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BEYOND BRASS PERFORMANCE: EXPLORING THE INTEGRATION
OF NON-INTRUSIVE HUMAN-COMPUTER INTERFACES IN
TROMBONE

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ABSTRACT

Beyond Brass Performance: Exploring the Integration of Non-Intrusive Human-Computer Interfaces (NIHCI) in Trombone addresses the challenge of integrating attachable tangible user interfaces (TUIs) into brass performance without hindering conventional playability. While advances in instrument augmentation have expanded the expressive boundaries of acoustic instruments, many existing implementations remain bespoke or artist-specific, limiting their generalizability across performers and contexts. This dissertation asks how attachable interfaces can bridge embodied trombone performance practice with digital and cyber-physical environments.

In its broader scope, this study establishes a performer-centered methodology for the design and evaluation of NIHCI. Non-intrusiveness is conceptualized not as a purely mechanical constraint, but as a multidimensional design condition encompassing physical ergonomics, cognitive load, perceptual thresholds, and affective response. From this perspective, technological augmentation is understood not merely as a tool for experimentation, but as a means of extending the instrument itself in an ecologically valid way. The study therefore proposes a structured NIHCI framework to guide performers, interface designers, and composers in the creation of TUIs that extend musical performance beyond acoustic sound while remaining integrated with established trombone practice.

The methodology comprises a sequential, three-phase explanatory mixed-methods design guided by ISO 9241-210 principles for human-centered design. Synthesizing these findings, the dissertation introduces a three-layer NIHCI design framework comprising (1) a Perceived Intrusiveness Index (PII) defining empirically bounded upper limits, (2) an affective interaction model addressing experiential qualities of interaction, including tactile feel, size, and visual integration, and (3) physical-cognitive viability constraints in relation to placement, control density, and mass thresholds. For the evaluation stage, the study developed an NIHCI-based prototype to evaluate the proposed framework, yielding consistently low intrusiveness ratings.

The dissertation concludes with *At Your Fingertips*, a multimodal composition that operationalizes the NIHCI framework within a co-creative cyber-physical environment. Functioning as an artistic evaluation, the work demonstrates how NIHCI telemetry supports gesture classification, corpus-based audio interaction, and score-level control. Together, the framework, prototype

evaluation, and artistic validation provide transferable guidelines for designing non-intrusive interfaces that invite performers and composers to reimagine brass performance between acoustic places and cyber-physical spaces.

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TABLE OF CONTENTS

ACKNOWLEDGMENTS	v
LIST OF TABLES	x
LIST OF FIGURES	xii
CHAPTER	
I INTRODUCTION	1
Need for Study	4
Research Questions	11
Definitions	13
II BACKGROUND	17
Historical Perspectives on Western Brass Emergence	17
Beyond Traditional Practices	20
HCI and Music Technology	22
Intrusiveness in the HCI Interface Design	29
Brass Instruments in the Electronic Era	45
III METHODOLOGY	71
UCD Methodology Overview	74
Phase One: Online Survey	81
Phase Two: In-Person Trials	84
Phase Three: Evaluation	104

IV	ANALYSIS AND RESULTS	111
	Phase One: Survey Results, Analysis, and PII Model	111
	Phase Two: Trial Results, Analysis, the Affective Model, and JND Thresholds	156
V	EVALUATION	216
	Phase Three: Evaluating the Trombone NIHCI Prototype	216
	Evaluating the JND Thresholds	224
	At Your Fingertips: Artistic Validation	228
VI	CONCLUSIONS: A FRAMEWORK DESIGN	246
	PII as the Upper Boundary of NIHCI Framework	247
	Affective Evaluation as Perceptual Mediation	249
	Physical-Cognitive Viability and Scaling Limits	251
	Addressing the Research Questions	254
VII	LIMITATIONS	259
VIII	FUTURE WORK	262
	BIBLIOGRAPHY	268
	APPENDICES	
A	PHASE ONE ONLINE SURVEY	281
B	FEEDBACK QUESTIONNAIRE FOR PHASE TWO	296
C	STUDY MATERIALS FOR PHASE TWO	300
D	PHASE THREE QUESTIONNAIRE	331
E	PHASE THREE MUSIC MATERIALS	336
F	COMPLEMENTARY FIGURES AND TABLES	347

G	STUDY CONSENT FORMS	379
H	SUPPORT LETTERS FROM ITA AND ATB	388
I	AT YOUR FINGERTIPS SCORE	392

LIST OF TABLES

1	Input Device Categories	87
2	Size Categories	87
3	Feedback Mechanisms	87
4	Phase 2.2 Steps Summary	100
5	Comparison of the median score given by participants with the PII model output.	155
6	Mechanical Specifications of Evaluated Tactile Switches	161
7	Device Dimensions, Volume, and Median Score	172
8	Participant Board Placement	202
9	Participant Battery Placement	202
10	Non-Intrusiveness Bucket (Scores 0–3). NaN values apply when there is insufficient data (≤ 1 item).	204
11	Most Frequently Selected Input Device (ID) per Category	205
12	Iteration 5M: Selected Single-Device Configuration (ordered by Mean)	206
13	Iteration 6M: Selected Two-Device Configurations (ordered by Mean, then n)	206
14	Iteration 7M: Selected Three-Device Configurations (ordered by Mean, then n)	206
15	Iteration 8M: Selected Four-Device Configurations (ordered by Mean, then n)	207

16	Progressive Device Combinations and Cognitive Load Across Iterations 5M–8M	207
17	Final Ideal Configurations (F10): Device Selection, Placement, and Mean Intrusiveness	210
F.1	Activation levels of core experiential themes for the clip-on tuner (S_k values).	361
F.2	IDs with the Best Tactile Feel	367
F.3	IDs with the Most Appropriate Size	368
F.4	IDs with the Most Visually Appealing	369
F.5	IDs with the Best Ease of Use Scores	370
F.6	IDs with the Best Overall Scores	371
F.7	All Board and Batteries used in Phase Two	372
F.8	All Tact Switches (TS) used in Phase Two	372
F.9	All Joysticks (JS) used in Phase Two	375
F.10	All Continuous Controls used in Phase Two	375
F.11	All Force-Sensitive Resistors (FSRs) used in Phase Two	376

LIST OF FIGURES

1	Gordon Mumma demonstrating the Hornpipe (1967). Source: last.fm.	47
2	The Mehta Trumpet with gluiph controller (Kartadinata, 2003, p. 182).	53
3	Examples of augmented trumpets. Source: Thibodeau and Wanderley (2013, p. 14).	54
4	Preliminary MIGSI design rendering showing integrated battery and force-sensing resistors. Source: Reid et al. (2016, p. 420)	55
5	Assembled tenor trombone. Source: Cambridge Dictionary.	56
6	Main trombone spare bandwidth highlighted on the bell section.	57
7	Tenor trombone left-hand contact points.	57
8	F-attachment trombone held by both hands.	58
9	Left-hand contact points on a bass trombone.	58
10	Trombone-propelled electronics with Kartadinata Gluion (photo provided by Kartadinata, July 8, 2024).	60
11	Axel Dörner performing with augmented trumpet using Gluion (photo by Ricardo Arbiza, Satellit, Berlin, April 21, 2024).	61
12	Slide with position sensor (Lemouton et al., 2006, p. 305)	62
13	The uSlide transmitter. (Farwell, 2006, p. 359).	63
14	The eMouth assembled in the trombone (Farwell, 2006, p. 360).	64
15	The eMute in use (Farwell, 2006, p. 362).	64

16	Feedback Trombone (FBT) performed by Jenny Beck (Snyder et al., 2018, p. 379)	65
17	Mubone: Joy-Con controller and orientation sensor on the fine-tuning slide (West and Leung, 2022, p. 9)	66
18	Components and assembly of the Slide-Mounted Trombone Interface (Buzzarté, Harvestworks project).	67
19	Smute: 3D-printed plunger mute with integrated smartphone interface.	69
20	Interdependence of human-centred design activities. Extracted from ISO 9241-210:2010(E) (International Organization for Standardization (ISO), 2010, p. 11).	73
21	Multimodal Interaction Between Human and Computer. Extracted from Bongers (2000, p. 45).	75
22	Usability problems found per number of users studied (Source: Nielsen Norman Group). Extracted from Lowdermilk (2013, p. 80).	79
23	Research Audio Lab, Steinhardt, 6th Floor: Room setup showing input device table, trombone, music stand, instructional tablet, stand with a white board for grip picture, and evaluator computer. Wide-angle view.	86
24	Input devices, board, and battery sheets arranged on the table in front of the participant for Phase 2.1, for ease of access.	89
25	ESP32C3 (Seed Studio) size reference.	94
26	Right: 180 mAh LiPo battery; left: 150 mAh LiPo battery.	95
27	F-attachment trombone with rule tape marking the three grip posts and reference lines at 0°, 90°, 180°, and 270° (white dotted line denotes 0° reference).	96
28	Incremental weight pouch mounted on the back of the F-attachment trombone, shown from front and reverse angles.	103

29	Left: F-attachment trombone total weight. Right: scale indicating the weight of each custom increment, equivalent to $\sim 1\%$ of the instrument's total weight (expressed in grams). This custom incremental belongs to the F-attachment trombone.	104
30	NIHCI-based first prototype.	106
31	Music Technology Background of Participants (Q12–Q16). Top left: Formal training in music technology (Q12). Top right: Self-reported comfort with music-related technology (Q13). Bottom left: DAW usage (Q14) and experience coding for music (Q15). Bottom right: Programming languages reported by the four coding participants (Q16).	116
32	Thematic Analysis of Integration of Technology into Music Practice (Q17). Left: Frequency of technology categories mentioned in open-ended responses. Right: Participant-level adoption summary derived from open-ended responses.	117
33	Thematic Analysis of Q20 - Wired vs. Wireless Microphone Preferences Left: Full distribution, all coded responses. Middle: Core subset, interpretable responses only. Right: Strict binary subset, wired vs. wireless only.	118
34	Thematic rationale for technology interest (Q23). Top left: Reasons cited by Q22=Yes group (multi-label). Top right: Reasons cited by Q22=No group (multi-label). Bottom left: Barrier mentions by group (stacked count). Bottom right: Barrier mentions with 95% CI by group.	120
35	Thematic analysis from responses on the most comfortable use of integrated technologies (Q24). Frequencies of reported comfort by theme (e.g., pedals, microphones, software).	121
36	Challenges Using Technology in Performance. Thematic Analysis(Q25). Top: Outcome Distribution. Bottom: Thematic Breakdown (Multi-hit Coding)	122

