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Using Vibrotactile Patterns for Conveying Orchestral Conducting Gestures to Blind and Visually Impaired Musicians

Pietro Buccellato, Leonardo Severi, Matteo Sacchetto, Emilie Ophelie Vieux, Cristina Rottondi
Dep. of Electronics and Telecommunications, Politecnico di Torino, Turin, Italy
pietro.buccellato@polito.it, leonardo.severi@polito.it,
matteo.sacchetto@polito.it, s322154@studenti.polito.it, cristina.rottondi@polito.it

***Abstract*—Orchestral conducting relies predominantly on visual gestures to convey timing, dynamics, articulation, cueing, and expressive intent, creating a significant accessibility barrier for Blind and Visually Impaired (BVI) musicians. This work investigates whether structured vibrotactile patterns, commonly referred to as tactons, can provide a non-visual channel for representing selected orchestral conducting cues, focusing on the design and perceptual evaluation of tactile encodings for conducting-related information. To this aim, a wearable sleeve equipped with vibrating motors in a simple layout was leveraged to implement established vibrotactile display principles such as spatially distributed stimulation, temporal patterning, and coarse intensity modulation. Preliminary experiments involving both sighted and BVI participants were conducted to assess stimulus localization, intensity discrimination, and the perception of combined vibrotactile features. The outcomes of these experiments informed the design of a set of tactons representing conducting intentions such as beat, entrance, cut-off, pointing, crescendo, and diminuendo. The resulting tacton set was subsequently evaluated with BVI participants through recognition tasks designed to assess its interpretability and effectiveness. Results demonstrate that the BVI cohort was able to reliably identify six tactons after limited training, achieving an average recognition accuracy of 77%, with individual accuracies ranging from approximately 60% to nearly 100%.**

***Index Terms*—Haptics, Conducting Gestures, BVI Musicians, Accessibility.**

I. Introduction

In orchestral performance, the conductor serves as the focal point of a complex, non-verbal communication channel, where gestures encode a simultaneous stream of information regarding tempo, dynamics, articulation, and phrasing. This visual language is essential for synchronizing the ensemble and shaping the interpretative nuances of the performance. However, the inherent reliance on visual signaling creates a significant accessibility barrier for Blind and Visually Impaired (BVI) musicians, often precluding their full participation in traditional orchestral settings.

Tactile and haptic feedback systems have been widely adopted as assistive technologies for BVI users across a broad range of applications, including navigation, obstacle avoidance, virtual and augmented reality interaction, and access to digital or artistic content [1]–[6]. These studies demonstrate the effectiveness of touch as an alternative communication channel for conveying spatial, temporal, and contextual information non-visually. In the musical domain, wearable haptic devices have also attracted increasing interest, being employed to support rhythm perception, instrument learning, real-time performance interaction, and musical accessibility for Deaf and Hard-of-Hearing (DHH) users [7]–[11]. Existing systems, however, mainly focus on enhancing the perception of musical content itself, for example tempo, pitch, melody, or emotional cues, rather than conveying the multidimensional expressive information communicated by an orchestra conductor. The few works addressing orchestral conducting assistance for BVI musicians often reduce conducting gestures to simplified temporal cues or rely on instrumented batons and constrained sensing setups that may interfere with the conductor's natural movements [12], [13]. The usage of wearable haptic systems aimed at conveying the expressive and multidimensional nature of orchestral conducting gestures through structured tactile patterns remains thus largely unexplored.

In this work, we address this research gap by investigating the design of vibrotactile patterns, commonly referred to as *tactons* [14], specifically tailored to communicate orchestral conducting cues through a wearable interface. Building upon the requirements and preferences previously identified through interviews with sighted and BVI musicians [15], our objective is to investigate how different tactile dimensions can encode conducting-related information while remaining distinguishable and interpretable for users; to this end, we conducted a first set of experiments involving both sighted and BVI participants to assess the perception and discrimination of intensity modulation and spatiotemporal activation patterns, using a wearable vibrotactile sleeve integrating multiple actuators. The outcomes of these preliminary experiments were then used to design a set of tactons representing orchestral conducting cues. Finally, the resulting tactons were evaluated with BVI participants to assess their recognizability. Results demonstrate an average recognition accuracy of 77%, while individual accuracies ranged from approximately 60% to nearly 100%.

The remainder of the manuscript is organized as follows: Section II briefly surveys related work, whereas Section III provides background notions on musical conducting and haptic feedback. Section IV presents the preliminary experiments on stimulus localization and intensity discrimination conducted with sighted and BVI participants. Section V describes the design of the proposed tactons and reports their evaluation with BVI participants. Limitations and future research directions are discussed in Section VI, while conclusions are drawn in the final section.

II. Related Work

The convergence of haptic interfaces, accessibility, and musical interaction constitutes a rapidly evolving research landscape. This section categorizes relevant literature on psychophysical foundations of haptic perception, vibrotactile feedback in musical contexts, specific systems for conducting gesture support, and arm-wearable haptic devices.

A. Haptic Perception

Willms et al. investigated vibrotactile two-point discrimination on the forearm, testing both longitudinal placements along the arm and transverse placements around the wrist. Their results show that discrimination improves as actuator spacing increases, with the most reliable performance observed for transverse placements at approximately 9 cm, where the actuators are positioned nearly opposite each other around the forearm [16]. These results are particularly relevant for the design of wearable vibrotactile arrays, as they highlight the need for sufficient spacing between actuators to prevent neighboring stimulation sites from being perceived as overlapping or diffuse cues.

The findings of this study informed the design of the arm-wearable device used in our test campaign. However, the final actuator spacing was also constrained by the anatomical dimensions of the forearm and by wearability requirements. The longitudinal actuators were positioned 8 cm away from the central motor, whereas the transverse actuators were placed at a distance of 6 cm. This layout was selected as a compromise between perceptual separability and compact wearable design.

B. Haptic Feedback in Musical Contexts

In the musical domain, haptic wearables have been explored to enhance the perception of sound for hearing-impaired individuals [9] or to provide temporal guidance. Vibrotactile metronomes are effective for basic beat alignment [8], [17]; however, they primarily address rhythmic synchronization and do not capture the expressive, multidimensional nature of conducting gestures.

Beyond time-keeping, haptics has shown significant promise in establishing non-verbal communication channels for music education. Lu *et al.* investigated this domain with the *Project TapTap*: their recent longitudinal study demonstrated that haptic signals can effectively mediate communication between sighted teachers and BVI students over extended periods [18]. Crucially, they found that users developed shared meanings and “haptic metaphors” over time, confirming that BVI musicians can internalize and retain complex abstract mappings.

