UNIVERSITY OF ICELAND

Development of a Vibrotactile Wearable for Real-Time Information Communication

Nashmin Yeganeh

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FACULTY OF INDUSTRIAL ENGINEERING, MECHANICAL ENGINEERING AND COMPUTER SCIENCE

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Dissertation submitted in partial fulfillment of a
Philosophiae Doctor degree in Industrial Engineering

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Abstract

In a digital environment saturated with information, there is an increasing need for new ways to deliver information quickly and reliably without relying on sight or hearing. This is especially critical when these senses are already overloaded or otherwise unavailable. Vibrotactile stimulation, where information is conveyed through vibrations on the skin, shows great promise as a way to utilize the body's sense of touch. The effectiveness of such systems, however, depends entirely on how the vibrations are structured and calibrated, particularly on regions of the body where the skin is less sensitive.

This thesis investigates how to design and fine-tune vibrotactile stimulation in wearable devices so that it communicates information reliably in real-time without causing cognitive fatigue. The forearm is well-suited for such equipment as it does not hinder hand movement and the device can remain nearly unobtrusive. However, the density of mechanoreceptors is lower and spatial perception is poorer there than, for example, in the fingertips, which imposes certain perceptual constraints. Therefore, it is necessary to systematically research how the location, frequency, and temporal patterns of vibration affect how we perceive the vibrations and interpret the messages encoded within them.

A custom-built wearable device was designed using voice coil actuators integrated into a flexible textile substrate with 3D-printed enclosures. The device is capable of delivering dynamic, independent, and spatially distributed vibrations. The research employed psychophysical methods to explore and quantify three core dimensions: spatial resolution, frequency effects, and the temporal structure of stimuli.

Thesis Objective 1 (TO1) This objective evaluated the minimum spacing required between actuators for users to distinguish between them. The results revealed that a 20 mm spacing yielded the highest accuracy (approximately 90–92%) on both the dorsal and ventral (upper and under) sides of the forearm.

Thesis Objective 2 (TO2) This objective investigated how different frequencies (100–250 Hz) and anatomical placements (wrist, mid-forearm, elbow) affected perception. The study showed that frequency alone had little effect, whereas location was crucial; accuracy was higher in areas near landmarks or bone, such as the wrist and elbow.

Thesis Objective 3 (TO3) This objective focused on how the timing of stimuli affects perception. Sequential stimulation, where vibration was delivered by one actuator at a time, was compared to simultaneous stimulation, where all relevant actuators were activated at once. The results confirmed that it is significantly easier to distinguish signals delivered sequentially (93.24% accuracy) than those deliv-

ered simultaneously (26.15%). Further investigation into inter-stimulus intervals (ISIs) revealed that accuracy is highest when intervals are between 100 and 500 milliseconds. Shorter patterns proved more effective than longer ones, and users remembered the beginning and end of the sequences best. Furthermore, performance improved with practice, demonstrating that users can learn to adapt to such systems over time.

These investigations provide a foundation for the design of wearable tactile systems that work efficiently with human perception. The findings are applicable to the development of assistive technologies, sensory substitution devices, silent alerting systems, and even virtual or augmented reality (VR/AR) interfaces. By demonstrating that complex information can be reliably conveyed through structured vibrations on the forearm, this thesis confirms that touch is a viable communication channel in human-computer interaction when other modalities are overloaded.

Útdráttur

Í stafrænu umhverfi þar sem upplýsingum rignir yfir okkur úr öllum áttum, eykst þörfin fyrir nýjar leiðir til að miðla upplýsingum fljótt og örugglega án þess að treysta á sjón eða heyrn. Þetta á sérstaklega við þegar þessi skilningarvit eru þegar ofhlaðin eða nýtast hreinlega ekki. Titringsörvun, þar sem upplýsingum er miðlað með titringi á húðina, lofar góðu sem valkostur til að nýta snertiskynjun líkamans. Skilvirkni slíkra kerfa veltur þó alfarið á því hvernig við byggjum upp titringinn og stillum hann af, sérstaklega á þeim hlutum líkamans þar sem húðin er síður næm fyrir snertingu.

Í þessari ritgerð er leitað svara við því hvernig má hanna og fínstilla þessa titringsörvun í klæðanlegum búnaði þannig að hann miðli upplýsingum á áreiðanlegan hátt í rauntíma án þess að þreyta hugann. Framhandleggurinn hentar vel fyrir slíkan búnað því hann hindrar ekki hreyfingar handarinnar og tækið getur legið þar nánast ósýnilegt. Hins vegar eru snertinemar þar færri og staðsetningarskyn lakara en t.d. í fingurgómum, sem setur skynjuninni ákveðin mörk. Þess vegna þarf að rannsaka kerfisbundið hvernig staðsetning, tíðni og tímamynstur titringsins hafa áhrif á það hvernig við skynjum titringinn og túlkum skilaboðin sem hafa verið kóðuð í hann.

Hannaður var sérsmíðaður, klæðanlegur búnaður sem byggir á raddspólum (e. voice coil actuators) sem komið er fyrir í mjúku efni með þrívíddarprentuðum umgjörðum. Tækið getur miðlað kvikum, sjálfstæðum og staðbundnum titringi á mörgum stöðum. Í rannsókninni var beitt sáleðlisfræðilegum aðferðum (e. psychophysics) til að kanna og mæla þrjá meginþætti: rýmisupplausn, áhrif tíðni og tímalega uppbyggingu áreita.

Fyrsta markmið (TO1): Hér var kannað hversu langt þarf að vera á milli titringsgjafa svo fólk greini á milli þeirra. Niðurstöðurnar leiddu í ljós að 20 mm millibil skilaði mestri nákvæmni (um 90–92%) á bæði fram- og bakhlið framhandleggs.

Annað markmið (TO2): Hér var skoðað hvernig mismunandi tíðni (100–250 Hz) og staðsetning á handlegg (úlnliður, miðja framhandleggs og olnbogi) höfðu áhrif á skynjunina. Rannsóknin sýndi að tíðnin ein og sér breytti litlu, en staðsetningin skipti hins vegar sköpum; nákvæmnin reyndist meiri á svæðum nálægt liðamótum eða beini, svo sem við úlnlið og olnboga.

Þriðja markmið (TO3): Hér var sjónum beint að því hvernig tímasetning áreitis hefur áhrif á skynjunina. Borin var saman raðörvun, þar sem titringsáreiti var miðlað með einni raddspólu í einu, og samhliða örvun, þar sem allar viðeigandi raddspólur voru virkjaðar samtímis (byggt á mynstri blindraleturs). Niðurstöðurnar staðfestu að mun auðveldara er að greina boð sem koma í röð (93,24% nákvæmni) en þau sem berast samtímis (26,15%). Frekari athuganir á hléum milli áreita (e. inter-stimulus intervals) leiddu í ljós að nákvæmnin er mest þegar hléin eru á bilinu 100 til 500

millisekúndur. Styttri merki reyndust betri en löng og fólk mundi byrjunina og endann á röðinni best. Einnig sást að fólk varð fljótara og betra að nema boðin með æfingunni, sem sýnir að hægt er að læra á slík kerfi yfir tíma.

Með þessum rannsóknum er lagður grundvöllur að hönnun klæðanlegra snertikerfa sem vinna á skilvirkan hátt með mannlegri skynjun. Niðurstöðurnar nýtast við þróun hjálpartækja, tækja sem koma í stað annarra skilningarvita, hljóðlausra viðvörunarkerfa og jafnvel í sýndarveruleika (VR/AR). Með því að sýna fram á að hægt sé að miðla flóknum upplýsingum á áreiðanlegan hátt með skipulögðum titringi á framhandlegg, staðfestir þessi ritgerð að snerting er raunhæf boðleið í samskiptum manna og tölva þegar aðrar leiðir nýtast illa.

To Reza, the love of my life;
to my beloved daughters, Mersana and Diana;
And to my wonderful mom and dad.

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Abbreviations

2AFC Two-Alternative Forced Choice

AD/DA Analog-to-Digital / Digital-to-Analog

ANOVA Analysis of Variance

AR Augmented Reality

EAP Electroactive Polymer

ERM Eccentric Rotating Mass (Actuator)

ISI Interstimulus Interval

LRA Linear Resonant Actuator

PLA Polylactic Acid (3D printing filament)

RQ Research Question

rPL Relative Point Localization

RA-I Rapidly Adapting Type I (Meissner)

RA-II Rapidly Adapting Type II (Pacinian)

SA-I Slowly Adapting Type I (Merkel)

SA-II Slowly Adapting Type II (Ruffini)

S1 Primary Somatosensory Cortex

SMA Shape Memory Alloy

SSD Sensory Substitution Device

TO1 Thesis Objective 1

TO2 Thesis Objective 2

TO3 Thesis Objective 3

VCA Voice Coil Actuator

VR Virtual Reality

VWFA Visual Word Form Area

Acknowledgments

First and foremost, I would like to express my deepest gratitude to my supervisor, Prof. Dr. Rúnar Unnþórsson, for his unwavering support, expert guidance, and insightful feedback throughout the course of this research. His leadership and encouragement have been invaluable to the completion of this work. I am sincerely thankful for the opportunity he gave me to pursue this project and follow my dreams.

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To my beloved daughters, Mersana and Diana, thank you for your endless patience, for filling my days with joy and laughter, and for being the light of my life. Your hugs, smiles, and little acts of love gave me hope and energy when I needed it most. You remind me every day of what truly matters, and this achievement is as much for you as it is for me.

Last but certainly not least, my deepest gratitude goes to my wonderful parents, my dear mom and dad, for their unconditional love, endless support, and countless sacrifices. No matter the distance, their love, prayers, and unwavering faith in me have been a constant source of strength throughout this journey. They have always believed in me, encouraged me to keep moving forward, and supported me every step of the way. Everything I have achieved carries a part of them, and I will forever be grateful for all that they have given me.

1 Introduction

1.1 Motivation

The evolution of human–computer interaction (HCI) in an increasingly digital and interconnected world has intensified the demand for multimodal communication interfaces. While visual and auditory channels remain dominant, they are often overburdened, unavailable, or impractical in a range of application contexts. In response, the sense of touch—particularly in the form of Vibrotactile feedback—has emerged as a compelling alternative and complementary modality for non-visual, non-verbal information transmission.

In augmented and virtual reality (AR/VR) systems, Vibrotactile devices are increasingly adopted to enhance immersion, improve interaction realism, and provide embodied feedback [1, 2, 3, 4]. In assistive technologies for individuals with sensory impairments, Vibrotactile feedback can compensate for missing or degraded sensory channels by conveying spatial, navigational, or symbolic information through touch [5, 6, 7, 8]. Additionally, in high-noise or hands-busy environments—where visual attention and auditory perception may be limited or unreliable—Vibrotactile communication offers a robust and unobtrusive means of information delivery.

Vibrotactile communication offers the potential for intuitive, low-latency interaction that operates independently of sight or hearing. Recent advances in wearable haptic technology have facilitated the integration of Vibrotactile systems into form factors that are lightweight, low-power, and minimally obtrusive [9, 10]. However, achieving effective and reliable tactile communication remains a significant challenge, particularly in wearable configurations that rely on body regions with comparatively low tactile acuity, such as the forearm [11].

The forearm presents several practical advantages as a site for haptic feedback: it is easily accessible, mechanically stable, and does not interfere with manual tasks, making it suitable for continuous, unobtrusive use in daily activities. Nevertheless, the forearm has a lower density of mechanoreceptors compared to highly sensitive areas like the fingertips, resulting in reduced spatial resolution and limited tactile discrimination. These perceptual constraints must be carefully considered when designing effective forearm-based Vibrotactile interfaces [12, 13].

This thesis is motivated by the need to enhance the perceptual accuracy, usability, and design efficiency of wearable Vibrotactile systems for the forearm. It specifically investigates the spatial, spectral, and temporal properties of Vibrotactile stimuli—namely actuator spacing, frequency sensitivity, and stimulus timing—and their influence on users' ability to perceive, localize, and interpret tactile cues. For instance, when actuators are placed too closely together, their vibrations may blend and become perceptually indistinct [14]. Inappropriate frequency selection may lead to suboptimal stimulation of mechanoreceptors. Poorly chosen interstimulus intervals can reduce recognition performance by making the stimuli harder to distinguish or by creating unclear timing between them. [15, 16].

Optimizing these parameters is essential for achieving perceptually clear and functionally robust tactile communication. This is especially critical in scenarios involving rapid sequential stimulation or complex pattern recognition, where the cognitive and perceptual demands on the user are elevated. Real-world applications—such as tactile displays for the visually impaired, silent alert systems, sensory substitution devices, and AR/VR environments—require systems that deliver information both quickly and accurately. These systems must be optimized not only in terms of hardware design but also in terms of how tactile information is structured, delivered, and learned.

To address the challenges associated with effective Vibrotactile communication, this research undertakes a systematic investigation of Vibrotactile perception on the forearm from a psychophysical perspective. The study focuses on three fundamental and interrelated dimensions of Vibrotactile stimulation—spatial resolution, spectral characteristics, and temporal dynamics—that govern how tactile information is encoded and perceived. Together, these dimensions determine how Vibrotactile stimuli are perceived, localized, and interpreted by users, particularly on the forearm.

A custom-designed Vibrotactile sleeve, embedded with multiple independently controlled voice coil actuators, serves as the experimental platform. This wearable system enables precise manipulation of spatial and temporal stimulus features, supporting controlled investigation of perceptual effects both independently and in combination. Psychophysical methods are applied throughout the study to provide rigorous, quantitative assessment of the relationship between physical stimulus parameters and perceptual performance.

This thesis explores the hypothesis that tactile perception on the forearm varies as a function of the spatial, spectral, and temporal properties of Vibrotactile stimulation. By identifying perceptually effective parameter ranges within each dimension, the research aims to support the development of wearable Vibrotactile interfaces that enable reliable, intuitive, and user-centered transmission of spatial, symbolic, and navigational information through touch.

To operationalize this hypothesis, the research is organized around the following core research questions:

1. **What is the minimum actuator spacing required to achieve high spatial discrimination accuracy?**
   This question determines the forearm's spatial resolution by identifying the minimum distance at which Vibrotactile stimulation is reliably distinguishable, enabling fine-tuning of actuator layout (TO1).

2. **How does Vibrotactile frequency influence tactile localization accuracy across the forearm?**
   As different mechanoreceptors exhibit distinct frequency response profiles, this question explores how variations in frequency affect localization accuracy across the forearm. The results guide spectral tuning strategies (TO2).

3. **What is the effect of pattern length on recognition accuracy?**
   This question investigates how the length of Vibrotactile sequences influences users' ability to accurately interpret them, particularly in information-dense contexts (TO3).

4. **How do Vibrotactile presentation methods impact recognition accuracy?**
   By comparing simultaneous and sequential actuator activation, this question evaluates their respective impacts on perceptual clarity, spatial resolution, and cognitive load, with implications for encoding strategies (TO3).

5. **How do stimulus order and interstimulus interval (ISI) affect tactile discrimination accuracy?**
   This question assesses how the temporal arrangement of stimuli influences tactile discrimination accuracy, examining whether performance varies depending on stimulus order and the time interval between successive stimuli. Both shorter and longer interstimulus intervals may influence discrimination by affecting sensory processing, interference, and the ability to retain and compare tactile information across stimuli. (TO3).

6. **Does sequential presentation accuracy improve with repeated exposure?**
   Finally, this question explores the impact of learning and repetition on tactile recognition performance, informing the design of tactile systems in which user performance improves with experience (TO3).

Each research question is addressed through carefully controlled experiments using psychophysical paradigms. These investigations contribute to a deeper scientific understanding of forearm-based Vibrotactile perception and support the development of tactile interfaces that are perceptually optimized, cognitively compatible, and ergonomically viable.

The outcomes of this thesis have broad implications across multiple application domains, including assistive wearables for individuals with sensory impairments (such as Braille-inspired displays for the visually impaired), AR/VR feedback systems, rehabilitation technologies, silent alerting mechanisms, sensory substitution tools, and prosthetics. In all these contexts, tactile feedback must be delivered with precision, clarity, and minimal cognitive load—requirements that this research directly addresses.

Ultimately, this work aspires to elevate the sense of touch to a primary communication channel in human-machine interaction. By enabling users to receive and interpret tactile information as naturally and efficiently as they would visual or auditory cues, this research supports the development of more inclusive, immersive, and responsive interactive systems.

1.2 Thesis Objectives

1.2.1 Main Thesis Objective

This thesis aims to design and fine-tune vibrotactile stimulation parameters to enhance the performance of a multimodal wearable sleeve for forearm-based communication. The core objective is to systematically investigate and quantify the effects of spatial, temporal, and spectral stimulation parameters on vibrotactile perception on the forearm, thereby providing an empirical foundation for effective tactile information delivery.

The research is intended to inform the development of advanced wearable Vibrotactile displays, with a specific emphasis on forearm-mounted systems. By establishing evidence-based design principles, this work seeks to improve the clarity, accuracy, and usability of Vibrotactile feedback.

Ultimately, the findings will contribute to the creation of robust, user-centered haptic interfaces for use in assistive technologies, sensory substitution devices, and non-visual communication platforms—particularly in environments where visual or auditory channels are limited, unavailable, or overloaded.

1.2.2 Specific Thesis Objectives

This research is guided by three interrelated thesis objectives (TOs), each addressing a core perceptual dimension that underpins the design of effective Vibrotactile interfaces. Together, these objectives contribute to a foundational understanding of how tactile information can be encoded, delivered, and perceived through wearable haptic systems. The insights gained from each objective are intended to inform design principles for robust, high-performance, user-centered Vibrotactile communication systems—particularly those implemented on the forearm for non-visual or multimodal interaction.

TO1: Fine-tune actuator interspacing to optimize Vibrotactile spatial discrimination.

The first objective is to fine-tune the spatial configuration of Vibrotactile actuators on the forearm to optimize spatial discrimination. A critical consideration in tactile interface design is how closely actuators can be placed without compromising the user's ability to distinguish between adjacent stimuli. If actuators are positioned too closely, users may experience perceptual overlap or confusion, reducing the clarity and precision of tactile messages.

This objective addresses the spatial resolution of the human forearm and explores how actuator placement affects tactile localization performance. Insights from this investigation are essential for designing compact yet effective tactile displays that can convey complex information within the limited surface area of wearable devices. It also has implications for applications requiring high-density arrays—such as those used in navigation aids, communication interfaces, or haptic feedback systems for augmented and virtual reality.

TO2: Investigate the Influence of Stimulus Frequency and Anatomical Location on Tactile Perception

The second objective focuses on understanding how variations in stimulus frequency and anatomical placement along the forearm affect the user's ability to perceive and localize Vibrotactile stimuli. The human skin exhibits varying sensitivity across different regions due to differences in mechanoreceptor density, skin thickness, and tissue composition. Additionally, the perception of Vibrotactile stimuli is influenced by the frequency of the vibration, which determines which types of mechanoreceptors are activated and how stimuli are interpreted.

By examining these physiological and perceptual variables, this objective aims to inform actuator placement strategies and frequency selection in wearable systems. A deeper understanding of these factors allows for the customization of Vibrotactile feedback based on the forearm's sensory landscape, ensuring that tactile cues are both perceptible and distinguishable. This is particularly relevant in contexts where system responsiveness, comfort, and reliability are essential—such as in assistive devices for individuals with sensory impairments or in environments with limited visual or auditory cues.

TO3: Explore the Effects of Temporal Presentation and Sequencing on Tactile Pattern Recognition

The third objective investigates how temporal presentation parameters influence the perception and recognition of Vibrotactile patterns. In wearable haptic systems, the timing and sequencing of stimuli—such as whether they are presented simultaneously or sequentially, the duration between successive stimuli (interstimulus interval or ISI), and the overall length and order of tactile patterns—can significantly affect a user's ability to accurately decode information.

This objective examines the role of temporal structure in shaping tactile experiences. It considers how humans process time-based tactile cues and how these cues interact with memory and attention to influence recognition accuracy. Additionally, it explores how learning and familiarity with repeated patterns may enhance performance over time, highlighting the adaptive nature of tactile perception.

Understanding these temporal dynamics is vital for designing intuitive and efficient haptic communication strategies, particularly for sensory substitution systems and non-visual user interfaces. This objective supports the development of Vibrotactile coding schemes that are cognitively aligned with users' natural perceptual and processing capabilities, thereby improving the overall usability and effectiveness of wearable haptic technologies.

Figure 1.1 depicts the chronological progression of the TO, from the initiation to the completion of the doctoral research. It outlines the sequential milestones associated with each TO and highlights the methodological procedures employed to advance the study of Vibrotactile stimulation on the skin.

The interconnection among the TO is depicted by the blue arrows, symbolizing the direct transfer of knowledge acquired in one phase to the subsequent step.

Finally, the flow diagram in Figure 1.1 offers a visual depiction of the TO addressed in each of the publications outlined in Chapter 4.

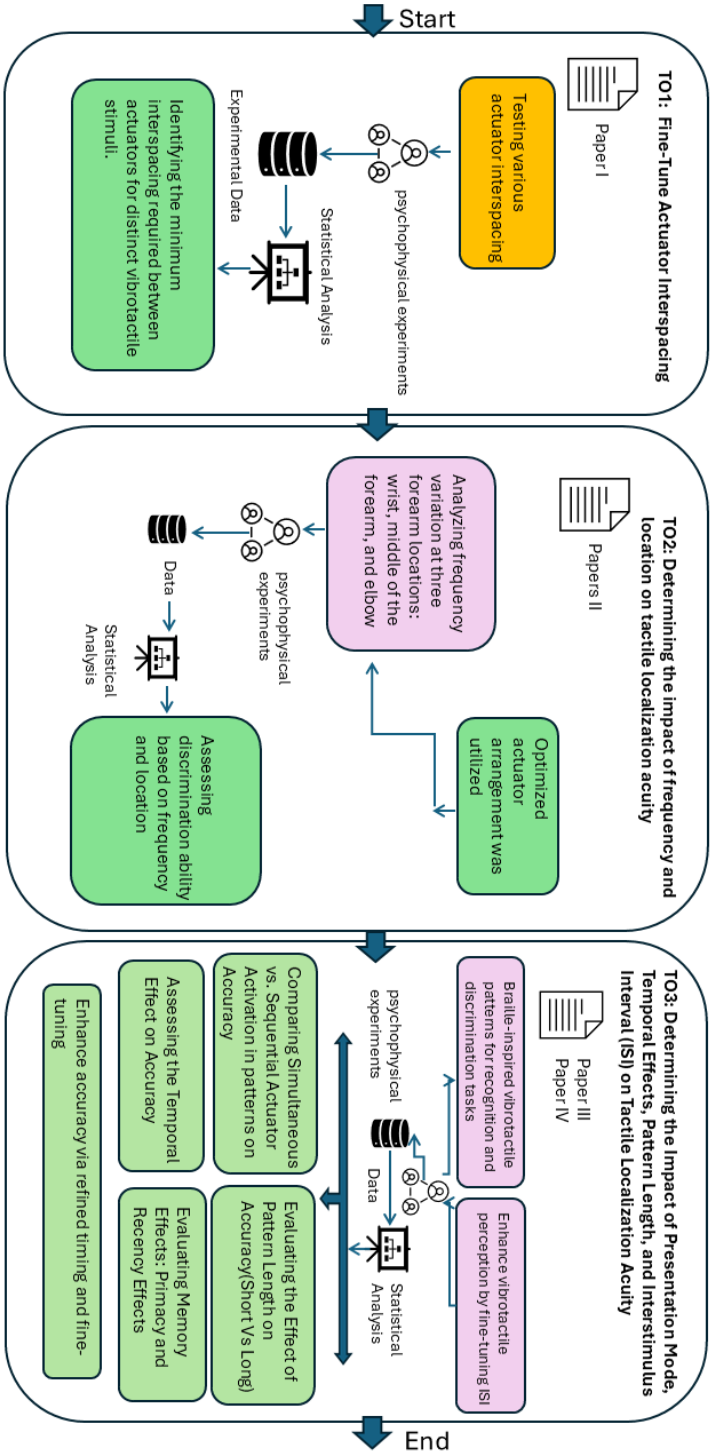

Figure 1.1. Flow diagram of the thesis outline and the achieved publications.

1.3 Outline

This thesis adopts a cumulative format, in which the research objectives (TOs) are addressed through a series of peer-reviewed publications. These publications, listed in Section 1.4.1, form the foundation of the thesis and are directly aligned with the core objectives outlined in Section 1.2. The structure of the thesis is designed to contextualize, support, and integrate these contributions within a coherent research narrative.

1.4 Thesis Structure

The thesis is organized into six main chapters, as follows:

- **Chapter 1: Introduction**
  Introduces the research scope, motivations, and objectives. It also outlines the relationship between the thesis objectives and the associated peer-reviewed publications.

- **Chapter 2: Background and Theoretical Framework**
  Provides an overview of the foundational concepts relevant to the research, including human tactile perception and haptic interface design. This chapter offers theoretical context for the investigations conducted under TO1 and TO3.

- **Chapter 3: Methodology and System Design**
  Describes the experimental methods and analytical approaches employed in this research. It also presents the design and technical specifications of the custom-built wearable Vibrotactile sleeve used in the studies.

- **Chapter 4: Publications and Research Contributions**
  Offers an integrated summary of the journal papers that constitute the core contributions of this cumulative thesis. The chapter explains how each publication addresses one or more thesis objectives and highlights their significance within the broader field.

- **Chapter 5: Discussion**
  Provides a critical analysis of the main findings across the studies, situating them within the broader literature and discussing their theoretical and practical implications.

- **Chapter 6: Conclusions and Future Work**
  Summarizes the key findings of the thesis and reflects on their overall scientific and practical contributions. This chapter provides explicit answers to the research questions introduced in Chapter 1, discusses the limitations of the research, and outlines potential directions for future investigations. The chapter is followed by the full-text versions of the primary publications listed in Section 4.

The thesis concludes with a **Bibliography**, which includes all sources cited throughout the manuscript.

1.4.1 Publications

- **Paper I**
  N. Yeganeh, I. Makarov, S. S. Stefánsson Thor, A. Kristjánsson, R. Unnthorsson, *Evaluating the Optimum Distance between Voice Coil Actuators Using the Relative Point Localization Method on the Forearm*, Actuators, vol. 12, no. 1, 2023, https://doi.org/10.3390/act12010006.

- **Paper II**
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- **Paper III**
  N. Yeganeh, I. Makarov, A. Kristjánsson, R. Unnthorsson, *Discrimination Accuracy of Sequential Versus Simultaneous Vibrotactile Stimulation on the Forearm*, Applied Sciences 2024; 14 (1): 43, https://doi.org/10.3390/app14010043.

- **Paper IV**
  N. Yeganeh, I. Makarov, A. Kristjánsson, R. Unnthorsson, *Vibrotactile Pattern Recognition: The Influence of Interstimulus Intervals*, Virtual Reality & Intelligent Hardware, 2025: 7 (5): p. 483–500, https://doi.org/10.1016/j.vrih.2025.06.001

1.5 Contributions

This thesis addresses three interrelated Thesis Objectives (TOs), each corresponding to a set of empirical investigations published across four peer-reviewed papers (see Table 1.1 and Figure 1.1). The overarching aim is to investigate and fine-tune the spatial and temporal parameters of Vibrotactile stimulation for wearable forearm-mounted haptic systems. Key areas of focus include tactile localization acuity, pattern recognition, and non-visual information transmission through the skin. Each objective builds upon the findings of the previous one, forming a cohesive and iterative research trajectory that culminates in a set of validated design principles for Vibrotactile communication interfaces.

TO1: Fine-tuning Actuator Spacing for Spatial Discrimination (Addressed in Publication I)

The first thesis objective investigates the minimum spatial separation needed between Vibrotactile actuators on the forearm to produce distinct and perceptually separable tactile stimuli. Understanding spatial resolution is foundational for designing compact, multi-point tactile interfaces that avoid perceptual interference.

This objective was addressed through a series of psychophysical experiments that systematically varied actuator spacing and evaluated users' localization performance. The outcomes informed the fine-tuning of actuator placement, ensuring that feedback remains spatially precise while enabling dense actuator configurations in wearable devices.

The insights gained from TO1 were instrumental in developing the Vibrosleeve prototype—used as a standardized experimental platform in subsequent thesis objectives.

TO2: Fine-tuning Frequency and Anatomical Placement for Perceptual Sensitivity (Addressed in Publications II)

The second thesis objective builds on TO1 by exploring how Vibrotactile stimulus frequency and anatomical location along the forearm affect tactile discrimination. While TO1 established spatial boundaries, TO2 investigates how sensitivity varies across different regions of the forearm and within various frequency ranges.

This objective involved testing stimulus perception at multiple forearm locations (e.g., wrist, mid-forearm, elbow) and across a controlled frequency range. The goal was to fine-tune actuator deployment and signal characteristics to align with users' physiological sensitivity and optimize interface performance.

TO2 contributes a deeper understanding of how spatial and frequency parameters interact, supporting more perceptually aligned and user-centered haptic system design.

TO3: Fine-tuning Temporal Parameters and Encoding Strategies for Tactile Communication (Addressed in Publications III and IV)

The third thesis objective addresses the temporal dimension of tactile feedback by investigating how timing and sequence influence users' ability to perceive and recognize Vibrotactile patterns. Variables such as interstimulus interval (ISI), presentation mode (sequential vs. simultaneous), pattern length, and serial order were systematically evaluated.

Inspired by tactile communication frameworks such as Braille, this objective focused on how timing affects perceptual clarity and cognitive processing. Psychophysical experiments were conducted to assess the impact of these temporal variables, alongside memory-related effects like primacy and recency.

TO3 builds directly on the actuator layout and sensitivity findings from TO1 and TO2. It fine-tunes the timing of stimulus delivery to reduce interference, enhance recognizability, and support more intuitive haptic interaction. This objective emphasizes cognitive and perceptual design principles necessary for delivering tactile messages effectively.

Summary of Contributions

Collectively, TO1, TO2, and TO3 form a unified and empirically validated framework for the design and fine-tuning of wearable Vibrotactile interfaces for the forearm. Each thesis objective contributes uniquely to this framework:

- **TO1:** Fine-tunes the spatial spacing between vibrotactile stimuli to achieve reliable spatial discrimination.
- **TO2:** Examines the influence of anatomical location and vibration frequency on tactile sensitivity and localization performance.
- **TO3:** Investigates the effects of stimulus timing, presentation method, sequence order, learning, and training on vibrotactile perception and recognition, with the aim of optimizing pattern-based tactile communication strategies.

These contributions support the design of high-resolution, user-centered Vibrotactile systems. The knowledge developed through this thesis is transferable across domains such as assistive technology, sensory substitution, mobile interaction, rehabilitation, and immersive environments including augmented and virtual reality.

Table 1.1. Relation of publications to the TOs.

	Paper I	Paper II	Paper III	Paper IV
TO1	×			
TO2		×		
TO3			×	×
Transferable Knowledge	×	×	×	×

2 Background

Vibrotactile perception is a critical component of the human somatosensory system, enabling the detection and interpretation of mechanical vibrations applied to the skin with remarkable temporal and spatial acuity. This perceptual modality facilitates nuanced touch-based interactions, allowing individuals to sense surface textures, interpret motion cues, and respond dynamically to changes in their physical environment.

2.1 Haptic and Vibrotactile Perception

Haptic perception refers to the process through which humans acquire information from the environment via the sense of touch, integrating both cutaneous (skin-based) and kinesthetic (muscle- and joint-based) feedback. A key component within this domain is Vibrotactile perception, which involves the detection of high-frequency mechanical vibrations applied to the skin. Vibrotactile feedback has become increasingly valuable in modern haptic systems, particularly within wearable, assistive, and sensory-substitution technologies, where visual or auditory feedback may be unavailable, overloaded, or insufficient [17, 18].

