactile feedback is the crux of my thesis, a truly general-purpose tactile display cannot rely on vibration alone. Many material properties such as temperature, rigidity, skin stretch (when exploring the material) are not sufficiently addressed through vibrotactile stimulation. Universal tactile displays should therefore integrate multiple tactile output modalities including variable stiffness, temperature control, and localized deformation. This integration could be perceived as embodied based on the foundation of motion-coupling, thus allowing material impressions to emerge through coordinated modulation of multiple physical parameters rather than through isolated effects. Current limitations in this direction include the lack of a multi-modality haptic output device as well as the way in which our body interprets thermal and vibratory perceptual stimuli.

10.2.3 Developing Standardized Evaluation Protocols

Standardized evaluation protocols need to be developed for Universal tactile displays, which would be capable of rendering multiple material effects over more than one tactile modality. Current evaluations of vibrotactile interfaces, including those in this thesis remain task specific, focusing on specific properties such as induced force sensations (Chapter 4, connectedness (Chapter 6) or compliance (Section 7.1.1). While these studies are necessary, Universal tactile displays will require broader benchmarking frameworks that can simultaneously capture a range of induced material experiences, and quantify embodiment. Similar to how in Chapter 4, we showed that Sensory Attenuation can be used as a metric for quantifying embodiment, establishing cross-task perceptual metrics, and shared experimental paradigms that allow different classes of tactile experiences to be compared within the same evaluation space, need to be developed. These protocols will improve reproducibility, enable systematic comparisons and be essential for translating Universal tactile displays from isolated research prototypes towards scalable, consumer centered tactile display systems.

10.2.4 Closed-Loop Tactile Modeling as a Design Framework

Ahissar et al. (2016) and Noë (2004) have provided strong evidence of perception being a closed-loop perceptual process. The findings in my thesis further posit that tactile perception follows a closed-loop perceptual mechanism and this perception can be augmented by rendering real-time vibrotactile feedback coupled to user action. Thus Motion-Coupled Vibration can be situated within a closed-loop theory of perception, in which tactile meaning emerges through continuous sensorimotor coupling rather than through passive stimulus delivery. Although difficult due to the variety of perceptual experiences being created due to similar tactile stimuli, a critical next step is to formalize this perspective into computational design and rendering models. Future work should develop closed-loop perceptual models that explicitly link motor variables, such as position, velocity, acceleration, and applied force to expected vibrotactile outcomes. By embedding such models into haptic control architectures, feedback parameters could be tuned to render more robust material experiences which are more perceptually stable. This would allow tactile displays to adapt to individual user movement strategies and interaction styles, thus narrowing the gap between psychophysics and practical haptic interface engineering.

10.2.5 Standardized Motion-Coupled Vibration Primitives

A key future direction emerging from this dissertation is the development of a standardized library of motion–vibration primitives for general-purpose vibrotactile rendering. Across the studies presented previously, the same foundational principles of Motion-Coupled Vibration successfully rendered roughness, compliance, resistance, and force-like sensations across a wide range of interfaces, including sliders, pedals, bimanual systems, and handheld devices. These observations suggest that a finite set of parametric primitives such as granularity, waveform asymmetry, temporal distribution and sensorimotor coupling laws, are sufficient to span a large portion of the vibrotactile design space. Next steps in this direction should identify a minimal basis set of such primitives, systematically mapping them onto perceptual material dimensions and develop device independent abstractions that enable the same primitive to be executed over multiple hardware configurations. Establishing such a framework would move vibrotactile design closer to the paradigm of audio synthesis, where reusable filters and oscillators give access to expressive flexibility scientific reproducibility, while taking a foundational step towards scalable general-purpose tactile displays.

10.3 Conclusion

In this chapter, I outlined two concrete directions for extending the work of this thesis in ways that directly address the grand challenges identified by Colgate et al. (2025). First, I proposed *Embodied Vibrotactile Feedback* as a paradigm to enhance motor learning, leveraging motion-coupled vibrations to provide temporally precise, intrinsic, and phase-specific guidance that is aligned with human sensorimotor capabilities rather than imposed on top of them. Second, I articulated a research agenda *Towards Universal Tactile Displays*, arguing that multi-point motion-coupled rendering, multimodal output, standardized evaluation protocols, closed-loop tactile models, and motion–vibration primitives together form a realistic pathway towards generalized and reconfigurable haptic displays. Taken together, these directions translate the conceptual and empirical contributions of this dissertation into actionable steps for future research, showing how motion-coupled vibrotactile feedback can help both to deepen our understanding of tactile perception and to inform the design of richer, more versatile haptic technologies.

The next and final chapter of the thesis completes the loop by returning to the overarching question. It reflects on how the empirical findings, theoretical contributions, and future research directions developed throughout this dissertation collectively change the way of designing touch technologies. By revisiting the original motivations through the lens of the results and implications articulated in the preceding chapters, I synthesize the contributions of this dissertation, and clarify their significance for the field of haptics and human–computer interaction.

11 Concluding Thoughts

"Technology should feel like a part of us, not apart from us."

I started this dissertation with a simple but profound observation: that touch is not merely a channel of receiving information, but a way of *being in the world*. From a child grasping a mother's hand to the practiced movement of an athlete or a musician, touch is woven into how we learn, act, and understand. Over the course of this work, I approached touch not as a technical problem of rendering vibrations, but as an experiential question: how technology might participate in the same sensorimotor loops through which meaning already arises in everyday life. What emerged is not a single device, algorithm, or study, but a perspective: that Motion-Coupled Vibration can function as a bridge between engineered systems and embodied human experience.

Looking back, the ideas presented in this thesis from augmented hardware like Tangible User Interface (TUI) and foot pedals to motion-coupled asymmetric vibration and crosstalk-based vibrotactile rendering algorithms, and the many prototypes in between, can be seen as different ways of asking the same question: *When does vibration stop being a signal and start becoming an experience?* Again and again, I observed that when vibration is tightly coupled to action, it is no longer perceived as an external message imposed on the body. Instead, it becomes part of the action itself—-experienced as resistance, weight, friction, compliance, or force. This shift from "buzz" to ""material" is a transformation in how the body relates to technology. In such moments, the interface retreats from attention and what comes forward is the experience of acting in a world that feels physically responsive. In this sense, Motion-Coupled Vibration became, throughout my work, not just a rendering technique, but a method for designing *embodied relations* between humans and technology.