C. Conducting Systems and BVI Support

The specific challenge of assisting BVI musicians in following the directions of a conductor has been addressed by a limited number of studies. The DIAMI system represented a pioneering effort, capturing gestures via an instrumented baton and transmitting them to a tactile bracelet [13]. More recently, *Human Instruments* developed the *Haptic Baton*, i.e., a wireless system that captures the kinematics of the conductor’s hand (specifically speed, angle, attack, and sway) and transmits these parameters via an in-ear monitoring system directly to vibration receivers worn by the musicians [19], [20].

However, a critical perspective was introduced by Baker *et al.* [12], who critiqued this “sighted perspective” of attempting a faithful transfer of 2D arm movements to haptic signals. Their findings suggest that technologies should focus on the *meaning* the conductor intends to convey rather than the physical motion itself.

It is worth noting that auditory strategies have also been implemented in inclusive ensembles to bypass visual barriers. A prominent example is the *BIO - Blind Inclusive Orchestra*, which employs a centralized audio communication system where the conductor uses a microphone to transmit verbal instructions, counting, and breathing cues directly to the musicians’ in-ear monitors via a wireless radio system [21]. While this approach effectively coordinates mixed ensembles of sighted and BVI performers, it inherently increases the load on the auditory channel, which is the musician’s primary tool for monitoring performance and ensemble acoustics.

D. Wearable Vibrotactile Sleeves for Spatial Information Encoding

Wearable vibrotactile sleeves have emerged as a promising platform for conveying spatial and symbolic information through distributed tactile stimulation. Several studies have demonstrated that the forearm provides a practical compromise between tactile sensitivity, available surface area, wearability, and compatibility with daily activities, making it suitable for multi-actuator haptic interfaces [22], [23].

Prabhu *et al.* introduced *VibroSleeve*, a forearm-worn interface comprising a 4×4 array of vibration motors embedded in a compression sleeve for arm-motion guidance [22]. Their work demonstrated that users could reliably localize vibrotactile stimulation, discriminate intensity levels, and perceive directional cues generated through apparent motion patterns. Importantly, the study highlighted the relevance of actuator placement, spatial mappings aligned with the natural coordinate system of the arm, and preliminary psychophysical characterization as prerequisites for effective information encoding. These findings, together with the outcomes of interviews to sighted and BVI musicians conducted in [15], motivated our decision to employ the forearm as the primary stimulation site and to perform dedicated localization and intensity-discrimination experiments before designing higher-level tactile cues.

More recently, Rossi *et al.* presented a modular vibrotactile sleeve designed to investigate tactile perception across the entire arm, from wrist to shoulder [24]. Their results showed high localization accuracy for spatially distributed vibrotactile stimuli and demonstrated the feasibility of generating directional cues through cross-shaped actuator configurations and apparent haptic motion paradigms. The modularity of their design and the use of psychophysical evaluation to characterize perceptual capabilities influenced our methodological approach. In particular, their findings support the use of spatially organized actuator layouts and reinforce the importance of assessing localization performance before introducing more complex tactile patterns.

Wearable sleeves have also been explored in musical contexts. Yeganeh *et al.* developed a forearm-mounted vibrotactile sleeve employing three voice-coil actuators to enhance music perception for cochlear implant users [23]. Their work demonstrated that users could learn associations between vibrotactile patterns and musical content, highlighting the potential of tactile feedback as an alternative communication channel for conveying temporally structured information. Although their application domain differs from orchestral conducting, the study provides evidence that vibrotactile stimulation can effectively support the interpretation of music-related cues.

From a hardware perspective, Dementyev *et al.* proposed the Vibrotactile Haptics Platform (VHP), a flexible wearable haptics platform supporting multiple independently controllable actuators and wireless operation [25]. Rather than targeting a specific application, VHP was conceived as a research platform enabling rapid prototyping and psychophysical evaluation of wearable haptic interfaces. This philosophy closely aligns with the role of the sleeve employed in our work, which was conceived primarily as an experimental platform for studying tactile mappings rather than as a finalized assistive device.

The present work builds upon these contributions while targeting a different application domain. Similar to previous studies, we employ a forearm-worn vibrotactile interface featuring spatially distributed actuators. However, unlike VibroSleeve and the modular sleeve of Rossi *et al.*, which primarily investigated localization and directional guidance, our objective is to design tactile representations of orchestral conducting cues. Furthermore, while several previous systems employed dense actuator arrays, voice-coil actuators, or Linear Resonant Actuators (LRAs), our prototype adopts a simpler cross-shaped arrangement of five Eccentric Rotating Mass (ERM) motors. This choice was primarily motivated by considerations of implementation simplicity, robustness, cost-effectiveness, and ease of replication during the exploratory design phase. Although ERM actuators exhibit higher actuation latencies than alternative technologies, they provide a practical solution for rapidly prototyping and evaluating tactile interaction paradigms[1]. Consequently, the device presented in this work should be regarded as an experimental platform for the design and assessment of conducting-related tactons rather than as a finalized assistive system. Future performance-oriented implementations will require a dedicated hardware design process in which actuator technology, latency, weight, power consumption, battery autonomy, wearability, acoustic noise, and integration with musical performance constraints are jointly optimized.

[1]Latency measurements conducted on our prototype revealed mean actuation delays ranging from 166.4–226.7 ms at low intensity, 95.6–107.0 ms at medium intensity, and 68.0–77.3 ms at maximum intensity. These values are characteristic of Pulse Width Modulation (PWM)-driven ERM motors, whose rise time is strongly affected by rotor inertia and the torque available at different drive levels.

III. Background and Design Requirements

To ground the design of the proposed haptic interface, this section outlines the fundamental principles of orchestral conducting, defines the theoretical framework for haptic feedback, and summarizes the user-centered requirements derived from our preliminary investigation [15].

A. Notions on Musical Conducting

Conducting is a sophisticated multimodal discipline where visual gestures encode a complex layering of information. Theoretically, this gestural vocabulary is often organized into four main categories: *Articulation*, *Dynamics*, *Attack*, and *Cut-off*, where movement shapes combine with hand configurations to produce recognizable meanings [26].

A fundamental characteristic of this practice is the *functional asymmetry* of the hands. The dominant hand (typically the right one) is primarily responsible for temporal precision, marking the *ictus* (i.e., the instant the beat occurs) and defining the tempo pattern. Conversely, the non-dominant hand is dedicated to expressive communication, signaling dynamics, articulation, and cueing specific sections. This separation poses a specific challenge for haptic translation, as a system must be capable of transmitting discrete rhythmic pulses (time) and continuous expressive variations (dynamics) simultaneously, potentially targeting different body locations to mirror this physical asymmetry.