Mechanoreceptors form the biological basis for haptic perception. These specialized sensory receptors transduce mechanical stimuli—such as pressure, stretch, touch, and vibration—into neural signals that travel through the somatosensory system. They are distributed across the skin and deeper tissues, each exhibiting distinct response properties, adaptation behaviour, and receptive field characteristics, allowing the nervous system to encode a wide range of tactile information [19, 20].

The skin contains four principal classes of mechanoreceptors (cf. Figure 2.1):

- **Merkel Cells (SA-I)**
  Located primarily in the basal layer of the epidermis, Merkel cell–neurite complexes are associated with slowly adapting type I (SA-I) afferents that respond continuously during sustained contact. Characterized by small receptive fields, SA-I afferents play a critical role in fine spatial discrimination and the detection of edges and surface features. Their contribution to high-resolution tactile processing is particularly evident in highly sensitive regions such as the fingertips. In contrast, the forearm exhibits lower tactile acuity and coarser spatial resolution than the fingertips, highlighting an important perceptual constraint for forearm-based tactile interfaces [21, 22].

- **Meissner's Corpuscles (RA-I)**

Situated within the dermal papillae of glabrous skin, including the fingertips, palms, lips, and soles, these rapidly adapting type I receptors respond to light touch and low-frequency vibration. They play an essential role in detecting dynamic tactile events such as slip during object manipulation and contribute to temporal sensitivity in touch perception. These properties are important for understanding how low-frequency Vibrotactile stimuli are processed, even though such receptors are less densely represented on the forearm [23, 24].

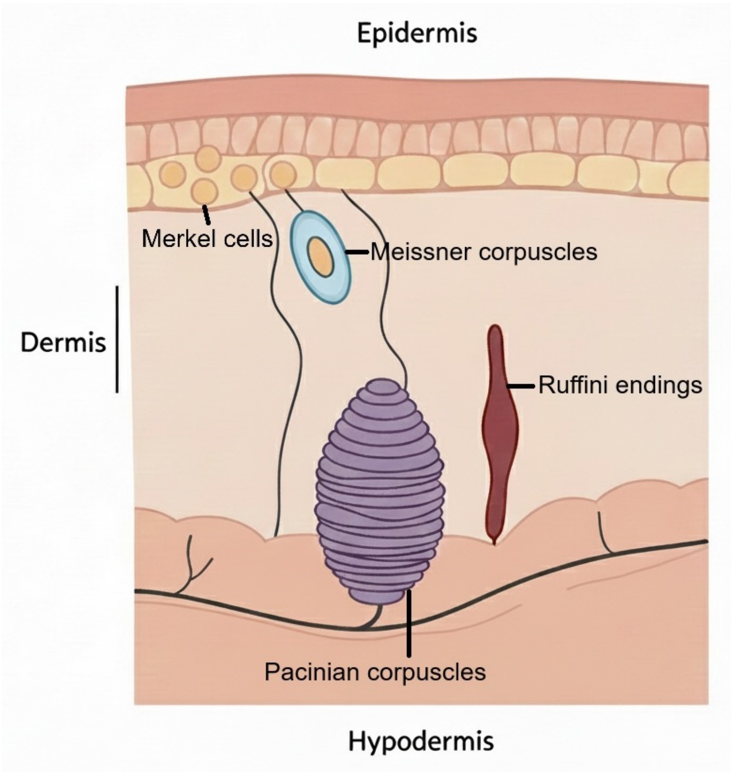


Figure 2.1. Cutaneous Sensory Receptors in the Skin Layers. This diagram illustrates a cross-section of the outer layer (Epidermis) and the underlying layer (Dermis), showing the precise location of key cutaneous sensory receptors. These structures are vital for tactile sensation and proprioception. They include: the Merkel's disk, located near the base of the Epidermis for sustained pressure and fine tactile detail; the Meissner's corpuscle (Light Touch Receptor), found in the upper Dermis to detect light touch and low-frequency vibration; the Ruffini ending (Stretch Sensor), situated deeper in the Dermis and Hypodermis to perceive skin stretching and sustained pressure; and the Pacinian corpuscle (Pressure & Vibration Detector), located deepest to sense transient deep pressure and high-frequency vibrations.

- **Pacinian Corpuscles (RA-II)**
  Located deeper in the dermis, hypodermis, and connective tissues around

joints, Pacinian receptors are rapidly adapting type II mechanoreceptors that are highly sensitive to high-frequency vibrations (approximately 100–500 Hz). Their broad frequency tuning and large receptive fields make them the dominant contributors to Vibrotactile perception in many haptic systems. These properties enable the perception of remote vibration and tool-mediated feedback and are particularly relevant for Vibrotactile stimulation applied to body regions such as the forearm [25, 26].

- **Ruffini Endings (SA-II)**
  Found in the dermis, hypodermis, and joint capsules, Ruffini endings are slow-adapting type II receptors that respond to sustained skin stretch and pressure. They provide information related to finger position, hand configuration, and movement direction, thereby contributing to proprioceptive integration and the perception of limb posture. These properties are relevant for understanding how tactile and proprioceptive cues interact during sustained contact and movement [27].

Although mechanoreceptor density varies across the body—with the fingertips being highly innervated while regions such as the forearm or back exhibit lower tactile acuity [28, 29]—the brain compensates through somatotopic magnification. In the primary somatosensory cortex (S1), body regions with high tactile significance, such as the hands and face, occupy disproportionately larger cortical representations. This somatotopic mapping, famously demonstrated through stimulation studies and illustrated by the cortical "homunculus", highlights the functional prioritization of certain body areas in tactile processing [30].

Mechanoreceptive information travels through the dorsal column–medial lemniscal pathway to the thalamus and then to the primary somatosensory cortex. There, tactile signals are integrated to enable the perception of texture, pressure, shape, vibration, and limb position, forming the basis for natural and artificial haptic communication.

2.2 Vibrotactile Communication

Vibrotactile communication represents a significant advancement in human-computer interaction, leveraging the sense of touch to deliver real-time, nuanced vibratory feedback. These systems employ distinct vibration patterns to discreetly convey information through the skin, offering a novel channel for interaction that bypasses traditional visual and auditory pathways. Such devices enhance accessibility for individuals with sensory impairments and expand the range of communication modalities in both assistive and general-purpose contexts. The proposed project aims to contribute to this growing field by designing and developing a precise, wearable Vibrotactile device with broad applicability, promoting inclusivity, interactivity, and user autonomy.

The absence of a sensory modality, particularly from birth, profoundly impacts neural and perceptual development. Congenital blindness, for instance, often leads to the adoption of alternative perceptual strategies and the formation of distinct neural representations of space and object identity. Accumulating evidence supports the concept of sensory substitution, wherein one sensory modality—such as touch—can compensate for the loss of another, such as vision [31, 32, 33]. Early systems like Bach-Y-Rita's tactile vision substitution device demonstrated that visual input could be successfully translated into Vibrotactile feedback on the back, enabling users to identify environmental features through touch [34, 35]. These findings laid the foundation for modern sensory substitution devices (SSDs).

Recent Vibrotactile systems build upon these foundational principles and are now used in various assistive and mainstream domains. For individuals with visual impairments, wearable devices such as smart canes integrate Vibrotactile feedback to communicate directional cues and obstacle information, thereby enhancing navigation and spatial awareness [36, 37]. Neuroscience research supports the efficacy of such systems, revealing that the brain's sensory cortices can be repurposed following deprivation. Classical theories of strict modularity have been challenged by evidence of cross-modal plasticity [38, 39]. For instance, visual cortices in blind individuals can be activated by tactile or auditory stimuli [40, 41]. These effects are not limited to low-level perception. The visual word form area (VWFA), traditionally associated with visual reading, is activated by Braille reading and even tactile grammar processing [38]. Similarly, tactile face exploration can activate the fusiform gyrus, and auditory cortices can be incorporated to process visual information in the deaf [42, 43]. Neuroscientific evidence further illustrates the capacity of tactile input to support meaningful information processing. In industrial settings, Vibrotactile wearables offer proximity alerts to enhance worker safety by signaling hazardous areas or machinery [44, 45]. In tourism, these systems guide visitors through unfamiliar environments using tactile cues, thereby enriching the user experience with location-specific feedback [46].

One emerging application of Vibrotactile systems is in structural firefighting. In low-visibility conditions, such as smoke-filled environments, wearable Vibrotactile gear can alert firefighters to hazards. For example, Vibrotactile headbands with ultrasound sensors can convey the proximity of walls via forehead tactors, while Vibrotactile gloves help navigate blind scenarios [47, 48]. These systems improve situational awareness and response time, although further integration and validation are required.

In music perception, Vibrotactile feedback has shown potential to improve auditory experiences, particularly for individuals with cochlear implants or hearing loss. Research indicates that whole-body and fingertip vibrations can enhance musical perception by encoding acoustic features such as rhythm, amplitude, and pitch [49]. Haptic chairs, Vibrotactile armchairs, and wearable devices offer users tactile access to musical structure, contributing to emotional engagement and sound comprehension in multisensory environments [50].

In gaming and virtual reality (VR), Vibrotactile technologies contribute to immersive environments by simulating physical sensations. Game controllers, gloves, vests, and full-body haptic suits provide tactile feedback to mirror in-game actions, such as collisions, recoil, or environmental changes [51, 52]. These innovations not only heighten realism but also expand the range of sensory input available to users, enabling intuitive and responsive interaction with digital content.

Health and fitness applications also benefit from Vibrotactile feedback. Athletes use these systems to receive real-time corrections in form and technique during exercises, improving performance and reducing injury risk [53]. In rehabilitation, Vibrotactile cues assist in recovery by providing feedback during postural or mobility exercises, particularly for patients recovering from surgery or managing balance disorders [54]. Devices tailored for specific sports, such as golf or running, use vibration to reinforce correct posture and motion patterns [55, 56].

In summary, Vibrotactile communication systems are transforming the landscape of human interaction across accessibility, safety, entertainment, health, and education. By leveraging the adaptability of the human brain and the flexibility of tactile feedback, these technologies offer inclusive, multi-sensory solutions to complex perceptual challenges. As development continues, interdisciplinary research combining neuroscience, engineering, and psychophysics will be essential to refine these systems and unlock their full potential.

While these examples illustrate the versatility of Vibrotactile systems, many remain at the level of research prototypes or domain-specific pilot implementations rather than widely adopted commercial products. Large-scale deployment is often limited by factors such as hardware constraints, user training requirements, variability in perceptual performance, and the absence of standardized design guidelines. This highlights the need for empirically grounded frameworks that move Vibrotactile communication from proof-of-concept demonstrations toward reliable and scalable real-world applications.

Despite a growing body of research on Vibrotactile systems, applications targeting the forearm remain critically underexplored. The forearm is a highly promising site for wearable interfaces, as it enables Vibrotactile cues to be delivered without interfering with manual activities—an especially valuable feature for users with sensory impairments who rely heavily on their hands. However, key design factors such as actuator placement and spacing, frequency and amplitude response, anatomical sensitivity, and temporal dynamics remain insufficiently investigated, leaving fundamental questions about perceptual optimization unanswered. Prior studies have also been constrained by the technical limitations of conventional Vibrotactile actuators, such as eccentric rotating mass (ERM) motors and linear resonant actuators (LRAs), which are characterized by restricted bandwidth and limited independent control of frequency and amplitude. To address these gaps, this thesis employs voice coil actuators, which overcome these limitations by providing a broad and continuous range of frequencies and amplitudes, independent parameter control, and fine-grained temporal precision. Leveraging this capability, the thesis introduces and experimentally evaluates the Vibrosleeve, a controlled, wearable platform designed to systematically investigate forearm-based Vibrotactile perception. In doing so, it advances both the scientific understanding of spatiotemporal tactile processing on the forearm and the practical development of novel assistive devices that extend tactile literacy and support sensory substitution.

Our research group has extensively investigated the properties of Vibrotactile stimulation, particularly in the context of sensory augmentation devices over the past several years. One notable system the group has explored is *The Sound of Vision*, a sensory substitution platform designed for individuals with visual impairments. This system integrates time-of-flight (ToF) and stereo cameras to map the surrounding environment and translate spatial information into tactile and auditory feedback. A key component is a tactile belt that communicates obstacle distance and direction through intuitive vibration patterns, thereby enhancing users' spatial awareness and mobility [8, 32, 57, 58, 59].

2.3 Fine-Tuning Vibrotactile Signal Parameters and Stimulation Location

The effectiveness of Vibrotactile communication systems relies on the precise calibration of signal parameters—such as intensity, frequency, and temporal structure—along with the careful selection and spatial arrangement of stimulation sites on the body. These factors collectively determine perceptibility, discriminability, comfort, and cognitive interpretability. Without such optimization, Vibrotactile feedback risks being ineffective or even counterproductive.

Signal intensity, or amplitude, significantly influences detectability [60, 61]. However, the optimal intensity range varies by location on the body due to differences in skin properties, receptor densities, and mechanoreceptor thresholds. Higher-intensity vibrations are more easily perceived, but excessive stimulation can lead to sensory adaptation, discomfort, or even pain—especially in more sensitive areas like the face or fingertips [62]. Conversely, lower-intensity signals may go unnoticed, particularly on less sensitive body parts such as the lower back or thighs [63, 64]. The perceptual threshold thus depends on both intensity and location, necessitating body-site-specific calibration.

Frequency tuning is equally essential. Different mechanoreceptors exhibit distinct frequency sensitivities: Pacinian corpuscles are tuned to high-frequency vibrations (approximately 100–500 Hz), while Meissner corpuscles respond best to lower frequencies (approximately 30–50 Hz) [65, 23]. Delivering stimuli at mismatched frequencies can impair signal salience or even render signals imperceptible. Cholewiak et al. [66] demonstrated that both detection thresholds and localization accuracy are frequency-dependent, with mid-to-high frequency signals being more reliably detected across larger body areas, especially when combined with optimal amplitudes.

The sensitivity of different body parts introduces another layer of complexity. Tactile spatial acuity and vibratory detection thresholds vary widely across anatomical sites. The fingertips, face, and lips possess high receptor density and thus provide excellent spatial and temporal resolution. In contrast, the forearm, abdomen, and back have lower tactile sensitivity and require stronger or more distinct signals for comparable performance [67, 63]. Consequently, applications involving fine pattern recognition—such as tactile Braille or symbolic input—are better suited to high-resolution locations like the fingertips, while alerting or directional cues can be effectively delivered to coarser-resolution regions such as the torso or upper arm [68].

The spatial arrangement of Vibrotactile actuators also plays a pivotal role in perceptual clarity and information encoding. Increasing the distance between actuators can improve localization accuracy by reducing perceptual overlap between neighboring stimuli, as shown by Cholewiak et al. [69]. However, if spacing is too wide, it limits the spatial resolution of encoded information. Conversely, tightly packed arrays may suffer from Vibrotactile masking, wherein neighbouring stimuli interfere with each other and reduce perceptual clarity [70]. Therefore, actuator density must be adapted to body region and intended application, balancing resolution with comfort and discrimination thresholds.

Moreover, sensor layout—linear, circular, grid, or custom spatial mapping—can significantly affect user performance and learning. Van Erp [71] showed that directional cues delivered through torso-worn linear arrays allowed rapid and accurate spatial orientation. In contrast, circular or concentric arrays are more effective for signaling heading changes or rotation. For mobile applications, body-worn arrays must also account for motion artifacts, as skin stretch or displacement can alter perceived signal direction or intensity [72].

Lastly, interindividual differences in skin properties, tactile sensitivity, and cognitive processing—due to age, skin type, experience, or medical conditions—further justify the need for adaptive or personalized feedback [73]. Some modern systems use calibration routines to match Vibrotactile signals to a user's perceptual profile, ensuring consistent perception and avoiding overstimulation or information overload.

To sum up, fine-tuning Vibrotactile signal parameters and selecting appropriate stimulation sites are essential to the success of tactile communication systems. Factors such as intensity, frequency, body site sensitivity, inter-sensor spacing, and individual differences must be carefully considered to maximize performance, comfort, and interpretability. These insights guide the design of next-generation wearable systems capable of delivering intuitive and robust tactile information across varied application domains.

2.4 Types and Functional Principles of Vibrotactile Actuators

Vibrotactile actuators are essential components in haptic feedback systems, particularly in wearable technologies designed to communicate information through the sense of touch. These actuators convert electrical energy into mechanical vibrations, stimulating the skin's mechanoreceptors to convey alerts, spatial cues, or complex patterns. Selecting the appropriate actuator is crucial, as each type differs in frequency response, energy consumption, size, controllability, and tactile resolution—factors that directly influence user perception and system performance.

1. **Eccentric Rotating Mass (ERM) Actuators**
   ERM actuators generate vibrations by spinning an unbalanced mass. They are low-cost and widely available but limited in control and responsiveness

(typically 80—150 Hz), making them suitable mainly for simple alerts [74].

2. **Linear Resonant Actuators (LRAs)**
LRAs vibrate along a single axis at their resonant frequency, offering better efficiency, faster response, and stronger tactile signals within the 150—250 Hz range. However, their narrow frequency bandwidth restricts flexibility [75].

3. **Piezoelectric Actuators**
Piezoelectric actuators deform rapidly when electrically stimulated, producing precise, localized vibations vibrations (100—1000 Hz). These actuators offer excellent temporal resolution and are ideal for high-fidelity haptics, though they require high voltage and are relatively costly [76].

4. **Voice Coil Actuators (VCAs)**
VCAs operate over a broad frequency range (10—500+ Hz) using Lorentz forces to deliver custom, high-amplitude waveforms with low latency. They are preferred in advanced VR and research applications but are larger and more power-intensive [77].

5. **Electroactive Polymers (EAPs)**
EAPs are soft, flexible materials that deform under electrical stimulation. They support integration into textiles and bio-compatible wearables but require high voltages and exhibit slow response and weak force output [78].

6. **Shape Memory Alloys (SMAs)**
SMAs like Nitinol change shape in response to heat and are used in slow, low-frequency haptic interfaces where silent, large-strain movement is needed. However, they are energy inefficient and thermally slow [79].

7. **Pneumatic and Air-Based Actuators**
Pneumatic haptic systems generate tactile feedback through controlled air pressure or brief air pulses delivered via inflatable chambers or air jets. These actuators can produce localized pressure, skin deformation, or dynamic puff stimuli and are often used in soft wearable interfaces and mid-air haptics. Pneumatic systems offer advantages in safety, compliance, and comfort; however, they typically require external pumps or compressed air sources, limiting portability and response speed. Their relatively slower temporal precision compared to electromagnetic actuators can restrict applications requiring high-frequency Vibrotactile encoding [80].

In conclusion, actuator selection must be guided by application-specific requirements—balancing resolution, form factor, responsiveness, and energy demand to achieve effective and comfortable tactile communication (cf. Table 2.1)

Table 2.1. Comparison of Haptic Actuators and Their Characteristics

Actuator Type	Operating Principle	Typical Frequency Range	Key Characteristics
Eccentric Rotating Mass (ERM)	A DC motor spins an off-center mass to produce vibration.	80—150 Hz	Low cost and widely used; simple alerts, but slow response and limited control.
Linear Resonant Actuator (LRA)	A mass—spring system oscillates at its resonant frequency.	150—250 Hz	Efficient and faster than ERM, but limited to a narrow frequency band.
Piezoelectric Actuator	Piezo materials deform when voltage is applied.	100—1000 Hz	Very fast and precise; suitable for high-fidelity haptics but requires high voltage.
Voice Coil Actuator (VCA)	A coil moves in a magnetic field using the Lorentz force.	10—500+ Hz	Wide frequency range with precise waveform control; often used in research systems.
Electroactive Polymer (EAP)	Soft polymers deform under electrical stimulation.	1—100 Hz	Flexible and wearable-friendly, but with low force output and slower response.
Shape Memory Alloy (SMA)	Metal alloy changes shape when heated by an electric current.	0—10 Hz	Large deformation and silent motion, but slow and energy inefficient.
Pneumatic / Air-Based Actuator	Air pressure inflates chambers or produces air pulses.	0—50 Hz	Produces pressure or air-puff feedback; safe and soft but requires pumps and responds slowly.

3 Methodology and Materials

This chapter outlines the experimental design, apparatus, and analytical procedures used to investigate the spatial, spectral, and temporal dimensions of Vibrotactile perception on the forearm. The methodological approach was designed to systematically evaluate perceptual performance under controlled stimulus variations, aligning directly with the thesis research questions. A combination of psychophysical testing paradigms and quantitative statistical analysis was employed to ensure rigorous and reproducible assessment of tactile discrimination and recognition accuracy.

3.1 Method

Forced-choice paradigms were used in the discrimination experiments, where participants evaluated the relationship between consecutively presented stimuli. Depending on the experimental condition, participants indicated whether the stimuli were perceived at the same location or in different directions relative to each other. This approach enabled precise evaluation of perceptual sensitivity to variations in frequency, intensity, and spatial configuration.

For vibrotactile pattern identification, participants received patterned vibration sequences presented either sequentially or simultaneously and were instructed to reproduce the perceived pattern using a keypad interface. This method directly assessed vibrotactile pattern recognition, memory encoding, and reconstruction ability, providing insight into how tactile information is processed and translated into symbolic responses. Recognition accuracy served as the main performance metric.

Together, these complementary methods formed a robust experimental framework for examining Vibrotactile perception. By integrating discrimination-based forced-choice testing with keypad-based pattern reproduction, the thesis provides an in depth understanding of how users perceive, differentiate, and recognize structured Vibrotactile information.

Ethical considerations were addressed in accordance with standard research practices for human-participant studies. A general application covering the tactile perception experiments conducted in this thesis was submitted to the National Bioethics Committee of Iceland (Vísindasiðanefnd). The committee reviewed the application and determined that the project falls outside the scope of health research and therefore does not require formal ethical approval.

All experimental procedures were conducted in accordance with established ethical principles for human-participant research. Participation was voluntary, and informed consent was obtained in writing from all participants prior to the experiments. Participants were informed of the study procedures and their right to withdraw at any time without consequence. All collected data were anonymized and handled confidentially.

Vibrotactile stimuli were generated using an audio-based hardware system, which provided precise control over parameters including frequency, amplitude, duration, and location of application on the forearm. Depending on the experimental condition, stimuli were delivered to different forearm regions, and participant responses were collected using a custom-designed keypad that automatically recorded key performance metrics such as accuracy and reaction time.

Statistical analysis of the data was conducted using Analysis of Variance (ANOVA) to assess the effects of various stimulus parameters and their interactions. Repeated Measures ANOVA was utilized for within-subject comparisons across experimental conditions. Where appropriate, post-hoc comparisons were performed.

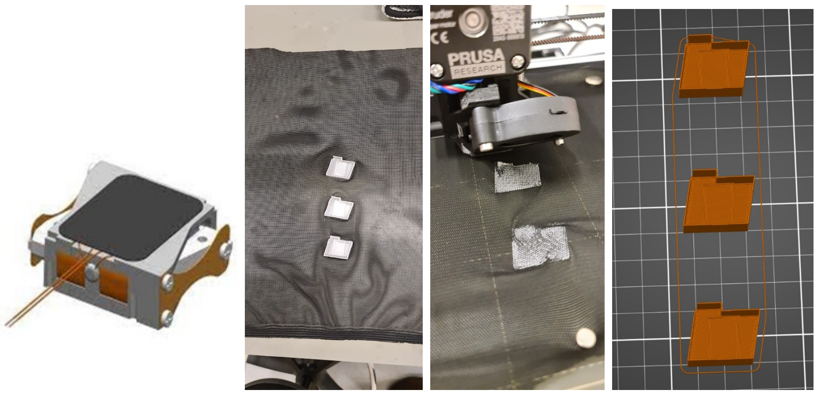
3.2 Overview of Vibrosleeve

The Vibrosleeve was designed as a flexible experimental platform to systematically investigate how spatial, spectral, and temporal properties of Vibrotactile stimulation influence tactile perception on the forearm. Voice coil actuators (VCAs; Model: Lofelt L5) were utilized to generate Vibrotactile stimulation, as illustrated in Figure 3.1. VCAs offer several distinct advantages, including rapid response times, high force density, and broad versatility for integration into wearable systems. Most importantly, they allow independent control of both frequency and amplitude, enabling the delivery of rich and customizable Vibrotactile feedback. These capabilities were essential for the aims of this research: the wide frequency range and precise controllability of VCAs directly supported the investigation of frequency sensitivity and anatomical effects, while their fast response and low-latency operation were critical for examining temporal sequencing and interstimulus intervals. The system is not limited to binary on—off feedback but allows continuous Vibrotactile modulation. Alternative actuators such as ERMs, LRAs, or piezoelectric devices were considered but ultimately dismissed due to limitations in bandwidth, controllability, or latency. In the initial design, the actuators were mounted on a soft, thin fabric to ensure a snug fit and efficient transmission of tactile stimuli to the forearm.

Voice coil actuators (VCAs) were positioned longitudinally along the forearm; however, the direction of their vibrational motion was transverse to the forearm, i.e., perpendicular to its longitudinal axis and parallel to the skin surface. This orientation was intentionally selected to limit the propagation of mechanical vibrations along the length of the forearm. Vibrations propagating longitudinally may increase mechanical coupling between neighboring stimulation sites, potentially resulting in perceptual overlap and reduced spatial discrimination. By directing the actuator motion transversely across the forearm, rather than along its length, the configuration was intended to reduce longitudinal vibration propagation and inter-actuator interference, thereby promoting greater spatial separability and more accurate localization of individual tactile stimuli.

The experimental setup incorporated a custom-designed Vibrotactile sleeve, referred to as the *Vibrosleeve*, constructed from Power Mesh fabric composed of 90% nylon and 10% spandex. This material was selected for its balance of comfort, flexibility, and wearability.

To accommodate varying forearm sizes, adjustable stretch straps with Velcro fasteners were employed to secure the sleeve in place. Actuator enclosures were 3D-printed directly onto the fabric using a Prusa MK3s 3D printer and Prusa Slicer software, with PLA as the chosen material. This direct printing approach ensured that the actuators could vibrate without obstruction. Crucially, there were no intervening fabric layers between the actuator enclosures and the skin.



(a) *(b)* *(c)* *(d)*

Figure 3.1. (a) Voice coil actuator (Model: Lofelt L5), (b) Enclosure on fabric mesh before actuator insert, (c) The printing was executed using a Prusa MK3s 3D printer and Prusa Slicer, (d) Enclosure slicing preparations. Paper-I

The Lofelt L5 actuators used in the system measure 17.0 mm in width, 20.5 mm in depth, and 6.2 mm in height.The custom-designed enclosures were used to house the actuators, with each actuator and its enclosure vibrating as a single unit, allowing the actuators to move freely without contacting the enclosure walls, even at maximum displacement.

Inside the enclosure, the actuator is positioned to generate vibrations parallel to the skin surface and perpendicular to the longitudinal axis of the forearm. This orientation facilitates effective transmission of vibratory stimuli while minimizing the risk of discomfort or injury. The enclosure plays a critical role in ensuring safe and stable Vibrotactile feedback delivery. Its precise fit with the actuator allows the two components to operate as a unified system, eliminating the possibility of exposure to sharp actuator edges that could irritate the skin or compromise the structural integrity of the fabric.

Fabricated with a smooth outer surface, the enclosure remains lightweight and unobtrusive. This design prioritizes both functional reliability and user comfort during prolonged use.

For stimulus presentation, the system utilized a high-fidelity audio signal chain comprising a digital audio interface (RME MADIface XT), digital-to-analog converters (Ferrofish A32), multi-channel amplifiers, and Lofelt L5 voice coil actuators. The RME MADIface XT managed multi-channel audio output, which was converted into analog signals via the Ferrofish A32. These signals were then amplified and delivered to individual actuators embedded in the Vibrotactile sleeve.

The actuators were connected through wired channels, allowing precise and independent control of frequency and amplitude for each unit. This setup ensured low-latency, synchronized, and high-resolution tactile stimulation, suitable for delivering complex and dynamic Vibrotactile patterns across the forearm.

In the initial version of the Vibrosleeve, three actuators were positioned longitudinally along the forearm to produce tangential vibrations perpendicular to the forearm's length. This minimal configuration was deliberately chosen to facilitate early-stage psychophysical testing, enabling controlled and simplified experiments focused on evaluating basic tactile perception. Empirical studies conducted with this prototype generated foundational insights that directly informed subsequent design iterations.

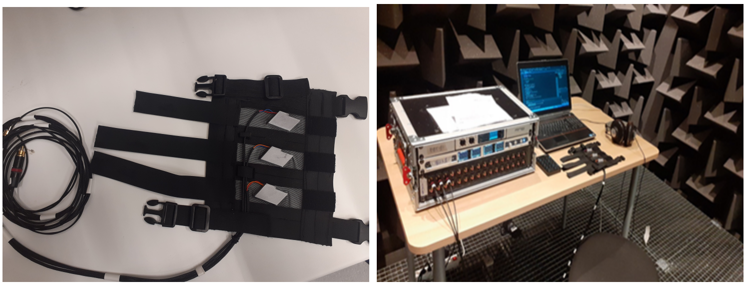
While increasing the number of actuators could, in theory, enhance the resolution and bandwidth of Vibrotactile communication, practical constraints—such as the physical dimensions of the forearm and the need to avoid signal overlap—necessitated careful consideration of inter-actuator spacing.To determine actuator spacing that enables high discrimination accuracy, psychophysical experiments were conducted using five different inter-actuator distances.

The results demonstrated that inter-actuator distances of 20 mm yielded discrimination accuracy rates between 90% and 92%, outperforming smaller spacing conditions that led to perceptual confusion and lower accuracy. These findings supported the fine-tuning of actuator spacing to approximately 20 mm, providing a practical balance between information density, perceptual performance, and wearable design constraints.

In the second revision of the Vibrosleeve, six Vibrotactile actuators were incorporated to convey Braille-like tactile patterns through the skin of the forearm. Increasing the number of actuators allowed for more complex and information-rich tactile representations, expanding the communication capacity of the system. The actuators were arranged in a 3×2 grid, inspired by the traditional six-dot Braille cell layout, and aligned longitudinally along the forearm.

This design iteration was evaluated in a study aimed at developing a wearable Vibrotactile sleeve capable of effectively conveying symbolic tactile information.

The results demonstrated significantly high accuracy in pattern recognition, with an average performance of 93.24% for Braille-like stimuli presented sequentially. These findings highlight the benefits of sequential stimulation, which offers enhanced perceptual clarity and minimizes signal overlap. The outcomes strongly support the feasibility of delivering symbolic information through tactile stimulation on the forearm and have been published in Papers III and IV.