This work has been shaped profoundly by ideas of embodiment, mediation, and non-dualistic views of action and perception. The semi-structured interviews we conducted based on post-phenomenology inspired methods, helped articulate how technologies shape our relation to the world. In many strands of Indian philosophy–whether in yoga, classical music, or craft–knowledge is not something one merely possesses, but something one *enacts through the body.* Motor skill matures not through abstract instruction alone, but through attentive repetition, sensation, and refinement of movement. In this light, the pursuit of embodied vibrotactile feedback for motor learning feels more like a continuation of an ancient insight: that the body itself is the primary site of understanding. Motion-coupled vibration, when it works well, does not teach by telling, it teaches by reshaping how movement feels.

There is also a quieter lesson that this research has taught me. Across workshops, public demos, laboratories, and informal trials, people often began by asking, *"What is this vibration supposed to mean?"* And yet, after a few moments of interaction, the question changed to, *"Oh—I feel it now."* That moment of transition-—from confusion to felt understanding-—captures something essential about haptics and on a broader level, about learning more broadly. Some forms of knowledge cannot be explained; they must be grown through experience. This has influenced how I now think about interface design, and how if technology is to genuinely support human skill, it must speak the language of the body, not only the language of symbols.

Finally, this thesis reflects my own journey as a researcher moving between engineering, perception, design, and philosophy; between laboratory experiments and lived experiences; between Germany and India; between badminton and prototyping. The questions that guided this work were never only technical. They were also personal: How can I feel a more personal and comforting vibration when my mom calls as opposed to a more tense or alerting when the caller is a stranger? How do we learn? How do we feel in control? When and how does a tool become part of us? And how can digital systems be designed not to distract from our bodies, but to return us to them? I do not see the answers offered here as final. Rather, I see them as a set of openings—toward tactile technologies that are calmer, more embodied, more expressive, and more humane. If this thesis contributes even a small step toward technologies that feel less like machines we operate and more like worlds we can inhabit through touch, then it has fulfilled what I quietly hoped for when I began.

Closing the Loop

As my dissertation comes to a close, I return to the question that opened it: how touch shapes our way of being in the world. From the infant's first grasp to the skilled gestures of an expert hand, tactile experience unfolds not as passive sensation but as lived engagement. Through this work I have tried to translate this deeply human mode of knowing into technological form, through motion-coupled vibration that does not merely signal, but participates in action. In this sense, the contributions of this thesis are not only technical or scientific, but also reflective of an older insight shared by both phenomenology and Indian philosophy: that perception is inseparable from action, and that the boundary between self, tool, and world is not fixed, but continuously changes through bodily experience.

Glossary

affordances	Action possibilities offered by an object, environment, or interface, as perceived by a user based on their capabilities and the object's properties. (*p. 48, 172*)
Ballistic Movements	Ballistic movement are rapid, explosive, voluntary actions in the body, like a forceful punch or quick jump, characterized by maximum speed/acceleration, brief muscle contractions, and high firing rates, where the movement is usually pre-programmed.. (*p. 192*)
Calm Technology	Calm technology or calm design is a type of information technology where the interaction between the technology and its user is designed to occur in the user's periphery rather than constantly at the center of attention.. (*p. 185*)
Eccentric Rotating Mass	An ERM (Eccentric Rotating Mass) motor is a haptic motor that uses a DC signal to spin an off-center mass on its shaft, generating omni-directional centrifugal force that results in a more general, low-frequency 'rumble' vibration.. (*p. 187*)
elastic	Describing a material or interaction that deforms under applied force and returns to its original shape when the force is removed; in HCI, often used to characterize input techniques or virtual objects that simulate spring-like or compliant behavior. (*p. 172*)
Embodied	Relating to how perception, action, and cognition arise through the body's interaction with the world; grounded in sensorimotor experience rather than abstract reasoning alone. (*p. 8, 10*)
Embodiment	The integration of a tool, interface, or technology into a user's sensorimotor experience such that it becomes experienced as part of the body rather than an external object; in HCI, embodiment refers to how interactions feel natural, intuitive, and seamlessly connected to a user's actions and perception. (*p. 182*)
Eurohaptics	The EuroHaptics Conference is a major international conference on haptic science and technology. It serves as a gathering for researchers and engineers from academia and industry to present and discuss the latest findings across all aspects of haptics, including: human haptic perception, haptic interface design and technology, haptic modeling and rendering, AR/VR, human-computer interaction, and robotics.. (*p. 179*)
Exploratory Procedures	Based on (Lederman et al., 1987), exploratory procedures can be defined as distinct patterns of hand movements that people perform to extract specific information about an object's properties. An example could be rubbing fingers across the surface of the understand the roughness of the surface.. (*p. 2, 173, 184*)

Gaussian Mapping	A mapping between input and output in which the relationship is shaped by a Gaussian (normal) function, typically producing a smooth, bell-shaped response curve; in interaction design, it can be used to modulate feedback intensity or sensitivity so that outputs peak around a central input value and taper off gradually. (*p. 177*)
glaborous skin	Glabrous skin is the type of skin that is devoid of hair follicles (non-hairy). It is primarily found on the palms of the hands and the soles of the feet, and also on the lips and certain parts of the external genitalia.. (*p. 177*)
Haptic Servos	Haptic Servos are self-contained vibrotactile systems which which encapsulate all timing-critical elements and can create or augment virtual material experiences. (*p. 11, 12, 172, 185, 187*)
hapticians	Based on (O. Schneider et al., 2017), a haptician is someone who is skilled at designing and developing haptic sensations, technology, or experiences. (*p. 13*)
Hermeneutic	Pertaining to interpretation; often used to describe how tools or technologies shape the way users interpret, understand, or make meaning of the world. (*p. 8, 10, 106*)
isometric	Describing an interaction or muscle action involving constant length while force changes; in haptics, often refers to input where position is fixed and force varies. (*p. 48, 172*)
isotonic	Describing an interaction or muscle action involving constant force while the length changes; in haptics, often refers to input where force is steady and position varies. (*p. 48, 172*)
Linear Mapping	A mapping between input and output in which changes in the output are directly proportional to changes in the input; in interaction design, it provides a predictable, constant relationship often used for controlling parameters such as speed, position, or feedback intensity. (*p. 176, 177*)
Linear Resonant Actuators	An LRA (Linear Resonant Actuator) is a haptic motor that uses an AC signal to typically drive a magnetic mass suspended with springs to produce a faster, more precise, and energy-efficient vibration along a single axis, typically operating near its resonant frequency.. (*p. 187*)
Magnitude Estimation	A psychophysical method in which participants assign numerical values to the perceived intensity of a stimulus, allowing researchers to measure subjective perception on a ratio scale; commonly used in HCI to quantify users' judgments of force, vibration strength, or other sensory attributes. (*p. 182*)
Mediation	The process by which a tool or technology transforms, shapes, or extends the user's perception or action in interacting with the environment. (*p. 8, 10*)