Crucially, the communication of a conductor extends beyond hand motions. Significant non-verbal cues, such as breathing, facial expressions, and eye contact, play a vital role in signaling entrances and shaping the ensemble's emotional response [27].

Furthermore, conducting styles are highly individual and context-dependent. While standard patterns exist, the amplitude and trajectory of gestures vary significantly between conductors and between settings (e.g., exaggerated instructional gestures in rehearsals vs. subtle, compact cues in performance) [28], [29]. This variability suggests that a robust gesture recognition system should not rely on a fixed model, but should instead allow calibration or tuning to the specific conductor's stylistic signature.

B. Haptic Feedback Fundamentals

Designing vibrotactile feedback for musical interaction requires understanding the psychophysical dimensions of touch. Following the definition by Brewster and Brown [14], we adopt the concept of *tactons* (tactile icons), which are structured, abstract messages that encode information through the manipulation of vibration parameters. The primary parameters available for encoding conducting cues are:

- **Pace and Duration:** The temporal pattern of the vibration. The skin is highly sensitive to temporal changes, making this the most robust parameter for conveying beat and tempo.
- **Spatial Location:** The site of stimulation on the body. As established in psychophysical literature, the ability to discriminate two points of stimulation varies across the body; a separation of at least 6 to 9 cm, depending on the body location, is typically required to avoid "masking" effects [16], [30].
- **Intensity:** The perceived strength of the vibration. While useful for mapping dynamics (e.g., *piano*, *forte*, etc.), human resolution for intensity differences is lower than for spatial or temporal changes, requiring coarse quantization (e.g., Light/Medium/Strong levels) rather than continuous mapping [14].

C. User-Centered Design Requirements

In our previous work [15], we conducted in-depth interviews with 10 BVI and 16 sighted musicians to gather design requirements for introducing haptic feedback in orchestral settings. The qualitative analysis of the responses highlighted that acceptance of such technology relies heavily on minimizing physical and cognitive intrusion. The derived design guidelines can be summarized as follows:

- **Non-intrusiveness and Comfort:** The device must not hinder the musician's movements or instrument handling. The study revealed that placement preferences are highly instrument-dependent (e.g., cellists identified legs as a suitable location to keep arms free, whereas flute players showed mixed preferences for arm or wrist wearables), necessitating a flexible or modular hardware design that can be adapted to different body parts.
- **Perceptual Clarity:** To avoid sensory overload, musicians emphasized that vibrations should be "perceptible yet subtle." Crucially, they advised against continuous stimulation, which was described as distracting or numbing over time. This insight suggests that cues should be encoded as discrete, structured patterns rather than direct, continuous stimuli.
- **Wireless Autonomy:** To enable realistic usage on stage, the system must operate wirelessly and guarantee sufficient battery life for typical rehearsal durations.
- **Independence:** For BVI users, the ability to wear, activate, and calibrate the device without sighted assistance emerged as a mandatory requirement for usability and autonomy.

IV. Preliminary Assessment of Vibrotactile Cue Perception

A. Experimental Setup

Our custom-made vibrotactile sleeve consists of a wearable device composed of a control unit and a wearable sleeve (shown in Fig. 1).

TABLE I: Demographic characteristics of the 14 sighted (S) study participants.

Participant	Age	Music Backgr.	Participant	Age	Music Backgr.
S1	63	No	S8	27	Yes
S2	28	No	S9	82	No
S3	17	No	S10	84	No
S4	28	Yes	S11	58	No
S5	39	Yes	S12	23	No
S6	28	Yes	S13	23	Yes
S7	26	No	S14	23	No

The electronic module is built around a custom PCB integrating an Arduino Nano ESP32 (microcontroller), selected for its native support of Bluetooth Low Energy (BLE), compact form factor, and ease of development. The microcontroller manages the wireless reception of commands and drives the actuation stage.

The haptic feedback is generated by five low-profile ERM DC motors (3V, 12000 rpm). Each motor is independently driven by the microcontroller through discrete driver circuits as output stages. Power can be supplied either via USB or by a lightweight Li-ion battery providing complete wireless autonomy.

The wearable sleeve is realized in 2 mm-thick neoprene, following its effective application in spatialized haptic systems [16], [31], where it is employed to limit vibration propagation and ensure discrete cue perception.

The motors are arranged in a cross-shaped constellation (see Fig. 2), creating a somatic reference frame comprising one central motor (M3), which acts as a focal point, and four directional motors: Elbow (M1), Wrist (M5), Inner Arm (M4), and Outer Arm (M2). The spacing between motors is defined relative to the central focal point (M3): the longitudinal actuators (M1, M5) are positioned at a distance of 8 cm from the center, while the transverse actuators (M2, M4) are placed 6 cm far from the center.

B. Experimental Assessment

A structured user study was conducted to assess the efficacy of haptic conveyance via our wearable device, involving 14 sighted and 7 BVI participants (demographics are detailed in Tables I and II). All the subjects provided informed consent to the participation to the test session and processing of the associated data.

During the test, participants wore headphones and were asked to listen to music of their choice to mask the auditory noise produced by the motors, which could otherwise have eased the identification of their vibration level.

1) Experimental Protocol: The protocol was designed to evaluate the following three tasks of progressive perceptual and cognitive complexity, totaling 150 trials per participant (detailed in Table III):

1) **Localization Recognition:** Detection of single versus simultaneous activation within predefined motor pairs,