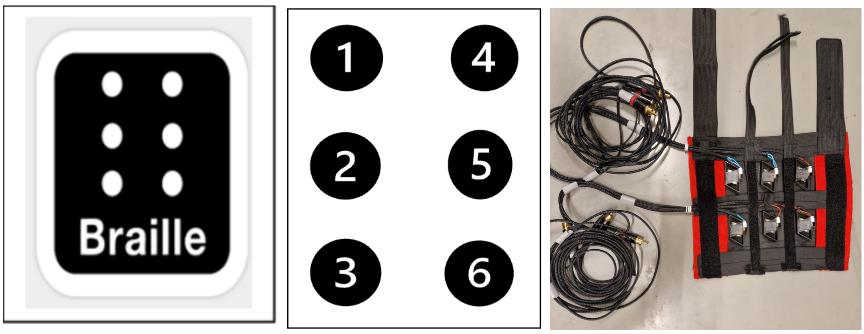


(a) (b)

Figure 3.2. (a) The Vibrosleeve (b) The audio hardware consists of a digital audio interface (RME MADIface XT), digital-to-analog converters (Ferrofish A32), multi-channel amplifiers, and parallel vibrating voice coil actuators (Lofelt's L5). Using this setup, up to 32 tactile channels can be controlled independently. The multi-channel amplifier is an in-house design based on a Texas Instruments amplifier and recommended circuit design. The MADIface XT receives information from a computer via a USB cable and sends the signal to the Ferrofish A32 analog-to-digital/digital-to-analog (AD/DA) converter. The Ferrofish A32 then sends the signal to the amplifier, which in turn delivers the amplified signal to the actuators. Paper-I

(a) (b) (c)

Figure 3.3. (a) Overview of the primary design of the Vibrosleeve, Enclosures were 3D-printed onto the fabric. ;(c) Vibrosleeve on forearm, generating Braille patterns through sequential actuator activation in our primary investigation. (c) Vibrosleeve is connected to an audio interface. Paper-III



(a) (b) (c)

Figure 3.4. (a) Braille dots; (b) Assignment of six Braille dots to the six actuators in the primary design of the Vibrosleeve;(c) Placement of six voice coil actuators assigned for six Braille dots on the Vibrosleeve. Paper-III

4 Summary of Publications

This chapter presents the empirical core of the thesis by summarizing the peer-reviewed publications that directly address the three thesis objectives (TO1–TO3). Each summary highlights the research questions, experimental approach, key findings, and contributions, thereby integrating the results into the broader framework of the thesis.

4.1 Evaluating the Optimum Distance between Voice Coil Actuators Using the Relative Point Localization Method on the Forearm

N. Yeganeh, I. Makarov, S. S. Stefánsson Thor, A. Kristjánsson, R. Unnthorsson, 'Evaluating the Optimum Distance between Voice Coil Actuators Using the Relative Point Localization Method on the Forearm', Actuators, vol. 12, no. 1, 2023 https://doi.org/10.3390/act12010006

This study examines the minimum spacing between Lofelt L5 voice coil actuators on the forearm necessary for accurate spatial discrimination of Vibrotactile stimuli. As Vibrotactile feedback becomes increasingly important in wearable and assistive technologies, the forearm presents a practical site for hands-free interaction. However, its relatively low tactile acuity compared to the fingers demands careful actuator placement to ensure perceptual clarity. If actuators are placed too closely, users may be unable to distinguish between distinct stimuli.

To address this, a Relative Point Localization (rPL) task was employed. The experiment involved eight participants, each completing 240 trials on both the upper and underside of the forearm. In each trial, pairs of Vibrotactile stimuli were delivered sequentially in a randomized order between each two adjacent actuators on the tactile sleeve. Participants were instructed to identify the perceived direction of the second stimulus relative to the first (up, down, or same). Five custom-designed sleeves with actuator interspacings of as close as physically possible, 5 mm, 10 mm, 15 mm, and 20 mm, were evaluated on both the upper and underside of the forearm.

Each sleeve contained three longitudinally aligned actuators embedded in 3D-printed enclosures on stretchable Power Mesh fabric. Tangential vibrations were delivered using a calibrated multichannel audio system, maintaining constant stimulus intensity across trials. The prototype was connected to the audio hardware via wired interfaces.

(a) (b)

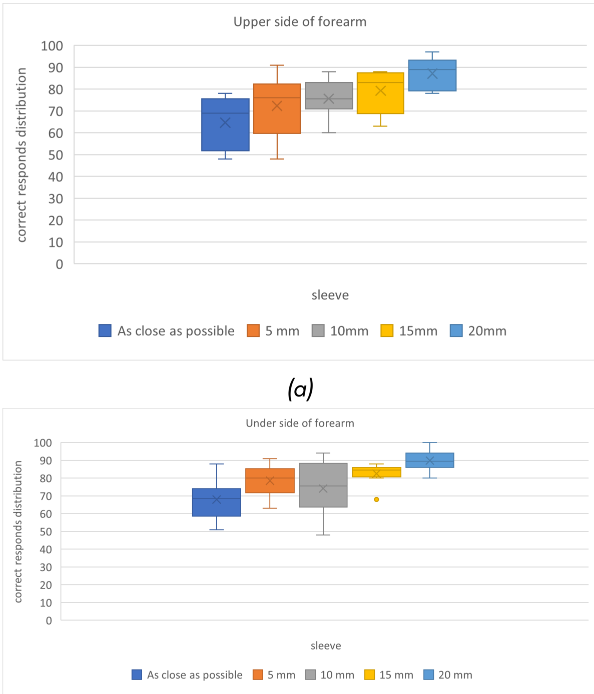
Figure 4.1. (a) The five Vibrotactile sleeves with different interspacing between actuators that were used in the experiment;(b) A participant wearing a Vibrotactile sleeve with his hand on the cushion, using the headphone to block out external cues and responding to the Vibrotactile feedback by pressing the correct key on the wireless keyboard. Paper-I

The audio hardware consisted of four main components: a digital audio interface (RME MADIface XT), digital-to-analog converters (Ferrofish A32), multichannel amplifiers, and the parallel vibrating voice coil actuators (Lofelt L5). The MADIface XT received information from a computer via a USB cable and transmitted the signal to the Ferrofish A32 analog-to-digital/digital-to-analog (AD/DA) converter. The Ferrofish A32 then conveyed the signal to the amplifier, which subsequently sent the amplified signal to the actuators.

A two-way repeated measures ANOVA was conducted with the factors *forearm side* (upper vs. lower) and *actuator interspacing* (as close as physically possible, 5 mm, 10 mm, 15 mm, 20 mm), followed by Bonferroni-corrected post hoc tests to assess the significance of differences in localization accuracy between spacing conditions and forearm surfaces. The two-way ANOVA also enabled analysis of the interaction between these two factors—specifically, whether the effect of interspacing varied between the upper and lower forearm.

The results revealed that a 20 mm spacing between Lofelt L5 actuators produced the highest localization accuracy, reaching 90% on the upper forearm and 92% on the underside. Post hoc analysis indicated a significant difference in discrimination accuracy when using the wearable device with 20 mm inter-actuator spacing. However, no significant difference was observed between the upper and underside of the forearm.

These findings indicate that a spacing of 20 mm is necessary for reliable spatial discrimination, providing key design guidance for forearm-mounted haptic devices (all detailed statistical data are available in Paper I, Chapter 6).



(b)

Figure 4.2. Box-whisker plot comparing the accuracy (percent correct, y-axis) between the five different tactile sleeves with various inter distances between enclosures (x-axis) Distribution of correct localization responses on the upper forearm for different inter-actuator spacings. Boxplots show the median, interquartile range, and overall spread of responses. An upward shift in the distributions is observed as actuator spacing increases, indicating higher localization accuracy and reduced variability at larger spacings. : (a) The percent correct for the upper side of the forearm; (b) The percent correct for the underside of the forearm. Paper-I

4.2 Effects of Stimulus Frequency and Location on Vibrotactile Discrimination Performance Using Voice Coil Actuators on the Forearm

N. Yeganeh, I. Makarov, R. Unnthorsson, A. Kristjánsson, 'Effects of Stimulus Frequency and Location on Vibrotactile Discrimination Performance Using Voice Coil Actuators on the Forearm', Actuators, 2024, 12, 224 https://doi.org/10.3390/act12060224.

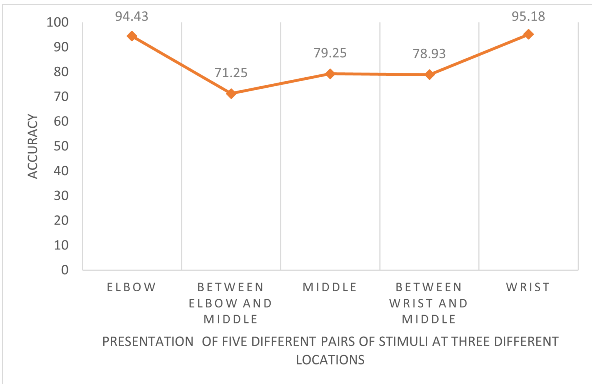
Precise localization of Vibrotactile stimuli is essential for applications that convey tactile information, such as wearable communication systems and sensory substitution devices. This study investigates how vibration frequency and stimulation location influence the ability to localize Vibrotactile stimuli on the forearm.

To evaluate the ability to distinguish Vibrotactile stimuli based on frequency and anatomical location on the forearm, a Relative Point Localization (rPL) method was employed. Eight participants took part in the experiment, with each participant presented with 96 pairs of sequential Vibrotactile stimuli delivered at three distinct locations on the forearm. Participants were asked to determine whether the second stimulus occurred at the same location as the first or not. Stimulation frequencies of 100 Hz, 150 Hz, 200 Hz, and 250 Hz were tested, covering the range to which human observers are most sensitive, while the stimulation amplitude was held constant. The results indicate that discrimination performance was not significantly affected by variations in vibration frequency within the tested range. In contrast, localization accuracy was strongly dependent on stimulation location, with the highest accuracy observed near the wrist and elbow—regions that may function as tactile anchor points. These findings highlight the critical role of anatomical location in precise Vibrotactile localization and underscore the importance of location-aware design in forearm-mounted Vibrotactile systems.

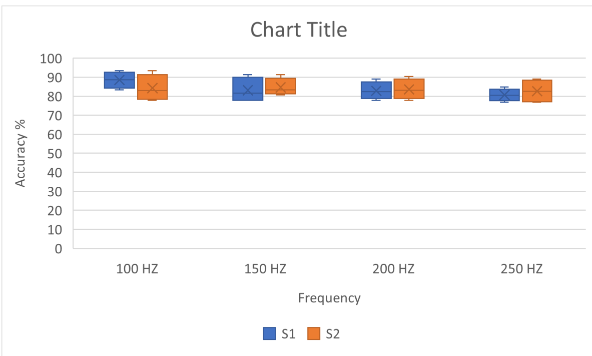
The ability to localize Vibrotactile stimuli was not significantly affected by frequency variations within the tested range. However, based on ANOVA statistical analysis, stimulation location had a strong impact on localization performance. The highest accuracy was observed at positions near the wrist and elbow, suggesting these regions may serve as tactile anchor points due to anatomical or perceptual factors.

Although frequency variation between 100–250 Hz does not impair localization accuracy, stimulus location plays a critical role in Vibrotactile spatial perception on the forearm.The observed effect of stimulation location can be interpreted in light of the receptive field properties of Pacinian corpuscles, which have large receptive fields and are particularly sensitive to high-frequency vibration. These receptors are more effectively activated near bony structures, joints, and tendons—such as those found near the wrist and elbow—where mechanical transmission of vibration is enhanced. In addition,Prior work by Cholewiak and colleagues has shown that salient anatomical landmarks can function as perceptual anchor points [69]. supporting more reliable spatial localization by providing stable reference locations along the body. The wrist and elbow may therefore serve as such landmarks, facilitating improved localization performance compared to more uniform regions of the forearm.

The stimulation frequencies selected for this experiment (100–250 Hz) fall within the range of highest human Vibrotactile sensitivity [81] , ensuring that stimuli were perceptually detectable across all frequency conditions tested. Frequency alone did not significantly affect localization performance, and no significant interaction between frequency and stimulation location was observed. Nonetheless, the location-dependent effects are likely influenced by regional differences in receptor recruitment, mechanical coupling, and the availability of anatomical reference cues across the forearm. These findings highlight the importance of strategic actuator placement in the design of forearm-mounted haptic devices to ensure reliable and effective tactile communication.



(a)



(b)

Figure 4.3. (a) Discrimination accuracy across five stimulus pair conditions on the forearm: (1) both stimuli near the wrist, (2) both near the elbow, (3) both at the middle actuator, (4) one at the middle and one at the wrist, and (5) one at the middle and one at the elbow (or vice versa). (b) Accuracy distribution for the first stimulus S1 and the second stimulus S2 as a function of vibration frequency. Paper-II

4.3 Discrimination Accuracy of Sequential Versus Simultaneous Vibrotactile Stimulation on the Forearm

N. Yeganeh, I. Makarov, A. Kristjánsson, R. Unnthorsson, 'Discrimination Accuracy of Sequential Versus Simultaneous Vibrotactile Stimulation on the Forearm', Applied Sciences 2024; 14 (1): 43, https://doi.org/10.3390/app14010043.

This study investigates the effectiveness of different presentation modes—specifically, sequential versus simultaneous Vibrotactile stimulation—in conveying Vibrotactile patterns to the forearm using a haptic wearable sleeve. The overarching goal is to enhance tactile communication systems for the visually impaired by identifying optimal stimulus presentation methods and design parameters.

A custom-designed Vibrotactile sleeve, inspired by the Braille dot structure and equipped with a 3×2 array of voice coil actuators (Lofelt L5), was used to deliver Vibrotactile patterns to the upper forearm. Eight normally sighted participants, without prior knowledge of Braille, took part in the experiment. Each participant completed 168 trials in which Vibrotactile patterns were presented using either simultaneous stimulation (1000 ms duration) or sequential stimulation (500 ms per actuator with 450 ms interstimulus intervals).

The goal was not to assess the participants' ability to identify the meaning of the patterns, but rather their ability to accurately reproduce them. Fourteen Icelandic Braille-based patterns—classified as *short* (2–3 actuators) or *long* (4–5 actuators)—were tested across 168 randomized trials. Participants were asked to reproduce the perceived patterns using a keypad.

Based on ANOVA results, accuracy was significantly higher for sequential presentation (93.24%) compared to simultaneous presentation (26.15%), with shorter patterns (97.19%) outperforming longer ones (89.29%).Additionally, a significant interaction was observed between these two factors, indicating that the effect of pattern length on recognition accuracy depended on the presentation method. The marked performance reduction observed during simultaneous stimulation is attributable to spatial masking and perceptual fusion. Primacy and recency effects were observed during sequential trials, indicating stronger memory retention for stimuli presented at the beginning and end of sequences. A clear learning effect also emerged across six experimental blocks, with recognition accuracy improving over time. These findings emphasize the importance of incorporating training sessions prior to device use.

Sequential stimulation is markedly more effective than simultaneous stimulation for presenting Vibrotactile patterns on the forearm, particularly for shorter patterns. The presence of memory and learning effects underscores the importance of temporal dynamics and user training in tactile communication.

These findings inform the design of wearable Vibrotactile displays for hands-free, on-body Braille reading and support the development of future sensory substitution and assistive technologies for individuals with visual impairment.

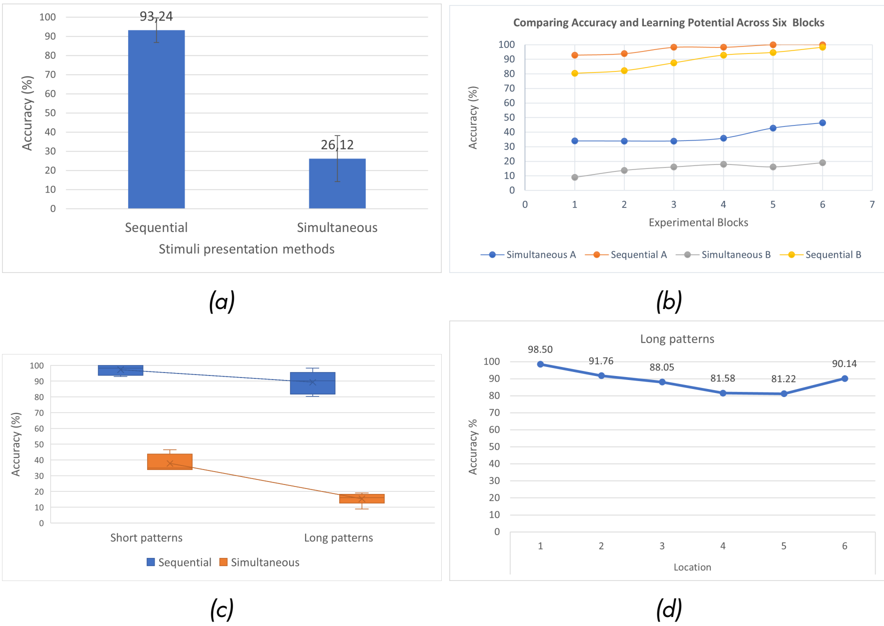


Figure 4.4. (a) Accuracy for the two different stimulus presentation methods (b) Performance across the six experimental blocks. The figure shows a clear learning effect over time for both presentation methods and different pattern length (Short (A) versus long (B) patterns). (c) Box-whisker plot comparing the accuracy (y-axis) between the two different pattern lengths with different Vibrotactile presentation methods, (x-axis). (d) Accuracy as a function of serial position of each individual Vibrotactile stimulation during sequential presentation for long patterns (4-5 actuators). Paper-III

4.4 Vibrotactile Pattern Recognition: The Influence of Interstimulus Intervals

N. Yeganeh, I. Makarov, A. Kristjánsson, R. Unnthorsson, 'Vibrotactile Pattern Recognition: The Influence of Interstimulus Intervals', Virtual Reality & Intelligent Hardware, 2025: : 7 (5): p. 483–500, https://doi.org/10.1016/j.vrih.2025.06.001

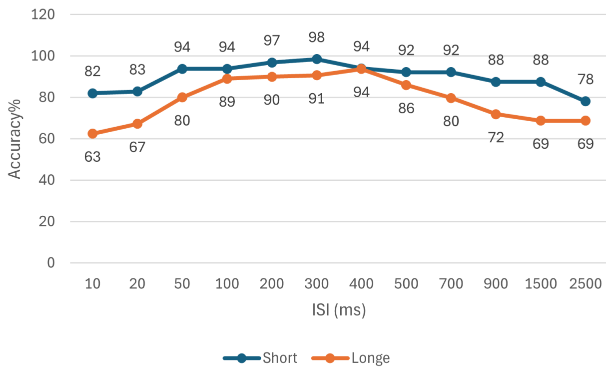
The timing of interstimulus intervals (ISIs) plays a critical role in users' ability to perceive and interpret Vibrotactile patterns accurately. Fine-tuning ISIs can enhance system effectiveness, improve user interaction, and support intuitive, reliable tactile communication across a range of applications.

This study examined how varying ISIs affect the accuracy of Vibrotactile pattern recognition. Participants wore a forearm-mounted device featuring six Lofelt L5 voice coil actuators arranged in a 3×2 grid. Braille-based Vibrotactile patterns were delivered sequentially at ISIs ranging from 10 to 2500 milliseconds (ms).

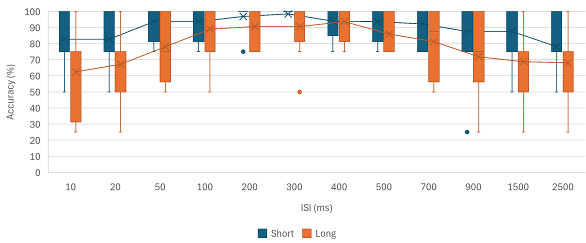
A total of eight participants took part in the study, with each participant completing 192 trials.Eight participants completed identification tasks using Icelandic Braille patterns categorized as *short* (2–3 actuators) or *long* (4–5 actuators). Repeated measures ANOVA was used to evaluate the effects of interstimulus interval (ISI), pattern type, and practice (across two testing blocks) on recognition accuracy.

For short patterns, the highest accuracy (92%–98%) was observed at ISIs between 50–700 ms, with peak performance at 300 ms. For long patterns, accuracy ranged from 86%–94%, peaking at 400 ms. Participants consistently performed better with short patterns, and recognition accuracy improved significantly over time for both pattern types, highlighting the importance of practice and training.

These findings underscore the need for careful selection of ISIs in Vibrotactile feedback systems to ensure accurate pattern recognition. The results offer practical insights for designing effective wearable tactile interfaces, enhancing tactile communication in applications that rely on precise Vibrotactile information delivery.



(a)



(b)

Figure 4.5. (a) The graph illustrates accuracy in recognizing short patterns (blue) and long patterns (orange) across a range of interstimulus intervals (ISIs). Recognition accuracy is highest for both pattern types within a specific range of ISIs, reflecting optimal conditions for perception, (b) Box Plots Showing Accuracy Distribution for Short and Long Patterns Across ISIs, ranging from 10 to 2500 ms. Each box plot represents the median accuracy, interquartile range, and outliers for each ISI. Short patterns generally show higher accuracy compared to long patterns across most ISIs, with the highest accuracy occurring within a specific ISI range. The spread and distribution of data highlights the variability in participant performance. Paper-IV

5 Discussion

The thesis set out to investigate the feasibility and fine tuning of forearm-based Vibrotactile communication by systematically examining spatial, spectral, and temporal parameters through psychophysical studies. When viewed collectively, the four empirical studies form a coherent body of evidence that both extends psychophysical understanding and establishes concrete design principles for wearable haptic systems. The central narrative that emerges is that the forearm—long regarded as a site of limited tactile acuity—can, under carefully fine-tuned conditions, support reliable, information-rich communication.

The first study demonstrated that actuator spacing is a fundamental constraint for spatial discrimination, underscoring its critical importance in the design of wearable Vibrotactile devices.The first study demonstrated that actuator spacing constitutes a fundamental constraint for spatial discrimination on the forearm. In systems where multiple actuators are positioned in close proximity, establishing a spacing that maintains perceptual separability between stimulation sites is critical. Under the tested conditions, an inter-actuator spacing of approximately 20 mm emerged as a practical distance that preserves high localization accuracy, while also significantly improving Vibrotactile pattern recognition. At smaller spacings, localization performance degraded due to increased mechanical coupling and overlap of tactile receptive fields. Maintaining high Vibrotactile localization accuracy is particularly crucial in assistive technologies and sensory substitution devices, where reliable perception directly affects usability, safety, and effective information transfer. At the identified spacing, Vibrotactile stimuli remained reliably distinguishable, yielding consistently high localization accuracy across participants. Importantly, this value should not be interpreted as a universal anatomical limit, but rather as a design-relevant benchmark specific to forearm-mounted voice-coil actuators and the experimental parameters employed. As tactile sensitivity varies substantially across body regions, spatial design constraints must be adapted to the local perceptual characteristics of the stimulation site.

The second study revealed that, within the mid-frequency range of 100–250 Hz, variation in stimulation frequency had less impact on localization performance than might be expected when amplitude was held constant. Several factors account for this outcome. First, this range falls within the region of peak human Vibrotactile sensitivity, where perceptual differences are less pronounced because the skin responds broadly and robustly across the entire band. Second, Pacinian corpuscles—the mechanoreceptors primarily responsible for detecting high-frequency vibration—are optimally tuned to this range and exhibit overlapping sensitivity profiles, reducing perceptual distinctiveness between frequencies. These findings suggest that, in practical forearm-mounted systems, anatomical location exerts a stronger influence on perceptual accuracy than frequency variation within this range. Indeed, the data show that tactile acuity is consistently enhanced near joint regions such as the wrist and elbow, indicating that the perceptual "map" of the forearm is structured rather than uniform. This challenges the long-standing assumption that the forearm is characterized by uniformly low sensitivity and highlights the importance of anatomical landmarks as anchor points in the design of wearable haptic systems.

The third study advanced this line of investigation by exploring whether complex information could be transmitted through touch, refining the Vibrosleeve platform to deliver structured and transparent Vibrotactile cues. Braille-inspired patterns were evaluated on the forearm to assess users' ability to discriminate Vibrotactile information. The results revealed that sequential presentation significantly improved pattern recognition accuracy compared to simultaneous stimulation, confirming the central importance of temporal sequencing in tactile communication. Additional factors, including pattern length and the influence of learning over repeated exposures, were also found to affect discrimination performance, with practice improving accuracy over time. By defining these parameters, the study provided a methodological baseline for presenting structured information through the sense of touch and laid the groundwork for sensory substitution devices capable of extending tactile literacy beyond the fingertips, such as anchor points.

The fourth study examined temporal dynamics in greater detail, confirming that sequential stimulation yields far superior recognition than simultaneous presentation. By systematically varying interstimulus intervals (ISIs) between 100 and 500 ms, the study identified timing windows that optimized the balance between speed and accuracy for sequential Vibrotactile codes. Furthermore, repetition effects demonstrated that users could learn and adapt to novel Vibrotactile patterns, reinforcing the potential for training-based scalability.

Studies on tactile acuity [63, 64] established that receptor density decreases markedly from the fingertips to the forearm, which led many researchers to conclude that the forearm is unsuitable for detailed tactile communication compared to more sensitive regions such as the fingertips. The present work challenges this long-standing assumption by demonstrating that, although the absolute sensitivity of the forearm is indeed lower, effective communication is still achievable when actuator spacing, and temporal sequencing are carefully calibrated. In other words, perceptual limitations can be overcome through appropriate design strategies, positioning the forearm not as a deficient site but as a viable substrate for scalable Vibrotactile communication.

The insights gained in this work have broad implications across multiple domains. In sensory substitution, Vibrotactile devices provide alternative channels for conveying symbolic information, with Braille-inspired patterns on the forearm illustrating how tactile literacy can be extended beyond the hands. In the context of literacy and accessibility, systems such as the Vibrosleeve demonstrate high accuracy in recognizing Braille-like patterns on the forearm, freeing the hands for other tasks and enhancing user mobility. Unlike electronic Braille notetakers, these wearables integrate seamlessly into daily life, offering dynamic real-time feedback and the capacity to display calendar information, navigation cues, or graphical content through spatially encoded tactile signals. Beyond literacy, in assistive technology, Vibrotactile systems can deliver silent and reliable cues for individuals with hearing or vision impairments, while in prosthetics they may compensate for lost sensation by providing artificial tactile input through the device. In AR/VR environments, forearm-mounted haptic arrays can enrich immersion without interfering with manual interaction, and in professional contexts they can provide discreet notifications or situational alerts when auditory or visual channels are overloaded. In rehabilitation, Vibrotactile feedback may support motor retraining by supplying supplementary cues aligned with movement. Collectively, these applications underscore the broader significance of this thesis, demonstrating that fine-tuned Vibrotactile communication extends well beyond controlled experiments to enable inclusive, functional, and context-aware human–technology interaction.

In conclusion, this thesis contributes to both fundamental knowledge and applied design. It provides definitive answers to six interlinked research questions, synthesizes four empirical studies into a coherent framework, challenges longstanding assumptions about the forearm's perceptual limitations, and establishes actionable guidelines for system design. The overarching message is clear: Fine-tuning the spatial, spectral, and temporal features of Vibrotactile stimulation can substantially enhance the accuracy and reliability of Vibrotactile perception. Importantly, the forearm functions as a largely passive body site, providing an opportunity to transmit Vibrotactile cues without interfering with the hands, which remain free for everyday tasks.

By integrating psychophysical insights with engineering practice, this work advances the field of haptics and lays the groundwork for next-generation wearable systems that are practical, inclusive, and transformative. From an engineering perspective, the work contributes empirically validated design principles for real-time, non-visual information communication using wearable devices. The findings demonstrate that frequency-controlled Vibrotactile stimulation is not primarily used to encode information directly, but rather to ensure perceptual salience and consistent activation of relevant mechanoreceptor populations across anatomical locations. While frequency variation within the tested range did not independently improve discrimination accuracy, its controlled use supported reliable stimulus perception when combined with optimized spatial layouts and carefully tuned temporal encoding strategies.

The outcomes of this research have direct applications across multiple domains, including assistive technologies for visually or hearing-impaired users, sensory substitution systems, silent alerting and navigation aids, rehabilitation and motor training tools, and immersive AR/VR interfaces. By enabling structured, low-latency information transfer through touch, the proposed Vibrotactile framework supports the development of systems that are practical, inclusive, and adaptable to environments where visual and auditory channels are limited or overloaded.

6 Conclusions

The primary objective of this thesis was to design and fine-tune Vibrotactile stimulation parameters to enhance the accuracy and usability of forearm-based wearable communication systems. This objective was achieved through three interrelated investigations: fine-tuning actuator spacing (TO1), examining the effects of frequency variation and anatomical factors (TO2), and analyzing temporal factors and pattern recognition (TO3).

Together, these studies form a coherent and evidence-based framework for advancing Vibrotactile communication. The central outcome of this work is that careful fine-tuning of spatial, spectral, and temporal features significantly improves Vibrotactile perception on the forearm. The contributions of this research can be summarized as follows:

- **Spatial fine-tuning**: Establishing empirically derived adjustments to actuator spacing that support reliable stimulus discrimination
- **Anatomical and spectral insights**: Providing guidelines on how stimulation location and vibration frequency interact to influence tactile perception.
- **Temporal encoding principles**: Identifying timing parameters and sequencing strategies that maximize recognition accuracy.
- **Methodological advancement**: Developing validated psychophysical approaches for assessing wearable haptic systems.
- **Prototype development**: Development of the Vibrosleeve as an experimental platform for investigating forearm-based vibrotactile communication.

Collectively, these contributions address longstanding gaps in haptic interface design by shifting the focus from anatomical limitations to design optimization. They provide actionable principles for developing perceptually fine-tuned, user-centered Vibrotactile systems with relevance for assistive technologies, sensory substitution, immersive AR/VR environments, prosthetics, and silent communication platforms.

6.1 Answers to the research questions

This section provides explicit answers to the research questions presented in Chapter 1. The answers synthesize the findings across the included publications and demonstrate how the thesis objectives were achieved.

RQ 1: What is the minimum actuator spacing required to achieve high spatial discrimination accuracy?

The experiments reported in Paper I demonstrated that actuator spacing significantly influences tactile localization accuracy on the forearm. A spacing of approximately 20 mm was found to provide reliable spatial discrimination, yielding localization accuracies of approximately 90–92% across the forearm. Localization accuracy was comparable on the dorsal and ventral forearm surfaces, with no statistically significant differences observed between them. These findings establish a practical spatial resolution limit for forearm-based vibrotactile interfaces and indicate that actuator interspacing is a critical parameter for achieving high spatial discrimination accuracy.

RQ 2: How does Vibrotactile frequency influence tactile localization accuracy across the forearm?

Results from Paper II showed that Vibrotactile frequency within the tested range of 100–250 Hz did not significantly influence localization accuracy when amplitude was controlled. However, anatomical location had a strong effect on performance. Stimuli delivered near anatomical landmarks such as the wrist and elbow produced higher localization accuracy than stimulation at mid-forearm locations. These findings indicate that actuator placement is more critical than frequency selection within the tested range while the amplitude remains constant.

RQ 3: What is the effect of pattern length on recognition accuracy?

Findings from Papers III and IV demonstrated that recognition accuracy decreases as the Vibrotactile pattern length increases. Shorter patterns resulted in higher accuracy and lower cognitive demand compared to longer patterns. This indicates that tactile communication systems should favor compact pattern designs in order to maximize usability and recognition performance.

RQ 4: How do Vibrotactile presentation methods impact recognition accuracy?

Paper III demonstrated that Vibrotactile presentation methods strongly influence recognition accuracy. Sequential stimulation significantly outperforms simultaneous stimulation, with recognition accuracy of about 93% compared to approximately 26% for simultaneous presentation. Sequential presentation reduces perceptual overlap among actuators and enables clearer processing of stimuli. Therefore, sequential encoding provides a more effective strategy for Vibrotactile communication on the forearm.

RQ 5: How do stimulus order and interstimulus interval affect tactile discrimination accuracy?

Results from Paper IV showed that Vibrotactile recognition accuracy depends strongly on interstimulus interval (ISI). Optimal performance was observed within a temporal window of approximately 100–500 ms. Serial position effects were also observed, with stimuli presented at the beginning and end of sequences being recognized more reliably than those in intermediate positions

RQ 6: Does sequential presentation accuracy improve with repeated exposure?

Experimental results in Paper III demonstrated a clear learning effect across experimental blocks. Recognition accuracy improved with repeated exposure, indicating that users adapt to Vibrotactile communication systems over time. This suggests that training can significantly enhance system performance in real-world applications.

Overall, the results confirm that Vibrotactile stimulation can be systematically fine-tuned to support reliable and cognitively efficient information communication on the forearm. Together, the findings establish empirically grounded and perceptually fine-tuned design principles for wearable Vibrotactile communication systems.