Microphenomenology	A qualitative interview method used to elicit fine-grained descriptions of lived experience, focusing on the sensory, attentional, and temporal details of a participant's subjective experience, often used in HCI to understand subtle aspects of interaction. (*p. 9, 11, 16*)
Motor Learning	The process through which users acquire, refine, and retain movement skills through practice and experience; in HCI, it refers to how interaction techniques become more efficient and embodied as users adapt their motor actions over time. (*p. 12, 189*)
Semi-structured Interview	A qualitative data collection method in which the interviewer follows a flexible guide of key questions while allowing participants to elaborate, introduce new topics, and shape the conversation; widely used in HCI for exploring user perspectives, practices, and interpretations. (*p. 9*)
Sense of Agency	The subjective experience of controlling one's own actions and their effects in the world; in HCI, it refers to the feeling that interactions and system responses are initiated and governed by the user's intentions. (*p. 10, 13, 75*)
Sensory Attenuation	A reduction in the perceived intensity of sensations that are self-generated, allowing the nervous system to distinguish between the sensory consequences of one's own actions and external events; in HCI, it helps explain why action-coupled feedback may feel more natural or less intrusive. (*p. 10, 182*)
Sports HCI	The SportsHCI conference brings together researchers and practitioners to discuss and shape the future of Human-Computer Interaction (HCI) in sports, focusing on its broad impact from improving performance and preventing injury to enhancing the athlete and fan experience.. (*p. 179*)
Universal tactile displays	Universal tactile displays are a theoretical or aspirational class of haptic interfaces designed to recreate the full range of haptic sensations humans can perceive, much like a universal visual display (e.g., a screen) can display any image or video.. (*p. 12, 176, 189, 192–194*)

Acronyms

EVF	Embodied Vibrotactile Feedback. (*p. 189–192*)
FSR	Force Sensitive Resistor. (*p. 167*)
FTV	Finger Tendon Vibration. (*p. 105*)
GUI	Graphical User Interface. (*p. 9, 11, 107, 168, 187*)
HCI	Human-Computer Interaction. (*p. 6, 8, 10, 14, 15, 106, 135, 183, 187*)
IMU	Inertial Measurement Unit. (*p. 167, 168*)
MCAV	Motion-Coupled Asymmetric Vibration. (*p. 75, 176*)
MCV	Motion-Coupled Vibration. (*p. vii, 5–11, 13, 15, 16, 47, 48, 74, 75, 106, 107, 134, 135, 169, 171–176, 178–188, 191, 192, 194, 196*)
SA	Sensory Attenuation. (*p. 48, 182, 183, 194*)
SoA	Sense of Agency. (*p. 48, 180*)
TUI	Tangible User Interface. (*p. 9, 107, 187, 196*)
VR	Virtual Reality. (*p. vii, 75, 135, 179*)

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Appendices

A Examples for Controlling Haptic Servos

Listing A.1 demonstrates how to cycle through the Haptic Servo's material experiences (5 s for each experience) using the Arduino servo library. This code can be flashed on any Arduino compatible microcontroller. This microcontroller connects to the Haptic Servo using a standard servo cable (GND, VCC, Signal – see Pulse Control in **Figure 2.3**).

```
#include <Servo.h>

// create an instance of the Arduino servo library
Servo haptic_servo;
// define the pin where the haptic servo is connected
static int servo_pin = 9;
static int max_angle = 180;
// set the initial value for the configuration
int current_angle = 0;

void setup() {
  haptic_servo.attach(servo_pin);
}

void loop() {
  // set the haptic servo's configuration
  haptic_servo.write(current_angle);
  if (current_angle == max_angle) {
    // reset the configuration position
    current_angle = 0;
  } else {
    // increment the vibration config (servo angle)
    current_angle++;
  }
  // wait for 5 seconds
  delay(5000);
}
```

Listing A.1: *Cycle through the material experiences of a Haptic Servo.*

Listing A.2 demonstrates connecting three Haptic Servos to a microcontroller (e.g., Arduino). In this example we assume that there is a tangible UI with three elements, such as sliders, potentiometers, or buttons. The designers have, through tweaking and experimentation found a configuration (config_A) that stands out compared to another (config_B). This can be used to tactually highlight a single UI element. In the current application each UI element is highlighted for a minute, sequentially. In a final implementation one might make such highlights contextually relevant.

```
#include <Servo.h>

static int hs_num = 3;
// create 3 instances of haptic servos
Servo hs[hs_num];
// define the pin where the haptic servos are connected
static int hs_pins[hs_num] = {9, 10, 11};
// 100 bins at 250 Hz, feels like bright but deep press
static int config_A = 167;
// 10 bins at 40 Hz, feels dull and bumpy
static int config_B = 42;


void setup() {
  for (uint8_t i=0; i<hs_num; i++) {
    // attach haptic servos to GPIO pins
    hs[i].attach(hs_pins[i]);
    // and set vibration config (servo angle)
    hs[i].write(config_A);
  }
}

void loop() {
  //use the first haptic servo as tactual highlight
  hs[0].write(config_A);
  hs[1].write(config_B);
  hs[2].write(config_B);
  // wait for 60 seconds
  delay(60000);

  //use the second haptic servo as tactual highlight
  hs[0].write(config_B);
  hs[1].write(config_A);
  hs[2].write(config_B);
  // wait for 60 seconds
  delay(60000);

  //use the third haptic servo as tactual highlight
  hs[0].write(config_B);
  hs[1].write(config_B);
  hs[2].write(config_A);
  // wait for 60 seconds
  delay(60000);
}
```

Listing A.2: *Use multiple Haptic Servos at once with individual material experiences (vibration configurations).*