37	Smart Device and Operating System Usage (Q26-Q27-Q28). Left: Smart devices used most often (Q26), showing near-universal smartphone adoption. Center: Smartphone operating systems (Q27), with a near flat distribution for iOS and Android. Right: Computer operating systems (Q28), with Windows and macOS most commonly used.	124
38	Bluetooth Familiarity, Browser Use, and Network Awareness (Q30-Q32). Left: distribution of responses regarding participants' familiarity with Bluetooth connectivity. Middle: most frequently used web browsers among participants (top 8 + Other). Right: participants' ability to locate their device's network IP address. Note: Percentages reflect valid responses (no-response cases excluded).	125
39	Willingness to Attach Temporarily an Electronic Device and Perceived Placement Constraints (Q36-Q37) Top Left: Distribution of willingness to temporarily attach a device to the trombone. Top Right: Areas of the instrument identified as unsuitable for attachment. Bottom Left: Reported reasons for placement restrictions. Bottom Right: Co-occurrence heatmap showing relationships between restricted areas and justification types.	127
40	Willingness to Attach a Permanent Device(Q39-Q40) Top Left: distribution of willingness to permanently modify the instrument. Top Right: unsuitable areas for permanent attachment. Bottom Left: primary reasons for avoiding certain areas. Bottom Right: co-occurrence heatmap of placement restrictions.	128
41	Preferred Controller Placement and Rationale (Q42) Top left: Primary placement. Top right: All mentioned placements (multi-mention) Bottom left: Reasons for placement preference Bottom right: Placement \times Reason co-occurrence matrix	130
42	Per-digit score distributions (0–10) with median and IQR range (Q44).	132
43	Histograms of intrusiveness scores for ten trombone attachments with median and IQR markers (Q47–Q66).	134

44	Core theme impact on intrusiveness score (Q47–Q66). Boxplots comparing scores when each theme is absent or present. MW = Mann–Whitney test; δ = Cliff’s delta; n_1 = responses with theme present; n_0 = responses without theme; total = 1058 valid responses (“No Response” excluded).	137
45	Top subthemes (Q47–Q66). Boxplots comparing scores when each theme is absent or present. MW = Mann–Whitney test; δ = Cliff’s delta; n_1 = responses with theme present; n_0 = responses without theme; total = 1058 valid responses (“No Response” excluded).	139
46	Effect of Perceived Intrusiveness on Device Usage Frequency (Q67).	140
47	Normalized weights of six core experiential themes contributing to perceived intrusiveness (Q47–Q66, Temporal excluded)	144
48	Normalized weights of seven core experiential themes contributing to perceived intrusiveness with temporal intrusiveness enabled	145
49	Tactile Switches (TS): Tactile Pleasantness Ratings (Q3.1). Boxplots showing participant ratings (0–10) for nineteen tactile-switch devices.	160
50	Joysticks (JS): Tactile Pleasantness Ratings (Q3.1). Distribution of ratings across three joystick modules (no significant intra-group difference).	163
51	Continuous Controllers (CC): Tactile Pleasantness Ratings (Q3.1). Boxplots comparing eight continuous-controller designs with considerable variation in surface friction and resistance.	164
52	Force-Sensing Resistor (FSR): Tactile Pleasantness Rating (Q3.1).	165
53	Tactile Switches (TS): Size Appropriateness Ratings (Q4.1).	167
54	Joysticks (JS): Size Appropriateness Ratings (Q4.1).	168
55	Continuous Controllers (CC): Size Appropriateness Ratings (Q4.1).	169

56	Force-Sensing Resistor (FSR): Size Appropriateness Rating (Q4.1). Single-device evaluation showing high approval for compact, low-profile design well-suited to finger pressure control.	170
57	Relationship between size-appropriateness scores and geometric dimensions (Area/Height and Volume).	172
58	Tactile Switches (TS): Visual Appeal Rating (Q5.1)	176
59	Joysticks (JS): Visual Appeal Ratings (Q5.1).	177
60	Continuous Controllers (CC): Visual Appeal Ratings (Q5.1).	178
61	Force-Sensing Resistor (FSR): Visual Appeal Rating (Q5.1)	179
62	Tactile Switches (TS): Ease of Use Rating (Q6.1)	181
63	Joysticks (JS): Ease of Use Rating (Q6.1)	182
64	Continuous Control (CC): Ease of Use Rating (Q6.1)	183
65	Force Sensitive Resistor (FSR): Ease of Use Rating (Q6.1)	184
66	Tactile Switches (TS): Overall Impression Ratings (Q7.1).	186
67	Joysticks (JS): Overall Impression Ratings (Q7.1).	187
68	Continuous Controllers (CC): Overall Impression Ratings (Q7.1).	188
69	Force-Sensitive Resistor (FSR): Overall Impression Rating (Q7.1).	189
70	Overall theme mentions across all comments (Q8.1).	190
71	Mentions of noisy (mechanical feedback) aspects across tactile switches (Q8.1).	193
72	Level 1: Ease as a function of Tactile, Size, and Visual ratings.	195
73	Residual analysis: Additional variance explained beyond Ease.	197
74	Composite decomposition of overall affective variance.	198
75	Progressive Cognitive load per number of devices	208
76	Ideal setup per participant with their intrusiveness scores.	211

77	Incremental weight trials.	215
78	NIHCI WebUI served locally from CodeCell.	220
79	NIHCI Prototype, front view.	222
80	NIHCI Prototype placed on Trombone Post 1. Right view.	222
81	NIHCI Intrusiveness Ratings (Q5). Left: Box-and-swarm plot of NIHCI intrusiveness scores. Right: Distribution of NIHCI intrusiveness responses (0-10).	223
82	Mic-Transmitter Intrusiveness Ratings.	225
83	Smartphone Added Mass (% of 2-kg Baseline) versus Intrusiveness score.	227
84	At Your Fingertips pipeline architecture, displaying a high-dimensional representation of the different processes involved.	230
85	Snapshots from the live demo showing real-time gesture classification and confidence outputs for the three performance modes.	233
86	Live demonstration snapshot of different moments from the semantic keyword builder (top 3 tables) and in the bottom, the resulting corpus visualization on an interactive 2D corpus map allowing for hover- or NIHCI-based audio preview.	236
87	QR code linking to a live recording of <i>At Your Fingertips</i> .	245
88	Evolution of the second prototype 3D-printed housing, showing successive enclosure iterations leading to the final TPU clamp-based design.	264
89	Evolution of the second prototype 3D-printed housing with different designs and materials	264
F.1	Age (left) and Years of Experience (right) distributions among participants ($n = 128$). Bar plots show frequency distributions for age and trombone experience. Dashed vertical lines indicate medians; dotted lines mark the interquartile range (IQR) (Q2–Q3).	347

F.2	Gender Identity and Country of Residence of Participants (Q4–Q5). Left: Distribution of self-identified gender identities among respondents ($n = 127$). Right: Country of residence for the top ten most represented countries plus grouped “Other” responses ($n = 128$).	348
F.3	Musical Profile of Participants (Q6, Q7, Q8, Q10; $n = 128$). Top: (left) highest level of formal education; (right) primary musical genre. Bottom: (left) frequency of public performances per year; (right) usual performance setting (solo, ensemble, or both).	348
F.4	Genre Co-occurrence Based on Participant Preferences (Q7). Heatmap showing how often musical genres co-occur by respondents, weighted by reported preference order (1st = 1.00; 2nd = 0.60). Darker cells indicate stronger co-occurrence between genres.	349
F.5	Performance Venues Reported by Participants (Q9). Bar plot showing the distribution of the primary performance venue. Concert halls and auditoriums were most frequently cited, followed by theaters/cultural centers. Less common responses included clubs, religious venues, and outdoor/festival settings.	350
F.6	Involvement in Tech-Related Musical Projects (Q11). Bar plot showing participant responses to whether they have been involved in musical projects incorporating technology. The result is not statistically significant ($p = 0.2888$).	351
F.7	Thematic Analysis of Q18 — Microphone Preferences for Trombone. Top left: Participant-level response distribution to the open-ended question on microphone preferences. Bottom left: Aggregated mentions of microphone types, derived from both explicit and inferred responses. Right: Most-mentioned microphone models, consolidated across synonymous references.	351
F.8	Thematic Analysis of Q21 — Use of Real-Time Sound Processing in Public Performance. Left: Participant responses were categorized as Yes, No, or Other. Right: Among those who use real-time processing ($n = 41$), thematic analysis coding revealed dominant use of microphones and pedal/effects units.	352
F.9	Interest in Integrating Technology in Future Musical Performances (Q22). Binary comparison of Yes vs. No responses only.	352

F.10	Thematic analysis from exclusive categories, hardware and software comfort (Q24). Distribution across mutually exclusive groups: hardware-only, software-only, both, or neither.	353
F.11	Smartphone Brands, Models, and Reported Weights (Q29). Top left: Distribution of smartphone brands most frequently used by participants. Top right: Most frequently mentioned smartphone models (top 12 + Other). Bottom: Histogram of reported device weights (grams) showing the median value. Percentages reflect mentions in a multi-select context and are not mutually exclusive.	354
F.12	Comparative availability across all ten digits: box-and-swarm summary (Q44).	354
F.13	Left- versus right-hand availability (mean across fingers): box-and-swarm comparison (Q44).	355
F.14	Median intrusiveness ratings with interquartile range for ten trombone attachments (Q47–Q66).	355
F.15	Distribution of intrusiveness ratings by interpretive band (Q47–Q66).	356
F.16	Co-occurrence Matrix of Subthemes.	357
F.17	Frequency of Subtheme Mentions: Dominance of Weight, Comfort, and Placement Concerns.	357
F.18	Thematic Density of Responses by Device Score Band (Q47–Q66).	358
F.19	Distribution of Technological Enhancement Mentions (Q70).	359
F.20	Phase Two: Participants' Age and Gender Distribution. Left: Histogram showing age distribution. Right: Bar chart displaying self-reported gender.	360
F.21	Mentions of tactile aspects across devices (Q8.1).	363
F.22	Mentions of ease-of-use aspects across devices (Q8.1).	363
F.23	Mentions of size across devices (Q8.1).	364
F.24	Mentions of visual aspects across devices (Q8.1).	364
F.25	Level 2: Overall impression as a function of ease of use.	365

F.26 Comparative model summary (Ease-only vs. Ease + Residuals). 366

“We do not hear what we hear . . . only what we remember.”