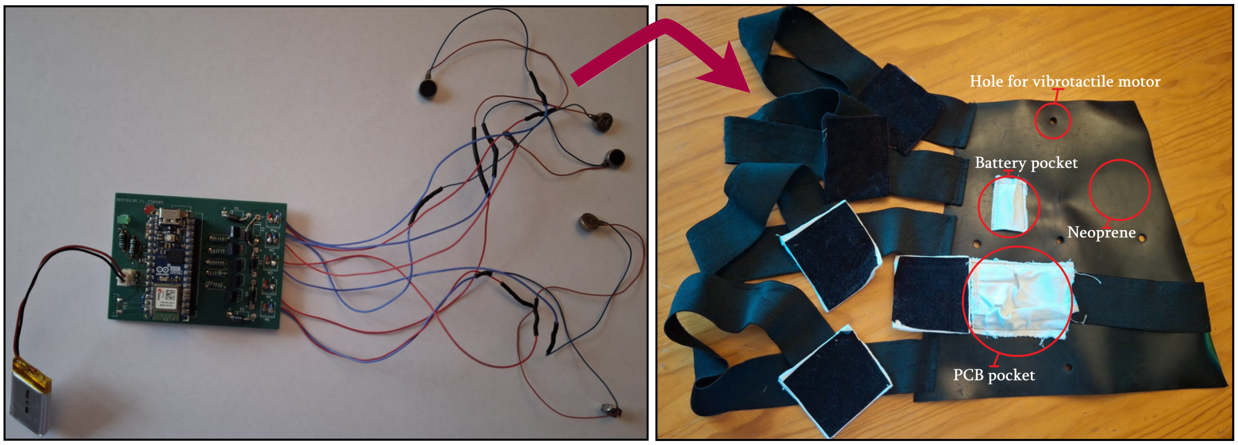


Fig. 1: Complete wearable prototype, showing (left) the custom PCB with Arduino Nano ESP32, vibrotactile motor and battery, and (right) the neoprene sleeve with dedicated pockets for the electronics.

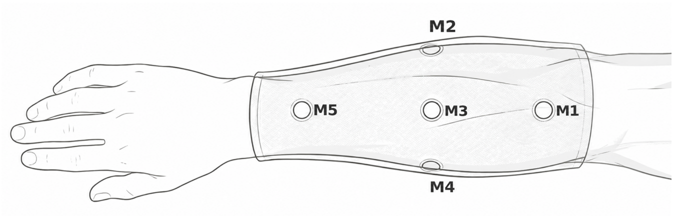


Fig. 2: Schematic representation of the wearable sleeve, showing the neoprene layer and the cross-shaped motor constellation.

TABLE II: Demographic characteristics of the 7 BVI (B) study participants.

Participant	Age	Visual Impairment Type	Duration Since Onset (years)	Music Background
B1	29	Moderate impairment	10	Yes (Guitar)
B2	30	Severe impairment	Congenital	Yes (Harmonium)
B3	36	Severe impairment	Congenital	No
B4	37	Severe impairment	Congenital	No
B5	27	Severe impairment	Congenital	No
B6	70	Blind	2	No
B7	64	Blind	49	No

and identification of the activated motor's location in single-activation trials, to evaluate spatial resolution.

2) **Intensity Differentiation:** Discrimination between *light*, *medium*, and *strong* vibration levels of a pre-selected vibrating motor.
3) **Complex-Signal Interpretation:** Recognition of complex patterns involving multiple motors, combining spatial and intensity variations.

Trials were organized into blocks of 10 or 15, as shown in Table III. Each block was preceded by a familiarization phase in which every stimulus to be identified in that block was presented at least three times. All participants completed tasks in the same order. Within each task, the order in which the stimuli were presented was randomized once and then kept fixed across all participants to ensure comparability. Per-subject results are reported in Fig. 3 and are commented on in detail in the following paragraphs.

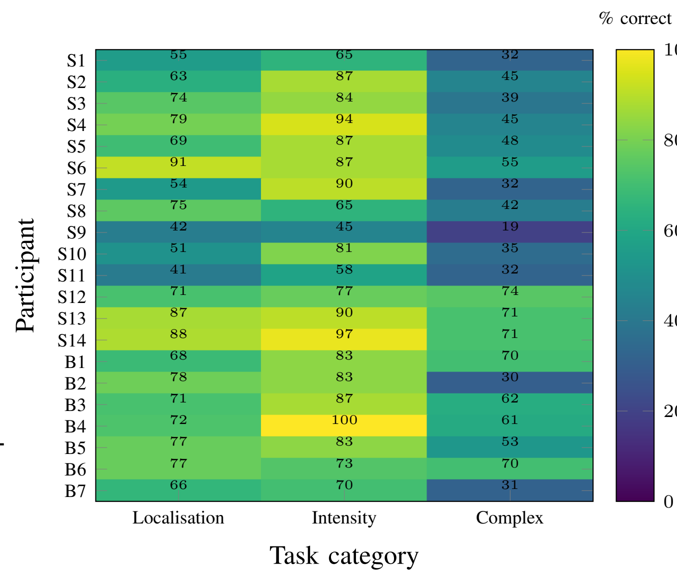


Fig. 3: Category-level accuracy (% correct) per participant.

2) Localization Test: The initial phase of the user study evaluated spatial resolution capabilities, specifically examining the participants' ability to discriminate the active actuators. Stimuli were applied to one of two possible sites, or simultaneously to both, across three anatomical axes:

- M1 (Elbow) / M3 (Center).
- M2 (Outer Arm) / M3 (Center),
- M5 (Wrist) / M3 (Center),

To assess the impact of signal strength on spatial perception, each pair was tested at three intensity levels (*light*, *medium*, *strong*) with ten repetitions per condition, resulting in a total of 90 trials per participant.

As reported in Table IV, both sighted and BVI participants exhibited a clear intensity-dependent improvement in localization accuracy. For all motor pairs, performance increased

TABLE III: List of 150 conditions used in user testing.

ID	Test Category	Condition Description
1. Localization Detection Test (1–90)		
1–10	M5 (Wrist) / M3 (Center) - *light*	M3 (Center) / M5 (Wrist) / Both with *light* intensity (10 signals)
11–20	M5 (Wrist) / M3 (Center) - *medium*	M3 (Center) / M5 (Wrist) / Both with *medium* intensity (10 signals)
21–30	M5 (Wrist) / M3 (Center) - *strong*	M3 (Center) / M5 (Wrist) / Both with *strong* intensity (10 signals)
31–40	M2 (Outer Arm / M3 (Center) - *light*	M3 (Center) / M2 (Outer Arm) / Both with *light* intensity (10 signals)
41–50	M2 (Outer Arm) / M3 (Center) - *medium*	M3 (Center) / M2 (Outer Arm) / Both with *medium* intensity (10 signals)
51–60	M2 (Outer Arm) / M3 (Center) - *strong*	M3 (Center) / M2 (Outer Arm) / Both with *strong* intensity (10 signals)
61–70	M1 (Elbow) / M3 (Center) - *light*	M1 (Elbow) / M3 (Center) / Both with *light* intensity (10 signals)
71–80	M1 (Elbow) / M3 (Center) - *medium*	M1 (Elbow) / M3 (Center) / Both with *medium* intensity (10 signals)
81–90	M1 (Elbow) / M3 (Center) - *strong*	M1 (Elbow) / M3 (Center) / Both with *strong* intensity (10 signals)
2. Intensity Detection Test (91–120)		
91–100	M3 (Center) - *light*, *medium*, *strong*	M3 (Center) with *light* / *medium* / *strong* intensities (10 signals)
101–110	M5 (Wrist) - *light*, *medium*, *strong*	M5 (Wrist) with *light* / *medium* / *strong* intensities (10 signals)
111–120	M1 (Elbow) - *light*, *medium*, *strong*	M1 (Elbow) with *light* / *medium* / *strong* intensities (10 signals)
3. Complex Signal Test (121–150)		
121–135	M5 (Wrist) / M3 (Center) - All intensities	Movement / Both / One-side, under *light*/*medium*/*strong* intensities (15 signals)
136–150	M2 (Outer Arm) / M3 (Center) - All intensities	Movement / Both / One-side, under *light*/*medium*/*strong* intensities (15 signals)