B Motion-Coupled Asymmetric Vibration

B.1 Technical Evaluation

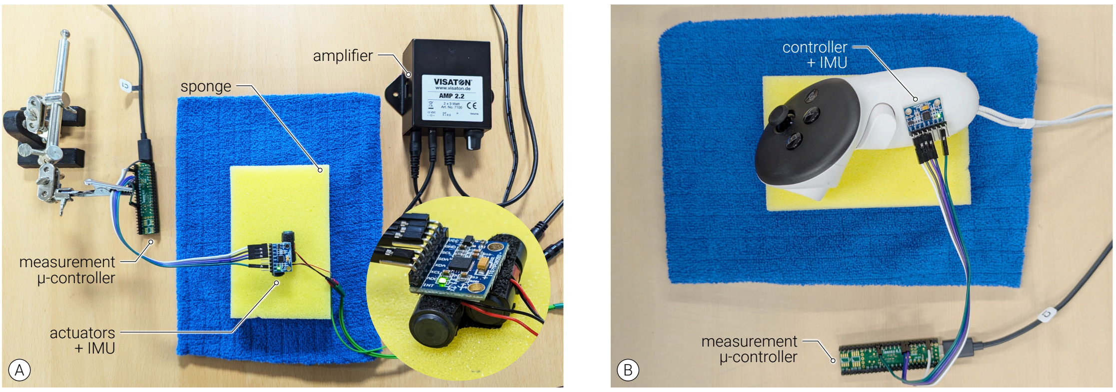


Figure B.1: *Technical setup used for measuring the output accelerations of the TacHammers (left) and the hand controller (right).*

The technical setup used for measuring the output accelerations of the actuators and hand controller is shown in Figure B.1-left and Figure B.1-right, respectively. An MPU6050 inertial measurement unit (IMU) with an on-board accelerometer is attached to the actuators with a medical grade double-sided tape to ensure that there is no slipping between the actuator and the IMU sensor, and no dampening of the vibrations. For accurate acceleration measurements of the actuator, the IMU-actuators system was placed on a sponge to ensure that the recorded accelerations were representative of the actuator's true dynamic output. The sponge served as a vibration isolator while reducing mechanical coupling with external surfaces Hwang et al., 2012; Ferguson et al., 2018. The IMU was calibrated to measure the accelerations in G-values up to a maximum of 8 G. The sampling frequency of the IMU is 1 kHz. The pulses for motion-coupled asymmetric vibration were generated by sampling the movement trajectory of a participant from Study 1 as input. The continuous asymmetric vibration was generated by stitching together the generated pulses during the motion-coupled asymmetric vibration (see Section 4.4).

Figure B.3- Ⓐ shows the measured acceleration of the TacHammers for the four input conditions with three amplitudes used in Study 1. The input pulses are rendered with high-fidelity as observed in the measured accelerations in Figure B.2, indicating little to no phase difference being introduced by having two actuators connected to each other. The differences in the driving signal (Figure B.2, blue) and measured acceleration (Figure B.2, red) can be attributed to actuator characteristics, additional mass of the IMU, and the mechanical coupling between the sensor and the actuator. Further, we observed a delay of ~10 milliseconds between the oscilloscope and the accelerom-

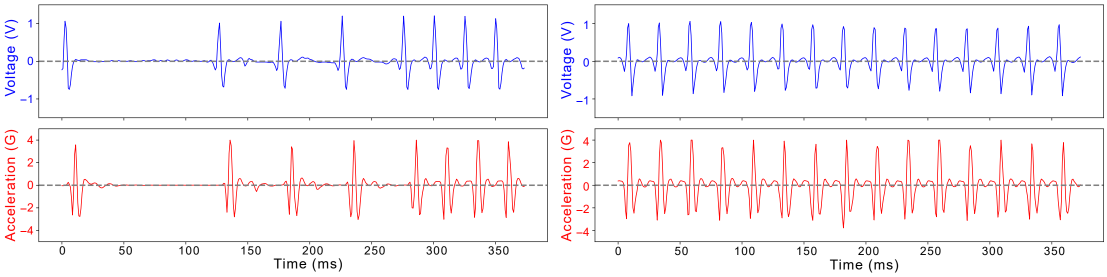


Figure B.2: *The driving signal (blue) used for generating motion-coupled asymmetric vibration (left) as well as continuous asymmetric vibration (right) along with the measured accelerations (red). These are the same signals at the 100% amplitude level for MotionCoupled and ContinuousStationary in Figure B.3.*

eter output, adhering to the actuator latency [1]. The output acceleration of the hand controller is shown in Figure B.3-Ⓑ. To characterize the signal and provide summary statistics, we calculated the sliding window RMS (*slidingRMS*) with 50 samples window size (i.e., 50 ms interval) to account for the difference in the number of pulses of all the measured output signals. We also calculated the mean of the maximum accelerations (*MeanPeak*) for each condition to account for low-frequency oscillatory behavior. Referring to Table B.1, the *slidingRMS* and *MeanPeak* closely follow the amplitude of the input signal. The results show that the *HandController* has lower vibration intensity compared to the *TacHammers*.

Table B.1: *Summary statistics of measured acceleration.*

Condition	Amplitude (%)	Sliding RMS	Mean Peak (G)
MotionCoupled (A)	40	0.57 (40.15%)	1.60 (40.68%)
	70	0.99 (70.22%)	2.75 (69.72%)
	100	1.41 (100.00%)	3.94 (100.00%)
MotionDecoupled (B)	40	0.57 (40.15%)	1.60 (40.68%)
	70	0.99 (70.22%)	2.75 (69.72%)
	100	1.41 (100.00%)	3.94 (100.00%)
ContinousMoving (C)	40	0.51 (34.13%)	1.64 (40.94%)
	70	1.01 (67.12%)	2.99 (74.63%)
	100	1.50 (100.00%)	4.00 (100.00%)
ContinuousStationary (D)	40	0.51 (34.13%)	1.64 (40.94%)
	70	1.01 (67.12%)	2.99 (74.63%)
	100	1.50 (100.00%)	4.00 (100.00%)
HandController	40	0.36 (36.81%)	0.51 (38.72%)
	70	0.71 (72.45%)	0.93 (71.22%)
	100	0.98 (100.00%)	1.31 (100.00%)

---

[1] Latency in the TacHammer Datasheet: `https://titanhaptics.com/wp-content/uploads/2023/05/TacHammer-Drake-Datasheet-1.pdf`