—Morton Feldman, *Give My Regards to Eighth Street*.

CHAPTER I

INTRODUCTION

This study proposes a structured framework design to guide performers, composers, and interface designers in creating and integrating attachable technologies into trombone performance without hindering playability. The framework establishes principles for designing Non-Intrusive Human-Computer Interfaces (NIHCI), conceived as tangible user interfaces (TUIs) that enable performers to interact with digital environments, including multimedia and cyber-physical spaces, while preserving the instrument's conventional physical and acoustic characteristics. This study also includes the development of a prototype interface to test and validate the framework, as well as the creation of a multimodal performance system and composition that illustrate its creative possibilities.

Brass instrument performance has moved beyond traditional idiomatic conventions, incorporating extended techniques, physical modifications, and digital interfaces that bridge expressive practice between the acoustic and digital domains. While these developments have expanded creative possibilities, many technological interventions overlook critical ergonomic factors such as finger dexterity, weight distribution, and the physical effort required for control in specific musical contexts. Paradiso and O'Modhrain (2003, p. 3) note that attaching electronic components to handheld instruments can disrupt balance

and ergonomics, ultimately constraining performers' expressive range. Addressing these limitations calls for a design approach that prioritizes the performer's embodied interaction with the instrument, ensuring that technological integration supports musical expression without compromising physical fluency or control.

With the development of gesture-sensing technologies, one can observe a shift in how physical gestures are used in music-making, transforming them from peripheral, supportive actions into active means of shaping, and sometimes augmenting sound and performer agency. The role of gestures in musical performance, previously considered ancillary due to their acoustic irrelevance yet perceptual importance (Schutz and Manning, 2012, p. 4), has evolved significantly with the advent of these technologies. As Jensenius (2007, pp. 47–50) categorizes, music-related body movements include (1) sound-producing actions (excitation and modification), (2) ancillary movements (e.g., support and phrasing), (3) sound-accompanying movements, and (4) communicative gestures, each contributing differently to musical embodiment. Ancillary movements, long considered as a by-product, have been shown to shape phrasing and even influence acoustic output through bodily orientation and subtle instrumental adjustments (Wanderley, 1999, p. 43). Gesture-sensing technologies now enable such movements to function as intentional control mechanisms for digital sound parameters, reframing bodily expression as a site of direct sonic agency.

For instance, violinist Mari Kimura developed MUGIC[®], a motion sensor mounted on a glove that enables bowing gestures to be incorporated into real-time sonic manipulation. Through its integration into various perfor-

mative works, Kimura exemplifies this shift, allowing bodily movement to extend sonic agency while preserving the instrument's physical and acoustic integrity¹. It illustrates how technological augmentation, when thoughtfully embedded in performance, can expand expressive potential without obstructing conventional performative technique.

Attaching a TUI to a handheld instrument, such as the trombone, involves addressing specific challenges related to its structure, including material, shape, bore size, and bell dimensions, all of which affect tonal quality, resonance, and intonation. This study emphasizes design strategies that preserve key performance elements such as freedom of movement, balance, and ergonomic posture. However, it does not limit its focus to physical ergonomics alone. The framework also considers cognitive, epistemological, and aesthetic dimensions of interaction, acknowledging that technological augmentation must support not only the mechanics of performance but also the perceptual, conceptual, and artistic continuity of the instrument. In doing so, it seeks to ensure that technological integration remains supportive rather than intrusive, expanding performative possibilities without compromising the trombone's acoustic and performative core elements.

Finally, this dissertation places the development of the trombone within the broader history of electronic augmentation in brass instruments, highlighting how past approaches inform current design challenges. Building on this context, it proposes a design framework that integrates technological augmen-

¹<https://www.marikimura.com/work/works>

tation into brass performance in a way that supports digital interaction while preserving the instrument's acoustic function and embodied musical practice.

Need for Study

The integration of electronics and computing into music performance has evolved significantly, transitioning from early experiments with mechanical and electromechanical systems such as the Telharmonium in the late 1890s to today's embedded, networked, and smart technologies. This trajectory has allowed composers and performers to develop novel forms of sonic manipulation and performance, fundamentally transforming how musical gestures are mediated and interpreted.

In the aftermath of 1945, several avant-garde movements such as serialism (e.g., Boulez, Stockhausen), stochastic composition (e.g., Xenakis), and early electronic music (e.g., Koenig), sought to minimize personal or stylistic expression, often reducing performance to the neutral execution of formalized systems. As Taruskin notes, this impulse emerged from a broader postwar disillusionment, where “the only responsible decision left was to [...] stamp out the artist's puny person and allow something ‘realer’ to emerge. And what could be realer than number?” (Taruskin, 2009, p. 74). Ligeti's description of compositional choice as selecting among self-constructed “Automaten” (vending machines) articulates this position of procedural abstraction, in which the composer “constructs his own prison” and remains “freely active within those walls [...] not entirely free, but not totally constrained either” (Taruskin, 2009, p. 71).

In contrast, contemporaneous movements such as Fluxus, Dada, and free improvisation practices emphasized immediacy, embodiment, and performer agency, challenging the separation between composition and execution. These divergent tendencies highlight performance as a site of expressive negotiation between structure and freedom, foregrounding the performer as an interpretive, contextually situated agent.

Historical avant-garde examples are used here to frame broader questions of agency, embodiment, and technological mediation, while the present study evaluates interfaces for mainstream trombone performance settings. Against this historical background, performance remains central to the history of music technology, where instruments and digital tools function not merely as utilities but as mediators of material transformation, a core mechanism through which technology participates in the production of musical meaning. As Leman (2007) argues, technological transparency allows instruments to “disappear” in the hands of an experienced performer, transforming them into conduits for musical intent. Although transparency is desirable in many conventional performance settings, some artistic practices may intentionally foreground technology as part of the aesthetic experience.

In recent decades, miniaturization and accessibility of technology, particularly in computing, electronic components, and communications, have radically transformed the interaction with digital systems. The exponential growth in processing power, exemplified by the miniaturization of the transistor by a factor of one million (Schaller, 1997), has enabled compact, powerful tools such as smartphones, real-time DSP systems, and wireless audio interfaces. These developments underpin transformative technologies like big data, AI,

and the Internet of Things (IoT). Yet despite this technological revolution, traditional handheld instruments such as the trombone have largely remained unchanged. As Campbell et al. (2021, p. 408) note, “It appears that the world of brass instrument manufacture and performance has been little affected by this whirlwind of change: the trumpets, trombones, french horns and tubas in modern bands and orchestras are remarkably similar to the instruments which would have been played in similar ensembles a century ago.” This decoupling from technological advancements reveals not a deficiency, but rather a missed opportunity to incorporate multimodal and gestural affordances without compromising the instrument’s acoustic identity.

With the introduction of the MIDI protocol in the early 1980s, musicians gained the ability to control electronic sound through real-time manipulation of parameters such as pitch, amplitude, and duration. According to De Poli (2004, p. 191), such mapping renders digital sound expressive, preventing it from becoming “dull and inexpressive, akin to a text read without any prosodic inflection.” However, while real-time mapping enables expressive nuance, its success depends on intuitive and transparent interface design. As Paradiso and O’Modhrain (2003) argue, the action-response relationship in acoustic instruments is directly comprehensible to audiences, who can easily appreciate virtuosity. By contrast, electronic instruments, especially those using hidden or opaque mapping techniques, “can often confuse an audience, who often can’t follow and relate to what the performer is doing” (Paradiso and O’Modhrain, 2003, p. 347).

This issue becomes increasingly significant in light of the evolving landscape of music synthesis. Advanced techniques like physical modeling, as discussed by

Smith (1996), require more intricate channels of articulation to unlock their full expressive potential. As Smith (1996, p. 52) states, “The big advantage of making a virtual instrument based on a physical model is to obtain the entire range of expressive variations in the instrument in response to intuitive controls. Unfortunately, controlling physical models gracefully in real time can be quite difficult, especially with sustained instruments such as bowed strings, woodwinds, and, most particularly, the human voice”. The challenge, therefore, lies not only in expanding sonic possibilities but also in designing interfaces that remain expressive, have an appropriate learning curve, and are idiomatic to performers.

As musical interface design continues to evolve, the focus of institutional and corporate research in music technology is shifting towards the control aspects of music synthesis, rather than solely on synthesis itself (Paradiso and O’Modhrain, 2003, p. 347). Electronic interfaces, particularly those that feature advanced mappings or interfaces that are not immediately visible or intuitive (such as laptop keyboards or biomechanical sensors), “can often confuse an audience, who often can’t follow and relate to what the performer is doing” (Paradiso and O’Modhrain, 2003, p. 346). In this scenario, handheld instruments present a unique opportunity to expand both acoustic and electronic sound vocabularies through the creation of multidimensional interactions. The implementation of wireless communication, such as Bluetooth and Wi-Fi technology, provides the freedom that was previously unavailable to augmented instruments because of cables, allowing for greater movement by the player (Campbell et al., 2021, p. 416).