consistently from light to medium and strong vibration levels, confirming that vibration intensity plays a key role in enhancing the perceptual salience of spatial cues.

Among sighted participants, localization accuracy ranged from approximately 58–66% for light stimuli and increased to about 74–75% for strong stimuli across all motor pairs. A similar trend was observed in the BVI cohort, but with a steeper improvement as intensity increased. While performance at light intensity was comparable to that of sighted participants (53.6–60.0%), medium and strong stimuli yielded slightly higher accuracies, reaching values between 78.6–85.7%. The highest performance was observed for the M1–M3 and M5–M3 pairs at strong intensity, where BVI participants achieved average accuracies close to 85%.

Interestingly, localization performance in the BVI cohort was generally equal to or higher than that of sighted participants at medium and strong intensities. Although the limited sample size prevents drawing strong conclusions regarding population-level differences, these results suggest that the spatial mappings adopted in this study remain interpretable and effective for BVI participants.

TABLE IV: Localization accuracy (percent values) for different motor pairs across vibration intensity levels. Ranges indicate inter-participant variability.

	Motor Pair	Light (%)	Medium (%)	Strong (%)
Sighted	M1 (Elbow) – M3 (Center)	60.7 [10–100]	64.3 [30–100]	75.0 [20–100]
	M2 (Outer Arm) – M3 (Center)	57.9 [20–90]	65.7 [20–100]	74.3 [30–100]
	M5 (Wrist) – M3 (Center)	66.4 [30–100]	70.7 [20–100]	75.0 [30–100]
BVI	M1 (Elbow) – M3 (Center)	53.62 [30–100]	78.57 [60–100]	85.71 [60–100]
	M2 (Outer Arm) – M3 (Center)	60.0 [40–70]	71.43 [40–90]	82.86 [70–100]
	M5 (Wrist) – M3 (Center)	57.14 [30–90]	78.57 [40–100]	85.71 [60–100]

As shown in Fig. 3, considerable inter-individual variability was observed in both cohorts. Some participants achieved consistently high localization accuracies across all conditions, whereas others exhibited substantially lower performance. This variability is also reflected in the broad min–max ranges reported in Table IV, and may be attributable to differences in tactile sensitivity, attentional strategies, prior experience with haptic stimuli, or adaptation during the experiment. Notably, the variability observed within each cohort appears larger than the average differences between cohorts, further suggesting that individual perceptual characteristics may play a more important role than visual status alone.

3) Intensity Discrimination: The second test evaluated participants' ability to distinguish between three vibration amplitudes (*light*, *medium*, *strong*) across three anatomical sites: M1 (Elbow), M3 (Center), and M5 (Wrist). Each location was tested with ten repetitions, for a total of 30 trials.

The average accuracies obtained for this task are reported in the upper part of Table V. Participants in both cohorts demonstrated reliable discrimination of vibration intensity, with average accuracies ranging between 78.6% and 85.0% for sighted participants and between 80.0% and 88.6% for BVI participants (Table V). Performance was generally highest at the wrist, while the center location yielded the lowest accuracies in both groups, but still well above chance level. Again, the BVI cohort achieved performance comparable to, and in some cases slightly higher than, that of the sighted participants, which supports the suitability of intensity-based cues for the target user group.

It is worth noting that the comparatively lower accuracy observed at the center location may be related to mechanical crosstalk or "parasitic propagation" within the neoprene sleeve. At lower drive levels, mechanical waves may propagate

TABLE V: Average accuracy results for the intensity discrimination test and the complex-signal test. Ranges indicate inter-participant variability.

	Condition	Accuracy (%)
Sighted	*Intensity Discrimination Test*	
	M1 (Elbow)	85.0 [60–100]
	M3 (Center)	78.6 [30–100]
	M5 (Wrist)	81.4 [40–100]
	Complex-Signal Test	
	M2 (Outer Arm) – M3 (Center)	45.2 [6.7–80]
	M5 (Wrist) – M3 (Center)	49.5 [20–80]
BVI	*Intensity Discrimination Test*	
	M1 (Elbow)	80.0 [50–100]
	M3 (Center)	80.0 [50–100]
	M5 (Wrist)	88.57 [70–100]
	Complex-Signal Test	
	M2 – M3	50.98 [20–66.7]
	M5 – M3	56.86 [26.7–80]

through the material, creating a diffuse or "phantom" sensation that makes the vibration source feel ambiguous or spatially shifted. At higher intensities, the localized energy generated by the actuator is likely sufficient to perceptually mask these conducted vibrations, thereby improving discrimination accuracy.

As illustrated in Fig. 3, similarly to the first set of tests, substantial inter-individual variability was observed. While several participants achieved near-perfect performance across all intensity conditions, others exhibited noticeably lower accuracies, suggesting that individual perceptual factors may influence performance. Qualitative feedback collected during the experiments further indicated that the selected intensity levels were not equally distinguishable for all users. In particular, the *light* level was occasionally perceived as too weak, whereas the *medium* and *strong* levels were sometimes reported as insufficiently separated. These observations suggest that the current three-level quantization could benefit from further tuning, either by increasing the perceptual distance between adjacent intensity levels or through user-specific calibration procedures. Such refinements may reduce inter-participant variability and further improve the reliability of intensity-based tactile cues.

4) Complex-Signal Tests: The third experimental phase assessed participants' ability to interpret compound haptic patterns involving spatial changes, intensity variations, or both. Two location pairs were tested:

- M2 (Outer Arm) / M3 (Center),
- M5 (Wrist) / M3 (Center).