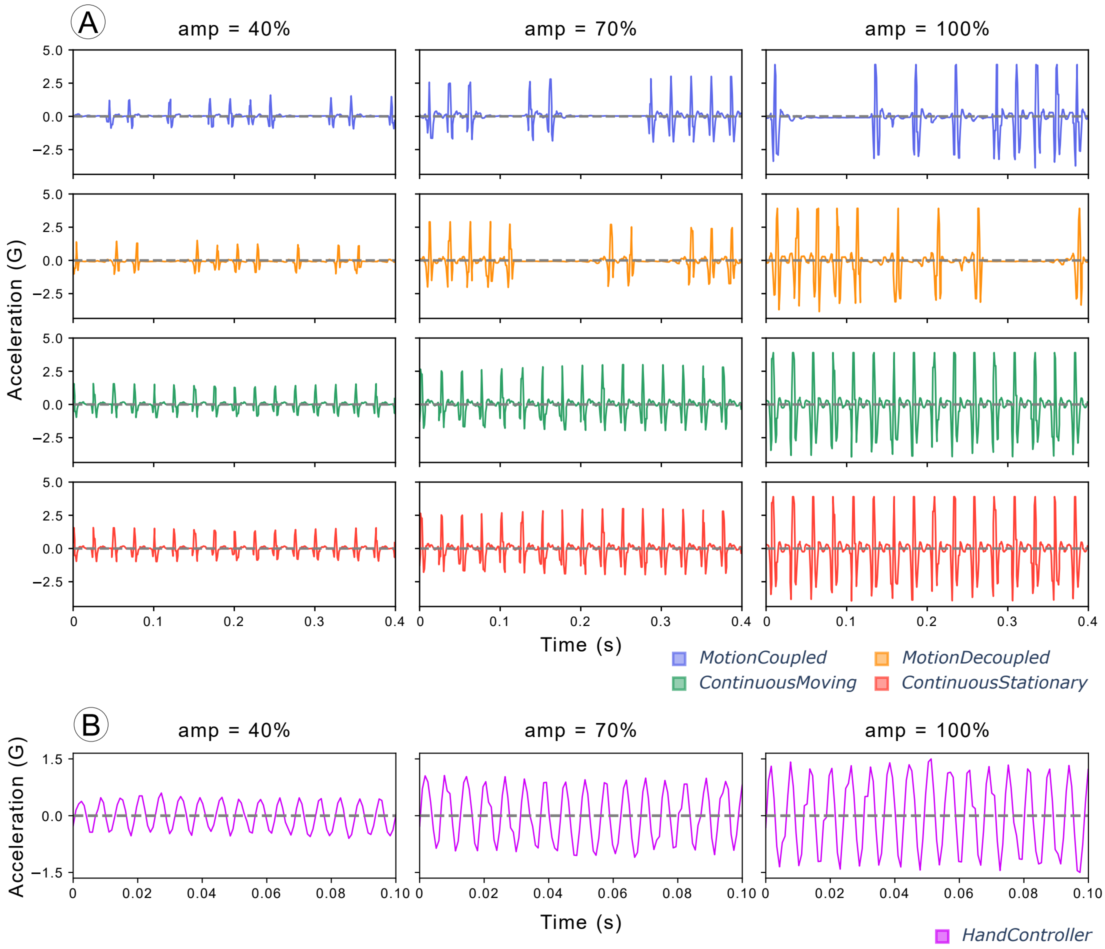


Figure B.3: *Measured acceleration (cropped) of the actuators are shown for each of the signals used in Study 1. The measured hand controller vibrations used in Study 2 are also shown in pink.*

B.2 Grain-Based Behavior

Referring to Figure B.4, the rugged line corresponding to each magenta dot represents one pulse of the asymmetric vibration for the specific condition. In the motion-coupled asymmetric vibration condition Ⓐ, the amount of pulses triggered corresponds to the speed of movement, and no pulses are triggered in the absence of movement. For motion-decoupled asymmetric vibration Ⓑ, the vibration pulses are replayed from the sequence of triggered pulses for condition Ⓐ in reverse. In contrast, for the continuous asymmetric vibration, the pulses are played continuously at a frequency of 40 Hz, independent of whether the user moving Ⓒ or stationary Ⓓ.

B.3 Detailed Results

Figure B.5 shows the individual conditions of the vibration stimuli compared in Study 1 along with the results of the comparison at all three amplitude levels: 40%, 70% and 100% of the maximum amplitude. Post-hoc results with Bonferroni correction showed that the differences between intensity levels were significant whenever the main effects

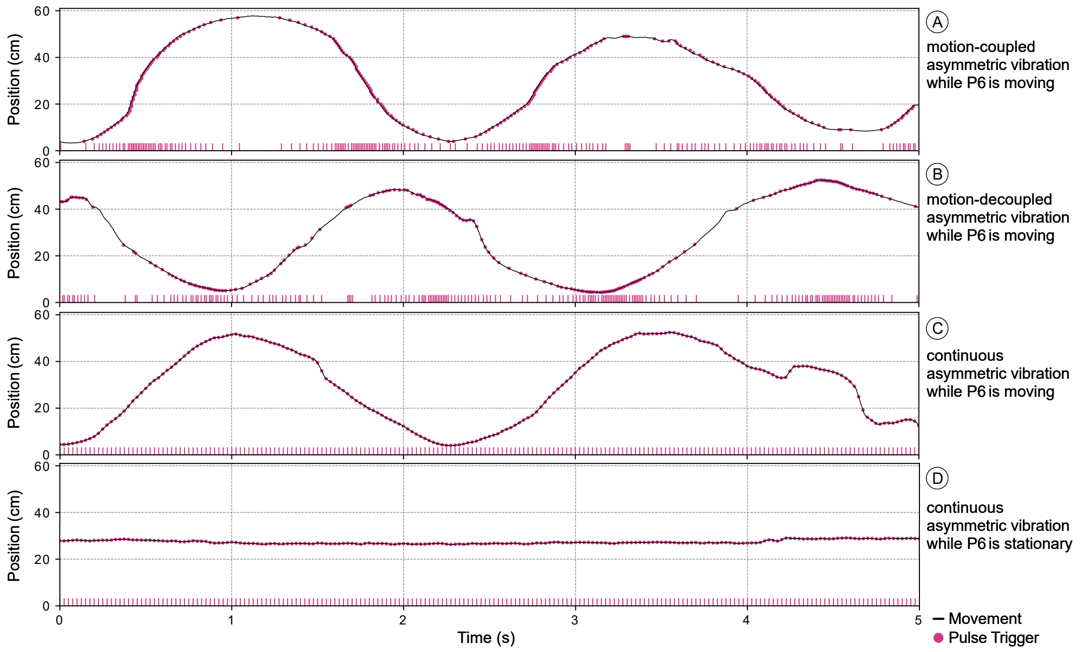


Figure B.4: *Four cropped sequences illustrate the movement profiles (black line) of a participant (P6) during Study 1 for four test conditions along with the corresponding vibrotactile feedback (magenta dots). The rugged lines below each movement profile show the density of played pulses (asymmetric vibration).*

were significant and vice versa.