In this sense, mapping constitutes a key aspect of human-instrument interac-

tion, posing the challenge of “matching the capabilities of the human sensorimotor system to the parameter space of the instrument being played” (Paradiso and O’Modhrain, 2003, p. 346). While controllers have undergone diverse developments, the absence of a robust connection and control over the instrument’s sound production mechanism reduces its playability. The coupling of movement, or gesture, with specific sounds requires musicians to be aware of incorporating new performative dimensions, thereby extending the canonical technique beyond the instrument’s inherent capabilities.

From a performer’s perspective, as described by Thibodeau and Wanderley in *Trumpet Augmentation and Technological Symbiosis*, “augmenting an acoustic instrument through the attachment of electronics expands its identity as a controller and producer of sound without discarding the years of practice that a performer may already have invested in his or her instrument” (Thibodeau and Wanderley, 2013, p. 12). However, most augmentations have been highly individualized, tailored to specific performers, thereby preventing widespread adoption or standardization (Thibodeau and Wanderley, 2013, p. 12). Paradiso and O’Modhrain (2003) reinforce this observation, noting that “no common set of standards exists to evaluate designs, and as goals are so varied in different applications, it is unclear whether this can ever be effectively accomplished” (Paradiso and O’Modhrain, 2003, p. 6).

The methodological challenge of evaluation is further problematized by the trial-and-error ethos that governs brass instrument modification. As Campbell et al. (2021) note, innovation in this domain has been driven by "experience-guided trial and error" rather than systematic design protocols (Campbell et al., 2021, p. 409). This ad hoc approach contributes to the "impermanence

of technical setups, including all types of support and instruments, complicating the establishment of favorable conditions for adequate performances" (Toro-Pérez, 2018, p. 7). Without reliable evaluation criteria, it becomes difficult to improve systems over time or compare results across different platforms.

While technological advancements continue rapidly, the core factors of trombone performance remain—and will likely remain—largely unchanged. The acoustics and mechanics of the trombone, along with the established techniques of its performance and the fundamental principles of human ergonomics and acoustics, have not significantly changed, nor is there clear evidence that any of these aspects will change in the near term. The framework presented here intends to support the design and evaluation of non-intrusive, idiomatic digital extensions, serving expressive musical intent while remaining compatible with the embodied knowledge already embedded in brass performance.

This study aims to foster innovation in brass instrument interface design, contributing to a more integrated and expressive technological ecology in contemporary music. It aligns with current efforts in the fields of Human-Computer Interaction (HCI) and New Interfaces for Musical Expression (NIME) to design technologies that are transparent, expressive, and ecologically valid.

Personal Relation to the Study

As a classically trained trombonist and a composer shaped by a holistic, exploratory approach, my work seeks to bridge performance and creation through new modes of musical dialogue. This study emerges directly from that in-

tersection, grounded in my lived experience as a performer, yet driven by a compositional curiosity toward the boundaries of sound, embodiment, and interaction.

My introduction to music began at the age of eleven in a marching band program in Fray Bentos, Uruguay, a small town located 306 kilometers northwest of Montevideo. Like many of my peers, I could not choose my instrument based on personal desire, but rather from those that were available. Eventually, after spending some time in the percussion section, I was assigned an old Orsi Milano trombone passed down from a former player who had stopped playing long ago. With no trombone teacher—only a clarinet teacher—and no formal resources, I began a process of self-guided discovery, mapping slide positions and pitch using my ear and intuition.

Without access to online media, recordings, or reference materials in the early 2000s, my understanding of the trombone's sound had to be constructed from fragments: songs heard on the radio, concerts by regional music groups, and the physical response of the instrument itself. In retrospect, this early experience continues to shape how I conceive of sound, not as a fixed object, but as something emergent, situated, and constantly negotiated. I often return to the question: What is the sound of my trombone? Where does it begin, where does it end, and where does it reside?

This study does not aim to answer those questions definitively. Rather, it represents a continued attempt to expand the boundaries of my instrument, not only through the buzzing air I blow into it, but through the physical space it inhabits, the digital environments into which it can extend, and the evolving

relationship between gesture, interface, and intent. The development of the NIHCI system and framework is one step in that ongoing inquiry, a means of probing the limits of embodied sound and, perhaps, in doing so, contributing to new avenues for others engaged in similar explorations.

Research Questions

The following questions guide the current study.

Main Research Questions:

1. How can this research inform the design of NIHCI for augmented trombone practices?
2. What capabilities and control mechanisms can be implemented through the strategic placement of input devices on the trombone to maximize expressive potential without compromising conventional playability?

Sub-Questions:

1. What are the potential uses of NIHCI to augment performance beyond the music/audio possibilities, such as video, tablet page-turn functions, lighting, stage control, and effects?
2. How can the NIHCI framework design be applied to different hand-held acoustic instruments?

These questions frame the study’s goal of establishing a design framework that balances technological innovation with the physical, expressive, and aesthetic demands of trombone performance. Rather than aiming to create a fixed interface design solution, the research explores a system that enables multiple configurations, each responding to different musical, performative, or environmental needs.

Aligned with Cook’s (2001) argument that “existing instruments suggest new controllers” and that “everyday objects suggest amusing controllers” (Cook, 2001, p. 2), this study examines the use of ubiquitous technologies, such as smartphones, not merely as external controllers but as a potential platform for different interface needs, such as processing hubs or WebUI support for interface configuration.

A main consideration is the strategic placement of input components. Factors such as slide movement, valve access, grip stability, and the subtle physical gestures intrinsic to trombone playing must be preserved. As Paradiso and O’Modhrain (2003, p. 4) explain, mapping strategies are not confined to sound synthesis; they can be extended to other media outputs, allowing performance gestures to influence elements beyond the sound domain, including visual and spatial cues that are tightly related to the audio components. The NIHCI framework is therefore conceived as a multimodal tool, allowing integration with audio, visual, and other stage-control systems to create cohesive performance environments.

The overarching aim is to advance a performer-centered framework that al-

lows for flexible, expressive, and ecologically valid integrations of interactive technologies within trombone performance.

Definitions

This section aims to establish clear distinctions between terms that are used in this study.

Non-intrusive refers specifically to external attachment devices that integrate with the trombone without disrupting core performance practices or altering the musician's natural interaction with the instrument. Non-intrusive does not imply the complete absence of intrusiveness, but rather an acceptable threshold at which augmentation remains compatible with conventional trombone performance practice. Beyond considerations of physical comfort or utility, non-intrusiveness emphasizes preserving the instrument's inherent balance, tactile feedback, and inherited playing techniques, ensuring that the fundamental experience of performing remains largely preserved.

Many existing trombone accessories, such as mutes, microphones, and ergonomic supports, are widely accepted despite varying degrees of intrusiveness. In further analysis, it is possible to observe how mutes can be perceived as intrusive due to their impact on instrument balance and resonance. However, their functional need often places them within an acceptable range of intrusiveness. Thus, intrusiveness levels are context-dependent, often tolerated when clearly serving performance or artistic objectives. The central design question is therefore not whether augmentation introduces any burden,

but whether the musical benefits justify the perceptual, physical, or cognitive demands introduced. This study seeks to define and clarify musicians' perceptions of intrusiveness, acknowledging that these judgments depend on the accessory's practical impact on playability and its role in supporting the musician's expressive intentions.

Human–Computer Interaction (HCI) is a discipline concerned with the design, evaluation, and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them (Shneiderman, 1997). This framing positions HCI as an interdisciplinary field drawing from computer science, psychology, design, and the humanities. Contemporary HCI research extends beyond technical performance to include usability, user experience (UX), accessibility, and the social and cultural contexts in which interaction occurs.

Within this broader field, a human–computer interface denotes the specific technological mediation layer through which interaction is instantiated. Accordingly, this dissertation situates the proposed Non-Intrusive Human–Computer Interface (NIHCI) at the level of interface design, while engaging with HCI as the overarching theoretical and methodological domain.

Augmented instruments, as defined by Miranda and Wanderley (2006), augmented instruments involve “the addition of several sensors, providing performers the ability to control extra sound or musical parameters” (Miranda and Wanderley, 2006, p. 21). In this study, the concept is extended beyond the sonic domain to include control within the broader performance ecology, inte-

grating cyber-physical space, multimedia elements, lighting, and other stage interactions.

Framework, as described by O’Modhrain (2011), “The term framework is often used in the context of HCI to describe a conceptual scaffold that can help to elucidate relationships between design approaches within a given design space. Frameworks that are generative in nature, that is, those that lay out spaces of design possibilities, serve to systematize thinking and promote reflection that may uncover new design ideas” (O’Modhrain, 2011, p. 30).

Sensor, as defined by Fraden (2016) “...is a device that receives a stimulus and responds with an electrical signal” (Fraden, 2016, p. 2). Examples of sensors include microphones, accelerometers, pressure sensors, and optical sensors, which detect changes in sound, movement, pressure, or light and convert them into electrical signals for further processing.

Gestures, described by Carfi and Mastrogiovanni’s (2023), are “... body actions that humans intentionally perform to affect the behavior of an intelligent system” (Carfi and Mastrogiovanni, 2023, p. 499).

Expression, refers to the intentional shaping and communication of musical ideas by the performer through timing, dynamics, timbre, articulation, phrasing, and gesture. The term expressive is also used in a secondary design sense to describe interfaces that preserve or extend this capacity by facilitating nuanced control.

Real-time, in the scope of HCI, particularly in audio perception and cognitive dynamics, refers to the system’s ability to detect, process, and respond to user input within a time frame that preserves the perception of immediacy. This requires sufficient temporal precision to align technological responses with the continuous, nonlinear transitions of human cognition, where changes between mental states occur fluidly rather than in discrete steps (Spivey and Dale, 2006, p. 208).