Each motor pair was tested under three intensity levels, with fifteen repetitions per condition (30 trials in total). Stimuli included single-actuator activations, simultaneous dual-site activations, and sequential "movement-like" cues.

TABLE VI: List of common conduction gestures.

Gesture	Description
Beat	Vertical motion indicating the pulse/ictus
Accelerando	Quick, energetic gesture indicating tempo increase
Rallentando	Soft, relaxed gesture indicating tempo decrease
Crescendo	Expanding gesture indicating volume increase
Diminuendo	Contracting gesture indicating volume decrease
Sustain pitch	Adjust to compensate falling pitch
Sharp entrance	Firm gesture indicating begin of musical phrase
Gentle entrance	Delicate gesture indicating begin of the piece/phrase
Sharp cut-off	Firm stop motion indicating end of a piece/phrase
Gentle cut-off	Delicate stop motion indicating end of a piece/phrase
Legato	Smooth, flowing motions for connected notes
Staccato	Crisp, quick motions for detached notes
Pointing	Directed impulse aiming at specific performers

The resulting average accuracies are summarized in the lower part of Table V. Recognition of complex multi-actuator patterns proved more challenging than the localization and intensity-discrimination tasks for both cohorts, with average accuracies ranging between 45.2–49.5% for sighted participants and 51.0–56.9% for BVI participants. It should be noted that, unlike the previous tests, in this phase participants were not only required to identify the spatial configuration of the stimulation, but also to correctly discriminate its intensity level. Consequently, each response involved selecting among a set of 15 possible combinations, resulting from the interaction between 5 stimulus categories and 3 intensity levels. A response was considered correct only when both the stimulus type and the associated intensity were correctly identified. The moderate accuracies observed in this test should therefore be interpreted in light of the substantially higher task complexity compared to the localization and intensity-discrimination experiments.

As for the previous two sets of tests, BVI participants achieved slightly higher average accuracies than sighted participants for both motor pairs and, as shown in Fig. 3, performance varied substantially across individuals. While several participants achieved accuracies exceeding 70%, others struggled with more ambiguous patterns, particularly when multiple spatial locations and intensity levels were combined. This variability is consistent with the broad min–max ranges reported in Table V.

V. Tactons Design and Assessment

A. Tactons Design Principles

In collaboration with an experienced choir and orchestra conductor (male, aged 76, with more than 40 years of conducting experience in classical repertoires), we identified a subset of commonly used conducting gestures (see Table VI) representing different communicative functions, including articulation and phrasing cues, tempo regulation, and dynamics control. From this set, we selected a representative subset of gestures aimed at covering the four major conducting categories identified in [26], together with tempo-related cues:

- **Attack:** entrance;
- **Cut-off:** cut-off;
- **Articulation:** directed pointing;
- **Dynamics:** *crescendo* and *diminuendo*;
- **Tempo:** beat.

For each gesture, we designed a corresponding tacton by mapping salient characteristics of the conductor's movement onto combinations of spatial activation, temporal structure, and vibration intensity.

The first design principle was *spatial correspondence*. Whenever possible, salient spatial characteristics of the conducting gesture were preserved in the tactile domain. For example, upward or expanding gestures, such as a *crescendo*, were represented by a progression of activations from the wrist toward the elbow, whereas downward or contracting gestures, such as a *diminuendo*, were encoded through the opposite trajectory. Similarly, lateral conducting cues engaged the corresponding side actuators, e.g., during the *beat* pattern. This mapping strategy was intended not only to establish an intuitive tactile metaphor between conductor motion and somatic perception, but also to preserve coherence with the conductor's physical gestures, allowing partially sighted musicians to potentially integrate residual visual information with tactile feedback.

The second principle concerned the *temporal texture* of the tactons. Rhythmic and discrete gestures, such as beat indications, were encoded through pulsed activation patterns separated by pauses, whereas continuous expressive gestures such as *crescendo* and *diminuendo* were rendered through smooth spatiotemporal progressions. This distinction was intended to preserve, in the tactile modality, the contrast between punctual and continuous conducting events.

Finally, vibration *intensity* was employed as an additional expressive dimension: increasing dynamics (*crescendo*) were mapped onto progressively stronger vibrations, whereas decreasing dynamics (*diminuendo*) employed descending intensity profiles. This strategy allowed the tactile rendering to preserve not only directional information but also the expressive evolution associated with the conductor's gesture.

An important constraint guiding the final tacton vocabulary was the adoption of a *prefix-free* design principle [32]. Specifically, each tacton was designed to begin with a unique activation sequence or motor configuration, preventing ambiguity during the early stages of pattern perception. This ensured that the onset of one tacton could not be confused with the beginning of another, thereby improving recognizability during real-time interaction.

B. Tactons Implementation

The specific structure and parametrization of the tactons, reported in Table VII, was directly informed by the outcomes of the preliminary perceptual experiments reported in Section IV.

First, the spatial organization of the tactons was constrained by the localization experiments, which showed that participants achieved the highest accuracies when vibrations were spatially isolated and delivered at medium or strong intensities, whereas simultaneous multi-motor activations and low-intensity stimuli often generated ambiguity and perceptual masking effects. For this reason, the final tacton vocabulary intentionally avoids excessively articulated spatial trajectories and limits the number of simultaneously active actuators whenever possible.

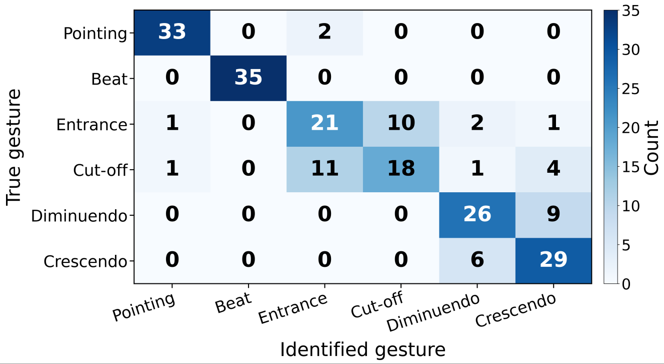
This consideration particularly influenced the design of the *entrance* and *cut-off* tactons, which were designed as compact two-step sequences: the *cut-off* consists of a brief distributed activation followed by a short central impulse, while the *entrance* tacton was designed as its temporal inverse. Moreover, the duration of these tactons was intentionally kept short (0.6 s) to support immediate reactions during performance, since entrance and cut-off cues require rapid musician responses and minimal temporal latency. Indeed, durations should ideally remain on the same order of magnitude as human visual reaction latency [33] to avoid introducing systematic delays that could disadvantage BVI musicians relative to sighted performers.