Table B.2 shows the perceived vibration and perceived force scores for controller vibration, continuous asymmetric vibration, and motion-coupled asymmetric vibration for the different scenes explored in Section 6.5 Referring to Figure B.6 and Table B.2, the RM-ANOVA showed a statistically significant effect of vibration condition on participants' vibration estimates for all the scenes. Post-hoc analysis with Bonferroni correction showed that *Continuous* was perceived to be significantly stronger in vibration. For perceived force, the *Continuous* and *MotionCoupled* conditions were higher rated compared with the *Controller* condition for the bow-arrow and weights scenes. However, for the Magnets, only the difference between *Continuous* and *Controller* force scores was significant. In neither of the scenes was there a statistical difference between the force ratings for the *Continuous* and *MotionCoupled* conditions.

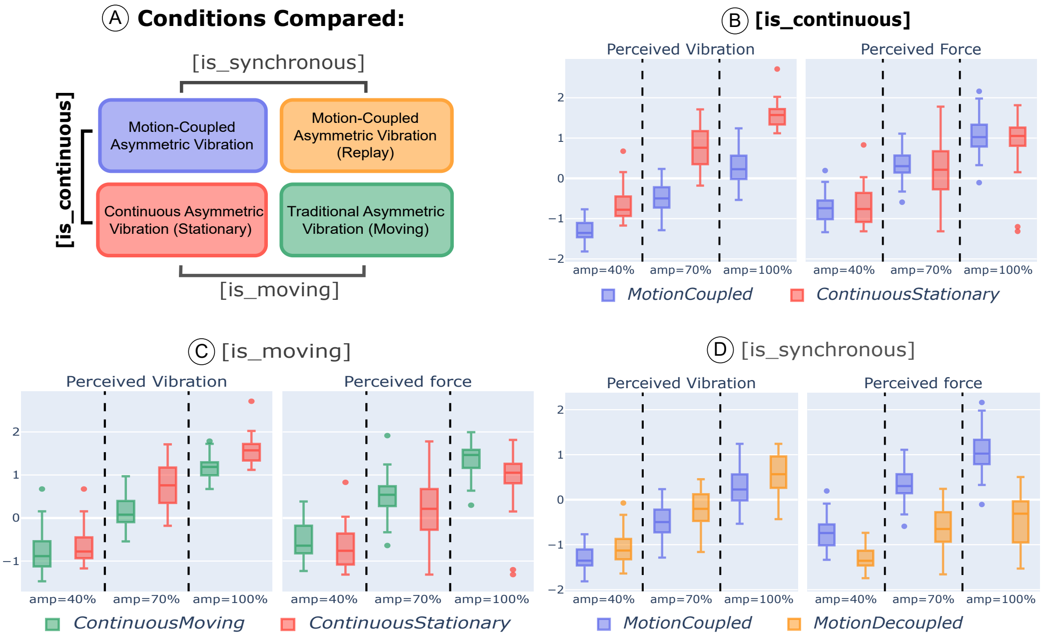


Figure B.5: Ⓐ *shows the conditions compared,* Ⓑ, Ⓒ, *and* Ⓓ *show the comparisons at every intensity for the independent variables.*

Table B.2: *Post-hoc vibration and force perception scores for different scenes and feedback conditions in Study 2.*

Scene	Perceived Quantity	Comparison	t(df)-value	p-value
Bow-Arrow (B)	*Vibration*	Controller vs Continuous	t(7) = 2.99	p <0.05
		Controller vs MotionCoupled	t(7) = 0.17	Not Significant
		Continuous vs MotionCoupled	t(7) = 5.78	p <0.05
	Force	Controller vs Continuous	t(7) = 4.26	p <0.05
		Controller vs MotionCoupled	t(7) = -3.06	p <0.05
		Continuous vs MotionCoupled	t(7) = -0.27	Not Significant
Magnets (M)	*Vibration*	Controller vs Continuous	t(7) = 2.41	p <0.05
		Controller vs MotionCoupled	t(7) = 0.50	Not Significant
		Continuous vs MotionCoupled	t(7) = 2.27	p <0.05
	Force	Controller vs Continuous	t(7) = 5.19	p <0.05
		Controller vs MotionCoupled	t(7) = -1.51	Not Significant
		Continuous vs MotionCoupled	t(7) = 1.06	Not Significant
Weights (W)	*Vibration*	Controller vs Continuous	t(7) = 3.48	p <0.05
		Controller vs MotionCoupled	t(7) = -0.57	Not Significant
		Continuous vs MotionCoupled	t(7) = 4.22	p <0.05
	Force	Controller vs Continuous	t(7) = 12.06	p <0.05
		Controller vs MotionCoupled	t(7) = -5.03	p <0.05
		Continuous vs MotionCoupled	t(7) = 0.25	Not Significant

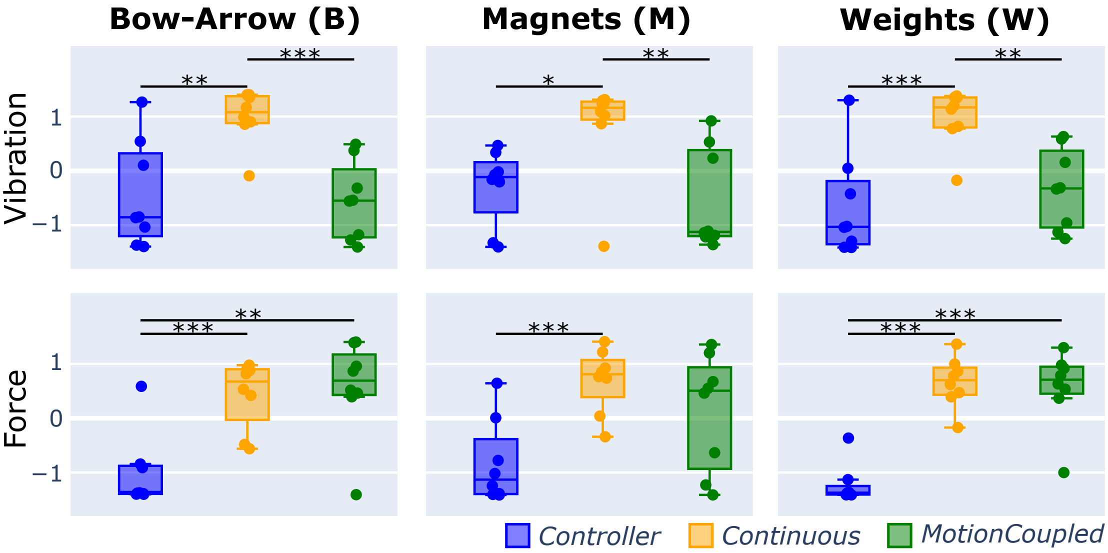


Figure B.6: *Perceived vibration and force estimates for each vibration condition: Controller, Motion-Coupled, Continuous for each scene is shown. Each box-plot represents the median and the interquartile range. Each point is a user estimate.* ($* : p < .05$; $** : p < .01$; $* * * : p < .001$)

C Tactile Symbol Design

C.1 Appendix: Tactile Symbols

Here, we include all the tactile symbols designed by the participants, which were not shown in the paper.