6.2 Limitations

While this thesis advances understanding of forearm-based Vibrotactile communication, several limitations must be acknowledged. All studies were conducted in controlled laboratory environments using a wired prototype. These conditions minimized noise and distraction but do not capture the complexities of real-world use, where users are mobile, multitasking, and exposed to competing sensory inputs. The Vibrosleeve relied on a single actuator type (Lofelt L5 VCAs) in a fixed configuration, providing experimental precision but restricting the generalizability of findings to other actuator technologies, body sites, or wearable form factors. Participants were drawn largely from student populations, resulting in a relatively homogeneous group that limits insights into how factors such as age, sensory impairments, skin type (e.g., hairy versus glabrous skin), or prior haptic experience may influence perception. Moreover, the studies isolated spatial, spectral, and temporal parameters for clarity, whereas practical systems will need to integrate these dimensions simultaneously, raising questions of scalability and complexity. In addition, the research focused on short-term perceptual performance, leaving unanswered questions about long-term learning, adaptation, retention, comfort, and fatigue during extended use. Finally, the experiments employed a uniform setup for all participants and did not account for individual differences in tactile sensitivity. Since perceptual thresholds vary widely across individuals, future systems should incorporate adaptive calibration—potentially using machine learning—to tailor stimulation parameters to personal sensitivity profiles and user preferences.

6.3 Future Work

Each of these limitations points directly toward promising avenues for future research:

1. From laboratory to real-world environments
   Future studies should evaluate performance in dynamic, everyday contexts where users are mobile, multitasking, and surrounded by competing sensory input. This will validate ecological robustness and practical usability.

2. Expanding actuator and body-site diversity
   Research should explore alternative actuator technologies, smaller actuators, and other body sites such as the torso, upper arm, or back. This will enable adaptable, generalizable design principles.

3. Inclusive and diverse user testing
   Future work should involve participants with diverse tactile sensitivity profiles, including older adults and individuals with sensory impairments. Expanding the participant base in this way will enhance inclusivity and ensure that wearable haptic systems are designed for broader usability and real-world applicability.

4. Longitudinal studies on learning and retention
   Extended investigations are needed to examine how users internalize Vibrotactile codes, how recognition performance evolves with practice, and how factors such as adaptation, fatigue, and cognitive load influence long-term and sustained use.

5. Adaptive and intelligent systems
   Machine learning—driven personalization, incorporating calibration signals based on individual tactile sensitivity profiles, could enable wearable systems to dynamically adjust stimulation parameters to each user's perceptual thresholds. Such adaptability would enhance comfort, improve efficiency, and support long-term adoption by ensuring that Vibrotactile feedback remains both perceptually salient and tailored to the user over time.

Paper I

Evaluating the Optimum Distance between Voice Coil Actuators Using the Relative Point Localization Method on the Forearm

N. Yeganeh, I. Makarov, S. S. Stefánsson Thor, A. Kristjánsson, R. Unnthorsson.

https://doi.org/10.3390/act12010006, 2023 actuators

Article

Evaluating the Optimum Distance between Voice Coil Actuators Using the Relative Point Localization Method on the Forearm

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Abstract: While vibrotactile stimulation shows promise for sensory substitution devices, a crucial question concerns vibrotactile spatial resolution. We examined the optimum distance between three voice coil actuators (model: lofeltL5) on the forearm. Three actuators were embedded in a fabric-based vibrotactile sleeve where the actuators were placed in enclosures 3D-printed on the fabric. We used the relative point localization method where observers must discriminate whether two successive stimulations are in the same location or not. The resolution was measured for five vibrotactile sleeves, each with different distances between the actuators on the longitudinal axis of the forearm. The various distances were tested in a random order. In experiment one, pairs of stimuli were delivered sequentially in a random order to two adjacent actuators of the tactile sleeve on the upper side of the forearm. The task was to identify the perceived direction of the second stimulation (up, down, or the same) relative to the first one. Experiment two involved the same procedure but for the underside of the forearm. Taking the restrictions of the physical dimensions of the forearm and the design considerations into account, our results suggest that 20 mm is the optimum distance between the voice coil actuators (Model: Lofelt L5) for successful discrimination with high accuracy between the two stimulus locations on the forearm. There were no significant differences between the upper and undersides of the forearm.

Keywords: vibrotactile; voice coil actuator; wearable device; tactile stimulation; vibratory stimulus; spatial acuity; stimuli localization

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1. Introduction

Vibrotactile stimulation shows promise for sensory substitution in assistive devices for people with visual or auditory impairment [1,2]. Vibrotactile devices can be used to compensate for lost information by providing vibratory stimulus signals that can convey information that cannot otherwise be used because of perceptual deficiencies. Understanding the most feasible number and locations of tactile stimulation is one of the critical questions that must be answered before vibrotactile sensory substitution displays can be implemented. The interspacing between the actuators will have a decisive effect on the perception of the vibrotactile stimulation and on whether the signals can be spatially differentiated from each other. The minimum distance between two objects that can be discriminated has been investigated since the 19th century using various techniques [3–5]. Weber introduced a psychophysical two-point threshold (2PT) method for assessing the minimum distance between two simultaneously stimulated points where the two stimuli can be spatially discriminated [5]. Many studies of tactile spatial acuity have used this 2PT method, where the purpose has been to determine the detection threshold between two stimulus locations—whether the two stimulations are perceived at the same or different locations [6–14]. Some studies have indicated that results on the 2PT task can be contaminated by non-spatial cues that may result in inflated estimates of spatial acuity. For instance, two points might feel further apart than they actually are. These cues can also be temporal. If the two points stimulations are not applied simultaneously, the participant may perceive two contacts even if they are unable to spatially discriminate the points. Magnitude cues, where interactions between stimuli are not expected at the single-neuron level, can also affect performance. The two-point orientation threshold (2POT), where participants must discriminate the orientation (horizontal vs. vertical) of two points of contact, may be a better measure of spatial acuity, since it avoids the non-spatial cues [15–17].

It is also important to note that tactile spatial acuity differs by body part [18]. For example, the 2PT is much larger on the forearm than on the fingertips [4,19,20]. Reports of 2PT results should always be accompanied by a detailed description of how the test was conducted [16,21,22], because different protocols and tools have been used [23]. Notably, other findings show that training may influence 2PT measurements [24,25]. Moreover, other methods, such as tracking of absolute point localization (PL), have revealed a lower value than the 2PT [4,6]. Despite these controversies, 2PT remains a valuable resource [4].

Even though acuity for tactile point stimulation has been investigated extensively, less is known about vibrotactile spatial acuity. Our research group has studied vibrotactile devices over the last few years [26–29]. The aim has been to gain knowledge about the qualities of vibrotactile perception for potential use in sensory substitution devices [29]. We have, for example, investigated the relative vibrotactile spatial acuity in the back region of the human body using coin cell motors, finding the minimum threshold by decreasing the center-to-center inter tactor distance. The measured minimum threshold was 13 mm from center to center (c/c). Note that this threshold only applies to the central area of the back and cannot easily be generalized to other body parts [26].

Another way of measuring the spatial accuracy of the interspacing between localized stimuli in tactile displays is by applying the point localization (PL) method. The method has been widely used to analyze spatial acuity for different interspacings between stimulators. This method has been used to measure absolute spatial acuity [30], where the vibrotactile stimulus was presented at fixed distances. The task was to identify the location of the vibrating actuator in the array. Lindeman and Yanagida [31] tested absolute localization accuracy using prototypes with different numbers of tactors embedded on the subjects' backs. The highest accuracy was found for inter-tactor spacings of 60 mm, with 84% accuracy on the discrimination task. Cholewiak [30] investigated spatial accuracy using the PL method, presenting the stimuli on the abdomen. Performance was a function of separation among loci and, most significantly, of the location on the trunk.

Because of potential problems with the 2PT and PL methods as discussed above, some researchers have instead recommended the use of the relative point localization method (rPL) [32–34], where observers must discriminate whether two successive stimulations are in the same location or not, and this is the method that we chose for our measurements.

2. Materials and Methods

2.1. The Current Goals

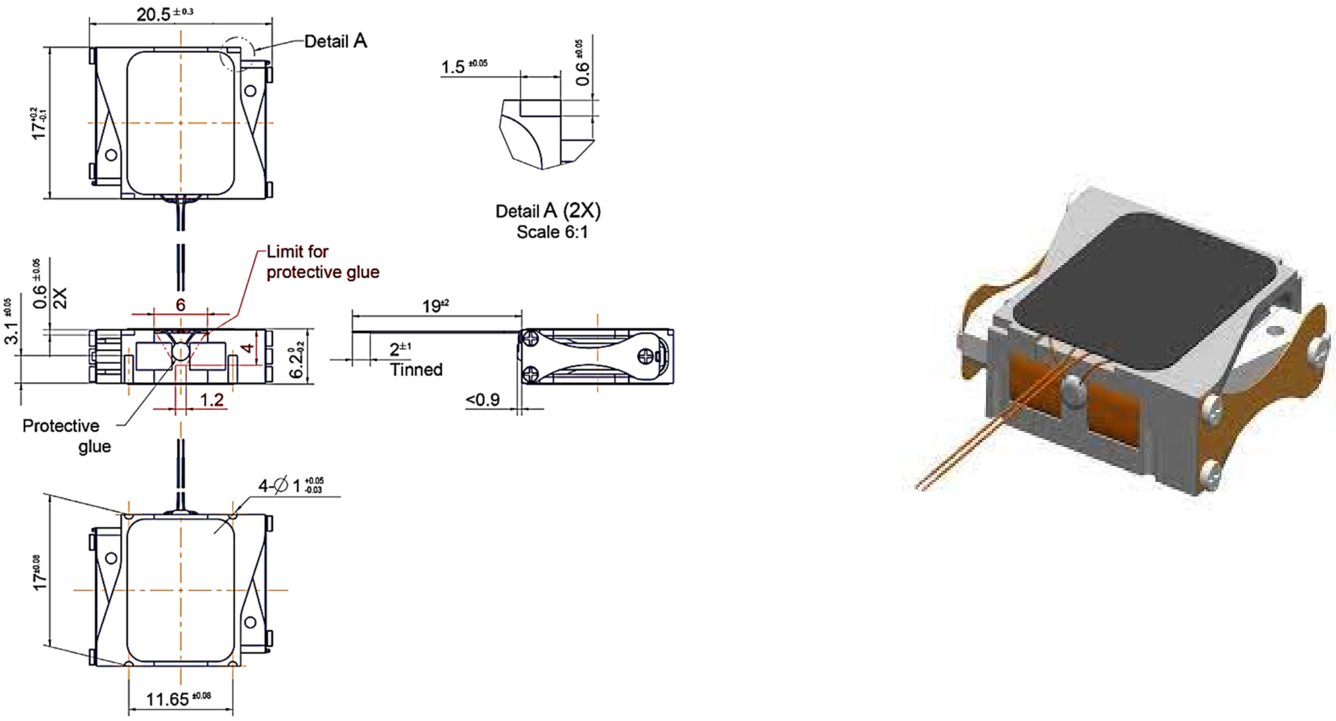
Our aim was to evaluate the optimum interspacing between Lofelt L5 voice coil actuators on the forearm. Our aim was to find the minimum distance where two vibrotactile stimulations can be discriminated with high accuracy. The goal was to use the results to optimize the structure of a vibrotactile sleeve in sensory substitution devices. We used the relative point localization method (rPL) on both sides of the forearm, measuring the relative spatial acuity for vibrotactile stimulation. The aim was to formulate guidelines for minimum intervals for successful separation of different loci of stimulation from the voice coil actuators (Lofelt L5) on the forearm. The relative point localization task measured observers' ability to determine the direction of a second stimulus relative to the initially presented one on each trial. The forearm has limited space to place multiple actuators next to each other laterally, and we therefore tested different distances in the longitudinal direction. The feasible upper limit is therefore set by how far apart the actuators can be placed, considering that the forearms of potential users will differ in length.

Our results indicate that a distance of 20 mm is the best distance between actuators on both sides of the forearm, when the spatial limits on design are considered. The results of this study will be helpful for the continued development of our current design of the vibrotactile sleeve and provide valuable insights for the creation of forearm-mounted vibrotactile displays using voice coil actuators (Model: Lofelt L5) by providing information regarding the optimum distance between actuators along the forearm.

2.2. Equipment and Setup

2.2.1. Actuators

Voice coil actuators (model: Lofelt L5) were employed to generate vibratory stimulation (Figure 1A,B). The L5 actuator is an extended-band actuator that allows independent manipulation of the frequency and amplitude utilized in implementing haptic stimulation for many scientific purposes. Their high acceleration, light weight, high efficiency, and inexpensiveness, along with other advantages, make voice coil actuators ideal for various vibrotactile displays. The Lofelt L5 voice coil actuator provides parallel vibrations on the skin [35]. In this study, the actuators were embedded in housings that were 3D-printed on a power mesh fabric material. Tables 1 and 2 show the physical, haptic, and electrical characteristics of the Lofelt L5 [35].



(a) **(b)**

Figure 1. (**a**) Technical and dimensional information for the L5 voice coil actuator, and (**b**) the voice coil actuator (Model: Lofelt L5) used in this study [35].

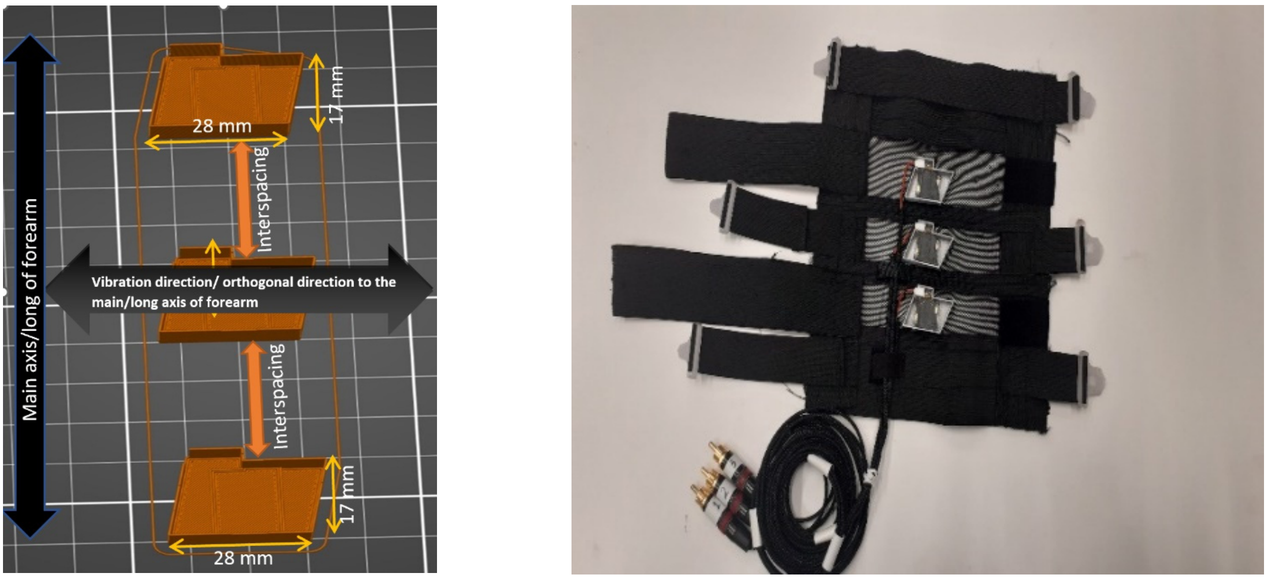
Table 1. Physical Characteristics of Lofelt L5 [35].

Dimensions (W × D × H)	At rest: 17.0 × 20.5 × 6.2 mm Max displacement: 17.0 × 25.5 × 6.2 mm
Weight	6 g +/− 0.5 g

Table 2. Haptic, Electrical, and Acoustic Characteristics of Lofelt L5 [35].

Maximal Voltage	1.4 Vrms at f0
Resonance Frequency (f0)	65 Hz ± 5%
Frequency Range	Min. 0.5 G over 35 Hz–1 kHz
Nominal Impedance	8 Ω at f0
Power Handling	Maximum: 320 mW
Current Consumption	Average at medium volume: 10 mA, bass music use-case Average at maximum volume: 57 mA, bass music use-case

Several different versions were tested for the enclosure design. The final design involved 3D-printing the enclosure for the actuator straight onto the fabric material (Figure 2B). The enclosures allow the actuator to vibrate freely. The physical dimensions of L5 actuators are W: 17.0 × D: 20.5 × H: 6.2 mm, and when vibrating at maximum displacement, they are W: 17.0 × D: 25.5 × H: 6.2 mm (Table 1). The dimensions of the enclosures are W: 17.0 × D: 28 × H: 6.2 mm (Figure 2A,B).



(**a**) (**b**)

Figure 2. (**a**) Overview of designing the Lofelt L5 actuators along the forearm; and (**b**) an example of a wearable vibrotactile sleeve and the configuration of the actuators.

A Prusa Slicer and a Prusa MK3s 3D printer were used to print the actuator housing. The fabric works as a scaffold to hold the actuators in place on a flexible and elastic surface. The actuators are firmly fastened inside the enclosures. There are no fabric layers between the actuators and skin on the stimulation surface (point of contact). In addition, the thin, flat surface of the plastic case is connected to the skin directly and transmits the vibration signals to the skin. Accordingly, the vibration is transmitted to the user's forearm through the thin (the thickness is approximately 2mm) surface of enclosures against the skin resulting in a back-and-forth vibration parallel to the skin's surface. Enclosures prevent the moving permanent magnet inside the L5 casing from scratching against the participants' skin or causing damage to the elastic material.

2.2.2. Tactile Sleeve and Hardware

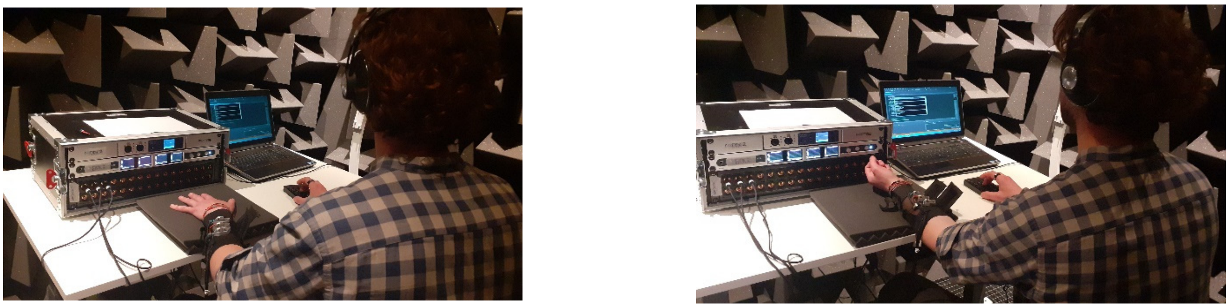
Five soft and thin fabric-based vibrotactile sleeves were used in this experiment. A Power Mesh fabric was used (Power Mesh fabric material: 90% nylon and 10% spandex), which made the wearable sleeve comfortable and user-friendly. Stretch straps with Velcro were used to secure the haptic sleeve onto the forearm and to make it easy to adjust according to the thickness of the user's forearm. The wearable tactile sleeves each consisted of three voice coil actuators (Lofelt L5) that were placed in housings that were 3D-printed onto the fabric. The actuators were laid along the forearm in 3×1 array (longitudinal orientation) that caused tangential vibration and lateral skin stretch. In this study, five vibrotactile sleeves with different inter-actuator spacings of 20 mm, 15 mm and 10 mm, 5 mm and as close as physically possible (no space between actuators, in other words 17 mm center-to-center) were used to evaluate the optimum inter-actuator distance that would make two stimuli differentiable with high accuracy (Figure 2A,B and Figure 3). For design reasons, the upper limit tested was the 20 mm separation between the actuators.

Figure 3. The five vibrotactile sleeves with different interspacings between actuators that were used in the experiment.

The prototype was connected to audio hardware via wired interfaces. The audio hardware had four main components: a digital audio interface (RME MADIface XT: IMM Elektronik GmbH, Mittweida, Germany) [36], digital-to-analog converters (Ferrofish A32), multichannel amplifiers, and voice coil actuators (Lofelt L5). The MADIface XT receives information from a computer via a USB cable and sends the signal to the Ferrofish A32 Analog-to-Digital/Digital-to-Analog (AD/DA) converter. Ferrofish A32 then conveys the signal to the amplifier, which then sends the amplified signal to the actuators [36].

2.3. Procedure

The sites assessed in the localization experiments were the upper and undersides of the forearm. The upper forearm has mostly hairy skin, with a set of mechanoreceptors that differs from those on the glabrous skin of the underside of the forearm [37]. Five different tactile sleeves were tested (five different spacings between the actuators), with three voice coil actuators placed on the longitudinal line on the forearm (causing tangential vibration and lateral skin stretch), while the hand rested on pad support. Before the main experiment, the procedure and tactile stimulation protocol were fully explained to the participants, and their written informed consent was obtained. Before the main experiment began, they completed a few training trials to familiarize themselves with the setup, apparatus, and the vibratory stimulus. The experiments were performed in an anechoic chamber. Two experiments were performed; one where the upper side of the forearm was stimulated (experiment one, see Figure 4A) and one where the underside of the forearm was stimulated (experiment two, see Figure 4B). The experiments were designed to determine the minimum interspacing between actuators that we could use so that the different sites of stimulation could easily be told apart.



(**a**) (**b**)

Figure 4. A participant wearing a vibrotactile sleeve with his hand on the cushion, using the headphone to block out external auditory cues and responding to the vibrotactile feedback by pressing the correct key on the wireless keyboard. There were two experiments: (**a**) on the upper side of the forearm in experiment one; (**b**) and on the underside of the forearm in experiment two.

The duration of the two experiments was approximately 40 min for each participant. Each experiment consisted of five steps of five tactile sleeves (with different interspacing between actuators) presented in a different random order for each participant. Twenty-four trials were conducted for each tactile sleeve. Each test consisted of the sequential activation of two adjacent actuators with an interstimulus interval of 50 ms. This time duration was chosen in light of the optimal delay range between sequential pulses (between 20–250 ms) to minimize potential mislocalization [38]. The selected actuators were turned on for 200 ms, and the intertrial time for the sequential trials was 500 ms. The frequency and amplitude of all the stimuli were the same during all trials (100 Hz and 0.125 of Min 0.5G acceleration, respectively) to ensure that the vibration acceleration was equal during all experiments due to the nonlinear frequency responses of our used actuators. This ensured that all signals resulted in the same vibration intensity on the skin during the test.

The participants were totally unaware of the particular vibrotactile patterns in a given trial and the sleeve differences to avoid any biases.

2.3.1. Participants

Eight healthy individuals (aged 21–38 years, with a mean of 29 years) participated in this study. They confirmed that they had no significant issues with exposure to hand-transmitted vibrations. Each participant signed a written informed consent form.

2.3.2. Experiment One

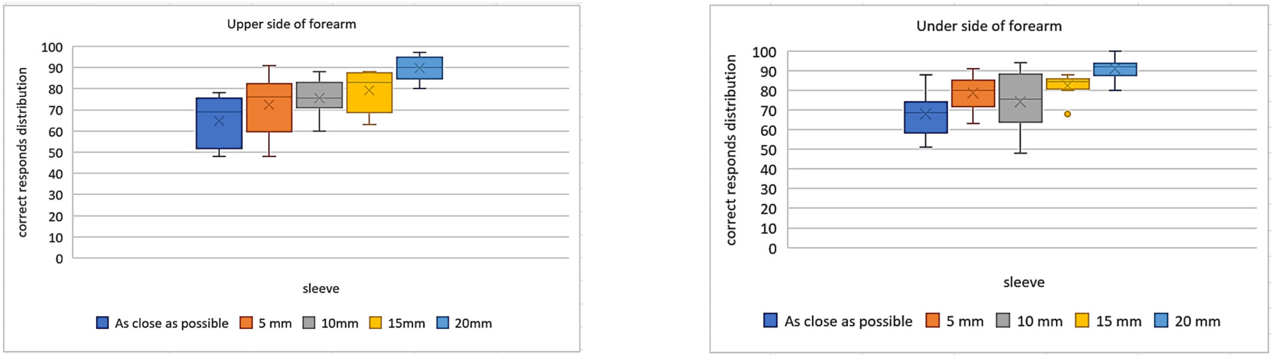
The participants sat on a chair in the anechoic chamber, with their left hand resting on the table on the padded support. During the experiments, the participants donned noise-cancellation headphones that played white noise to mask environmental and mechanical noises. The tactile sleeve was attached firmly to the forearm by thin double-sided adhesive Velcro. Five different vibrotactile sleeves were used, differing in the interspacing between their actuators. Twenty-four pairs of vibrotactile stimuli were conveyed through the voice coil actuators for each tactile sleeve. Each trial consisted of a pair of stimuli sequentially delivered to the forearm. The task was to indicate the perceived direction of the second stimulus relative to the initial stimulus' locus on each trial. In all the tests, the participants registered their responses by pressing one of the three buttons on a wireless keyboard they held with their hand, indicating whether the second response was closer to the fingers, closer to the elbow, or in the same location, relative to the first stimulation (Figure 4A).

2.3.3. Experiment Two

Experiment two involved the exact same procedure as experiment one, but this time, the stimulation was presented on the underside of the forearm. The same five vibrotactile sleeves used in experiment one were also used in experiment two, with the actuators placed equidistant in a line along the length of the underside forearm. This time, observers had their palm facing upwards (Figure 4B).

3. Results

Figure 5 shows the median correct responses for five different tactile sleeves for the observers, along with measures of dispersion. The box plot shows that the highest median accuracy was found for the tactile sleeve with a 20 mm inter-distance between enclosures on the upper side (90%, see Figure 5A) and underside of the forearm (92%, see Figure 5B) compared to all the other tactile sleeves used in this study, with smaller interspacings. The median accuracy was lowest for the tactile sleeve with no space between the enclosures (see Figure 5A,B) compared to other sleeves on the upper side and underside of the forearm (the median was 69% on both sides).



(**a**) (**b**)

Figure 5. Box–whisker plot comparing the accuracy (percent correct, *y*-axis) between the five different tactile sleeves with various inter distances between enclosures (*x*-axis): (**a**) the percent correct for the upper side of the forearm; and (**b**) the percent correct for the underside of the forearm. The box length represents the interquartile range (IQR), the 25% and the 75% limits, and the horizontal bar inside the box shows the median value. The ends of the box plot represent minimum and maximum values.

A two-way repeated measures ANOVA with the factors upper versus lower forearm and actuator interspacing (along with Bonferroni corrected post hoc tests) was calculated to assess the significance of the differences in accuracy for the different distances between the actuators and the differences between the accuracy for the underside and upper side of the forearm. The two-way ANOVA also enabled us to assess the interaction between these two factors, such as whether the effect of inter-distance varies between the upper side and the underside of the forearm.

The two-way repeated measures ANOVA revealed a large main effect of interspacing of the actuators upon detection accuracy (F (4,70) = 11.71; $p < 0.05$). There was no effect of the side of the forearm upon accuracy (F (1,70) = 1.21; $p = 0.27$), nor was there any significant interaction between these factors (F (4,70) = 0.29; $p = 0.88$).

This means that as the difference between the actuators increased, accuracy in the discrimination task improved significantly, reaching a very high accuracy level for the 20 mm distance (some participants had 100% accuracy). The accuracy for the under and upper sides of the forearm did not differ significantly on the other hand.

Post hoc tests (Bonferroni corrected) were performed to assess significant differences between different tactile sleeves. After the Bonferroni correction, the statistical threshold was adjusted to $p < 0.005$. The results of the post hoc test showed that on the upper forearm there were significant differences between the pair of sleeves where actuators were placed as close as physically possible ([ACAP], no space between actuators, in other words, 17 mm center to center) and the sleeve with a 20 mm interspace had [*p*-value = 0.0004] (Table 3). This was also the case for the underside of the forearm (Table 4).

Table 3. Post-hoc test *p*-values (upper forearm).

	5 mm	**10 mm**	**15 mm**	**20 mm**
ACAP	0.2552	0.0550	0.0186	0.0004 *
5 mm		0.5902	0.2809	0.0129
10 mm			0.4511	0.0107
15 mm				0.0342

* Significant at $p < 0.005$.

Table 4. Post-hoc test *p*-values (under forearm).

	5 mm	**10 mm**	**15 mm**	**20 mm**
ACAP	0.0624	0.03806	0.0096	0.0004 *
5 mm		0.4994	0.3255	0.0115
10 mm			0.1845	0.0164
15 mm				0.0139

* Significant at $p < 0.005$.

The data distribution was highest for the tactile sleeve with 20 mm between enclosures on the upper side of the forearm with a median level of 90%, and the accuracy range was from 80% to 97%. For the underside of the forearm, the median was 92%, and the accuracy ranged from 80% to 100%. The results for the 20 mm interspacing therefore reveal high response accuracy and all participants showed relatively high levels of stimuli identification on both sides of the forearm.

Although the median values for the underside of the forearm were slightly higher than for the upper ones, the ANOVA revealed no significant differences between the sides of the forearm. We therefore cannot draw strong conclusions about better stimulus recognition on the underside of the forearm compared to the upper side. Further investigations are needed for any firm conclusions on this.

The fact that accuracy is higher with increasing interspacing between actuators is interesting, but what does this mean for the design of a sensory substitution device with stimulation on the forearm? The forearm has limited space, and realistically, there are upper limits to the distance that can be used [39]. When information from our previous designs and practicalities of future designs is taken into account, we decided to have the 20 mm distance as our upper limit. Thankfully, our results indicate that the performance for the 20 mm distance on our relative PL task is very close to ceiling performance.

Our study, therefore, suggests that the tactile sleeve with a 20 mm distances between the voice coil actuators (model: Lofelt L5) can be considered the optimum design for a tactile sleeve using multiple voice coil (Lofelt L5) actuators, providing high accuracy of stimuli discrimination, considering the restrictions of the physical dimensions of the surface of the forearm as the site of the wearable vibrotactile devices.

4. Conclusions

Increased advances in vibrotactile displays highlight the necessity of psychophysical investigations into the mechanisms underlying human tactile perception. One of the main challenges in designing tactile devices is analyzing what information can be transmitted tactually and which stimulation parameters can effectively convey information. One issue involves an empirical investigation of the maximal throughput of the skin.

How many tactors can be configured, how densely can they be placed next to each other before their loci become indistinguishable, and how can high accuracy be maintained to convey the information effectively?

For designs using closely spaced tactors, vibrotactile localization accuracy on the skin is essential. Information will be lost if vibrotactile actuators are placed so close to each other that their signals cannot be distinguished. The interspacing of actuators has a crucial effect on the resolution of vibrotactile stimuli to be differentiated from each other. In addition, this evaluation is essential for designing tactile displays so that as many tactors as possible can be placed within a defined area.

Psychophysical studies on tactile spatial acuity of different body parts can provide the required empirical basis for determining the optimal stimulation type for tactile devices. Optimum interspacing between actuators can provide high-resolution distinguishable stimuli to convey tactile information effectively. There has been a considerable amount of research on the tactile sensory capabilities of the hands and fingers, but comparatively little research has been carried out on the forearm. Although forearms are generally less sensitive than the other part of the hand (for instance, the fingers [40]), we need to use more stimuli spread over a larger surface area to compensate for this decreased sensitivity. Nevertheless, determining the optimum loci of actuators on the forearm is crucial.

This study provides guidelines for forearm-mounted wearables using the Lofelt L5 voice coil actuator in terms of comparing the accuracy rate on the upper side and underside of the forearm and determining the optimum interspacing of actuators to keep the stimuli distinguishable with high accuracy.