Similarly, the *crescendo* and *diminuendo* tactons were constructed as short spatiotemporal progressions with fixed 0.2 s segments. This design was motivated by two complementary findings from the preliminary tests. On one hand, the intensity discrimination experiment demonstrated that users could reliably distinguish coarse vibration levels (light, medium, strong), supporting the use of intensity as an expressive dimension. On the other hand, the complex-pattern tests showed that long or highly overlapping sequences substantially degraded recognition accuracy, especially when multiple intensity levels and spatial locations were combined simultaneously. Setting each phase to 0.2 s reduced temporal overlap between consecutive ERM activations while maintaining the perceptual impression of continuous directional movement. However, differently from entrance and cut-off cues, dynamic gestures such as *crescendo* and *diminuendo* are inherently less time-critical and may therefore tolerate longer tacton durations in practical deployments (1.4 s in our design).

The *beat* and *pointing* tactons instead remained intentionally simple and highly localized. This choice was motivated by the observation that punctual, spatially isolated, high-intensity stimuli yielded the highest recognition rates in both localization and complex-pattern conditions. In particular, the *beat* tacton employs discrete strong pulses separated by pauses, leveraging the tactile system's high sensitivity to temporal discontinuities and minimizing ambiguity between consecutive ictus events. For the purpose of the present validation, the *beat* was implemented as a four-pulse sequence corresponding to a standard 4/4 meter at 150 BPM.

To provide a visual example of the tacton representation reported numerically in Table VII, Fig. 5 illustrates the actuation timelines of the *diminuendo* tacton.

However, it is important to note that, in real orchestral



Part.	B1	B2	B3	B4	B5	B6	B7
Acc. (%)	66.7	63.3	97.7	90.0	93.3	60.0	70.0

Fig. 4: Confusion matrix for gesture identification (top) and per-participant gesture identification accuracy (bottom).

applications, the structure of the tactons should remain adaptable to the expressive and temporal characteristics of the musical piece. For instance, beat-related tactons should reflect the actual meter and tempo of the composition, whereas the duration and intensity evolution of dynamic cues should vary according to the conductor's expressive intentions. Similarly, articulation cues such as entrances or cut-offs may require different temporal profiles depending on whether the intended gesture is sharp and abrupt or smooth and lyrical.

C. *Tactons Distinguishability Assessment*

To evaluate whether users could learn to distinguish these patterns, we conducted a recognition test with the 7 BVI participants. After a brief familiarization phase, following the same procedure as in Sec. IV-B1 (each tacton presented at least three times), each participant experienced 30 tacton presentations (5 repetitions of each of the 6 gesture types listed in Table VII). As before, the order in which stimuli were presented was randomized once and kept fixed across all participants.

The average recognition accuracy of approximately 77% reported in Fig. 4, substantially above the 17% chance level associated with six response alternatives, demonstrates that most of the proposed tactile patterns could be recognized successfully. These results indicate that users can learn to associate specific vibrotactile patterns with conducting intentions after a relatively brief familiarization phase, supporting the feasibility of employing tactons as a non-visual communication channel for selected conducting cues.

The confusion matrix shows that *beat* and *pointing* were the most easily distinguishable tactons. However, *entrance* and *cut-off* were frequently confused, likely because they use the same motor configurations in reverse order. Future refinements should therefore introduce an additional distinguishing feature, such as a different onset location, pulse count, or pause, and evaluate the revised pair through dedicated discrimination tests with BVI users. Nevertheless, the overall performance confirms that the combination of spatial location, intensity variation, and temporal structure provides a sufficiently expressive vocabulary to communicate multiple conducting-related concepts. As shown at the bottom of Fig. 4, individual recognition accuracies ranged from approximately 60% to nearly 100%, revealing a non-negligible degree of inter-participant variability. While several participants achieved near-perfect recognition after limited training, others exhibited more moderate performance levels, which suggests that practical deployments may benefit from personalized calibration procedures, adaptive training strategies, or user-specific refinements of the tactile vocabulary to accommodate individual perceptual characteristics.

VI. Limitations and Future Work

While the results demonstrate the feasibility of conveying selected orchestral conducting cues through vibrotactile tactons, several limitations must be acknowledged.

A. *Ecological Validity and User Involvement*

The study was conducted under controlled laboratory conditions and therefore does not fully capture the complexity of real-world musical performance: all haptic patterns were presented in isolation and without musical context. In real performance situations, musicians must simultaneously process auditory information, execute precise motor actions, and interpret conducting cues. This increased cognitive load may negatively affect recognition performance compared to the controlled experimental setting. Consequently, recognition performance measured in the present experiments may not directly translate to realistic performance conditions. Evaluating the proposed tactons during actual musical activities involving BVI musicians remains an essential next step.

Moreover, the vocabulary used in this study was intentionally small, comprising only six distinct patterns, which simplified the recognition task. Expanding this approach to a richer and more complete conducting vocabulary would likely increase ambiguity and confusion rates, particularly in the absence of additional contextual cues.

Training effects also warrant consideration. The brief familiarization phase provided limited opportunity for participants to develop stable associations between vibrotactile patterns and their intended meanings. Prior longitudinal studies, such as that by Lu *et al.* [18], demonstrate that extended exposure and practice significantly improve performance as users form robust "haptic metaphors."

A further important challenge concerns perceptual masking. During instrument playing, vibrations naturally generated by the instrument may mechanically propagate to the performer's body and potentially interfere with vibrotactile feedback. The extent to which instrument-generated vibrations affect cue detectability, perceived comfort, or attentional demands remains unknown. Future studies should therefore examine the interaction between wearable haptic feedback and instrument-specific vibration patterns, and investigate adaptive placement and calibration procedures to minimize masking effects.

TABLE VII: Transposed gesture-to-tacton mapping including gesture descriptions and vibrotactile step sequences. (M = Motor, I = Intensity [L = light, M = medium, S = strong], D = Duration). Durations are expressed in seconds. For step sequences corresponding to pauses inbetween vibrations, the absence of vibrating motors is indicated with "–".