Mapping addresses the process of translating a physical action detected by sensors into a corresponding computational operation. This involves defining the relationship between a performer’s gestures, such as hand movements, finger positions, or specific motion patterns, and the digital commands or parameters they control within software or interactive systems.

Cyber-physical space refers to “a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities. The ability to interact with, and expand the capabilities of the physical world through computation, communication, and control is a key enabler for future technology developments” (Baheti and Gill, 2011, p. 1). In this context, cyber-physical space can be understood as the dynamic interactive environment produced by such systems where digital computation and physical action are deeply interwoven, enabling embodied interaction, feedback, and control across physical and virtual domains.

CHAPTER II

BACKGROUND

Historical Perspectives on Western Brass Emergence

Two significant developments occurred in the world of brass instruments during the nineteenth century. First, the invention of new brass instruments, including keyed and valved varieties, as well as enhancements to the slide trombone; second, the shift towards mechanized manufacturing processes and mass production (Myers, 1997, p. 115). These changes increased accessibility and affordability, increasing their popularity, particularly in bands.

The introduction of keyed and valved instruments, alongside refinements to the slide trombone, expanded available timbres and extended the chromatic compass from contrabass to soprano registers (Myers, 1997, p. 115). One particularly transformative invention was the rotary valve, first introduced by Friedrich Blühmel in 1828 and later patented in its modern form by Josef Riedl in 1835 (Myers, 1997, p. 123). This design, which is still common in French horns, tubas, and thumb-valve trombones, significantly influenced playing techniques, allowing for more complex and virtuosic works. In the trombone, the thumb valve extended range and versatility (Myers, 1997, p. 123).

As valve technology evolved, valved horns and trumpets became preferred in orchestras and bands. Though initially resisted by musicians who valued the traditional sound, they gradually gained acceptance (Myers, 1997, p. 126). By the early twentieth century, they had become standard even for earlier repertoire originally written for natural trumpets and hand-horns, showing how practical and versatile innovations can overcome concerns about tonal purity (Myers, 1997, p. 126).

The convergence of military music traditions, conservatoires, and industrial manufacturing fostered the growth of solo and chamber brass music in cities such as Paris, London, Vienna, Prague, Leipzig, Stockholm, and St. Petersburg. Yet, the trombone and tuba largely remained orchestral instruments until the latter half of the twentieth century (Wallace, 2002, p. 236).

Historical Brass Pedagogy and Performance Practices: An Overview

The pedagogical legacy of the Paris Conservatoire, guided by pioneers such as Philippe Widerkehr (the first appointed professor of trombone from 1795 to 1802), established foundational principles that deeply influenced brass teaching methodologies. These early educators explored the trombone's potential and limitations, emphasizing musicianship, tone quality, agility, lyrical playing, and soloistic expression within the context of orchestral music (Herbert, 2006, p. 136). The high standing of the conservatoire faculty and their understanding of the trombone idiom shaped contemporary composers' approaches to writing for brass (Herbert, 2006, p. 136).

Between 1880 and 1930, two distinct solo trombone performance styles emerged

in the United States, reshaping notions of virtuosity (Herbert, 2006, p. 147). The first emerged from popular concert band virtuosos, known for their technical brilliance and precision. The second arose within the growing jazz movement, characterized by improvisation and expressive freedom. Both traditions influenced the trombone idiom and prompted conservatories to reassess and expand their pedagogical approaches (Herbert, 2006, p. 147).

From the late 1970s onward, technological developments such as microphone-based electronic amplification and, soon after, early digital effects became increasingly integrated into trombone performance, initially in experimental, jazz, and popular music contexts. One of the earliest dedicated electronic devices associated with brass performance was the Varitone. The Varitone name first appeared in the early 1960s with Gibson's multi-position tone-shaping circuit for electric guitars. By the late 1960s, Selmer adapted the name for a different system, the Selmer Varitone, a pickup-and-microphone-based preamp and effects unit for woodwinds and brass, used, for instance, by American trombonist Urbie Green in *Green Power* (Green, 1971). Other guitar-derived effects, such as the wah-wah pedal, famously featured by Miles Davis in *Live-Evil* (Davis, 1971), were also adapted by brass performers.

American trombonist J. J. Johnson, a relevant figure on the jazz stage during the mid-late twentieth century, incorporated pitch-tracking devices (such as the Gentle Electric Pitch Follower) to expand melodic and textural possibilities. An example of this can be found on the track "Mr. Clean" from his 1979 album *Pinnacles* (Johnson, 1980). In the decade of the 1980s and 1990s, trombonists, such as Robin Eubank, began using pedalboards with wah, distortion, looping, and delay to expand the instrument's expressive range. This trajec-

tory mirrored the earlier adoption of electronic effects by electric guitarists in the 1960s, highlighting a cross-instrumental migration of performance technologies. Taken together, these developments broadened the trombone's sonic possibilities and laid the groundwork for later explorations in augmented and electronically augmented instruments.

Real-time audio processing, and in more experimental contexts, gesture-based augmentation, began attracting performers in the 1990s, building on pioneering work from the previous decade. In the late 1980s, Tod Machover's Hyper-instruments project at MIT explored ways to augment acoustic instruments with sensors and computer processing (Machover, 1992), while in 1989 Dexter Morrill and Perry Cook developed a custom sensor-augmented trumpet system at Stanford's CCRMA for the composition *Invisible Man* (Morrill and Cook, 1989). These early efforts laid important groundwork, but it wasn't until the COVID-19 pandemic in 2020 that the use of technology in brass pedagogy saw a widespread and rapid adoption. With social distancing in place, teachers and institutions quickly turned to online platforms to maintain lessons. This shift required students to acquire audio skills such as operating microphones, audio interfaces, and DAW software.

Beyond Traditional Practices

While traditional instrumental design focuses on refining sound quality and enhancing standard playing techniques, extended techniques involve playing the instrument in unconventional ways, exploring new limits and sounds, while expanding its expressive capabilities. One of the most influential trombone

works exploring such practices is *Sequenza V* by Italian composer Luciano Berio (1925–2003). Part of a series of fourteen solo works titled *Sequenzas*, each dedicated to a single instrument, the pieces juxtapose dissimilar objects or gestures to elaborate new vocabularies from traditional practices. As Hansen (2010, p. 4) observes, Berio often drew on the “unidiomatic” aspects of each instrument, gestures, or techniques that lie outside conventional performance practice, and took these as starting points for composition.

Berio’s *Sequenzas* also extend performance into spatial and theatrical domains, integrating instrumental gestures that evoke staged representation. This dimension reflects Berio’s engagement with Bertolt Brecht’s dramaturgical concepts (Hansen, 2010, p. 4). In *Sequenza V*, for instance, the trombonist is instructed to wear specific attire and follow lighting cues, thereby transforming physical space into a compositional and performative element. In this way, the performer is required not only to execute the musical material but also to assume a staged role.

The expansion of technical and expressive resources through extended techniques, combined with the incorporation of theatrical elements, marked a departure from conventional musical practice. This shift broadened both the sonic and performative dimensions of trombone performance and anticipated later technological integrations, in which space and movement become integral components of the sonic experience.

HCI and Music Technology

HCI has taken ideas from the lab into rehearsal rooms, concert venues, and workshops, proposing ways to think about how people and technology meet. In music, particularly in brass performance, this view turns the focus from seeing the interface as just a tool to identifying it as something that can merge with a player's routine and expressive gestures. Some of these perspectives, such as embodied interaction, gesture studies, and ecological validity, provide a way to discuss the nuanced interplay of movement, perception, and meaning that occurs in performance. Others, such as user-centered and representative design, suggest ways to build and test new systems that fit the complex, evolving realities of musical practice, rather than forcing artistic practice to adapt to computer systems.

HCI and Its Integration into Music Technology and Brass Performance

In the early 1980s, computer use was beginning to be recognized as a distinct human activity, with the direct human-computer interaction seen as a significant new stage in computing's development (Card et al., 1983, p. 4). This new area drew interest from cognitive psychology, computer science, system design, human factors, ergonomics, and engineering, and sought to make interactive systems efficient and easy to use (Card et al., 1983, Preface vii–viii).

Mathews' pioneering work in digital sound synthesis in the 1950s and 1960s laid the foundation for computer music and interactive systems (Roads, 1996, p. 806). His MUSIC I–V programs were the first to generate sound on a digital

computer. In the 1980s and 1990s, tangible and gestural interfaces expanded the possibilities for integrating computation into music-making. For instance, projects such as Michel Waisvisz’s *The Hands* (Waisvisz, 1985) and Tod Machover’s Hyperinstruments (Machover, 1992) (conducted from 1987 to 1991) illustrated how HCI principles could create interactive performance systems that bridge the acoustic and digital domains. Brass-specific works, including Jonathan Impett’s Hypertrumpet (Impett, 1994), Morrill and Cook’s Trumpet Performance System (Morrill and Cook, 1989), and Ben Neill’s Mutantrumpet (Cook, 2001), anticipated later augmentation strategies by integrating sensors and mapping techniques that expanded timbral and gestural vocabularies beyond acoustic possibilities.

Embodied Interaction as a Design Philosophy

A central HCI contribution to musical interface design is what Dourish (2001) terms embodied interaction: “interaction with computer systems that occupy our world, a world of physical and social reality, and that exploit this fact in how they interact with us” (Dourish, 2001, p. 13). Drawing on phenomenology—particularly Heidegger’s concept of *ready-to-hand*—Dourish argues that, through repeated use, a tool (such as a hammer) becomes sufficiently familiar that “one is familiar enough with its use to stop having to maintain conscious awareness of how one is using it while one uses it. Instead, one becomes engaged in the practical activity of hammering” (Dourish, 2001, p. 3). Expanding on this, his notion of *coupling* describes how effective tool use depends on a continual process of engagement, disengagement, and reengagement. Tech-

nologies must therefore support fluid transitions between the *ready-to-hand* state, where the tool becomes an almost invisible extension of the body, and the *present-at-hand* state, in which it is treated as an object of attention and adjustment, enabling us “to act with and to act through artifacts” (Dourish, 2001, p. 119).