This paper systematically investigated the relative spatial acuity of the forearm using vibrotactile sleeves. Our objective was to determine the optimum distance where two vibrations of two voice coil actuators could be told apart spatially with high accuracy. Our research group has a long-term experience in investigating vibrotactile displays [1,2,26–29,41], and optimizing the configuration of actuators in our recent wearable vibrotactile sleeve was the inspiration for this study. The average forearm length based on the anthropometric parameters of the studied population is approximately 20.2 cm for females and 23.9 cm for males [39] which places constraints on our haptic designs.

Taken as a whole, the outcome of our study could be used to develop forearm mounted vibrotactile wearables using Lofelt L5 to obtain high-resolution signals and distinguishable vibrotactile information. First and foremost, we report localization rates for vibrotactile stimuli on the forearm for our purposes, using five different tactile sleeves consisting of three voice coil actuators on the upper side and underside of the forearm. We tried to determine the lowest interspacing that still allows discrimination with high accuracy. The results of the experiment indicate that 20 mm interspacing between actuators (Lofelt L5) yields very high performance with some participants at ceiling (Figure 5, that shows accuracy rates between 80% and 100% (median = 92%) on the under forearm and accuracy rates between 80% and 97% (median = 90%) for the upper forearm) and was therefore chosen as the optimal distance between the actuators. We found that placing the voice coil actuators (Lofelt L5) at a 20 mm inter-distance in the longitudinal arrangement resulted in significantly better discrimination accuracy than when there was no interspacing between the actuators on both sides of the forearm ($p < 0.05$). The results were similar for the upper and under sides of the forearm. We investigated both sides of the forearm to determine whether there was a significant difference between the accuracy of the responses and forearm sides. The evaluation and comparison of the results extracted from the current study revealed no statistically significant differences between the accuracy rate and the forearm's sides.

This information can be used to assist in formulating guidelines for inter-actuator spacing (voice coil actuator model: Lofelt L5) used in tactile displays that generate vibrotactile stimulation on the forearm (Figure 2A).

Several other authors have also designed forearm-mounted displays; Piateski and Jones designed a 3 × 3 array of tactors for the underside of the forearm. Using this device, they empirically studied the ability to recognize simple patterns, including activating lines of eccentric rotating tactors. The detection accuracy that they measured ranged between 80% and 96% [42].

The threshold found in our study is valid for the forearm site and the type of actuators (voice coil actuators model Lofelt L5) we used. The variance in findings of spatial acuity might have stemmed from different actuator types applied to different body parts and different methods of evaluation. Comparisons between findings of vibrotactile spatial acuity thresholds are difficult because of the complex nature of vibrotactile stimulations. Our results indicate that a distance of 20 mm is the best distance between actuators on both sides of the forearm, when the spatial limits on design are considered. The results of this study will be helpful for the continued development of our current design of the vibrotactile sleeve and provide valuable insights for the creation of forearm-mounted vibrotactile displays using Lofelt L5 voice coil actuators.

Author Contributions: N.Y. contributed to the methodology, formal analysis, investigation, data curation, and writing—original draft preparation. I.M. contributed to the methodology. S.S.S.T. contributed to the software. Á.K. contributed to the methodology, writing—review and editing and acted as a co-supervisor. R.U. contributed to the methodology, writing—review and editing, and supervision. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The experiments were run in accordance with the requirements of the local ethical committee and in accordance with the Declaration of Helsinki.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

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Paper II

Effects of Stimulus Frequency and Location on Vibrotactile Discrimination Performance Using Voice Coil Actuators on the Forearm.

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Article

Effects of Stimulus Frequency and Location on Vibrotactile Discrimination Performance Using Voice Coil Actuators on the Forearm

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Abstract: What are the effects of frequency variation of vibrotactile stimuli on localization acuity? The precise localization of vibrotactile stimuli is crucial for applications that are aimed at conveying vibrotactile information. In order to evaluate the ability to distinguish between vibrotactile stimuli based on their frequency and location on the forearm, we used a relative point localization method. Participants were presented with pairs of sequential vibrotactile stimuli at three possible locations on the forearm and asked to determine whether the second stimulation occurred at the same location as the first one in the pair or not. The stimulation frequency varied between 100 Hz, 150 Hz, 200 Hz and 250 Hz, which covers the range of frequencies that human observers are most sensitive to. The amplitude was kept constant. Our results revealed that the ability to discriminate between actuators remained unaffected by variations in the frequency of vibrotactile stimulation within the tested frequency range. The accuracy of the tactile discrimination task was heavily dependent on the location of the stimulation on the forearm, with the highest accuracy close to the wrist and elbow, locations that may serve as tactile anchor points. Our results highlight the critical role of stimulation location in precise vibrotactile localization and the importance of careful consideration of location in the design of forearm-mounted vibrotactile devices.

Keywords: vibrotactile stimulus; voice coil actuator; wearable device; vibratory stimulus; vibrotactile localization; vibrotactile frequency; vibrotactile discrimination

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1. Introduction

Technical advances over the last two decades have made wearable vibrotactile displays a very attractive option for various tactile presentation devices. Several variations of such devices have been introduced in both scientific papers and commercial products and a variety of vibrotactile stimuli can be conveyed within the same display [1–6]. Voice coil actuators have been widely used in such displays because of their numerous advantages [7], including their ability to be incorporated into fabric-based displays, making them portable and convenient to use. The use of arrays of these actuators, such as those employed in tactile sleeves, allows for the encoding of considerable amounts of information to users. Vibrotactile patterns can be presented by manipulating the sequencing of the vibrations across the actuators, enabling the presentation of a wide range of sensations to users. The use of voice coil actuators in wearable vibrotactile displays has opened up exciting possibilities for the development of novel and sophisticated haptic technologies [8,9].

Tactile feedback has proven to be a versatile tool for enhancing various sensory experiences. For instance, it has been employed to supplement auditory information, alert individuals to important signals, provide information to users of prosthetic devices, and even serve as a substitute for vision in devices designed for the visually impaired [10–13]. The versatility of tactile feedback arises from the fact that it can be easily integrated into a wide range of devices and interfaces, enabling individuals to experience rich and meaningful haptic sensations that can greatly enhance their overall sensory experience.

One recent development in the field of haptic displays is the use of tactile arrays in the form of wearable sleeves. These sleeves are designed to contain a relatively large array of vibrotactile actuators that can be used to deliver complex and nuanced haptic information to the wearer [14–18]. Such applied use calls for precise understanding of how reliable the perception of the vibrotactile information is and the resolution afforded by vibrotactile displays. Accurate perception of haptic stimuli is crucial for the reliable transmission of complex information encoded as haptic cues. It is, therefore, essential to investigate the accuracy of localization of tactile stimuli under diverse conditions and determine the influence of different parameters such as frequency, amplitude, duration, and location on haptic performance.

Several studies have addressed how different vibrotactile stimulation affects the localization of tactile stimuli [19]. Wong et al. evaluated the localization and information transfer of five tactors placed in a vibrotactile sleeve along the volar forearm and found that the locations of two to three actuators arranged along the length of the forearm could be reliably discriminated by human users when only the location of vibration was varied [15]. Zhao et al. examined stimulation with variation in frequency and vibrotactile patterns [20], finding significant differences in accuracy for vibrations on the dorsal side of the forearm at two frequencies (30 Hz and 250 Hz). The accuracy was better for 250 Hz than 30 Hz [20], consistent with the results of Ævarsson et al., who tested the optimal stimulation frequency for vibrotactile stimulation with L5 actuators on the wrist [1].

Several researchers have examined the impact of stimulus duration on tactile recognition accuracy and found significant variability, revealing that the duration of vibrotactile stimuli can significantly affect localization accuracy, with longer-duration stimuli generally leading to better performance [20,21]. Moreover, localization and discrimination of vibrotactile stimuli can differ by stimulation site as well as by the method used to deliver the stimulation, i.e., whether it is conveyed sequentially or simultaneously [22].

Another factor that can affect the results of tactile discrimination tasks is the method of stimulus presentation. The two-point threshold, which is a measure of the minimum distance at which two distinct points of contact on the skin can be perceived as separate stimuli, is typically measured using a pair of calibres or other devices that allow the experimenter to vary the distance between the two points of contact [23].

The two-point threshold is often used as an index of tactile acuity or sensitivity. Relative point localization, which we used in this study is, on the other hand, a method used to assess observers' ability to detect differences in the position of two tactile stimuli. In this task, two stimuli are presented on the skin and participants judge whether the second stimulus is in the same or a different location as the first one or they indicate the direction of the second stimulus relative to the first stimulus. This method is often used to assess the ability to perceive spatial details in tactile stimuli [24]. While both two-point threshold and relative point localization are measures of tactile sensitivity, they assess different aspects of tactile perception and results for the two measures are not necessarily the same. Results acquired with the relative point localization (rPL) method, as used here, are not directly comparable to other measurement methods, such as absolute point localization (aPL) [25] or two-point thresholds (2PT) [23].

Weinstein [26] found that spatial tactile acuity with the two-point threshold was two to four times lower than with the absolute point localization, although they were highly correlated. Results from the two-point threshold method cannot be directly applied to vibrating stimuli since decisions about whether one or two tactors are activated can be affected by additive tactor intensity. Even though many studies have used absolute point localization (aPL) [25,27]. Taken together, the ability to localize a point of vibrotactile stimulation may not accurately reflect relative spatial acuity [24]. Other reasons for discrepancies could reflect factors such as individual differences in sensory perception, variations in the contact force between the skin and the device, or location. Another possible reason could be related to the design of the device, such as the size and spacing of the tactile elements and the frequency and amplitude of the signals being used. Additionally, the concentration of tactile receptors on the skin is not evenly distributed, leading to a difference in sensitivity to touch and discrimination ability [26]. Psychophysical studies specifically investigate differences in outcomes for relative vibrotactile acuity measurements with different tactor types. Additionally, measurements of vibrotactile spatial acuity may depend on presentation direction because of directional anisotropies [28].

Another important finding is that tactile stimuli are most effectively perceived when presented near anatomical reference points, typically associated with the body's joints. In our case, with stimulation on the forearms, the elbow and wrist serve as anchor points. This concept of "anchors" or reference points was first proposed by Weber [23] and Boring [29], and subsequent studies have demonstrated that certain anatomical points on the body exhibit high sensitivity for localization [30–32].

The discrimination of vibrotactile frequency on both glabrous and hairy skin has been assessed [33]. For instance, one study compared discrimination thresholds for the fingertip (27.2 Hz) and forearm (33.9 Hz), revealing that discrimination was 20% more accurate on the fingertip [34]. Vibrotactile stimulation is detected by mechanoreceptors in the skin, and one type, the Pacinian corpuscles, is responsible for the detection and perception of high-frequency vibrations greater than approximately 80 Hz [35]. The density of Pacinian corpuscles is much higher in the fingertip's glabrous skin than in the forearm's hairy skin [36], which explains the higher vibrotactile frequency discriminability on the fingertip than the forearm.

It is important to note, however, that in certain contexts, the use of fingertips for tactile feedback may not be practical or desirable. For example, when developing devices designed for sensory substitution, the use of fingertips may be problematic as it can interfere with the user's daily activities. In such scenarios, alternative methods of delivering tactile feedback may need to be explored, such as the use of other parts of the body or specialized wearable devices. By carefully considering the context of use and the needs of the users, more effective and user-friendly tactile feedback solutions can be developed that enable individuals to better engage with their environment and achieve their goals [33,37]. Use of the volar forearm as a location for delivering vibrotactile stimuli has become increasingly popular in recent years, owing to several attractive features of this anatomical site. The forearm is a convenient site for delivering vibrotactile stimuli due to its accessibility, which makes it relatively easy to apply wearable devices and integrate vibrotactile feedback into various applications. This location is suitable for delivering high-resolution stimuli, and it is compatible with clothing-like forms for wearable devices. Additionally, the forearm offers a relatively large surface area for stimulation, which allows the delivery of precise and nuanced haptic sensations to users.

Furthermore, the use of the forearm as a location for delivering vibrotactile feedback is generally well-tolerated by users, making it a practical and effective option for a wide range of applications [38]. A number of studies are available where vibrotactile stimuli have been delivered to the volar forearm, and various actuator types and parameters have been used [1,16,17,34,39,40].

Cholewiak and Collins [27] investigated the effect of frequency on absolute point localisation in young and older subjects on the volar forearm, using long piezoceramic tactors, Differences in localization ability between younger and older persons were smaller than expected while the frequency changed between 100 Hz and 250 Hz. Our study investigated the effect of frequency on discrimination accuracy using a wearable vibrotactile sleeve on the dorsal forearm, keeping the amplitude constant while varying the frequency. We used voice coil actuators that enabled us to manipulate frequency and amplitude independently of one another. The actuators were used to provide parallel and lateral vibration on the forearm length. Results were obtained using the relative point localization method. We found no differences in discrimination accuracy by frequency variation between 100 Hz, 150 Hz, 200 Hz and 250 Hz with constant amplitude. Our study did not investigate sensitivity differences by age (participants were young adults). Notably, studies of frequency variation on the forearm with pressure and electro-tactile stimuli [41] cannot be generalized to vibrotactile stimuli. Different types of actuators and tactors, stimulus signal differences and properties, stimulation locations, and signal presentation methods can all affect performance [12,28]. Additionally, results acquired with the relative point localization (rPL) method, as used in our study, are not directly comparable to other measurement methods, such as absolute point localization (aPL) [25] and two-point thresholds (2PT) [23]. The ability to localize a point of vibrotactile stimulation may not accurately reflect relative spatial acuity.

Our research team has, in recent years, developed a series of vibrotactile displays, including the vibrotactile sleeve we examined in this study [1,12,16,17,37]. These displays have the potential to provide a vast amount of information to low-activity areas of the body, freeing up the hands for other tasks. This research has involved the investigation of several properties of vibrotactile stimulation in the context of sensory augmentation and sensory substitution [9,12,16,17,42–44].

The objective of the present study was to examine the discrimination accuracy for vibrotactile stimulation on the forearm as a function of frequency and location. Specifically, frequencies of 100 Hz, 150 Hz, 200 Hz and 250 Hz were employed while a constant vibration amplitude was maintained. This frequency range was chosen for two reasons: firstly, because of the high sensitivity of the Pacinian corpuscles to frequencies within this range, and secondly, because previous studies from our lab have demonstrated that this frequency range falls within the range of maximum tactile frequency sensitivity at the wrist [1]. We also investigated the effects of the location of the vibrotactile stimulation on the ability to discriminate between actuators and assessed any potential interactions with frequency.

2. Experiment

2.1. General Experiment Setup

The experiment was conducted in an anechoic chamber at the University of Iceland. Participants were seated on a chair in front of a laptop. The wearable vibrotactile sleeve was placed on the left forearm with the tactile actuators on the dorsal side. Participants placed their forearms on a foam pad (on a table) with the palm facing down. Their view of their left arm was blocked by placing foam in the line of sight to prevent any potential visual biases in responses (such as from visible vibrations).

To prevent audible cues from the tactile actuators, white noise was played through over-ear headphones to mask any sounds made by the actuators. Vibrotactile stimuli were delivered to the forearm via three voice coil actuators (Model: Lofelt L5, see Figure 2a).

Acceleration measurements were used to calibrate the intensity of the vibrotactile signal before recording data for each participant. A three-axis accelerometer (Brüel & Kjær Type 4520) was used to measure the acceleration of the vibration and calibrate its intensity.

To guarantee consistency and eliminate any sources of bias, this calibration process was performed individually for each participant prior to commencing the discrimination testing. Calibrating the vibrotactile sleeve on each participant's forearm enabled us to ensure that the same signal strength was perceived against the skin throughout the duration of the experiment.

Force measurements were also taken at the contact surface of enclosures and the skin of the forearm using a Force Sensitive Resistor (FSR), series FSR03, (Ohmite Manufacturing Company, Warrenville, IL, USA), and was obtained at 1.64 N. Table 1 provides the acceleration magnitude of the signal at the different frequencies used in the experiment.

Table 1. Amplitude and acceleration magnitudes across all frequencies in the study.

Frequency (Hz)	Acceleration (g)
100	9.6
150	7.6
200	6.9
250	6.7

We measured the forearm length of each participant, (four males and four females), and this information is presented in Table 2.

Table 2. The left forearm length measurements.

Participant	Gender	Length of Forearm (cm)
1	Female	21.04
2	Female	22
3	Female	22.5
4	Female	21.8
5	Male	23.8
6	Male	24.03
7	Male	24
8	Male	25

The study participants did not have significant differences in forearm length, so the average forearm length was used as a parameter to obtain biometric information. The average forearm length of the study participants was 23.3 cm. Figure 1 shows the biometric dimensions of the actuator placement along the forearm.

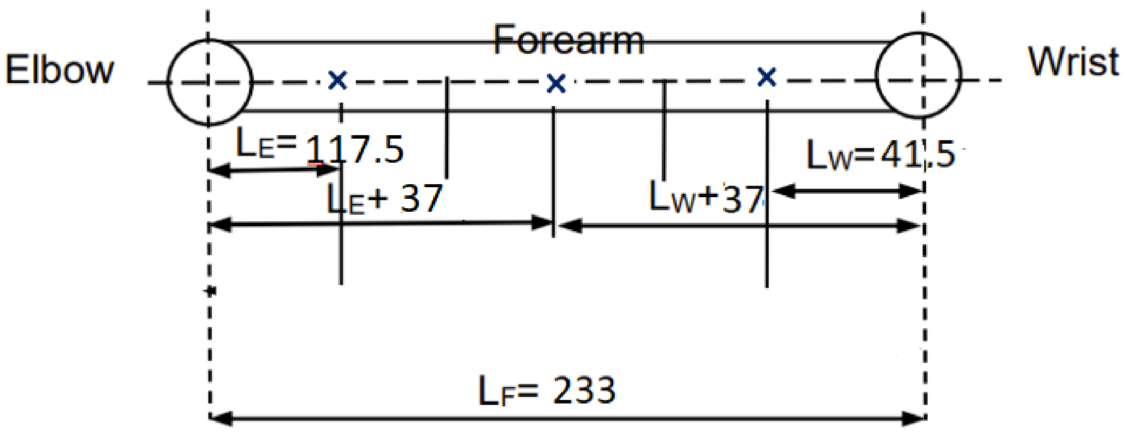
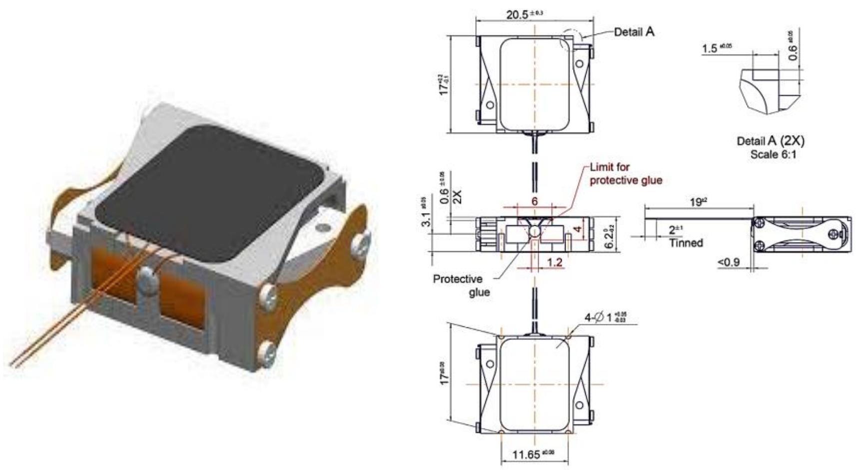


Figure 1. The biometric measurements utilized to determine the placement of the three actuators (×) along the forearm were derived from the average forearm length of the eight participants in the experiment. The centre points of the actuators were used for precise measurement. The inter-actuator distance was 20 mm, while the voice coil width was 17 mm. The distance of the centre point of the first actuator from the wrist was 41.4 mm, which accounted for the 33 mm stretch strap width and an extra 8.5 mm dimension from the centre of the first actuator.

The voice coil actuators were powered and controlled using audio hardware connected to a laptop computer, where custom-written Python code controlled the stimulus presentation. The actuators were connected to the audio hardware via wired interfaces. The audio hardware consisted of a digital audio interface (RME MADIface XT) [45], digital-to-analogue converters (Ferrofish A32), multi-channel amplifiers, and parallel vibrating voice coil actuators (Lofelt L5) [7]. Using this setup, up to 32 tactile channels can be controlled independently. Tactile actuators were placed on the dorsal forearm in the longitudinal direction which caused back-and-forth vibration perpendicular to the forearm length. Before the start of the main experiment, the participants completed a few training trials to familiarize themselves with the setup, apparatus, and tactile stimulus.

2.2. Actuators

The tactile stimulation was generated using voice coil actuators, specifically the Lofelt L5 model (as shown in Figure 2a,b). The L5 actuator is an extended-band type of actuator that enables the independent manipulation of stimulation frequency and amplitude and is widely used in the implementation of haptic stimulation for scientific purposes [18].



(**a**) (**b**)

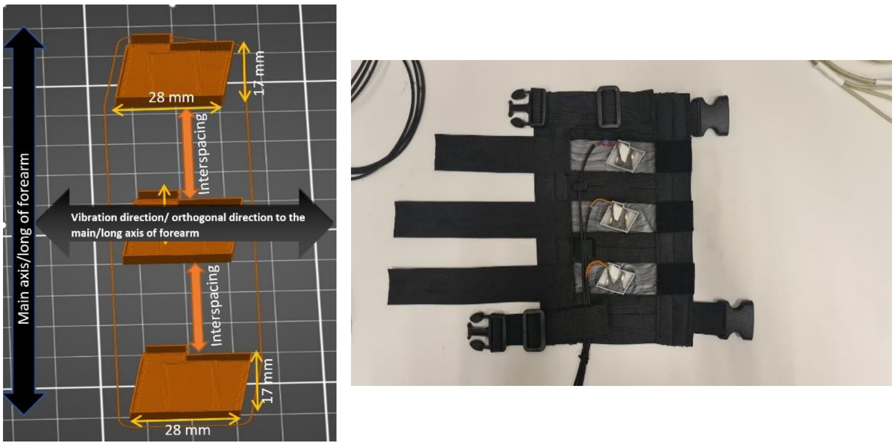
Figure 2. (**a**) The voice coil actuator (Model: Lofelt L5) used in this study; (**b**) Technical details and information about the spatial dimensions of the L5 voice coil actuator [7].

The L5 actuator is characterized by its high acceleration and efficiency, lightweight design, and cost-effectiveness, rendering it suitable for a range of vibrotactile displays, as outlined in Table 3. Furthermore, the Lofelt L5 voice coil actuator can produce vibration parallel to the skin, comprising tangential vibration [7].

Table 3. Haptic, electrical, and acoustic characteristics of the Lofelt L5 actuator [7].

Maximal voltage	1.4 Vrms at f0
Resonance frequency (f0)	65 Hz ± 5%
Frequency range	Min. 0.5 G over 35 Hz to 1 kHz
Nominal impedance	8 Ω at f0
Power handling	Maximum: 320 mW
Current consumption	Average at medium volume: 10 mA, bass music use-case Average at maximum volume: 57 mA, bass music use-case
Rise/stop times, 30 g attached mass, no DSP	5 ms/20 ms @ 150 Hz 12 ms/30 ms @ 100 Hz 15 ms/61 ms @ f0 18 ms/50 ms @ 50 Hz

The L5 actuators were placed in an enclosure that was specifically designed for the haptic sleeve. Several versions were tested for the enclosure design, and the final design was 3D-printed directly onto the fabric (Figure 3a,b). The purpose of the housing/enclosure was to prevent the actuator from coming into contact with other objects, which could dampen the vibrations. The physical dimensions of L5 actuators are W: 17.0 × D: 20.5 × H: 6.2 mm, and when they are vibrating at maximum displacement, their dimensions are W: 17.0 × D: 25.5 × H: 6.2 mm (the actuator may not be vibrating at its maximum, but it can do so). The dimensions of the enclosures were W: 17.0 × D: 28 × H: 6.2 mm (see Figure 3a).



(**a**) (**b**)

Figure 3. (**a**) Overview of the design of the sleeve used to apply the Lofelt L5 actuators along the forearm; (**b**) An example of a wearable vibrotactile sleeve and the configuration of the actuators.

2.3. Vibrotactile Sleeve

A soft and thin fabric-based vibrotactile sleeve was specifically made for this experiment. The tactile sleeve was made from a Power Mesh fabric (Power Mesh fabric material: 90% nylon and 10% spandex), which made the wearable sleeve comfortable and user-friendly. Stretch straps with Velcro were used to secure the haptic sleeve onto the forearm and make it easy to adjust according to the thickness of the user's forearm (see Figure 3b). The wearable tactile sleeve consisted of three voice coil actuators (Lofelt L5) placed in the 3D-printed enclosures printed onto the fabric. The fabric works as a scaffold to hold the actuators on a flexible and elastic surface.

A Prusa Slicer and a Prusa MK3s 3D printer were used for printing the actuator enclosure (PLA material (polylactic acid)). The coefficient of friction (COF) of PLA material can vary depending on several factors, such as the printing conditions ranging from 0.16 to 0.28. The actuators were firmly fastened inside the enclosures using glue [46]. Notably, there were no fabric layers between the enclosure and the skin (point of contact).

The tactile stimulation from the L5 actuators involves back-and-forth vibration parallel to the skin's surface. One benefit of the enclosure that we designed is that it keeps the moving part of the L5 actuator from scratching against the participants' skin or causing damage to the elastic material. The actuator is positioned inside the enclosure and designed to generate parallel vibration to the skin perpendicular to the forearm's length. The enclosure is crucial to ensure that the participant's skin and elastic material are not harmed during testing while enabling the actuator to stimulate the skin effectively through a smooth, lightweight, and thin (approximately 1.6 mm) enclosure surface. Since the actuator adheres to the enclosure, the actuator and the enclosure can function as a single unit. The vibration from the actuator is transmitted directly through the enclosure surface to the skin. This prevents the sharp edges of the voice coil actuators from irritating or harming the participant's skin or damaging the fabric during vibration.

The enclosures were placed along the dorsal forearm in a 3 × 1 array (longitudinal orientation) perpendicular to the forearm's length (Figure 3a,b). The spacing between the actuators was 20 mm. The decision to use this distance was based on our previous study [17], which was carried out to determine the spacing between voice coil actuators that provides the highest localization accuracy when design convenience with L5 actuators is considered.

2.4. Participants

Eight participants (four females and four males, aged between 23 and 37) took part in the study. All participants were right-handed and had normal haptic perception by self-report. They were healthy adults and did not report any cognitive or sensory impairments that could potentially affect their ability to complete the tasks. Before participating in the study, each participant signed a written consent form. The study was conducted in accordance with the requirements of the local ethical committee and the Declaration of Helsinki.

2.5. Procedure

The study was aimed at investigating whether the frequency of tactile stimuli on the forearm has any effect on the participant's localization acuity. Each participant was presented with 96 tactile pairs. Each tactile pair consisted of two sequential tactile stimuli provided by the actuators. The duration of each tactile stimulus was 250 ms, and the inter-stimulus interval was 100 ms. Ensuring accurate adjustment of stimulus duration requires consideration of the system's rise and stop times.

These times reflect the duration required for the system to attain a steady-state response upon stimulus onset or offset. In our study, we employed a vibration stimulus burst of sufficient magnitude to achieve a steady-state condition for all four frequencies. Since the aim was to investigate the effects of frequency by location, amplitude was kept constant during the study. For each pair, the actuators for the first and the second stimulus (S1 and S2) were randomly and independently selected—i.e., a pair could also involve the same actuator vibrating twice. Frequencies for the first and second stimulation were randomly selected from 100 Hz, 150 Hz, 200 Hz, and 250 Hz, again based on the results of a previous study from our lab [1], where the maximum sensitivity to vibrotactile stimulation at the wrist was measured.

After each tactile pair was presented, participants were asked to report whether the pair was provided by the same actuator or came from two different actuators (2AFC paradigm). Observers responded by pressing one of two keys on a numeric keypad on the table in front of them within the allocated response time (in the intertrial interval between the presentation of each tactile pair—maximum 2000 ms). Once they provided feedback or if more than 2000 ms had passed from the presentation of the pair of tactile stimuli, a new pair of vibrotactile stimuli was presented (Figure 4).

Figure 4. A participant wearing a vibrotactile sleeve with his hand on the cushion, using the headphones (playing white noise) to block out external auditory cues. Another cushion prevented observers from seeing their left hand. Observers responded to whether the vibrotactile stimulation was in the same or different locations by pressing the corresponding key on the wireless keyboard.

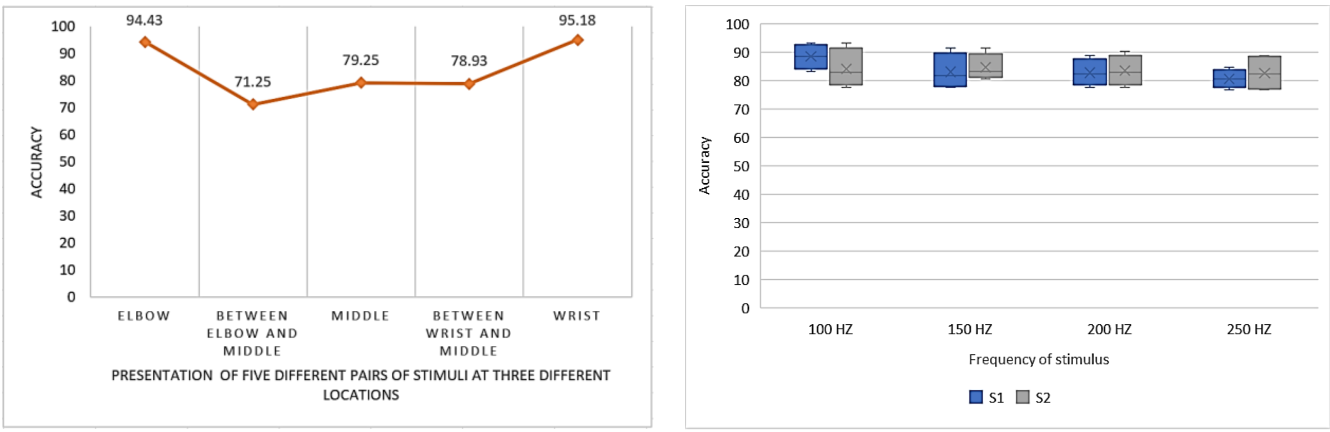
3. Results

We used a 2AFC paradigm to investigate how the frequency of vibration of each stimulus and its stimulation location affects the localization accuracy for pairs of vibrotactile stimuli. The observers' task was to indicate whether the two stimulations occurred in the same location or not, and the main variable of interest was the accuracy on this task.

The overall findings (in this case, irrespective of whether the stimulation was S_1 or S_2) are shown in Figure 5a,b. Figure 6 shows the results broken down by the frequency of the first stimulus (First stimulus (S1) in the panels and Second stimulus (S_2) shown by the different dots). A three-way ANOVA analysis was conducted to examine the effects of three independent variables: (1) the frequency of the first stimulus (S1), (2) the frequency of the second stimulus (S2), and (3) the location of the stimuli on the accuracy of localization.

The ANOVA revealed a main effect of location ($F (2, 18) = 20.58$; $p = 0.00002$). No effects of frequency (neither for S1 nor S2) were significant, nor were any interactions significant (all p-values > 0.54). These findings clearly demonstrate that the location of the stimulation had a significant effect on the accuracy of judgments of whether one or two different sites were stimulated in the sequence, as the large effect of location from the ANOVA clearly demonstrates. Specifically, the accuracy was significantly higher when both stimuli were presented on the actuators adjacent to the wrist and elbow (see Figure 5a). Conversely, when there was a displacement between the wrist and middle (e.g., S_1 appeared at the wrist and S_2 appeared in the middle or vice versa), when there was a displacement between S_1 and S_2 from the elbow to the middle or vice versa, or when both stimuli were presented on the middle actuator, the accuracy decreased to a range of 71.25% to 79.25% (Figure 5a).