Gesture	Description	S1 (M/I/D)	S2 (M/I/D)	S3 (M/I/D)	S4 (M/I/D)	S5 (M/I/D)	S6 (M/I/D)	S7 (M/I/D)	S8 (M/I/D)
Entrance	Hands still → upward → downward	3/S/0.2	{1,2,4,5}/M/0.4						
Cut-off	Arms open → close to torso	{1,2,4,5}/M/0.4	3/S/0.2						
Beat	Hand down → inward → outward → up	5/S/0.2	–/–/0.2	4/S/0.2	–/–/0.2	2/S/0.2	–/–/0.2	1/S/0.2	–/–/0.2
Pointing	Hand pointing toward a performer	3/S/0.1	–/–/0.2	3/S/0.1					
Crescendo	Hand down → middle height → up	5/L/0.2	{3,5}/{L,M}/0.2	{3,5}/{M,L}/0.2	3/S/0.2	{1,3}/{L,M}/0.2	{1,3}/{M,L}/0.2	1/S/0.2	
Diminuendo	Hand up → middle height → down	1/S/0.2	{1,3}/{M,L}/0.2	{1,3}/{L,M}/0.2	3/S/0.2	{3,5}/{M,L}/0.2	{3,5}/{L,M}/0.2	5/L/0.2	

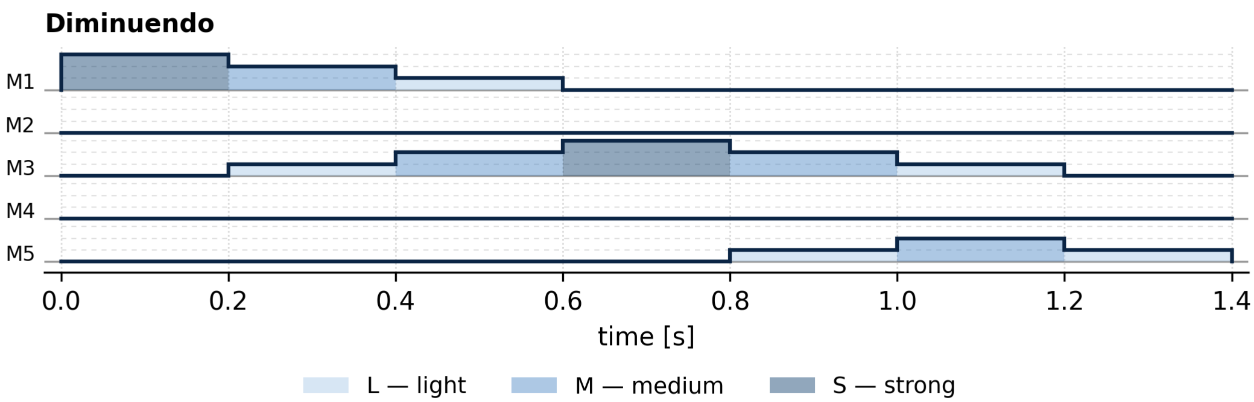


Fig. 5: Visual representation of the diminuendo tacton. The five horizontal rows correspond to motors M1–M5, while the horizontal axis represents time. The shaded blocks indicate each motor's activation interval and the corresponding vibration intensity.

More generally, the present study does not evaluate how factors such as divided attention, tactile gating, cognitive workload, and perception-to-action delays may affect tacton recognition during active musical performance. Understanding how these factors interact with vibrotactile communication in realistic ensemble settings remains an important research challenge.

Finally, the participant cohort involved in our tests is relatively limited in size and diversity. The present work should therefore be regarded as an intermediate step toward the development of accessible haptic communication systems for BVI musicians. Future studies should adopt a participatory co-design methodology involving a broader range of users, including amateur and professional BVI musicians, orchestral performers, and singers. Longitudinal evaluations would further enable the assessment of learning effects, long-term usability, user acceptance, and the evolution of user preferences over time.

B. Wearable Interface Design and Placement

The wearable sleeve employed in this study was conceived primarily as an experimental platform for investigating tactile mappings rather than as a finalized assistive device. For this reason, the hardware was designed to support rapid prototyping and controlled experimentation rather than deployment in professional musical environments. Factors such as actuator technology, power consumption, battery autonomy, vibration noise, weight, comfort, robustness, and integration with musical performance constraints were intentionally considered outside the scope of the present work. Future research should investigate alternative actuator technologies, including LRAs and voice-coil actuators, as well as more sophisticated rendering techniques based on haptic illusions [34] such as apparent motion, sensory saltation, and funneling.

In addition, the current evaluation focuses exclusively on forearm placement. Although this location was selected based on prior interviews and practical considerations, the influence of anatomical placement on tacton perception remains largely unexplored. Future work should systematically compare alternative body locations, including arm and leg placements, to determine whether different anatomical regions require specific tactile mappings or support common perceptual strategies. Such investigations could also inform personalized placement strategies tailored to individual users and instruments.

Future studies should also evaluate distributed mappings in which beat-related and dynamics-related cues are delivered to different body sites, potentially mirroring the functional asymmetry of the conductor's hands and reducing perceptual interference when temporal and expressive information must be conveyed concurrently.

C. Toward a Real-Time Conducting Assistance System

Finally, the present work does not evaluate a complete end-to-end conducting communication system. In a practical deployment, the overall response time would depend not only on tacton perception but also on conductor gesture acquisition, gesture recognition and interpretation, wireless communication, tactile cue generation, actuator response, and musician reaction time. Determining whether the cumulative latency introduced by these stages is compatible with the temporal constraints of ensemble performance requires a dedicated system-level investigation.

A key direction for future work is therefore the development of a real-time pipeline capable of automatically translating conducting gestures into haptic feedback. While the present study relied on predefined and manually triggered gesture–tacton mappings, a deployable system will require the integration of motion-tracking technologies to capture conducting gestures in real time and map them to vibrotactile patterns by means of automated algorithms, e.g., through supervised machine-learning models for gesture recognition. Such a framework would enable the continuous generation of conducting-related tactile cues while preserving the expressive and temporal characteristics of the conductor's gestures.

VII. Conclusions

This work investigated the feasibility of conveying orchestral conducting information through vibrotactile feedback, with the aim of improving the accessibility of ensemble performance for Blind and Visually Impaired (BVI) musicians. Building upon requirements previously identified through interviews with sighted and BVI musicians, we first conducted a set of experiments involving both user groups to assess the perception of fundamental tactile dimensions, including stimulus localization, intensity discrimination, and the interpretation of combined spatial–intensity cues. The outcomes of these experiments informed the design of a tactile vocabulary composed of vibrotactile patterns (*tactons*) representing selected conducting intentions. The resulting tactons set was subsequently evaluated with BVI participants, who achieved an average recognition accuracy of approximately 77% after a brief familiarization phase, with individual accuracies ranging from about 60% to nearly 100%. These results indicate that meaningful associations between vibrotactile patterns and conducting-related intentions can be established after limited training.

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