This is especially relevant to musical performance, where the instrument is experienced not as an external object but as an extension of the body’s expressive capacity. For Dourish, the goal of design is not simply to optimize efficiency or ergonomics, but to embed systems into the lived, interpretive fabric of practice (Dourish, 2001, p. 87). In musical HCI, developing interfaces that integrate transparently with the performer’s embodied technique and social-musical contexts supports interaction that is fluid, contextually aware, and rich in purpose between the musician and the acoustic instrument.

Gesture in Music: Typologies and Design Implications

From this embodied perspective, Jensenius situates *musical gestures* as human body movements that happen in relation to sounding music, and divides these into two categories: (1) either in producing the sound (musicians) and (2) in responding to it (listeners or dancers) (Godøy and Leman, 2009, p. 25). He prefers the term gesture over movement because gesture “blurs the distinction between movement and meaning” and “bypasses the Cartesian divide between matter and mind” (Godøy and Leman, 2009, p. 25), making it a conceptual bridge for embodied music cognition.

For HCI in music, this distinction defines the design space. An interface that

accurately replicates and extends musicians' gestural practice must account for both biomechanical realities (movement trajectories, physical constraints, home and start positions) and semantic-intentional layers (phrasing, intention). For instance, a trombonist's slide movement can simultaneously function as (1) a sound-producing gesture (altering the pitch), (2) a sound-modifying gesture (fine intonation adjustments mid-note), (3) a communicative gesture to an ensemble (indicating phrasing or dynamics), and (4) preparatory gestures that establish the physical conditions for sound production, such as airflow resistance and embouchure readiness.

Jensenius (2007) concept of gesture space and performance environment, including performance scene, home/start positions, and *kinesphere* (a term introduced by Laban (Laban and Ullmann, 1963), in reference to the imaginary three-dimensional boundary of maximum reach from a fixed point), have direct implications for DMIs sensing and mapping (Godøy and Leman, 2009, p. 32). Matching sensor range to a performer's customary gesture spaces avoids disrupting readiness-to-hand. His functional typology, sound-producing, communicative, sound-facilitating, and sound-accompanying gestures, underscores the multiplicity of functions in a single movement (Godøy and Leman, 2009, p. 34). For design, this implies avoiding one-to-one gesture-function mappings; on the other hand, for evaluation, it means testing how a system supports overlapping gesture functions in ecologically valid contexts.

Ecological Approaches to Sound and Performance Context

From an ecological standpoint, perception supports and enriches embodied and gestural perspectives. It treats sound not as an abstract stimulus but as a direct conduit to environmental events and their meaning for the listener (Windsor, 2000, p. 24). Windsor warns that much research has focused on "a rather idiosyncratic subset of sounds and sources," namely musical tones. At the same time, everyday and performance listening involve a wider spectrum—often inharmonic and temporally complex—that conveys rich causal and material information (Windsor, 2000, p. 23).

For interface design, this approach emphasizes preserving the performer’s ability to engage directly with the causal, material, and spatial properties of sound. Ecologically aligned systems avoid isolating musicians from the sonic variability they must navigate in performance, ensuring that both design and evaluation remain grounded in the innate aspects of musical practice.

Methodological Gaps in DMI Evaluation

While the present study concerns an augmentative human–computer interface rather than a Digital Musical Instrument (DMI) in the conventional sense—where the latter typically constitutes a primary sound-producing system—the evaluation challenges identified in DMI research remain methodologically relevant. Despite these conceptual tools, Barbosa et al. (2015) meta-review of DMI evaluation at NIME (2012–2014) identifies that there is “little consistency regarding the usage of the word [evaluation]” and, in some cases,

“not even basic information such as goal, criteria, and methods were provided” (Barbosa et al., 2015, p. 156). They stress: “It is completely acceptable to not evaluate the DMIs we create; However, if one wants to ‘evaluate’ something, it is important to provide basic information such as the goal of the evaluation, how it was performed (e.g., what methods and criteria were used), and what results were accomplished. Otherwise, the information provided is not meaningful to the community” (Barbosa et al., 2015, p. 160). Without shared methodological standards, results cannot be meaningfully compared, validated, or accumulated.

Toward a Standard: UCD, Representative Design, and Ecological Validity

One way forward is to draw on the established methodologies of HCI’s user-centered design (UCD), developed in the mid-1980s alongside the emergence of HCI as a field. Norman and Draper (1986) argue that “Concern for the needs of the users should be primary,” and that artifacts inevitably “have an effect on the people who use or inhabit them,” requiring “attention... at a variety of levels, from ergonomic concerns to organizational issues” (Norman and Draper, 1986, pp. 7–8). Norman’s Cognitive Engineering Model, an applied branch of cognitive science focused on using human action and performance knowledge to design complex devices, adds that design should be based on models “precise enough to lead to design rules” while supporting “cooperative, enjoyable interaction” (Norman and Draper, 1986, p. 8). The goal, as Norman stresses, is not only efficiency or ease of use, but systems that are satisfying and even enjoyable to use. For musical interface design, this means making

evaluation an ongoing part of the process and involving performers at every stage.

Brunswik’s idea of *representative design* adds another layer. Here, ecological validity means that the conditions in a study should match the real-world environment in both substance and statistics (Hammond et al., 2001, p. 53). It is not enough for a test to look or feel realistic; it must also include a representative range, and ideally, the same distribution of the kinds of tasks, environments, and participants found in real use. Without this, results may not be well generalized. Hammond et al. (2001) warn against the “false dilemma” between laboratory control and real-world relevance, advocating for designs that preserve the key patterns of the real environment while still allowing for experimental rigor (Hammond et al., 2001, p. 8).

For interface design evaluation, this means defining the *task ecology*, the set of sensory, cognitive, and social factors that shape actual musical performance. This might include the kinds of gestures used, the acoustic space, the monitoring setup, physical constraints, and even audience context. The aim is not to mimic every detail of a live performance—actually, something rarely possible—but to capture both the important features and their statistical patterns, such as how often they occur or how they vary. Windsor (2000) ecological perspective supports this point, stressing that musical performance and listening are embedded in complex, changing environments, and warning against removing the very variability musicians must navigate in authentic performance settings (Windsor, 2000, p. 23).

Intrusiveness in the HCI Interface Design

In HCI, intrusiveness, often used interchangeably with obtrusiveness, refers to the degree to which a technology disrupts or imposes on a user's experience. Although the term user experience may suggest a singular, cohesive process, it actually encompasses a range of related, goal-oriented experiences. Intrusiveness is not a unidimensional construct; it involves multiple, context-dependent factors that vary in influence for each user. In telehealth, for example, Hensel et al. (2006) defines intrusiveness as a subjective, user-driven evaluation shaped by (1) the cumulative impact of several features or by one particularly salient element, and (2) the fact that perception differs across individuals, underscoring the personalized nature of this assessment (Hensel et al., 2006, p. 430). The next section identifies and categorizes the systemic sources of intrusiveness, showing how these context-dependent factors manifest across different application domains, relevant to interface design.

Systemic Sources of Intrusiveness

Intrusiveness in HCI design has been a recurring concern across multiple sub-fields and application domains, as seen in works by Shen et al. (2007), Neben and Schneider (2015), Inbar et al. (2009), Barreto et al. (2007), and Moeslund et al. (2004) in areas such as distributed computing, embodiment, ambient displays, and movement-based or performative contexts. As technologies become increasingly embedded in everyday activities, this concept emerges not only from user interaction but also from the structural and systemic behaviors of technological systems.

The increasing integration of distributed and mobile systems has emphasized the difficulty of maintaining a balance between system functionality and minimal user disruption. According to Espinoza et al. (2007), intrusiveness can be traced to four recurring phenomena in the design of rapidly developing interactive technologies: “(1) focus-demanding and distinguishable artifacts like phones or PCs explicitly mediate interaction with the distributed context; (2) the functionality of services is traditionally based upon the assumption that communication is a deterministic flow of passive information, which does not include information about participants’ current context; (3) services in general perform individually and without coordinated communication schemes; and (4) switches between contexts introduce a high cognitive load as each distributed context typically has its own system of characteristic objects and rules” (Espinoza et al., 2007, p. 143). These phenomena point to a form of intrusiveness that arises from technological architectures and service models, one that precedes any physical interface or user perception that can undermine usability at a foundational level.

Embodiment offers an alternative design approach that can mitigate some of these systemic failures. Moving beyond symbolic or command-based interaction, embodied design seeks to integrate perceptual, motor, and gestural dimensions of human activity. As Dourish (2001) articulates, “The trend I have emphasized here is the gradual incorporation of a wider range of human skills and abilities. This allows computation to be made ever more widely accessible to people without requiring extensive training, and to be more easily integrated into our daily lives by reducing the complexity of those interactions” (Dourish, 2001, p. 14). This orientation has been expanded within

Tangible and Embedded Interaction (TEI) approaches, particularly in performative and artistic contexts. As Hornecker (2011) observes, TEI “investigates an augmented physicality that takes us away from the desktop and searches for other ways of interacting. As we start to embed computing in the everyday environment, this requires designing the digital and physical together. It also requires us to design new types of interaction that enable the user to directly interface with the computer in ways that require fewer intermediaries, and that fit better with our innate abilities” (Hornecker, 2011, p. 20). These perspectives frame intrusiveness not just as a by-product of hardware or interface, but as a misalignment between computational systems and embodied human capabilities.

Even in systems designed for expressive engagement, physical and systemic intrusiveness remain a challenge. In the domain of interactive music technologies, for example, Bouwer et al. (2013, p. 218) report that participants using dance mats experienced significant disruptions such as “keeping balance, changing feet, overshooting due to the small size of the mat, accidental presses, [and] not being able to move fast enough”. These constraints reflect not just physical discomfort, but how space constraints and poor feedback mechanisms can introduce unintended barriers in movement-based interaction.