Participants were better at localizing stimuli when they were presented at the endpoints of the array, i.e., the wrist and elbow, which, we speculate, operate as anchor points (see Introduction). Notably, the study revealed that the frequency of S1 and S2 did not have a significant effect on the accuracy of stimulus discrimination distinction, as revealed by the p-values of 0.81 and 0.65, respectively. The three-way interaction was also not significant. Moreover, there were no significant interactions between these stimuli and the location of the stimulus, as the p-values of 0.57 and 0.64 show, respectively.



(**a**) (**b**)

Figure 5. (**a**) The discrimination accuracy as a function of stimulation on the forearm. Three actuators were placed at three locations along the forearm: one close to the wrist, one close of the elbow, and one in the middle (see Methods). The stimuli were presented in five different pairs, consisting of (1) both stimuli presented on the wrist, (2) both stimuli presented near the elbow, (3) both stimuli presented on the middle actuator (middle), (4) where the first stimulus (S1) was presented on the middle and the second stimulus (S2) on the wrist or vice versa (displacement between wrist and middle), and (5) conditions where the first stimulus (S1) was presented on the middle and the second stimulus (S2) on the elbow or vice versa (displacement between elbow and middle). (**b**) The accuracy distribution for S_1 and S_2 as a function of frequency.

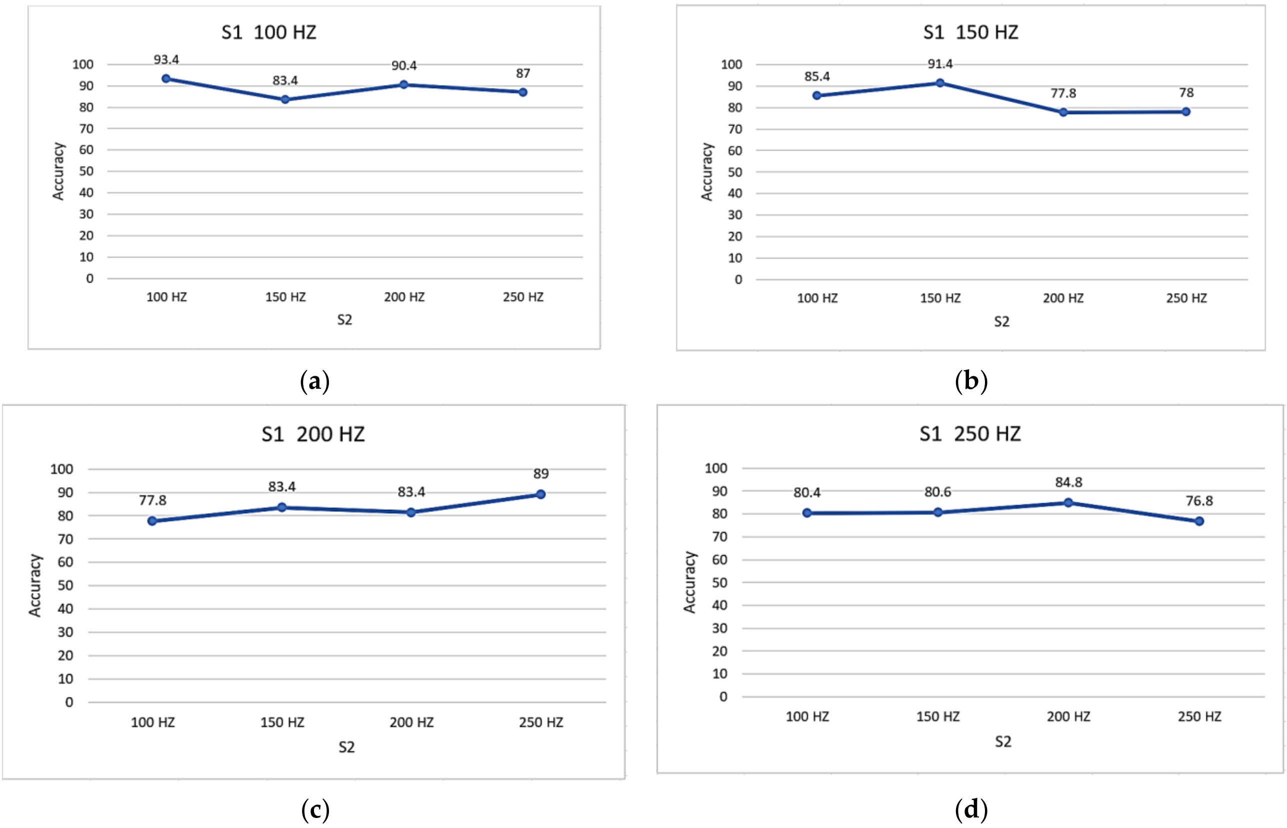


Figure 6. The average percent correct for different frequency combinations where the frequency of S_1 is denoted in different panels (**a**–**d**) and the different dots in each panel denote the frequency of S_2.

Overall, there was no statistically significant effect or interaction related to frequency, neither for S_1 nor S_2. This means that the frequency of the stimuli had a negligible effect on performance for both S_1 and S_2, at least within the tested frequency range (which, as explained above, should be optimal for vibrotactile stimulation), while the amplitude was kept constant. The average accuracy rate along the forearm ranged from 71.25% to 79.25%, which is notably lower than the accuracy rates near the wrist and elbow (94.43% and 95.18%, respectively).

The post-hoc analyses, with Bonferroni correction (p-values adjusted to 0.005; see Table 4), revealed statistically significant differences in localization accuracy and discrimination accuracy for the different stimulation locations, in particular showing how performance is best at the wrist and the elbow.

Table 4. The p-values from the post-hoc tests.

Groups **Locations of Presenting the First and Second Stimulus**	**Displacement between Middle and Elbow**	**Middle/Middle**	**Displacement between Middle and Wrist**	**Wrist/Wrist**
Elbow–Elbow	* 1.761×10^{-5}	* 7.748×10^{-5}	* 0.0001	0.358
Displacement between middle and elbow		0.033	0.0408	* 7.204×10^{-5}
Middle–Middle			0.462	* 2.406×10^{-5}
Displacement between middle and wrist				* 2.392×10^{-5}

* Significance at $p < 0.005$.

The results indicate significant differences in localization accuracy between tests where both stimuli came from the middle actuator compared to tests where both stimuli were presented on the actuator placed on the wrist ($p = 2.406 \times 10^{-5}$). Similarly, accuracy differed significantly when both stimuli were presented on the middle actuator and when both stimuli were presented near the elbow ($p = 7.748 \times 10^{-5}$). Discrimination accuracy was also significantly different between tests where both stimuli were presented on the actuator placed on the wrist and tests where there was displacement between the middle actuator and actuator placed on the wrist ($p = 2.392 \times 10^{-5}$).

Additionally, significant differences in discrimination accuracy were observed when both activations were presented on the actuator placed on the wrist and where the stimulus displaced between the middle and the elbow ($p = 7.204 \times 10^{-5}$). Furthermore, the post-hoc test revealed significant differences in discrimination accuracy between tests where both activations were presented on the elbow and tests where stimuli were displaced between the middle and wrist ($p = 0.0001$). Similar significant differences were found between tests where the stimuli moved between the middle and near the elbow and tests where both activations were presented on the elbow ($p = 1.761 \times 10^{-5}$).

These findings suggest that the location of stimulation of different actuators in the sleeve has a strong effect on discrimination accuracy. In sum, these results suggest that the location of the stimulus is a critical factor in accurately distinguishing between stimuli in a haptic feedback system. The frequency had no effect on accuracy, however.

4. Discussion

The development of vibrotactile displays for augmenting perception or for sensory substitution makes the understanding of the mechanisms underlying human tactile perception very important. In order to optimize the throughput of stimulus parameters of the skin, it is important to investigate how many actuators can be placed within a particular region before their loci become indistinguishable and how various parameters can influence accuracy, and the effective conveying of information.

To address these challenges, we conducted an experiment where we compared the localization of a sequence of tactile stimuli at different sites on the dorsal side of the forearm: the wrist, along the forearm length between wrist and elbow, and next to the elbow. Our aim was to explore the effects of the dimensions of the 3×1 array of voice coil actuators on vibrotactile localization. Our data, using relative point localization, demonstrated that the location of stimulation along the forearm significantly influenced discrimination accuracy.

However, frequency variation with constant amplitude had a minimal effect on accuracy. The results showed that discrimination performance is worse when the stimulation was applied in the middle of the forearm, even when the second stimulus was displaced from the midpoint to the endpoints of the array. In contrast, when both stimuli were presented on the actuators adjacent to the wrist and elbow, discrimination accuracy was significantly better. This raises the intriguing possibility that vibrotactile discrimination is better close to anchor points (elbow and wrist) compared to the middle of the forearm. This may have important consequences for the design of vibrotactile displays since it suggests that if the stimulation points fall adjacent to natural anchor points (such as the wrist or elbow), performance will be considerably better at those sites when compared to localization for sites far from such loci.

This information about the effect of stimulus location on the forearm will be beneficial in the future design of vibrotactile displays. In particular, the findings offer valuable insights into the design parameters for forearm-mounted displays, including the configuration of actuators and inter-actuator spacing, which can clearly affect accuracy. Specifically, placing actuators near the wrist and elbow on the forearm may significantly improve how accurately information with vibrotactile feedback can be conveyed.

Our previous results [17] show that the optimal distance between actuators is around 20 mm when both performance accuracy and convenience of the design (with L5 actuators) are considered. However, further investigations are necessary to test the hypothesis that using denser actuator placements near the wrist and elbow or higher vibration amplitude for actuators placed along the forearm will improve accuracy. An interesting proposal for future tests is whether there are anisotropies in vibrotactile localization on the forearm in that accuracy is higher close to the putative anchor points.

5. Conclusions

While achieving discrimination accuracy above chance levels may not necessarily guarantee effective information transmission, the required level of accuracy ultimately depends on the specific goals of a given application. Our experiment provides valuable insights into the design parameters of vibrotactile displays on the forearm, specifically regarding the configuration and placement of actuators. Stimulation location along the forearm strongly affects discrimination accuracy, while any effects of frequency variation (with constant amplitude) are minimal.

Our study has confirmed the findings of Cholewiak and Collins [27] regarding the positive effect of anatomical landmarks on higher discrimination accuracy. We used voice coil actuators (specifically the Lofelt L5 model) and our experimental setup to validate these results. These findings have significant implications for the design of efficient tactile displays. It is suggested that placing actuators near the wrist and elbow can enhance the conveyance of information through vibrotactile feedback. This information can be utilized to improve various aspects of tactile display design, including increasing the rate of information transfer, enhancing discrimination accuracy, and improving spatial localization.

Moreover, the experiment raises the possibility of investigating anisotropies in vibrotactile localization on the forearm. Further exploration is needed to determine whether using denser actuator placements near the wrist and elbow or employing higher vibration amplitude for actuators placed along the forearm can further enhance accuracy.

In sum, our study contributes to our understanding of the mechanisms underlying human tactile perception and provides valuable recommendations for the design of forearm-mounted vibrotactile displays. By incorporating these insights into the development process, it becomes feasible to create more effective and efficient systems that enhance the user's experience and interaction with tactile feedback, ultimately leading to improved performance and usability.

Therefore, this study advances our understanding of the factors that influence the effective transmission of vibrotactile information and may pave the way for the creation of more sophisticated haptic feedback technologies for forearm-mounted displays. Such development will only be successful with a clear understanding of the psychophysical properties of the perceptual mechanisms in question.

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Paper III

Discrimination Accuracy of Sequential Versus Simultaneous Vibrotactile Stimulation on the Forearm

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Article

Discrimination Accuracy of Sequential Versus Simultaneous Vibrotactile Stimulation on the Forearm

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Abstract: We examined discrimination accuracy of vibrotactile patterns on the upper forearm using a 2 × 3 array of voice coil actuators to generate 100 Hz vibrotactile stimulation. We evaluated participants' ability to recognize distinct vibrotactile patterns presented both simultaneously (1000 ms) and sequentially (500 ms with a 450 ms interval). Recognition accuracy was significantly higher for sequential (93.24%) than for simultaneous presentation (26.15%). Patterns using 2–3 actuators were recognized more accurately than those using 4–5 actuators. During sequential presentation, there were primacy and recency effects; accuracy was higher for the initial and final stimulations in a sequence. Over time, participants also demonstrated a learning effect, becoming more adept at recognizing and interpreting vibrotactile patterns. This underscores the potential for skill development and emphasizes the value of training for wearable vibrotactile devices. We discuss the implications of these findings for the design of tactile communication devices and wearable technology.

Keywords: vibrotactile stimulus; voice coil actuator; wearable vibrotactile device; vibratory stimulus; vibrotactile localization; vibrotactile frequency; vibrotactile discrimination; Braille reading

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1. Introduction

Approximately 826 million people worldwide live with some form of vision impairment [1]. Those who are blind or visually impaired largely depend on other senses, like touch and hearing, to navigate and interact with the world. These individuals often face considerable obstacles, especially in education. Their inability to read traditional text can restrict their access to essential information, hindering full participation in society [2]. The Braille tactile writing system addresses this by translating text into patterns of raised dots. These patterns, which individuals can sense with their fingertips, represent letters, numbers, punctuation marks, and other symbols, enabling those with visual impairments to access written information [2].

The use of vibrotactile feedback can improve user performance on touchscreen devices for tasks such as target selection [3], text entry [4], and list item selection [5]. Vibrotactile skin reading is a method of haptic communication where vibrotactile displays are used to transmit information through touch. These displays produce vibration patterns representing various symbols, enabling individuals with visual impairments to interact with digital information. Vibrotactile skin reading is a promising technique for providing information and facilitating communication for visually impaired people, potentially increasing their participation in society [6]. Proposed solutions include wearable displays featuring vibrotactile actuators to augment accessibility [7,8]. These wearable displays can be affixed to various body parts [9–11]. For instance, one approach employs three vibration motors on the users' arms to communicate calendar information, using distinct vibrational patterns for different alerts [9]. Another study demonstrated the use of two vibrotactile wristbands to assist blind individuals during orientation and navigation. These wristbands provide haptic information about the direction and distance to a target [12].

1.1. Can Braille Be Conveyed with Vibrotactile Stimulation?

Traditional Braille reading involves moving one's hand from left to right across lines of raised dots, primarily utilizing the fingertips. However, vibrotactile displays offer a potentially hands-free Braille reading alternative. Notably, previous studies suggest that blind individuals often possess superior tactile spatial acuity compared to their sighted counterparts, potentially enhancing their capacity to accurately interpret Braille patterns through vibrotactile stimulation [7,8,13–16].

Vibrotactile displays are emerging as a promising substitute for conventional Braille systems for those with visual impairments. Their appeal lies in their portability, versatility, and capability to represent a vast array of characters and symbols. Notably, designs like the sleeve-based variant that we tested here stimulate passive body areas, keeping hands free for other tasks. The efficacy of these displays is often determined by various factors, such as resolution, thresholds, frequency, amplitude, and stimulus duration [17–23]. These displays can employ varied vibrotactile stimulation patterns to convey diverse information, from images to navigation instructions [24–26]. The intensity and frequency of the vibrotactile stimuli are adjustable, allowing for a large number of possible stimulation combinations.

Our research group has delved deeply into vibrotactile stimulation properties, especially in sensory augmentation devices [7,8,27–34]. One notable system that we have developed is the "The Sound of Vision" sensory substitution platform for the visually impaired. The system uses time-of-flight (ToF) and stereo cameras to survey the surroundings, translating the data into tactile and auditory signals. A unique tactile belt communicates the direction of and distance to potential obstacles using vibrations. The system has yielded promising results in user tests [8].

1.2. Current Study

We evaluated the recognition of Braille-like vibrotactile patterns among sighted observers with a 2×3 array of voice coil actuators generating 100 Hz vibrotactile stimulation on the upper forearm. The patterns were categorized into two groups based on the number of actuators needed for their presentation, enabling us to assess the effects of pattern length—short (2–3 actuators) versus long (4–5 actuators)—on their recognition. Furthermore, we examined the potential for learning by observing performance improvement over time.

Our primary objectives were as follows:

1. **Presentation methods**: compare the efficacy of two vibrotactile pattern presentation methods on the forearm—simultaneous and sequential.
2. **Pattern length influence**: determine how varying the pattern length influences the accuracy of pattern recognition.
3. **Assessing temporal effects**: determine whether accuracy improves over time, and what the effect of stimulation order is during sequential presentation.
4. **Enhance user experience**: fine-tune these patterns to maximize user satisfaction and augment haptic feedback experiences.

Our overarching goals align with our broader mission: to advance tactile communication. This objective carries immense potential, from improving accessibility to pioneering novel communication methods. In particular, our efforts can prove crucial for aiding Braille-proficient individuals with visual impairments. Our aim is to improve tactile information conveyance, creating a more inclusive environment for those with sensory challenges.

Ultimately, we aspire to seamlessly integrate wearable technology into the daily routines of those with visual impairments. Through this, we envision expanding new opportunities for learning and interaction, thereby enriching their lives and fostering increasing societal involvement and participation.

This study stands out through the investigation of simultaneous and sequential presentation methods, examining the influence of pattern length on recognition accuracy, and observing temporal effects in the realm of tactile communication and wearable technology.

The primary objective is the seamless integration of innovative technology into the daily lives of visually impaired individuals, with a broader vision of fostering increased societal involvement in the future. The unique design of the vibrotactile forearm sleeve propels hands-free Braille communication, ensuring privacy and discretion. Beyond this, the study's implications extend to enhanced haptic communication, advancements in assistive technologies, and potential applications in virtual/augmented reality, which is particularly beneficial in low-visibility situations.

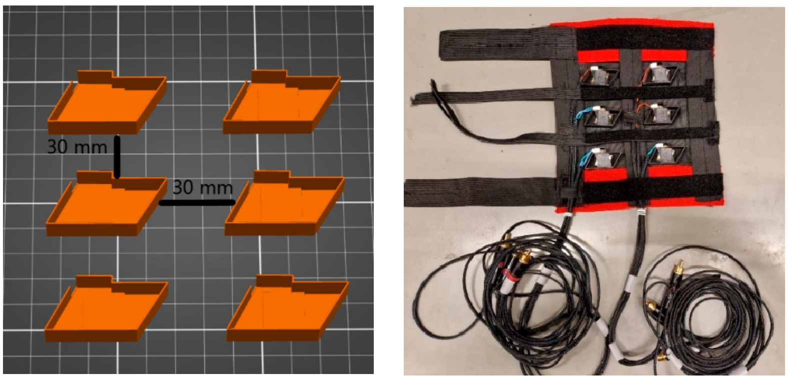
2. Voice Coil Actuator and Vibrotactile Sleeve

We used voice coil actuators (VCAs; model: Lofelt L5) for generating vibrotactile stimulation. VCAs offer a range of benefits over alternative actuator types. They are known for fast response times, high force density, and low power consumption. Furthermore, they are versatile and can be integrated into various devices and systems. These actuators are designed to deliver rich vibrotactile stimulation and, importantly, allow for the separate manipulation of both frequency and amplitude (details provided in Table 1).

Table 1. Characteristics of the Lofelt L5 actuator [35].

Performance Characteristic	Technical Specification
Operating voltage (V)	0–3.3
Frequency range (Hz)	0–15,000
Force (G-p.p.)	0–15
Rising time (ms)	5–15
Operation current (mA)	200–500+

For mounting, the actuators were affixed to a soft and thin fabric, ensuring a snug fit and efficient transfer of tactile information from the actuators to the skin. The six voice coil actuators were arranged longitudinally in a 3 × 2 array to produce back-and-forth vibrational movement perpendicular to the length of the forearm (Figure 1).



(**a**) (**b**)

Figure 1. (**a**) Overview of the design of the sleeve used to apply the Lofelt L5 actuators along the forearm; (**b**) an example of a wearable vibrotactile sleeve and the configuration of the actuators.

The experiment utilized a bespoke vibrotactile sleeve crafted from a Power Mesh fabric consisting of 90% nylon and 10% spandex. This choice of materials ensured that the sleeve was both comfortable and user-friendly. To accommodate various forearm sizes, stretch straps equipped with Velcro were used to secure the sleeve, allowing easy adjustment for individual participants. The L5 actuator enclosures were 3D-printed directly onto the fabric, ensuring that the actuators could vibrate without any hindrance. The printing was executed using a Prusa MK3s 3D printer and Prusa Slicer, with PLA as the chosen material. Importantly, there were no fabric layers obstructing the point of contact between the enclosure and the skin.

The L5 actuators had dimensions of W: 17.0 × D: 20.5 × H: 6.2 mm. The custom-made enclosures were slightly larger, measuring W: 17.0 × D: 28 × H: 6.2 mm. One significant advantage of this enclosure design is its protective quality, safeguarding both the participants' skin and the elastic material from potential abrasion or damage inflicted by the moving actuator. Within the enclosure, the actuator was oriented so that it produced vibrations parallel to the skin and perpendicular to the forearm's length.

The enclosure was vital for delivering vibrotactile stimulation safely. Its tight fit with the actuator ensured that it functioned seamlessly as a single unit. With a smooth surface, the enclosure was lightweight and thin, at an approximate thickness of 1.6 mm.

For stimulus presentation, the system included a digital audio interface (RME MADI face XT), digital-to-analog converters (Ferrofish A32), multi-channel amplifiers, and the Lofelt L5 voice coil actuators. The tactile sleeve interfaced with the audio hardware through wired connections.

3. Methods

3.1. Participants

Eight normally sighted people, ranging in age from 21 to 38 years (mean age: 29 years), participated in this study. All participants confirmed they had no known issues with vibrotactile stimulation. Before beginning the experiment, each participant provided their written informed consent. The study was conducted in alignment with the guidelines set by the local ethical committee and the Declaration of Helsinki.

3.2. Mapping Patterns to Vibrotactile Cues

Our primary aim was to assess the accuracy with which sighted participants could identify vibrotactile patterns on their skin with simultaneous versus sequential presentations. Additionally, we sought to understand how the length of these patterns (i.e., the number of activations participants needed to discern) influenced their recognition capabilities. The aim of this research is to lay a foundation for the future development of a wearable device that can present Braille-like patterns through vibrotactile stimulation.

We used a set of 14 unique patterns derived from the Icelandic Braille alphabet. These patterns were divided into 2 categories: short-length patterns, which involved the use of 2–3 actuators, and long-length patterns, requiring 4–5 actuators. The specifics of these patterns can be observed in Figure 2 and are detailed further in Table 2.

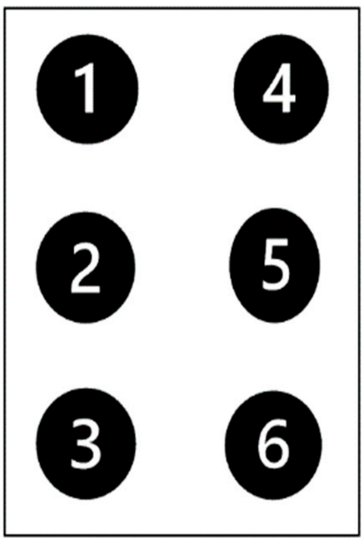


Figure 2. Assignment of pattern dots to the six actuators in this study.

Table 2. The patterns used in the experiment and the numbers of the actuators required to present each of the 14 vibrotactile patterns.

Short Patterns			Long Patterns		
á	⠡	1, 6	é	⠮	2, 3, 4, 6
c	⠉	1, 4	ý	⠯	1, 2, 3, 4, 6
o	⠕	1, 3, 5	x	⠭	1, 3, 4, 6
d	⠙	1, 4, 5	ó	⠹	1, 4, 5, 6
h	⠓	1, 2, 5	þ	⠫	1, 2, 4, 6
ð	⠱	1, 5, 6	q	⠟	1, 2, 3, 4, 5
l	⠇	1, 2, 3	ú	⠻	1, 2, 4, 5, 6

It is important to emphasize that our study did not require participants to have any prior knowledge of Braille reading or recognition of specific Braille characters. Instead, we aimed to assess their capability to accurately reproduce the vibrotactile patterns using a keyboard interface. This design allowed us to evaluate the efficacy of our vibrotactile system purely based on participants' ability to discern and reproduce the patterns they felt on a keypad.

There were a total of 168 trials in the study, divided into 24 miniblocks (each containing 7 trials): 12 miniblocks for short patterns and 12 for long patterns. Within each block, there were 28 trials. Half of these miniblocks involved simultaneous presentation, while the other half involved sequential presentation. Every trial began with the presentation of a pattern, and subsequently, participants were tasked with reproducing the pattern using a keypad. The order of presentation was randomized (details in Table 2).

Table 2 elucidates the characters, corresponding patterns, and the actuators used for each pattern.

For simultaneous presentation, all actuators were activated simultaneously for 1000 ms. A 4000 ms interval followed, during which participants responded. During sequential presentation, each actuator was triggered successively for 500 ms, separated by a 450 ms pause. As for simultaneous presentation, there was a 4000 ms response interval.

The stimulation was set at a constant frequency (100 Hz) and amplitude (9.6 g acceleration). Notably, this frequency aligns with the optimal detection range for human vibrotactile perception (based on our previous studies [36]). The entire experiment took approximately 35 min. for each participant.

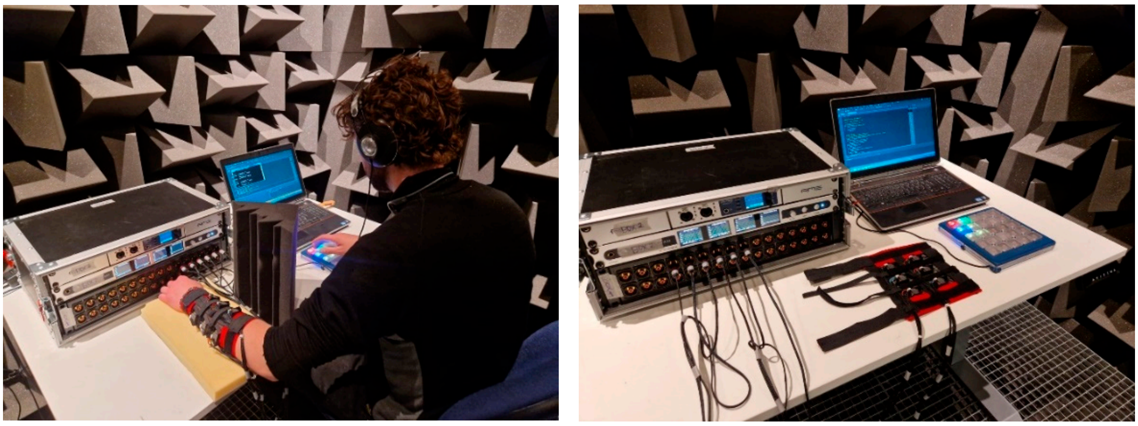
3.3. Familiarization Session

Prior to the main experiment, participants were thoroughly briefed on the procedure and the tactile stimulation. To familiarize participants with the actuators' stimulation, they were activated six times in quick succession. To ensure that the participants fully understood their expected task, a block of 28 trials was administered.

Participants used a keypad to reproduce the stimulation pattern on each trial, with each key corresponding to one of the 6 stimulation locations. These practice trials ensured that participants were adequately prepared and had a firm understanding of their task before the main experiment started.

3.4. General Procedure

To minimize external distractions, the study was conducted in an anechoic chamber. To prevent any potential auditory cueing, like from the subtle noise from the actuators, white noise was played through headphones (see Figure 3a,b). Before gathering data, we calibrated the intensity of the vibrotactile stimulation using acceleration measurements. A three-axis accelerometer (Brüel & Kjær Type 4520, Denmark, Virum) gauged the acceleration and intensity of the vibration. This meticulous calibration was performed for every participant to eliminate potential biases and ensure uniformity and guarantee that each participant received the same tactile frequency (100 Hz) and amplitude (9.6 g) on their skin throughout the experiment.



(**a**) (**b**)

Figure 3. (**a**) A participant in the anechoic chamber wearing a vibrotactile sleeve, with his hand resting on a cushion. The participants wore headphones playing white noise to block out external auditory cues and responded to the vibrotactile feedback by pressing the correct keys on the keypad. (**b**) The audio hardware consisted of a digital audio interface (RME MADI face XT), digital-to-analog converters (Ferrofish A32), multi-channel amplifiers, and parallel vibrating voice coil actuators (Lofelt L5), t L5). The MADI face XT receives information from a computer via a USB cable and sends the signal to the Ferrofish A32 Analog-to-Digital/Digital-to-Analog (AD/DA) converter. Ferrofish A32 then conveys the signal to the amplifier, which then sends the amplified signal to the actuators.

Notably, we performed force measurements at the contact surface between the enclosures and the forearm skin using a Force-Sensitive Resistor (FSR), specifically the FSR03 series, from Ohmite Manufacturing Company, Warrenville, IL, USA. The force was adjusted to be 1.64 N for all participants.

The experiment consisted of six blocks of tactile patterns, each involving four miniblocks presented in a randomized order—either sequentially or simultaneously. Each miniblock featured seven random patterns, and during the response interval, participants were tasked with replicating the presented pattern on a keypad.

4. Results

A repeated measures ANOVA was conducted to examine the effects of the presentation mode (simultaneous or sequential) and the length of the patterns (short or long) on the accuracy of vibrotactile pattern reproduction. The results showed that both the presentation mode (F (1, 20) = 1033; $p = 1.07 \times 10^{-18}$) and the length of patterns (F (1, 20) = 53.6; $p = 4.41 \times 10^{-7}$) had a significant effect on accuracy. Accuracy was significantly higher with sequential presentation than simultaneous, and performance was better for short vibrotactile patterns than long ones. Additionally, there was a significant interaction between these two factors (F (1, 20) = 12.4; $p = 0.02$; $p < 0.05$), indicating that the effect of pattern length on accuracy differed depending on the presentation method.

We defined 'accuracy' as the participant's ability to correctly recognize and report the vibrotactile patterns applied to the skin of their forearm. For sequential activation, a 'correct response' meant that participants accurately identified and reported all the activations in the presented sequence and, importantly, maintained their correct order. The order in which they reported the dots was therefore critical for accuracy. In contrast, for simultaneous presentation, a 'correct response' was determined by participants' accurate identification of the numbered actuators in the pattern. The order in which participants reported the vibrations therefore did not affect accuracy.

The data in Figure 4 reveal that the detrimental effect of simultaneous presentation was larger for the long patterns than the short ones. Overall, these findings suggest that the presentation method has a large effect on the accuracy of vibrotactile pattern recognition. In addition, there was a large effect of the pattern length (short versus long).

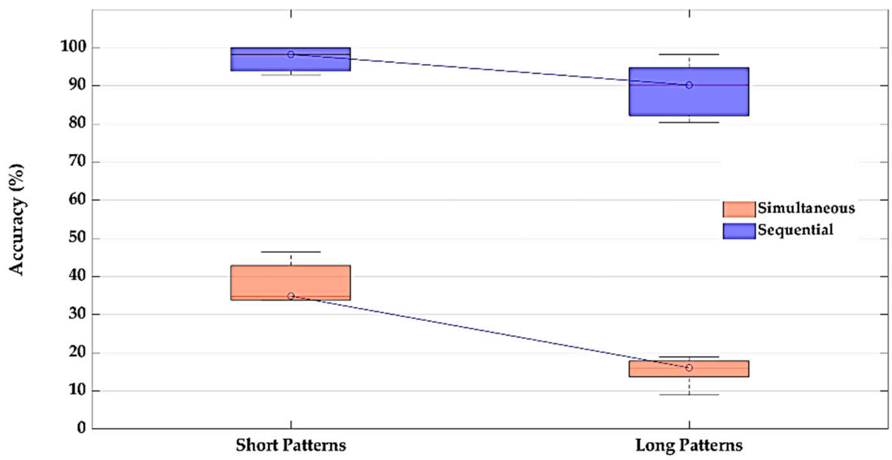


Figure 4. Box–whisker plot comparing the accuracy (y-axis) between the two different pattern lengths (short- and long-length patterns) with different vibrotactile presentation methods (x-axis): the graph shows the average accuracy in percentages on the upper side of the forearm for sequential (blue) and simultaneous presentations (orange). The box length shows the interquartile range (IQR) and the 25% and the 75% limits, and the horizontal bar inside the box shows the median value. The ends of the box plot represent minimum and maximum values.