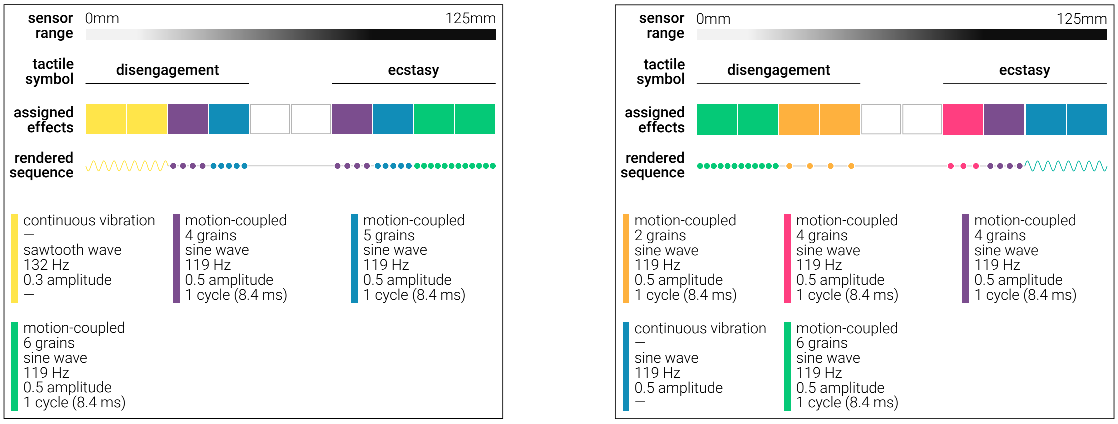
(a) *Participant 1*

(b) *Participant 3*

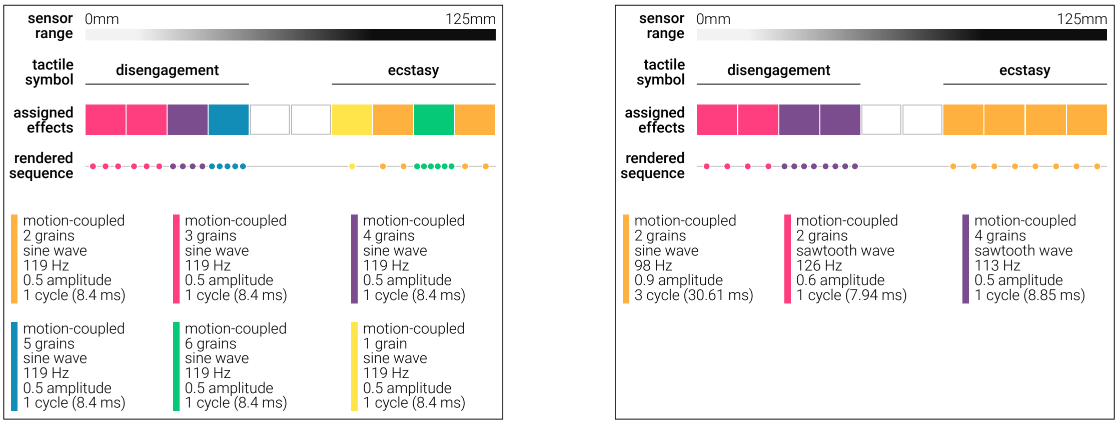
(c) *Participant 4*

(d) *Participant 5*

Figure C.1: *Tactile symbols designed by the participants to communicate reassurance and warning. These symbols were experienced on knobs.*

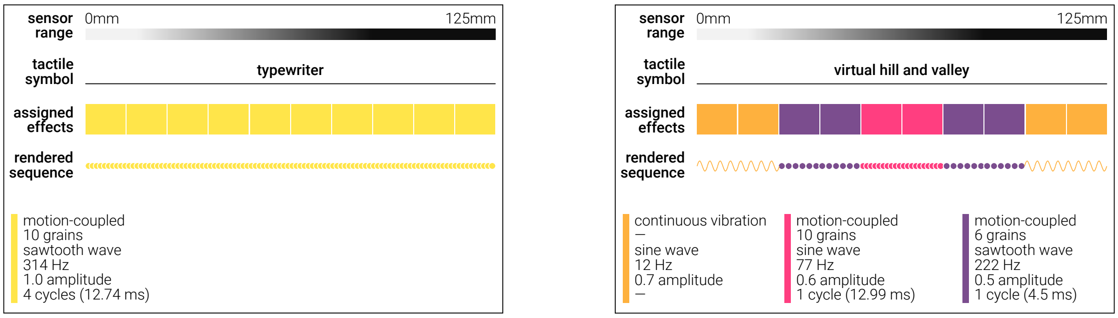


(a) *Participant 2* (b) *Participant 3*



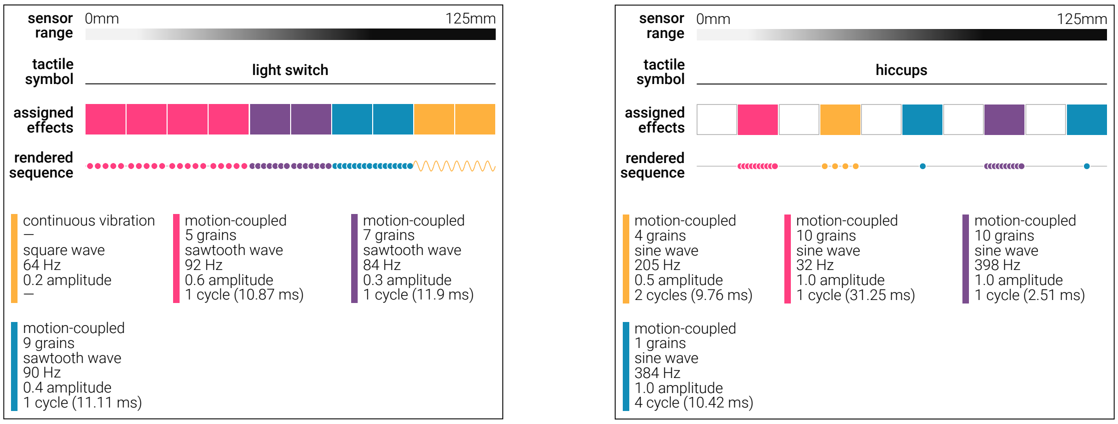
(c) *Participant 4* (d) *Participant 5*

Figure C.2: *Tactile symbols designed by the participants to evoke disengagement and ecstasy. These symbols were experienced on sliders.*