Non-musical applications of HCI provide additional insights. In the context of ambient displays (systems that convey information subtly through peripheral perception rather than demanding focused interaction), Shen et al. (2009) make a critical distinction: “Intrusive and non-intrusive seem more like endpoints on a continuous range than buckets for evaluation methods. The difference between these two evaluations is the level of user involvement.” Intrusive

evaluation seems to be good at quantitative measurement of parameters, but non-intrusive evaluation may not be. On the other hand, intrusive evaluation may have a higher cognitive load, which can affect the validity of results, but non-intrusive evaluation can have better results by having lower cognitive load" (Shen et al., 2009, p. 31). This insight sheds light on the systemic nature of intrusiveness, where it is not merely located in devices or interfaces, but in how users are placed in relation to technological processes and expectations.

Experiential Dimensions of Intrusiveness

In performance-driven contexts, such as music performance, interaction is deeply embodied, context-sensitive, and often affective, a concept that will be later developed. To account for these characteristics, this study conceptualizes intrusiveness as a multidimensional construct for evaluating how musical interfaces may disrupt or, conversely, harmonize with performance practices. With these in mind, this study proposes seven experiential dimensions of intrusiveness: (1) physical, (2) ergonomic, (3) cognitive, (4) attentional, (5) perceptual, (6) temporal, and (7) aesthetic.

Physical Intrusiveness

Physical intrusiveness refers to the tangible attributes of the interface, such as size, weight, shape, material composition, and the spatial volume it occupies relative to the performer's body and instrument. These features determine

whether a device feels bulky, heavy, or unwieldy. In music performance, even minimal mass or asymmetrical attachments can significantly alter playing posture and comfort. Volta and Di Stefano (2024) emphasizes that "wearable devices should be made more ergonomic, lightweight, and unobtrusive to ensure they do not detract from the performance experience and can be worn comfortably for extended periods"(Volta and Di Stefano, 2024, p. 16). For instance, in a trombonist performance setting, Fréour and Scavone (2011) compared a traditional strain gauge glued to the trombonist's lip, described as "quite invasive", with a modified mouthpiece capable of capturing lip motion in a "totally non-invasive" manner (Fréour and Scavone, 2011, p. 130).

Ergonomic Intrusiveness

Ergonomics refers not just to the static form of an object but to how it blends with the body in action. Ergonomic intrusiveness, therefore, captures the interface's impact on posture, balance, joint articulation, grip, and fine motor coordination. An interface can be physically minimal but ergonomically problematic, for instance, if it forces the hand into an unnatural angle, or becomes an input device that is so small it can't be controlled with precision. In Bouwer et al. (2013)'s study on foot-controlled musical systems, participants reported "keeping balance, changing feet, overshooting due to the small size of the mat, accidental presses, [and] not being able to move fast enough"(Bouwer et al., 2013, p. 30). These disruptions emerged from the placement and responsiveness of the interface, not its mass or volume.

Cognitive Intrusiveness

Cognitive intrusiveness alludes to the mental effort an interface imposes, or, in other words, how much thought or memory retrieval is required to operate or respond to it. This aspect is relevant since high cognitive load can disrupt ongoing tasks, particularly in multitasking contexts such as musical performance, where the span of attention is already divided across multiple tasks. Shen et al. (2009), studying the issues of ambient display evaluations—interfaces that communicate information subtly in peripheral attention—notes that intrusive setups can force users into “higher mental effort . . . [causing them to] concentrate on specific tasks poorly,” while designs that minimize cognitive demands allow “lower cognitive load . . . which benefits results.” (Shen et al., 2009, pp. 66-67).

Attentional Intrusiveness

Closely related to cognitive load is attentional intrusiveness, which concerns how much an interface diverts the performer’s focus. In live performance, maintaining attentional continuity is required for expressive timing, ensemble coordination, and emotional presence. Cera and Misdariis (2021) identify distraction as one of the four primary negative consequences of insensitive sound use, defining it as “due to excessive attentional or memory load, in competition with other tasks”. They further note that sound activates “an extremely complex (and not yet fully understood) web of relations between

automated physiological reactions, perceptual activities (attention direction, saliency evaluation, ...) and cognitive systems (listening abilities, mental categories, layers of memories, emotional architectures)" (Cera and Misdariis, 2021, pp. 186-187). Highly recognizable auditory elements exacerbate this effect, for instance, "pitched and rhythmic sound structures can become highly recognizable after a few listenings. This high recognizability can easily trigger annoyance" (Cera and Misdariis, 2021, p. 191). Translating this experience to the design of trombone interfaces, one can trace this parallelism to situations in which the sound produced by a loose mechanism, a loud click feedback generated by a button, or a pedal in a quiet passage compels the performer to redirect attention away from musical intent toward the device itself. Similarly, an interface that demands frequent checking, adjusting, reorientation, or constant calibration can fragment the performer's attention and compromise the quality and flow of the performance.

Perceptual Intrusiveness

Perceptual intrusiveness refers to the disruption that arises at the sensory level of interaction with a device. It describes stimuli that are too salient, harsh, or incongruous relative to the user's perceptual environment, disturbing sensory processing without requiring deliberate cognitive changes. In contrast to attentional intrusiveness, which burdens mental resources through competing informational demands, perceptual intrusiveness operates pre-attentively, altering how the interface is physically felt, seen, or heard during its operation.

As noted by McCrickard et al. (2003), “determining encoding strategies that allow rapid and efficient processing with the pre-attentive visual system is thought to decrease the impact of a notification on other tasks” (McCrickard et al., 2003, p. 511). This remark suggests that poorly designed pre-attentive sensory cues may disrupt ongoing activity by capturing attention before it is consciously processed.

In the context of a trombone-mounted interface, several factors may introduce perceptual intrusiveness, (1) tactile texture, for instance a sticky material caused by a trombonist’s sweaty hand may overstimulate tactile sensation; (2) feedback mechanisms, such as a poorly tuned button feedback; (3) visual salience, a status LED mounted near the mouthpiece that emit excessively bright light; (4) auditory feedback, such as notifications from the interface that can clash with the instrument’s acoustic output, causing involuntary sensory responses. These disruptions occur before cognitive processing, so the performer does not consciously “choose” to attend to them, as they are inherently difficult to ignore.

Temporal Intrusiveness

Temporal intrusiveness refers to how a device’s timing characteristics (such as latency, consistency, and rhythmic alignment) interfere with the natural coupling between the performer’s actions and the system’s responses. In a music performance scenario, even slight, often imperceptible delays can disrupt the physical and auditory feedback necessary for expressive control.

The systematic study of human sensory thresholds, both absolute thresholds (the minimum stimulus intensity detectable) and differential thresholds (the smallest detectable difference between stimuli), originated in nineteenth-century psychophysics. This field quantitatively analyzes the relationship between physical stimuli and sensory perception. Ernst Heinrich Weber first described the proportional relationship between stimulus magnitude and the minimum perceptible change, a principle later known as Weber's Law. Afterwards, Gustav Fechner expanded on Weber's findings, introducing the concept of Just Noticeable Difference (JND), defined as the smallest perceptible difference between two stimuli. This concept has broad applications, particularly in music, where perceptual thresholds have informed research on duration, pitch, and temporal displacement. In the context of auditory latency, Schmid et al. (2024) reports that "participants achieved a mean JND of 49 ms for a base latency of 0 ms and 27 ms for a base latency of 64 ms," noting that "base latency influences the perception threshold in a non-linear manner" (Schmid et al., 2024, p. 1). In the study, musically trained participants demonstrated greater sensitivity, detecting smaller changes than non-musicians. While these findings establish conscious detection thresholds for latency variations, they do not necessarily define the point at which latency begins to affect musical performance, raising the question: What is the minimum change necessary for something to become intrusive, musically speaking?

Jack et al. (2016), in their study of latency in digital musical instruments, report that "latency of 20 ms and $10 \text{ ms} \pm 3 \text{ ms}$ can degrade the perceived quality of an instrument, even when the amount of latency is too small to be perceived as a delay by the performer" (Jack et al., 2016, p. 116). They

further note that such conditions “degrade subjective impressions of an instrument...without significantly affecting timing performance” (Jack et al., 2016, p. 121). The study also underlines that not only the presence of latency but also its stability shapes performer experience, concluding that “this again highlights the importance of stability of latency” (Jack et al., 2016, p. 123). Temporal intrusiveness thus stems not only from absolute delay but also from temporal jitter, unpredictable timing variations that erode the performer’s sense of control intimacy, defined by Wessel and Wright (2002) as “a high degree of control intimacy . . . attained with compelling control metaphors, reactive low latency variance systems, and proper treatment of gestures that are continuous functions of time” (Wessel and Wright, 2002, p. 12). This concept is closely linked to tool transparency in embodied music cognition, where technology should “disappear” in use, giving the performer a “feeling of non-mediation” and enabling direct musical involvement with sound energy (Leman, 2007, p. 2).

This highlights an important distinction: the threshold at which latency is consciously noticed differs from the threshold at which it begins to disrupt sensorimotor control and expressive accuracy. While Schmid et al. (2024) reports a JND of 27-49 milliseconds for detecting latency, Jack et al. (2016, p. 116) shows that delays as low as 10-20 milliseconds can subtly degrade performance and reduce perceived instrument quality "even when the amount of latency is too small to be perceived as a delay by the performer". In musical interaction, the performer’s motor system relies on fast, subconscious feedback loops; even sub-threshold delays disturb this loop, leading to timing imprecision and a loss of expressive immediacy.