The box plots (Figure 4) show how the median accuracy was highest for sequential presentation for both short (97.19%) and long patterns (89.29%). The most notable result is that presenting vibrotactile patterns sequentially was vastly more effective for accuracy for both short and long patterns. Another important result is that accuracy during simultaneous presentation was much lower for long patterns (15.28%) than short ones (37.80%).

4.1. *Vibrotactile Pattern Length*

Short-length patterns were recognized with considerably higher accuracy than longer patterns. This implies that pattern length plays a crucial role in the accurate recognition of vibrotactile patterns on the skin. Longer patterns, due to their increased complexity, might challenge participants' ability to discern and interpret them accurately. In contrast, shorter patterns are more easily grasped, leading to better recognition accuracy (Figure 4). Note that this difference between short and long patterns may additionally reflect differences in demands on working memory and increased complexity for responding.

4.2. *Simultaneous Versus Sequential Presentation*

We also investigated the effects of two distinct presentation methods: sequential and simultaneous. Our results revealed a large and highly significant difference in accuracy between these two methods. Sequential presentation yielded an impressively high average accuracy rate of 93.24%, indicating that participants were highly adept at recognizing vibrotactile patterns when presented sequentially.

In contrast, the average accuracy for the simultaneous method was substantially lower (26.15%). This very large difference clearly demonstrates that the presentation order of the vibrotactile patterns greatly affects accuracy (Figure 5).

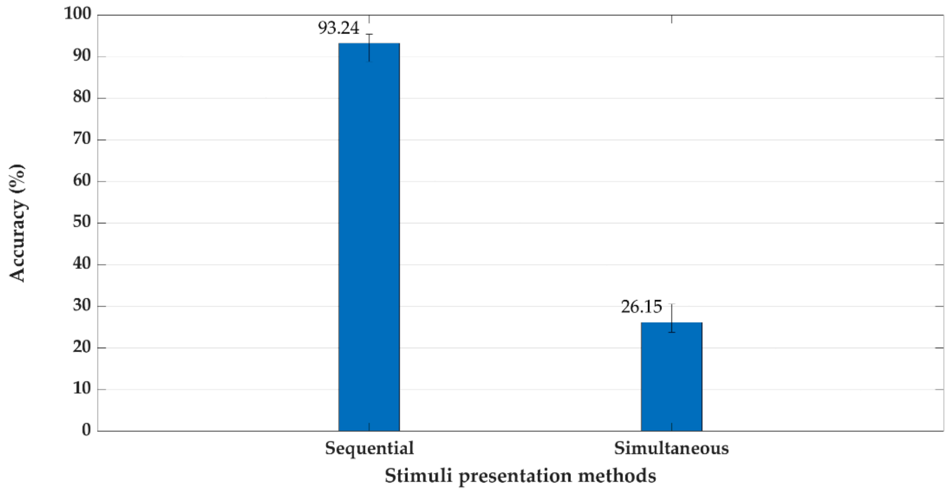


Figure 5. Accuracy for the two different stimulus presentation methods (sequential and simultaneous).

4.3. Stimulus Order Effects

Figure 6 illustrates how the average accuracy for the recognition of stimuli presented during sequential presentation is influenced by the serial position of the stimulation. The accuracy shows both of the well-known primacy and recency effects [37].

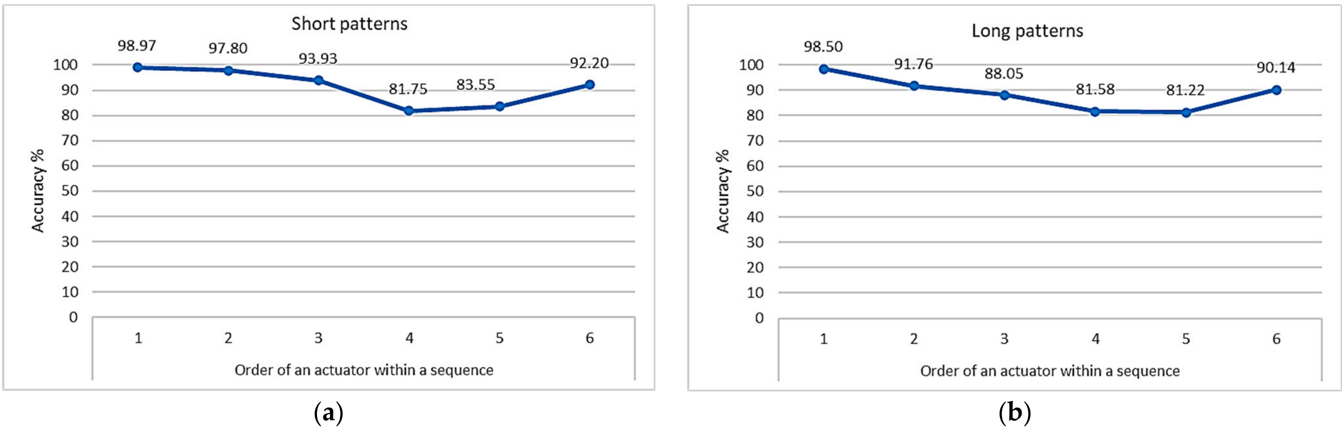


Figure 6. (**a**) Accuracy as a function of serial position of each individual vibrotactile stimulation during sequential presentation for short (2–3 actuators) and (**b**) long patterns (4–5 actuators).

The primacy effect entails that stimuli presented at the beginning of a sequence are more easily reported. The recency effect is seen in the fact that participants exhibited higher perceptual accuracy and recall for stimuli presented later in the sequence. These serial position effects and their influence on recognition of the patterns provide important insights into how the order of stimulus presentation impacts participants' perception and memory [38,39].

4.4. Learning Effects

An additional finding is that participants' average accuracy in recognizing vibrotactile patterns increased throughout the course of the six experimental blocks, showing a clear learning effect over time (see Figure 7). An ANOVA analysis revealed significant differences in accuracy among the six experimental blocks (F (5, 168) = 2.91; p = 0.015), showing how pattern reproduction improved as the experiment progressed.

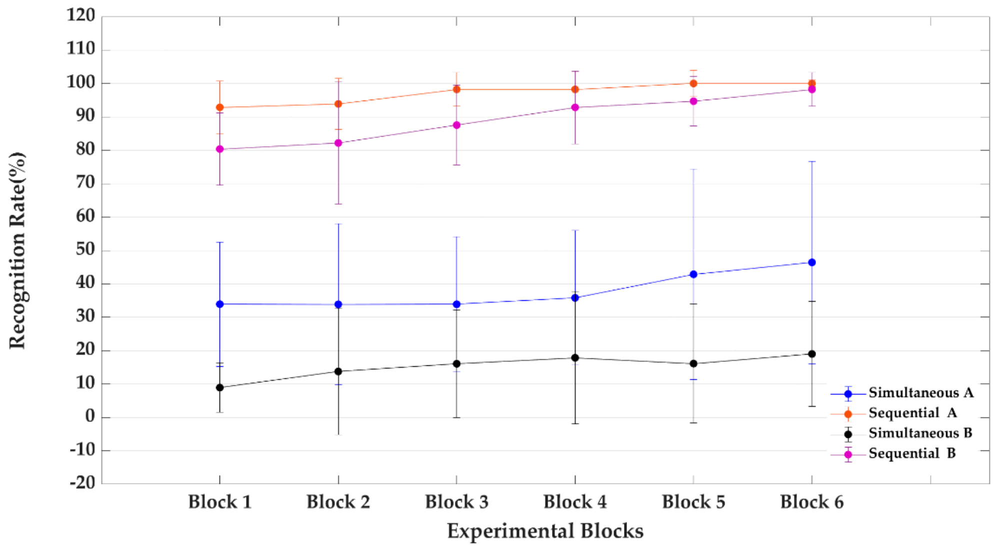


Figure 7. Performance across the six experimental blocks. The figure shows a clear learning effect over time (the 6 experimental blocks) for both presentation methods (simultaneous and sequential) and different pattern lengths (short (A) versus long (B) patterns). The error bars show the standard deviation within each group for each block.

This emphasizes the importance of considering training schedules for sensory substitution devices, in light of the considerable improvement that we see over only a 35 min. long experiment. Training should, therefore, be considered in addition to presentation methods and pattern lengths when designing experiments on the recognition of vibrotactile patterns, but even more importantly, it should be considered when sensory substitution devices are designed. Adequate training ensures that participants have the necessary knowledge and skills to perform the tasks or recognize the patterns that are being tested.

Without proper training, experimental results may be influenced by participants' lack of familiarity with the task in each case. The finding of a learning effect over a relatively short experiment duration emphasizes the dynamic nature of vibrotactile pattern recognition and the potential for rapid performance improvement. This knowledge is valuable for designing effective training schedules and optimizing the usability of sensory substitution devices. When planning experiments on vibrotactile pattern recognition, it is therefore essential to factor in not only training but also the potential for skill development over time, along with other variables such as presentation methods and pattern length.

Overall, Table 3 provides insights into how the performance indicators in this study differed in terms of their presentation methods, accuracy rates, pattern lengths, stimulation times, learning effects, serial position effects, and user feedback in the context of cognitive tasks.

Table 3. Comparison of performance indicators in this study.

Performance Indicators	I	II
Presentation Method	Sequential	Simultaneous
Accuracy Rate	High (93.24%)	Low (26.15%)
Pattern Length	Short patterns (2–3)/Long patterns (4–5)	Short patterns (2–3)/Long patterns (4–5)
Stimulation Time	500 ms with a 450 ms interval	1000 ms
Learning Effects	Positive	Positive
Serial Position Effects	Primacy and recency observed	-
User Feedback	Positive	Negative

5. Discussion

We introduced a novel approach to presenting vibrotactile stimulation patterns with a forearm-mounted wearable vibrotactile sleeve, where Braille-like patterns were conveyed with tactile actuators. Our investigation focused on comparing the effectiveness of sequential versus simultaneous presentations of vibrotactile stimuli, as well as evaluating the influence of pattern length on recognition accuracy.

The results provide evidence in support of sequential over simultaneous stimulus presentation. We observed a vastly higher average accuracy rate for sequential (93.24%) presentation than simultaneous (26.15%). It is nevertheless important to note that the total stimulation time was lower for simultaneous presentation (1000 ms) than sequential, which could take from 1450 ms (for two activations) to 4300 ms (for five activations). This difference in presentation time affects how much information can be transmitted and is a question that needs to be addressed in future studies.

It is also important to consider the practical implications of sequential versus simultaneous presentation. In real-world scenarios (such as reading Braille text), the efficient retrieval of information is crucial. The practicality of any Braille design therefore involves a delicate balance between accuracy and speed. Although this aspect was not the primary focus in this phase of study, it is nevertheless a consideration to be addressed in future research.

Furthermore, we observed large accuracy differences between the two vibrotactile pattern lengths (long versus short). Accuracy was significantly higher for the short patterns requiring 2–3 actuators than the long patterns requiring 4–5 actuators. Pattern length, therefore, has a large effect on accuracy, with short patterns leading to higher perceptual accuracy. This difference was seen for both simultaneous and sequential presentations. But here again, we should note that more information can be conveyed with longer patterns, and future studies need to determine the optimal combination of stimulus time and pattern length for conveying tactile information. It is also important to consider to what degree these differences between short and long patterns may reflect different demands on working memory and increased s for responding.

Moreover, we investigated potential learning effects on pattern recognition accuracy across the six blocks. The results revealed a consistent improvement in average accuracy over time, indicating that participants were able to improve their ability to reproduce the vibrotactile patterns. This was also the case for simultaneous presentation, although performance levels remained relatively low.

Overall, our findings emphasize the importance of considering stimulus presentation methods and vibrotactile pattern lengths when designing experiments related to haptic pattern recognition, in addition to taking learning into account. These insights are crucial for the development of effective vibrotactile pattern recognition devices and training programs.

We also investigated any potential serial position effects, which can shed light on the effects of the order of stimulus presentation on perceptual recognition. We observed both a primacy effect (better performance for stimuli at the beginning of a sequence) and a recency effect (higher accuracy for stimuli at the end of a sequence). Performance was, on the other hand, slightly poorer for activations during the middle of the sequences than for the initial and final stimuli.

Regarding the differences between presentation modes, during sequential activation, participants have the advantage of analyzing the activations one at a time, using their working memory to process and identify patterns. Conversely, simultaneous activation requires rapid, concurrent processing of multiple activations, which may surpass their working memory capacity.

Potential Applications to Braille Presentation

Our ultimate aim is to develop a wearable device for presenting Braille with vibrotactile stimulation. While our current experiments involved the performance of college students without prior Braille literacy, they are a necessary first step in this development. It is important to obtain reliable results for our equipment before engaging with a more specific and sensitive population. During this initial phase of our research, we therefore focused on the ability to reproduce vibrotactile patterns, irrespective of Braille expertise. We also aimed to assess the basic functionality and reliability of the wearable, ensuring that it can be a versatile tool in a wide range of scenarios beyond Braille reading.

One of our next steps is to test the performance of actual Braille readers with this device. Notably, visually impaired individuals often have an acute sense of touch, and there is good evidence of neural reorganization and enhanced abilities following sensory impairment [40].

For example, there is evidence that Braille reading recruits the visual cortex of blind individuals [7,41,42]. It will furthermore be of future interest to investigate the relation between such neural reorganization and the age of onset of sensory impairment in the context of our device. Other factors to consider include investigation into the biocompatibility of the vibrotactile stimulation system, cross-modal plasticity, innervation, skin composition, skin thickness, and individual variations in sensory processing.

We believe that Braille conveyed through tactile stimulation can offer significant benefits over other presentation methods. Consider the scenario of a blind person navigating an unfamiliar city. While audiobooks and voice-based navigation apps undoubtedly provide valuable information about their surroundings, the integration of tactile Braille patterns through a wearable device can complement and enrich their experience in several ways.

In densely populated urban environments, audio cues can be challenging to discern and may even become drowned out. In such instances, tactile Braille can convey directions or street names to the skin. This hands-free approach not only obviates the need to carry and operate additional devices but also ensures privacy and discretion. The tactile feedback can also serve as a tactile map, allowing users to better comprehend intricate environments such as subway systems or train stations.

Moreover, the benefits of tactile Braille may extend to situations where rapid responses are needed. In such scenarios, tactile alerts delivered to the skin can provide immediate guidance, allowing the visually impaired to react swiftly.

The implications of our research can also be extended to other uses, including haptic communication, assistive technologies, and virtual and augmented reality systems, where the effective presentation of vibrotactile stimuli is crucial.

6. Conclusions

Our primary objective was to investigate ways of optimizing information conveyance through tactile stimulation on the forearm. We pursued this by investigating optimal tactile information encoding and presentation and by designing user-friendly wearables for accurate delivery. Central to our research is the aim to improve tactile communication, with a focus on accessibility.

The results have the following implications:

1. Sequential vibrotactile stimulus presentation is, overall, preferable to simultaneous presentation.
2. Shorter patterns yield better performance than longer ones, offering insights into optimizing information conveyance and presentation durations.
3. We observed learning effects with repeated testing, underscoring the value of training for such devices.
4. Primacy and recency effects in stimulus order during sequential presentation deepen our understanding of perception and memory in sequential contexts.

These findings offer important insight for the design of effective vibrotactile pattern recognition programs and for fine-tuning parameters for vibrotactile presentations of Braille.

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contributed to the methodology, writing review, and editing and supervision. Á.K. contributed to the methodology, writing, and editing and co-supervision. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: Ethical review and approval were waived through the Icelandic bioethics committee "Vísindasiðanefnd" for this study, because the study is not scientific research in the health sector, as defined by the Act on Scientific Research in the Health Sector No. 44/2014.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy and project restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

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Paper IV

Vibrotactile Pattern Recognition: The Influence of Interstimulus Intervals

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Vibrotactile pattern recognition: Influence of interstimulus intervals

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Abstract: Background Vibrotactile feedback systems are widely used in assistive technology, wearable devices, and virtual environments to deliver precise tactile information. The timing of interstimulus intervals (ISIs) plays a critical role in determining how accurately users perceive and interpret vibrotactile patterns. The optimal use of ISIs can increase the effectiveness of these systems, improve user interaction, and enable reliable, intuitive feedback in diverse applications. We examined how different interstimulus intervals ISIs impact the accuracy of vibrotactile pattern recognition. **Methods** Participants wore a forearm-mounted device with six voice coil actuators arranged in a 3 × 2 grid, delivering Braille-based vibrotactile patterns sequentially at ISIs ranging from 10 to 2500 ms. Eight participants performed identification tasks involving Icelandic Braille patterns categorized as either short (2–3 actuators) or long (4–5 actuators). A repeated measures ANOVA was conducted to assess the effects of ISI, pattern type, and practice (across two testing blocks) on pattern recognition accuracy. **Results** For short patterns, accuracy was highest (92%–98%) at ISIs of 50–700 ms, with peak performance at 300 ms. For long patterns, accuracy reached 86%–94% at ISIs of 100–500 ms, peaking at 400 ms. Participants were more accurate with short patterns, and performance improved significantly over time for both short and long patterns, highlighting the importance of training for vibrotactile pattern recognition. **Conclusions** These results underscore the importance of careful selection of ISIs in vibrotactile feedback systems for accurate pattern identification. The findings provide valuable insights for conveying tactile information using wearable devices, contributing to better tactile feedback and performance in applications requiring precise vibrotactile information delivery.

Keywords: Voice coil actuator; Wearable vibrotactile device; Vibratory stimulus; Vibrotactile localization; Vibrotactile frequency; Vibrotactile discrimination; Interstimulus Interval (ISI).

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1 Introduction

Vibrotactile perception, which is the ability to detect and interpret vibrational stimuli applied to the skin, is a fundamental aspect of human sensory processing. Information conveyance with vibrotactile devices has increasingly been used across a wide range of applications [1–9]. By translating digital signals into vibrations, vibrotactile feedback can be used for sensory substitution when one sense is deficient, or unreliable due to environmental factors [10], and can provide users with immersive experiences in various contexts.

The potential of this technology has been demonstrated in various studies, revealing how it can improve accessibility for those with sensory challenges [10–14]. As vibrotactile systems are increasingly being used in various contexts, understanding the most efficient ways of conveying vibrotactile information in such devices is important for maximizing their effectiveness across diverse applications. Vibrotactile feedback is widely used across various fields to increase immersion in virtual reality (VR) [15], aiding exposure therapy for fear of flying by simulating turbulence [16], and improving haptic perception in virtual environments, allowing users to feel virtual objects [17]. Additionally, vibrotactile feedback can deepen gaming immersion by simulating physical impacts, increasing realism and players' sense of presence [18].

For individuals with visual impairments, vibrotactile systems have been of great use, such as the Sound of Vision device [12,19], where vibrotactile stimulation provides visually impaired users with directional cues, increasing confidence and mobility in unfamiliar environments [20]. Vibrotactile feedback has also been used in the development of Braille reading devices, such as UbiBraille, which translates written text into vibrational patterns felt on the fingertips, enabling tactile reading [21]. Vibrotactile feedback aids individuals with auditory impairments by converting sounds into vibrations, enhancing awareness of critical alerts [22].

Although vibrotactile devices can improve immersion across applications, optimizing their effectiveness for information transfer remains crucial. Therefore, a deeper understanding of tactile signal interpretation is important to refine data transmission through touch and ensure both accuracy and user comfort. For example, the vibrotactile feedback used in the previously mentioned Sound of Vision device was based on extensive research on the processing of vibrotactile stimulation of the human body [23,24,40].

To use vibrotactile feedback efficiently, it is essential to fine-tune key stimulation parameters to ensure that vibrations are clearly perceived, convey distinct information, and remain comfortable for users. The most important parameters to consider include intensity, frequency and amplitude of the stimulation, location chosen for stimulation, signal duration, and the main topic here: interstimulus interval (ISI). Each of these parameters is likely to play an important role in shaping how users perceive and interpret tactile stimuli and maximizing information content over time. Stimulus intensity refers to the strength of the vibrations. Higher intensities make vibrations more noticeable, which is particularly useful for tasks requiring precise tactile feedback [25].

The frequency of vibrotactile stimuli significantly affects how accurately users perceive and interpret tactile stimulation. In a recent study by our research group, we tested tactile stimulation on the wrist using frequency ranges from 25 to 1000 Hz and determined that the most accurate performance was obtained for frequency ranges from approximately 100 to 250 Hz [26]. In this frequency range (100–250 Hz), accuracy remained unaffected by frequency variations but was highly dependent on stimulation location when amplitude was constant [27,28]. Zhao et al. presented phonemes with a wearable vibrotactile stimulation device, finding significant differences in accuracy for vibrations on the dorsal side of the forearm at two frequencies (30 and 250 Hz). The accuracy was better at 250 Hz than 30 Hz [29], which is consistent with the results of Aevarsson et al., who investigated the frequency range that was most sensitive to human observers on the wrist [26]. Vibration amplitudes play a role in vibrotactile perception; higher amplitudes increase the intensity of sensation [30]. Several researchers have examined the effects of stimulus duration on tactile recognition accuracy and have found considerable variability, revealing that the duration of vibrotactile stimuli can significantly affect localization accuracy, with longer-duration stimuli generally leading to better performance [31].

Moreover, localization and discrimination of vibrotactile stimuli differ considerably by stimulation site, partly because of large differences in tactile resolution depending on location on the body [32]. However, another equally important consideration is the intended use and whether stimulating particular locations interferes with other activities. For example, while the fingertips have high resolution, they may not be optimal for all devices. They may work well when the goal is "tactile reading", as in the UbiBraille project [21], but stimulating the fingertips may not work well for sensory substation devices, which are intended for use while the user is actively moving around and engaging with their environment [10,33].

Tactile stimuli are generally perceived more accurately when delivered near anatomical reference points, which Weber [34] and Boring [35] have associated with body landmarks. Anchor points, such as the wrist or elbow, play an important role in tactile spatial acuity measurements. Research on pressure stimuli further suggests that body landmarks may serve as reference points for tactile localization, with the highest accuracy observed in joint regions [36]. Therefore, in our development of sensory substitute devices, we focused on stimulation with a vibrotactile sleeve on the forearm or on the lower back [10,12,14,19,23,24,27,28,37−40]. Another key question is whether information is conveyed sequentially or simultaneously [14]. Thus, an important tradeoff exists. Of course, the faster stimulation can be delivered, the better the information conveyance, but there is also the danger that signals will be confused with one another if they occur too close in time. We previously reported that simultaneous vibrotactile stimulation conveys less information than sequential presentation [14].

However, the crucial question here is how close in time can two successive vibrotactile stimulations be for meaningful information conveyance? Research has shown that ISI variations significantly influence key perceptual aspects, including intensity discrimination and apparent motion. The ability to distinguish between vibrotactile stimuli of different intensities is directly affected by the timing between successive stimuli [41].

Studies investigating the effects of vibratory frequency and temporal intervals have demonstrated that adjusting ISI can either increase or decrease the perception of continuous motion, which is crucial for designing haptic interfaces that simulate movement [42]. These findings highlight the importance of fine-tuning ISI to improve the clarity and effectiveness of vibrotactile feedback in various applications.

Although vibrotactile feedback systems are widely used in applications such as virtual reality, gaming, and sensory substitution, there is a notable gap in the understanding of optimal ISIs for accurate pattern recognition. Specifically, there is limited guidance on the optimal ISI ranges for different pattern lengths and complexities, as well as on the timing intervals that balance speed and accuracy.

In addition, the interaction between ISI and pattern length, along with the impact of learning effects over time, remain underexplored. Addressing these gaps is essential for designing vibrotactile systems that deliver precise and efficient tactile communications. This study aimed to bridge this gap by systematically investigating the effects of ISI on recognition accuracy, thereby contributing to the development of more effective vibrotactile feedback systems. The vibrotactile sleeve used in this study provided information on the forearm, a low-activity body area, freeing the hands for other tasks [10,12,14,24,26–28,34,43].

Our main research questions were as follows: i) Optimal Timing: What ISI range maximizes the accuracy of vibrotactile pattern recognition on the forearm? ii) Pattern Length Effects: How do the length and complexity of vibrotactile patterns, such as longer or shorter sequences, affect performance, and do these interact with the effects of ISI? iii) Training and Exposure: How do training and repeated exposure to vibrotactile stimuli influence performance across different ISIs?

2 Methods

2.1 Participants

The study involved eight participants (four females and four males) aged 23–38 years. All participants were right-handed, had normal haptic perception, and reported no cognitive or sensory impairments. Prior to the experiment, each participant provided written informed consent. This study was conducted in accordance with the guidelines established by the local ethical committee and Declaration of Helsinki.

2.2 Voice coil actuators and vibrotactile sleeve

Voice coil actuators (VCAs; Model: Lofelt L5, Figure 1(a)) were used to deliver precise vibrotactile stimulation. The L5 actuators have high force density and low power consumption, making them well-suited for applications requiring high-quality tactile feedback (Table 1). They allow independent control of both frequency and amplitude, which enables the creation of rich, dynamic vibrotactile experiences (refer to Table 1 for detailed specifications).

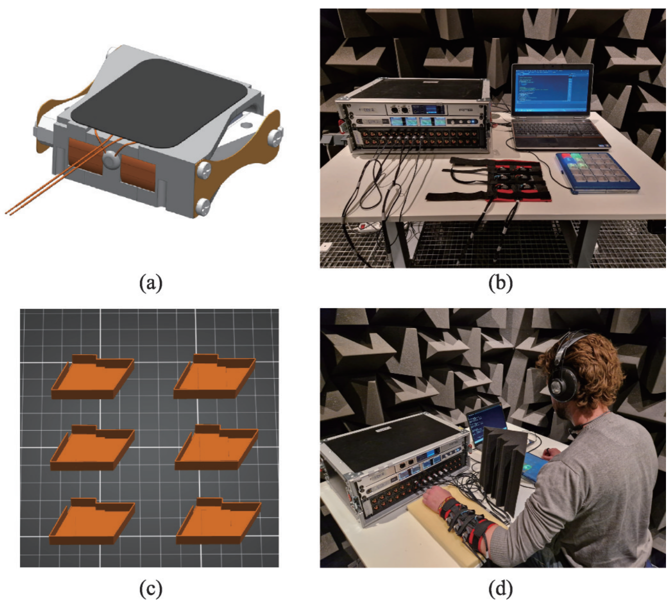
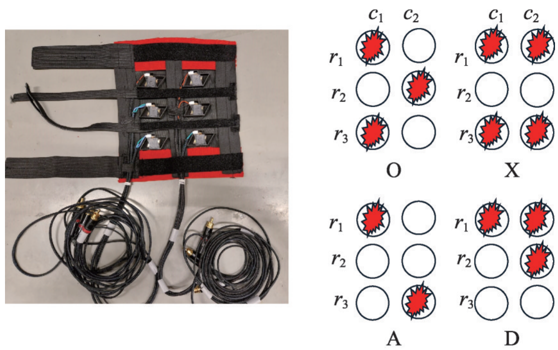


Figure 1 (a) Lofelt L5 voice coil actuator used in the study; (b) Hardware configuration for vibrotactile stimulation along with the response apparatus; (c) Layout of the 3D printed enclosures for actuators attached to the stretchable material that the sleeve was made of; (d) A participant in the experimental setup, with headphones playing white noise to mask the sound generated when the actuators vibrate. The participants responded to the vibrotactile feedback by pressing the correct keys on the response apparatus.

Table 1 Haptic, electric, and acoustic attributes of the Lofelt L5 actuator

Attribute	Specification
Maximal voltage	1.4 Vrms at f0
Resonance frequency (f0)	65 Hz ± 5%
Frequency range	Min. 0.5 G over 35 Hz–1 kHz
Nominal impedance	8 Ω at f0
Power handling	Maximum: 320 mW
Current consumption	Average at medium volume: 10 mA, bass music use-case Average at maximum volume: 57 mA, bass music use-case

Therefore, these actuators can be used to generate accurate and versatile tactile stimulation. The actuators were mounted on a soft, thin fabric arranged in a 3 × 2 grid along the forearm (oriented longitudinally) to produce vibrations perpendicular to the forearm (Figures 1(d) and 2(a)). This grid was integrated into a custom-designed vibrotactile sleeve made of Power Mesh fabric, composed of 90% nylon and 10% Spandex.



(a) (b)

Figure 2 (a) 3-by-2 tactile sleeve, consisting of 6 actuators, mounted on stretchable, wearable material; (b) Four examples of vibration patterns, denoting the letters O, X, Á, and D from the Braille alphabet (in panel b, c and r refer to columns and rows on the tactile sleeve, respectively).

The fabric was chosen for its comfort, breathability, and flexibility. Stretch straps with Velcro fasteners were used to secure the sleeve to the participants' forearms, allowing for an adjustable fit that could accommodate a wide range of forearm sizes, ensuring both comfort and stability during use. Custom-designed enclosures, 3D-printed using a Prusa MK3s printer and PLA material, housed the L5 actuators. These enclosures were printed directly onto the fabric to ensure the direct transmission of vibrotactile stimulation to the skin without any material layers in between. The L5 actuators measure *W*: 17.0 × *D*: 20.5 × *H*: 6.2 mm in their static state and expand to *W*: 17.0 × *D*: 25.5 × *H*: 6.2 mm when vibrating at maximum displacement (though they may not always operate at this level). The enclosures are slightly larger to accommodate the actuators, particularly along the axis of vibration, with dimensions of *W*: 18.0 × *D*: 29.0 × *H*: 7.2 mm and a wall thickness of 0.5 mm.

The enclosures were carefully designed to allow the actuators ample space to vibrate freely without touching the enclosure walls, even at maximum displacement. Securely mounted inside the enclosures, the actuators made direct contact with the skin at the stimulation surface, with no intervening fabric layers.

The thin, flat surface of the plastic casing was in direct contact with the skin to efficiently transmit vibration signals. This ensured that vibrations were delivered to the user's forearm through the approximately 2 mm thick enclosure surface at the point of contact. The actuators were mounted inside enclosures (Figures 1 and 2). The enclosures are essential for safe operation, designed to fit snugly and prevent sharp edges from irritating the skin or compromising the integrity of the elastic fabric.

2.3 Equipment for stimulus presentation

For stimulus presentation, our custom-made equipment included a digital audio interface (RME MADIface XT), digital-to-analog converters (Ferrofish A32), multi-channel amplifiers, and Lofelt L5 voice coil actuators. The vibrotactile sleeve was connected to the audio hardware through wired connections (see Figure 1(b)).

2.4 Mapping patterns to vibrotactile cues

We used a set of eight unique patterns derived from the Icelandic Braille alphabet, categorized into short (2–3 actuators) and long patterns (4–5 actuators; see Figure 2(b) and Table 2) patterns.