(a) *P1's design of typewriter's key press effect*

(b) *P5's design of a virtual hill and valley*



(c) *P1's design of a light switch*

(d) *P2's design of hiccups*

Figure C.3: *Additional free form designs by the participants using sliders.*

D Bimanual Motion-Coupled Vibration with Crosstalk

D.1 Technical Evaluation

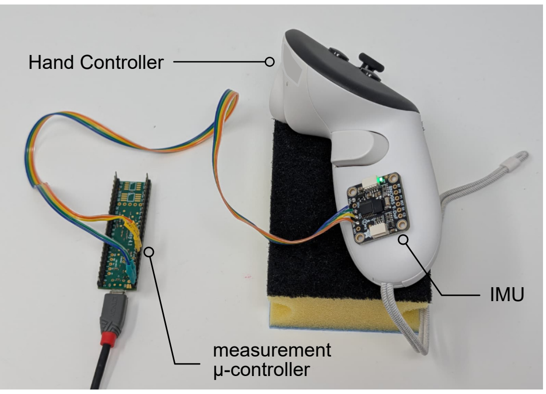


Figure D.1: *Technical setup used for measuring the latency between sensing and actuation as well as output acceleration of the Meta Quest 3 hand controller.*

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 [1] on one of the hand controller. 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 was placed on a sponge to isolate the system from any environmental vibrations and as shown in Figure D.1. 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 (registered by the external sensor) and the onset of the resulting haptic pulse (also registered by the external sensor). All measurements were sampled at 500Hz and averaged over 30 trials. The latency was measured to 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

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

accelerations 100%, 70% and 40% of maximum amplitude were 2.62 ± 0.24G, 1.83 ± 0.17G, 1.07 ± 0.12G respectively.

D.2 VR Rendering Parameters

Table D.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

D.3 Details: Study 1 All plots

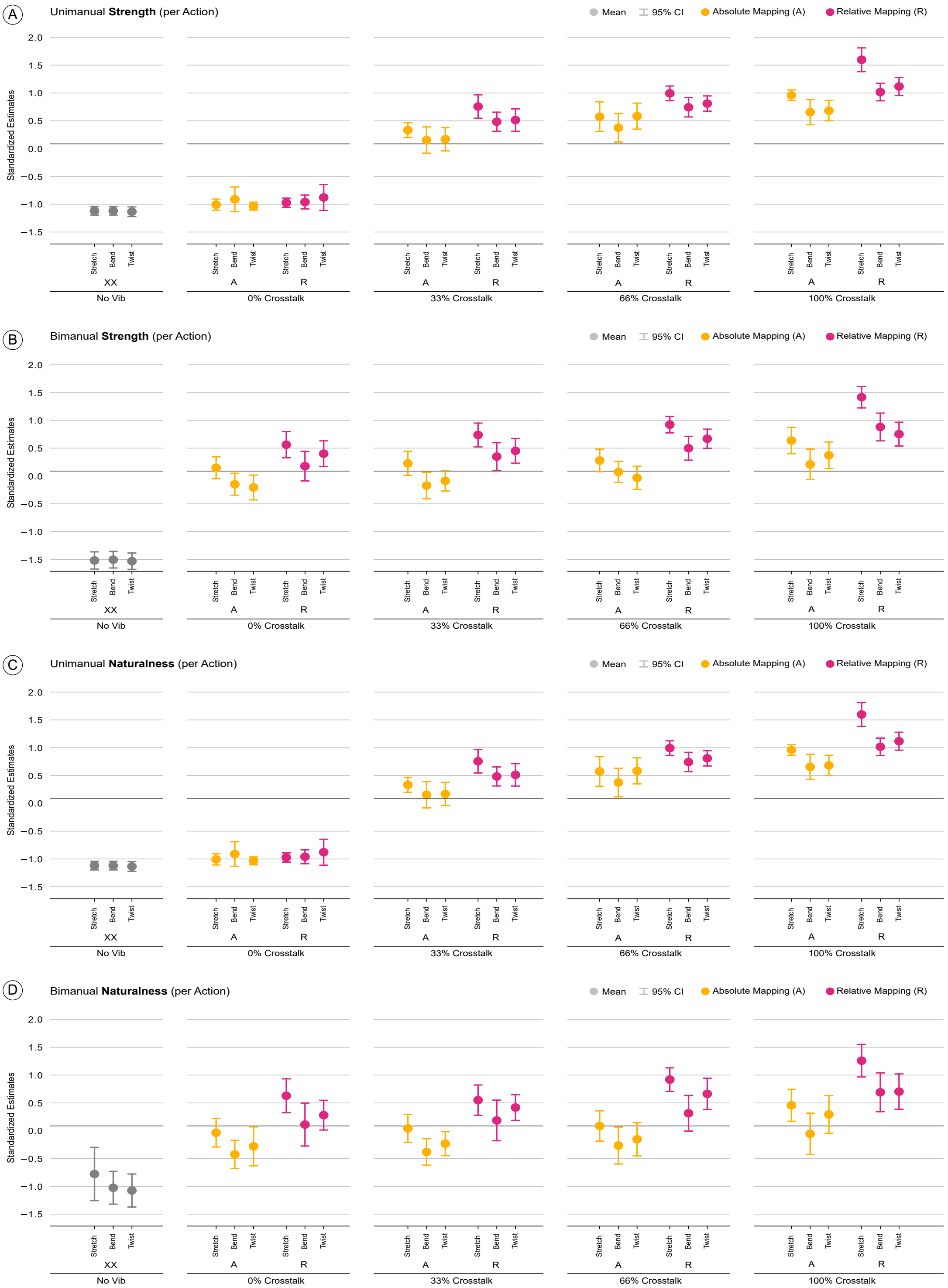

Figure D.2: *Results of study 1 for strength of connectedness* Ⓐ,Ⓑ *and naturalness* Ⓒ,Ⓓ *for unimanual and bimanual configuration with action, mapping type and crosstalk.*

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