Table 2 Overview of the selected Icelandic Braille alphabet characters, their Dot Patterns, and actuator requirements for presentation (Standard Braille is indeed based on a 6-dot cell system, and each dot is assigned a position numbered 1 through 6. In this study, six actuators were strategically assigned to the six positions of the Braille cell to replicate Braille-like patterns. Each actuator corresponds to one of the six standard dot positions)

Short patterns	Long patterns
á ⠡ 16	q ⠟ 12345
c ⠉ 14	ý ⠯ 12346
o ⠕ 135	x ⠭ 1346
d ⠙ 145	ó ⠹ 1456

They were used not for their linguistic or semantic meaning but to generate distinguishable tactile cues. Our aim was to ensure that the evaluation remained centered on participants' ability to perceive and replicate tactile patterns, independent of any prior knowledge or association with Braille (see Figure 1(d)).

The patterns were presented sequentially, where each actuator was activated successively for 500 ms, followed by a randomized interstimulus interval ranging from 10 to 2500 ms for each pattern (ISI was randomized between trials but was constant within each trial).

Sequential stimulation was selected over simultaneous activation to minimize sensory interference and vibrotactile masking. Simultaneous activation of multiple actuators can lead to overlapping sensory inputs, reducing pattern recognition accuracy due to the difficulty in distinguishing between vibrations occurring simultaneously. In contrast, sequential stimulation allows for temporal separation of each vibration event, enabling clearer temporal differentiation. This facilitates more distinct processing of each vibration, increasing pattern recognition accuracy and reducing cognitive load [14].

The chosen ISI range of 10–2500 ms balances the temporal resolution of the somatosensory system with the constraints of tactile working memory. Temporal summation in the somatosensory system leads to the fusion of ISIs below 10 ms, particularly at higher vibration frequencies [44]. Conversely, ISIs exceeding 2500 ms challenge tactile working memory [45]. After the presentation of each pattern, there was a response interval where participants had 5000 ms to reproduce the patterns presented by pressing the corresponding keys on the keypad. A response time of 5000 ms was selected based on prior research findings, as this balances task difficulty and aligns with similar studies [14].

The stimulation was set at a constant frequency of 100 Hz and constant intensity of 9.6 g because this generates strong and distinct sensations that are easily perceptible while remaining comfortable for users [14].

As mentioned before, 100 Hz falls within the frequency range to which human observers are most sensitive [14, 26], largely due to the high responsiveness of the Pacinian corpuscles—mechanoreceptors specialized for detecting high-frequency vibrations.

The experiment included three independent variables: i) Interstimulus Interval (ISI): This factor consisted of 12 levels, ranging from 10 ms to 2500 ms. ii) Pattern Type: Two conditions were used: short patterns (2–3 actuators activated) and long patterns (4–5 actuators activated). iii) Block: The experiment was divided into two blocks, where each participant was exposed to the same set of patterns twice to assess potential learning effects over time. Block 2 involved the presentation of the same trials under identical conditions as in Block 1, allowing for within-subject comparisons of recognition accuracy over time. The blocks were distributed progressively throughout the experiment. The dependent variable was the pattern recognition accuracy, measured as the percentage of correctly identified vibrotactile patterns.

2.5 Familiarization session

Before the main experiment, participants received a briefing on the tactile stimulation they experienced.

Each actuator was then activated six times in quick succession, allowing participants to familiarize themselves with the sensations, patterns, and stimulus locations on their forearm. The participants then practiced reporting the vibrotactile patterns using a keypad. To ensure that they were sufficiently well-trained on the task, they took part in a preliminary block of 24 randomized trials with varying ISIs and pattern lengths to ensure that they could confidently participate in the main experiment.

2.6 General procedure

To minimize external distractions, the study was conducted in an anechoic chamber with white noise played through headphones during the experiment to eliminate any auditory cueing from the low sound produced by the actuators when they vibrate (see Figure 1(d)). The participants were seated in front of a laptop wearing the vibrotactile sleeve on their left forearm, which rested on a soft pad to prevent fatigue throughout the experiment. To prevent visual cues, a pad was placed between the participants' hands and eyes to block their view. The vibrotactile intensity was calibrated using a three-axis accelerometer (Brüel & Kjær Type 4520) to a frequency of 100 Hz and intensity of 9.6 g.

To ensure consistency and eliminate potential sources of bias, a calibration process was conducted individually for each participant prior to testing. The force value at the contact surface was 1.64 N, measured with a Force Sensitive Resistor (FSR03 series). The procedure consisted of two blocks in which tactile patterns were presented in a random order across a total of 192 trials. During the trials, the vibrotactile sleeve delivered precise stimuli to the participants' forearms, allowing them 5000 ms to respond after each presentation of a pattern. ISIs varied across a range of 10–2500 ms, including 10, 20, 50, 100, 200, 300, 400, 500, 700, 900, 1500, and 2500 ms, ensuring a comprehensive assessment of participant discrimination abilities by ISI.

However, ISI was constant for each trial. The sequences of ISIs and pattern lengths were presented in a random order. Each session lasted approximately 40 min.

3 Results

A three-way repeated-measures ANOVA, along with post-hoc tests, were conducted to examine the effects of Pattern (Short vs. Long), Block (Block 1 vs. Block 2), and ISI (12 levels: 10 to 2500 ms) on participants' accuracy in vibrotactile pattern recognition.

To confirm the assumptions for the three-way repeated-measures ANOVA, we conducted Shapiro-Wilk normality tests across different conditions. The results indicated that the accuracy data were normally distributed (Blocks ($p = 0.820$, $p = 0.262$), Patterns ($p = 0.843$, $p = 0.636$), and ISI levels ($p > 0.05$)).

The analysis revealed a significant main effect of Pattern ($F(1, 7) = 18.46$, $p = 0.004$, $\eta^2 = 0.067$), indicating that accuracy differed significantly between short and long patterns. Specifically, the participants' accuracy was higher for the short than long patterns. Additionally, there was a significant main effect of Block, ($F(1, 7) = 22.41$, $p = 0.002$, $\eta^2 = 0.042$), with participants performing significantly better in Block 2 than Block 1, indicative of learning improvement over time.

Our main question of interest concerned the effects of ISI. There was a significant main effect of ISI ($F(11, 77) = 3.69$, $p < 0.001$, $\eta^2 = 0.139$), highlighting that varying ISI significantly influenced accuracy. The participants' performance fluctuated depending on the timing between stimuli, with different ISI levels affecting recognition accuracy. Moreover, there was a significant two-way interaction between Pattern (short or long) and Block ($F(1, 7) = 7.72$, $p = 0.027$, $\eta^2 = 0.006$), suggesting that the effect of Pattern on accuracy was moderated by practice over Blocks. This interaction indicates that the difference in accuracy between the short and long patterns decreased over the two blocks, possibly reflecting changes in participants' familiarity with the task over time. However, there was no significant interaction between Pattern and ISI ($F(11, 77) = 1.164$, $p = 0.326$, $\eta^2 = 0.019$), indicating that the effect of Pattern on accuracy was constant across different ISI levels.

Similarly, the interaction between Block and ISI was not significant ($F(11, 77) = 0.953$, $p = 0.496$, $\eta^2 = 0.009$), suggesting that the effect of Block on accuracy did not vary across ISI conditions. Finally, the three-way interaction between Pattern, Block, and ISI was not significant ($F(11, 77) = 1.069$, $p = 0.397$, $\eta^2 = 0.008$), suggesting that the main effects of these factors did not depend on the other main effects.

3.1 Effects of pattern

The repeated-measures ANOVA revealed a significant main effect of pattern length on accuracy, demonstrating higher accuracy for short than for long patterns (see Figure 3). This suggests that the length of vibrotactile stimulation is important for pattern recognition, with shorter patterns being easier to identify.

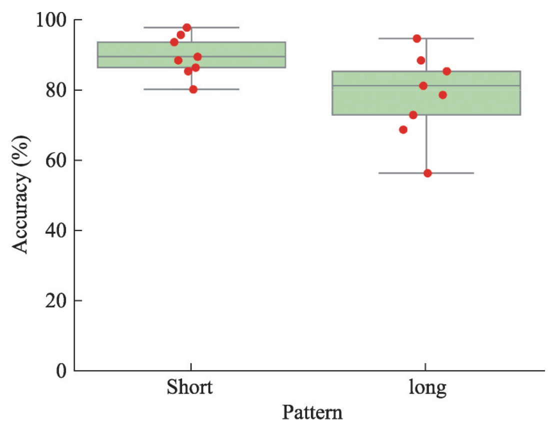


Figure 3 Box-whisker plot comparing accuracy (y-axis) between the two different Pattern lengths (x-axis). The graph shows the average accuracy in percentages on the upper side of the forearm for sequential presentation of actuators. The box length shows the interquartile range (IQR) (25% and 75% limits), and the horizontal bar inside the box shows the median value. The horizontal lines show the minimum and maximum values. The red dots show the accuracy values for individual participants.

These findings underscore the importance of considering pattern complexity in tasks involving vibrotactile stimuli, as the ability to accurately identify patterns is significantly influenced by stimulus length. A summary of the data distributions for both short and long vibrotactile patterns is presented in Table 3.

Table 3 Summary of accuracy distributions for short and long patterns

Metric	Short pattern	Long pattern
Mean accuracy	88.10%	79.45%
Median accuracy	88.96%	80.53%
Standard deviation	7.72	10.73
Range	79% to 98%	58% to 94%

3.2 Effect of blocks

A repeated-measures ANOVA revealed a significant main effect of Block on accuracy in vibrotactile pattern recognition ($F(1, 7) = 22.41$, $p = 0.002$, $\eta^2 = 0.042$).

In Block 1, the median accuracy was approximately 80.53%, indicating moderate accuracy as participants were introduced to the vibrotactile patterns for the first time. The interquartile range (IQR) for Block 1 ranged from 73.18% to 87.24%, reflecting some variability in participant performance.

In contrast, in Block 2, there was a notable improvement in accuracy, with a median of approximately 88.96%. The IQR for Block 2 ranged from 84.64% to 95.83%, reflecting greater consistency in participant accuracy. This substantial improvement in performance from Block 1 to Block 2 underscores the beneficial effects of practice and familiarity on the task, as participants became better at recognizing vibrotactile patterns over time across all ISIs. This suggests that the participants' ability to identify patterns increases with practice, improving both accuracy and consistency. Users may require training to maximize accuracy, particularly when interpreting complex and long patterns. Accuracy increased significantly from Block 1 to Block 2, suggesting that practice and repeated exposure enhance recognition accuracy. Notably, the blocks were not separated by scheduled breaks but represented repeated presentations of the same trials under identical conditions, progressively distributed throughout the experiment.

The results emphasize the importance of task training and increased familiarity for improving performance in vibrotactile pattern recognition tasks (see Figure 4). A summary of the data distributions for Blocks 1 and 2 is presented in Table 4.

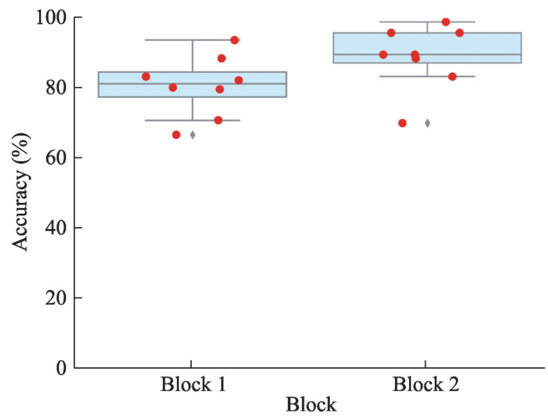


Figure 4 Box-whisker plot comparing accuracy (y-axis) between the two different blocks (x-axis). The graph shows the average accuracy in percentages on the upper side of the forearm for sequential presentation of actuators. The box length shows the interquartile range (IQR) (25% and 75% limits), and the horizontal bar inside the box shows the median value. The horizontal lines represent minimum and maximum values. The red dots show the accuracy for individual participants.

Table 4 Summary of accuracy distributions across blocks

Metric	Block 1	Block 2
Mean accuracy	79.45%	88.10%
Median accuracy	80.53%	88.96%
Standard deviation	9.55	7.30
Range	73.18% to 87.24%	84.64% to 95.83%

3.3 Effect of ISI

There was a significant main effect of ISI on accuracy ($F(11, 77) = 3.69$, $p < 0.001$, $\eta^2 = 0.139$), indicating that variations in the timing between stimuli significantly influenced participants' performance on the vibrotactile pattern recognition task.

These findings highlight the critical role of timing in tasks involving sensory processing, with certain ISI durations leading to higher accuracy. These results underscore the importance of selecting optimal intervals between individual stimuli for vibrotactile recognition. This ISI dependence demonstrates that the precise timing of stimulus presentation significantly affects pattern recognition in such contexts.

3.3.1 Accuracy as a function of ISI for short and long vibrotactile patterns

There was no interaction between ISI and pattern length, suggesting that the ISI effect is independent of pattern length. However, it is important to assess whether our results suggest that certain ISIs are better than others for sequential vibrotactile presentation. In the following, we describe what our post-hoc analyses suggest as the optimal ISI for both short and long vibrotactile patterns.

(i) Short patterns

For short patterns, accuracy was significantly higher at 300 ms than at shorter intervals (e.g., 10 ms; $t = -5.137$, $p = 0.027$), with performance peaking at 98% for the 300 ms ISI. Performance remained high between 300 and 500 ms, with no significant decreases in accuracy ($t = 0.634$, $p = 1.000$). This indicates that short patterns are best recognized within the 300 to 500 ms range of ISIs.

The post-hoc test between 200 and 300 ms showed no significant difference ($t = -0.781$, $p = 1.000$). Similarly, there was no significant difference between 100 and 300 ms ($t = -3.742$, $p = 0.121$), and the comparison between 50 and 300 ms also revealed no significant accuracy differences ($t = -5.137$, $p = 0.383$). The fact that 50, 100, 200, and 300 ms all showed very high accuracy—ranging from 94% to 98%—supports the idea that performance is good and stable within this range.

The post-hoc test comparison between 500 and 700 ms showed no significant difference in accuracy ($t = 1.843$, $p = 0.763$). This demonstrates that the performance at 700 ms, with 92% accuracy, was not significantly different from that at 500 ms, supporting the inclusion of 700 ms in the broader optimal range (Figure 5).

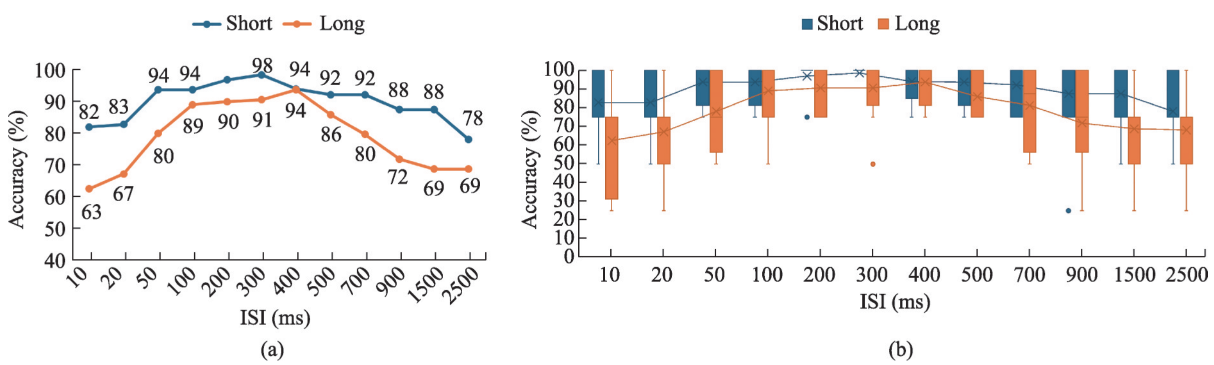


Figure 5 (a) The graph illustrates accuracy in recognizing short patterns (blue) and long patterns (orange) across a range of ISIs. Recognition accuracy is highest for both pattern types within a specific range of ISIs, reflecting optimal conditions for perception; (b) Box plots showing accuracy distribution for short and long patterns across ISIs, ranging from 10 to 2500 ms. Each box plot represents the median accuracy, interquartile range, and outliers for each ISI. Short patterns generally show higher accuracy compared to long patterns across most ISIs, with the highest accuracy occurring within a specific ISI range. The spread and distribution of data highlight the variability in participant performance.

The post-hoc comparisons confirm that there were no significant drops in accuracy between these intervals, indicating that the performance is comparable across these ISIs.

While the accuracy at an ISI of 300 ms was the highest (98%), the differences between 50, 100, 200, 500, and 700 ms were not sufficiently large to exclude them from the optimal range. The 50 to 700 ms range (accuracy range between 92% and 98%) can therefore be considered optimal for short patterns, with some indication that a 300 ms ISI may be the best ISI (98%), especially compared to higher ISIs, because the shorter the ISI, the faster the information transmission.

(ii) Long patterns

For long patterns, the accuracy peaked at 400 ms (94%), and performance was relatively constant within the 100 to 500 ms range. Specifically, accuracy steadily increased from 100 to 400 ms, peaking at 400 ms, with no difference between 100 and 300 ms ($t = -3.742$, $p = 0.121$), suggesting that the accuracy at 100 ms (89%) was not significantly lower than that at 300 ms (93%).

Similarly, there was no significant difference between 200 and 300 ms ($t = -0.781$, $p = 1.000$), further confirming stable accuracy within this range. At 500 ms, the accuracy began to decline (to 86%), but the difference between 400 and 500 ms was not statistically significant ($t = 0.664$, $p = 1.000$). Therefore, while 400 ms remained the most robust and clear optimal ISI for long patterns (accuracy 94%), the post-hoc analyses support that the 100–500 ms range may be the optimal ISI range, given the stable accuracy within this interval (accuracy range between 86% and 94%) (see Figure 5).

The interaction between ISI and pattern type ($F(11, 77) = 1.164$, $p = 0.326$) confirmed that the effect of ISI on accuracy was consistent for both short and long patterns. This suggests that the same ISI range—100 ms to 500 ms—may lead to the highest accuracy for both short and long patterns. This conclusion is reinforced by the post-hoc comparisons for both short and long patterns.

3.3.2 Average accuracy of vibrotactile pattern recognition across ISI

Figure 6 illustrates the average accuracy for short and long vibrotactile patterns combined across a range of ISIs. The graph provides a general overview of how accuracy is influenced by ISI without differentiating between short and long patterns, providing a broader perspective on performance trends when pattern length is not considered separately.

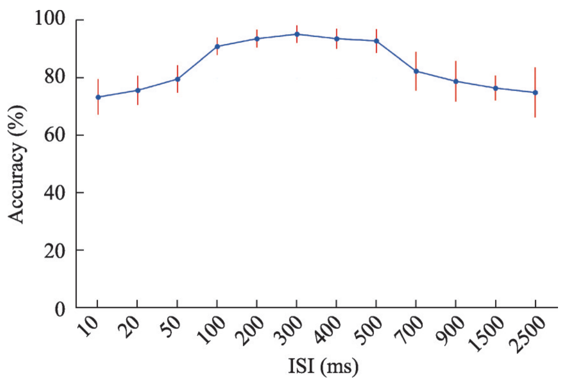


Figure 6 Average accuracy of vibrotactile pattern recognition across different ISIs for all patterns. The graph illustrates participant accuracy (%) in recognizing vibrotactile patterns at various ISIs ranging from 10 to 2500 ms. Accuracy increases from shorter ISIs, peaks between 100 and 500 ms, and declines at longer ISIs. The error bars represent variability in accuracy among participants, highlighting consistency at optimal ISI ranges and greater variation at very short and long ISIs.

At 10 ms, the average accuracy was approximately 73%, suggesting that participants struggled to recognize patterns due to the rapid presentation of stimuli (this may simply be too close to simultaneous presentation, which resulted in poor performance in our recent study [14]). As ISI increased to 50 and 100 ms, the accuracy improved steadily.

The post-hoc analysis revealed no significant difference between 10 and 20 ms ($t = -0.390$, $p = 1.000$), but accuracy showed a notable improvement at 100 ms. The optimal ISI range seemed to be between 300 and 500 ms, with accuracy peaking at 300 ms (95.32%). This peak was supported by post-hoc testing, which revealed a significant difference between 300 and 10 ms ($t = -5.137$, $p = 0.027$).

Accuracy was consistently high between 300 and 500 ms, with no significant decline observed within this range. The post-hoc comparison between 400 and 500 ms showed no significant difference ($t = 0.664$, $p = 1.000$), suggesting that this range could be optimal for pattern recognition. The post-hoc comparisons between 100 and 300 ms ($t = -3.742$, $p = 0.121$) and between 200 and 300 ms ($t = -0.781$, $p = 1.000$) revealed no significant differences. This indicates that the accuracies at 100 (91%) and 200 ms (93%) were not significantly lower than that at 300 ms (95.32%). Therefore, it seems natural to include 100 and 200 ms in the optimal range for vibrotactile pattern recognition.

Beyond 500 ms, accuracy begins to decline, as indicated by the downward slope in the graph. However, the post-hoc analyses revealed that the differences between 500 and 700 ms were not significant ($t = 2.510$, $p = 0.447$), and while further declines occurred at 900 ms ($t = 3.473$, $p = 0.162$) and 1500 ms ($t = 3.989$, $p = 0.092$), these comparisons did not reach statistical significance. However, the overall trend of decreasing accuracy with increasing ISI was clear. The error bars in the graph indicate a large variability in accuracy at both the shortest (10 ms, 20 ms) and longest ISIs (1500 ms, 2500 ms), suggesting that participants' recognition performance was less consistent at these extremes.

This variability likely reflects the difficulty of processing stimuli that are presented either too quickly or too slowly. The graph suggests that when short and long patterns are considered together, the optimal ISI range for vibrotactile pattern recognition is between 100 and 500 ms, where the accuracy remains both high and consistent (accuracy range between 91% and 95.32%). The performance declined beyond 500 ms, although the differences between certain ISIs were not always statistically significant.

The increased variability of both the shortest and longest ISIs highlights the importance of selecting ISI values outside this range to achieve reliable and accurate pattern recognition with sequential vibrotactile stimulation. We also highlight that shorter ISIs should, on average, be preferable because, – all being equal – they enable faster information transfer. Table 5 presents the accuracy rates and standard deviations across different ISIs.

Table 5 Accuracy and standard deviation of vibrotactile pattern recognition across different ISIs

ISI (ms)	Accuracy (%)	Standard deviation
10	73.44	17.60
20	75.78	14.34
50	79.69	13.67
100	91.07	9.45
200	93.75	8.84
300	95.32	8.68
400	93.75	10.02
500	92.97	11.78
700	82.47	19.18
900	78.92	20.29
1500	76.56	12.39
2500	73.44	24.78

4 Discussion

This study investigated the effect of ISIs on the recognition of sequential vibrotactile patterns delivered to the forearm. These findings demonstrate that ISI has a substantial influence on recognition accuracy for both short and long patterns. In addition to timing effects, a significant improvement in accuracy was observed with continued exposure to the task, indicating a clear learning effect. The participants became more accurate and consistent in identifying vibrotactile patterns over time. This finding is consistent with previous research on tactile perception and highlights the importance of training and familiarization in the effective use of vibrotactile feedback systems [14].

From an applied perspective, ISI selection should consider the specific demands of the intended application. Shorter ISIs may be more appropriate for contexts requiring rapid feedback, such as real-time alerts or interactive systems in gaming and virtual environments, where immediate and successive tactile cues can increase user engagement. In contrast, longer ISIs may be preferable for tasks involving more complex or information-rich feedback, such as navigational assistance or structured tactile communication, where additional processing time supports accurate interpretation.

Overall, the ability to adjust ISI based on task requirements supports more effective and context-sensitive tactile communications. These results underscore the importance of considering both temporal parameters and user experience in the design of vibrotactile systems across domains, such as assistive technology, wearable interfaces, and immersive environments.

4.1 The balancing act in selecting presentation times and interstimulus intervals

Achieving a balance among vibrotactile patterns, speed, accuracy, and timing is important for the design of various applications in which vibrotactile information is used to convey information to users. We have previously shown that sequential pattern presentation leads to higher accuracy than simultaneous presentation [14].

Our results suggest that ISI selection depends on specific applications and user tasks. For short patterns, applications requiring quick feedback and immediate responsiveness—such as virtual reality (VR) or casual notifications—can benefit from ISIs in the 50 to 700 ms range. In VR, immediate tactile feedback improves user immersion and responsiveness, enabling seamless interaction with virtual elements [47].

Similarly, in gaming, signaling through rapid vibrations can increase immersion and engagement [18]. In mobile apps, short vibrations can notify users of messages or reminders, keeping them engaged without constantly requiring them to check their screens [48]. Fitness tracking applications use brief tactile signals to notify users when they reach target heart rates or need to switch exercises, improving the quality of training and maintaining motivation. In wearable technology like smartwatches, short vibrations alert users about calls or calendar events, enhancing convenience and responsiveness.

Overall, short stimulation patterns foster quick interactions and enrich user experience through timely and relevant feedback. However, when ISIs become too short, they approach the sensory fusion threshold of the human somatosensory system. At this threshold, successive stimuli are perceived as simultaneous or continuous rather than distinct, leading to a loss of sequential pattern recognition. This results in feedback that feels parallel, thereby reducing its effectiveness in delivering precise and meaningful information.

To maintain clarity while benefiting from rapid responsiveness, ISIs should be carefully chosen and preferably calibrated.

For longer patterns, applications can be extended to areas requiring more detailed information or sustained feedback. In assistive technologies for the visually impaired, longer vibrotactile patterns can convey complex information, such as Braille characters or navigational cues, helping users better understand their environment. In gaming and VR, longer tactile feedback sequences may improve immersion and complement shorter feedback. By integrating longer vibrotactile patterns, applications may improve the user experience, especially when processing complex information over extended periods.

The identified ISI ranges can be used in devices such as tactile displays to improve the perception of sequential patterns, enabling smoother and more accurate Braille reading. Navigation aids can deliver distinct and reliable tactile cues for directional guidance, helping users navigate environments with greater confidence. Additionally, wearable assistive devices can provide timely and precise alerts, improve situational awareness, and reduce cognitive load. Tailoring tactile feedback to user needs should improve usability, accessibility, and independence. For the optimal design of vibrotactile devices, several factors must be considered, including vibration characteristics such as frequency, ISI, stimuli duration, intensity, and other parameters such as the location of stimuli and length of vibrotactile patterns. These elements, along with other considerations like user tasks and context, are important for selecting the most effective ISI for a given purpose.

Achieving the right balance between accuracy, speed of conveying information, and specific purpose of the application is essential for maximizing the effectiveness of vibrotactile feedback devices. Although our study primarily focused on the temporal effects of ISI, it is important to acknowledge the potential influence of spatial stimuli. In vibrotactile feedback systems, users may rely on both temporal and spatial cues to interpret patterns.

To minimize spatial confounds, we presented all patterns sequentially and maintained a consistent spatial layout across all ISI conditions. This design ensured that any variations in the recognition accuracy were primarily due to timing differences rather than spatial arrangement. Our findings showed a significant main effect of ISI ($p < 0.001$), with systematic variations in accuracy across different ISI values.

This demonstrates that timing was the primary determinant of pattern recognition. Additionally, no significant interaction was found between ISI and pattern type ($p = 0.326$), indicating that ISI effects were consistent for both short and long patterns. Nevertheless, future studies should explore the interplay between spatial and temporal stimuli to provide a more comprehensive understanding of vibrotactile perception.

We hope that the current results will provide guidelines for the timing of stimulation of wearable tactile devices for accessible information delivery. By establishing key parameters for accurate tactile pattern recognition, our research provides a design framework for the use of these devices for individuals dependent on alternative communication methods.

4.2 Limitations and future directions

Finally, we note some limitations. First, while the sample size of this study was relatively small ($N = 8$), the within-subjects design mitigated inter-individual variability, improving statistical power and reliability. Repeated measures allowed for direct comparisons within participants, reduced error variance, and enabled the detection of systematic ISI effects. Note that small sample sizes are common in preliminary studies exploring novel aspects of vibrotactile devices. Therefore, in future research, we will expand the participant pool to validate these findings across more diverse populations and examine individual differences in tactile sensitivity and learning effects.

In this study, the selected intensity level provided strong tactile feedback, ensuring consistent and easily perceivable sensations across all participants. By fixing these parameters, we were able to isolate the effects of ISI on pattern recognition accuracy, avoiding additional variability that could arise from changes in frequency or intensity, thereby allowing a focused examination of temporal processing in vibrotactile perception.

Nevertheless, it is important to recognize that frequency and intensity may interact with ISI in ways that could influence recognition performance. These potential interactions highlight opportunities for future research. Specifically, future studies should systematically vary the frequency and intensity to investigate how they interact with ISI and affect pattern recognition accuracy. This could provide a more comprehensive understanding of vibrotactile perception.

Although the present study demonstrates that ISI significantly influences vibrotactile pattern recognition accuracy, the generalizability of these findings to real-world applications requires cautious interpretation. Importantly, data were collected under tightly controlled laboratory conditions—specifically, within an anechoic chamber, eliminating external sensory interference and restricting body movement. These idealized conditions likely contributed to the high recognition accuracies observed and may not fully capture the variability in performance encountered in dynamic, real-world environments.

In practical settings, several contextual factors may affect tactile perception, including ambient noise, cognitive load from concurrent tasks, and attentional competition from other sensory modalities, such as vision or hearing. Additionally, body movements—such as walking, reaching, or interacting with objects—may alter the contact quality, attentional focus, or proprioceptive context in which vibrotactile cues are received, potentially affecting recognition accuracy. For example, in multitasking scenarios—such as navigating with tactile guidance while walking and attending to visual cues—performance may be affected by divided attention- and motion-related interference. Similarly, when multiple vibrotactile feedback sources are active on different body sites, the spatial and temporal overlaps of stimuli may lead to perceptual interference, further complicating recognition.

Furthermore, individual differences in tactile sensitivity and cognitive processing may influence the perception and interpretation of vibrotactile cues. Variability in factors such as skin mechanoreceptor density, age, or prior experience with haptic devices could result in different thresholds for effective ISI ranges, thereby affecting system performance across users.

These real-world and individual-level complexities may alter the balance between temporal and spatial processing of tactile information, indicating that ISI parameters may need to be adapted based on environmental, physiological, and user-specific conditions.

These findings provide robust evidence for the critical role of ISI in vibrotactile pattern recognition. The consistency and clarity of these results provide a solid foundation for understanding the temporal dynamics of tactile perception. Therefore, this study holds particular value for the early-stage development of haptic systems, where reliable parameterization is essential prior to real-world deployment. Future research should investigate how ISI interacts with spatial configuration, user movement, attentional load, individual sensory differences, and contextual distractions in more ecologically-valid settings. Such work will be essential for translating these foundational insights into practical design principles and enabling the development of robust, effective, and user-adaptive vibrotactile communication systems.

5 Conclusions

This study demonstrated that ISI significantly influences vibrotactile pattern recognition accuracy. Shorter ISIs enable faster feedback and are suitable for time-sensitive applications, while longer ISIs improve accuracy for more complex patterns. Fine-tuning ISI ranges by pattern length revealed that short patterns were best recognized between 50 and 700 ms and long patterns between 100 and 500 ms. Performance also improved with practice, highlighting the importance of training in tactile perception.

These findings offer a foundation for designing more effective vibrotactile systems across applications, including assistive technologies, sensory substitution devices, virtual and augmented reality, and wearable interfaces. Future research should investigate how ISI interacts with spatial layout, user movement, and contextual distractions in real-world settings.

Declaration of competing interest

We declare that we have no conflict of interest.

Credit authorship contributions statement

Nashmin Yeganeh: methodology, formal analysis, investigation, data curation, software, writing—original draft preparation. **Ivan Makarov:** contributed with methodology. **Runar Unnthorsson:** methodology, writing review, and editing and supervision. **Árni Kristjánsson:** methodology, writing, and editing and co-supervision. All authors have read and agreed to the published version of the manuscript.

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