This is supported by Chafe and Gurevich (2004) experimental study on networked musical performance, where paired musicians clapped in time while experiencing systematically varied one-way delays. Their results revealed that both extremely low and high latencies disrupted tempo stability. Delays below ≈ 11.5 milliseconds consistently caused acceleration, while delays above ≈ 14 milliseconds led to deceleration. The most stable performance occurred at a one-way latency of ≈ 11.5 milliseconds, suggesting that a small amount of delay may align better with natural perceptual expectations, while zero latency creates an unnaturally tight feedback loop (Chafe and Gurevich, 2004, p. 6). Unlike studies that focus on individual performer-instrument interaction, such as the Jack et al. (2016), which show that latencies as low as 10-20 ms can degrade control intimacy and perceived responsiveness, Chafe and Gurevich (2004) findings concern interpersonal coordination and suggest that slight delays may help stabilize ensemble timing. Taken together, these findings emphasize that different musical contexts, solo interaction versus ensemble synchronization, have different latency sensitivities.

In a trombone-mounted interface, temporal intrusiveness spans the entire interaction chain, from capturing and processing sensor data, discrete triggering actions, and signal processing to wireless transmission and multimodal feedback. Delays in sensor capture, such as slide position or trigger button events, can impair smooth modulation long before they are consciously detected. Physical feedback mechanisms also play a role; for instance, when a button responds sluggishly or lacks tactile confirmation, performers cannot precisely estimate when a signal is sent, further disrupting control intimacy.

To preserve expressive stability, interface designers must minimize both latency

and jitter throughout the system. Empirical findings indicate that latencies in the 10-20 millisecond range already degrade perceived responsiveness, while conscious detection occurs at approximately 27 milliseconds (with 64 ms base latency) to 49 milliseconds (with 0 ms base latency) (Jack et al., 2016, p. 116); (Schmid et al., 2024, p. 325).

Aesthetic Intrusiveness

Aesthetic intrusiveness describes disruptions that happen when the visual, stylistic, and meaning-making dimensions of an interface fail to integrate coherently within a musical performance. Unlike physical or ergonomic intrusiveness, which manifests as direct bodily strain or spatial obstacle, aesthetic intrusiveness subtly alters how the performer experiences, understands, and communicates with the instrument. In performance contexts, this involves more than visual harmony with the instrument and performer's body; it includes alignment with artistic identity, preservation of epistemic clarity, and coherent audience interpretation.

Building on Haimès (2021) and Folkmann (2018), aesthetic intrusiveness in HCI can be examined through five interrelated mechanisms: (1) multisensory embodiment, (2) cultural representation, (3) reflectivity, (4) epistemic framing, and (5) aesthetic friction, which arises dynamically from the interaction of the previous ones. These concepts expand the scope of aesthetics from early HCI's narrowed notions of visual attractiveness toward a more in-depth understanding of its impact on expressive, embodied musical interaction.

Multisensory Embodiment

Early HCI often simplified aesthetics to surface-level beauty. As Haimès (2021) observes, “the word aesthetics... tends to refer to visual characteristics of an interface... broadly taken to mean beauty, which, while significant, is not its only concern” (Haimès, 2021, p. 1). Such simplifications overlook how aesthetic qualities should resonate with the full sensorimotor engagement of performers.

Properly conceived, aesthetics is inherently multisensory and embodied. It involves how artifacts feel with the touch, how they sound when manipulated, and how transparently they couple with established motor skills. As Haimès (2021, p. 4) notes through Saito’s explanation, “the aesthetic value of a knife consists not only of its visual qualities... but, most importantly, in how smoothly and effortlessly I can cut an object with it.”

In musical performance, an aesthetically non-intrusive interface merges with gestures, posture, and instrumental technique, supporting continuous performative flow. On the contrary, unsuitable textures, disruptive haptic feedback, or poor sonic affordances create sensory conflict, breaking the illusion of instrument unity and distracting from musical intention.

Cultural Representation and Meaning-Making

Design is not merely functional or material since it also operates as a medium of representation. Folkmann (2018) states that design “is always embedded within cultural and social contexts... [and] always has effect as signifying entities for a symbolic meaning equally ascribed to the solutions and referring to meaning complexes beyond themselves”(Folkmann, 2018, p. 17). Interfaces, therefore, carry symbolic references that point to values, identities, and aesthetic traditions.

Aesthetic intrusiveness arises when the representational cues of an interface conflict with the performer’s artistic identity or the cultural conventions of a performance setting. For instance, attaching a visibly improvised controller, a bare circuit board secured with duct tape and exposed wiring, to a polished orchestral trombone would visually disrupt the ensemble’s formal aesthetic. Under stage lighting, such dissonance can unintentionally shift audience focus from musical expression to the technological novelty of the visible interface. This effect may be acceptable or even intentional in experimental or avant-garde contexts, but in traditional performance settings, it undermines the intended artistic message.

Reflectivity

Folkmann (2018) introduces reflectivity to illustrate how design objects may foreground their own artificiality, for instance, “a lemon squeezer . . . may not

only encourage pleasurable use . . . but also points to its own being as a design object”(Folkmann, 2018, p. 10).

In the HCI context, reflectivity in aesthetics becomes intrusive when an interface unintentionally draws attention to itself as a technological artifact. A controller with bright LEDs may capture both performer and audience attention, shifting focus away from the sonic narrative. While deliberate self-referentiality can be valid in experimental settings, in contexts seeking transparent expressive augmentation, such reflective features disrupt immersion and undermine creative continuity.

Epistemic Framing

Design objects as interfaces for human-world interaction do more than mediate function. They structure knowledge by shaping how humans perceive, understand, and experience their surroundings. Folkmann (2018) explains that HCI solutions “create structures of how humans engage with the world and, in this way, frame what human understanding and recognition may be” (Folkmann, 2018, p. 10). This statement highlights the first epistemological role of design, which is to configure access to meaning and recognition through its aesthetic and interactive properties. The second role is more generative. Drawing on Kant’s concept of the sublime, Folkmann shows how design artifacts can disrupt habitual modes of cognition and, as Kant describes, produce an “expansion of imagination” (cited in Folkmann (2018, p. 19)), allowing experience to extend beyond ordinary comprehension. Folkmann, drawing on Seel,

explains that human creations can “bring forward otherwise unrepresentable circumstances,” offering metaexperiences in which users not only encounter the world differently but also reflect on the very nature of experience itself (Folkmann, 2018, p. 20). Epistemic aesthetic intrusiveness occurs when an interface unintentionally shifts these cognitive frames. For example, a rotary knob on a trombone slide may visually suggest a simple volume control but instead modulates multiple timbral parameters in a nonlinear manner. This does more than cause functional confusion; it reframes what a familiar gesture means and requires the performer to reconstruct instrumental knowledge. In Folkmann’s terms, this type of design actively frames engagement and recognition, creating a fundamental epistemic shift rather than a superficial usability issue.

Emergent Aesthetic Friction

Aesthetics in HCI is not a matter of isolated surface qualities but an interwoven, multisensory phenomenon that shapes interaction and decision-making. Aesthetics serves as a structuring force that configures recognition, meaning, and modes of experience. When multiple forms of aesthetic misalignment occur simultaneously, such as embodied discomfort, cultural dissonance, unintended reflectivity, and epistemic conflict, they do not simply add up as separate flaws. Instead, they interact dynamically, giving rise to what is here discussed as aesthetic friction. Aesthetic friction emerges as a system-level property that progressively alters how the performer inhabits the instrument.

Unlike a single, localized design issue, this state unfolds over time during performance. For example, a controller that feels unnatural to grip (embodiment), visually disrupts the glossy coherence of a trombone (representation), unintentionally draws audience attention to its technological artifice (reflectivity), and reframes familiar gestures into unpredictable digital transformations (epistemic), creates an evolving tension. As the performance progresses, this tension fragments performative flow and destabilizes artistic presence, forcing the musician to continually renegotiate their relationship with both instrument and audience. Drawing on perspectives of design as shaping engagement and meaning through multisensory aesthetic integration, aesthetic friction can be understood as an emergent disruption of the performer-instrument ecology. It reflects a breakdown not attributable to any single dimension of aesthetic intrusiveness but to their compounded, interdependent effects. Addressing this phenomenon requires holistic design approaches that account for embodiment, cultural meaning, reflective signaling, and epistemic framing together, ensuring that augmentation does not progressively erode expressive and experiential coherence in musical HCI.

Brass Instruments in the Electronic Era

In 1919, the Russian physicist Lev Termen, later Leon Theremin, invented one of the first music circuit instruments, the "etherphone," later coined the "theremin" in honor of its inventor (Chadabe, 1997, p. 8). It was one of the earliest electronic instruments, and its unique sound quickly caught the attention of musicians and composers, including Clara Rockmore, a virtuoso

violinist and theremin performer (Chadabe, 1997, p. 9), and Robert Moog, who went on to invent the Moog synthesizer years later. The Moog synthesizer was one of the first commercially available electronic music instruments. It featured a keyboard interface and allowed musicians to create a wide range of sounds through voltage-controlled oscillators (VCOs), filters, and amplifiers. Another significant development in electronic music was the Buchla 100 series, created by Don Buchla and Morton Subotnick in the early 1960s through the company “Buchla and Associated” (Chadabe, 1997, p. 147). The Buchla 100 series was a modular synthesizer system that allowed the creation of complex sounds and textures. These instruments, particularly the Moog synthesizer and the Buchla 100, introduced musicians to a new sound dimension through the manipulation of VCOs (Voltage-controlled oscillators), filters, and amplifiers. However, during this time, the application of such technology to brass instruments, like trombone, faced significant limitations primarily due to the size and weight of the electronic components involved. The physical bulkiness of the early synthesizers, driven by the need to house large capacitors, resistors, and early versions of integrated circuits on circuit boards, made them impractical for integration or attachment to mobile or hand-held instruments. Figure 1 shows Gordon Mumma, whose work is explored in more detail later in this study, playing one of the earliest examples of an augmented brass instrument: the Hornpipe.



Figure 1: Gordon Mumma demonstrating the Hornpipe (1967). Source: last.fm.

Terminologies and Trajectories in Hybrid and Augmented Brass Instruments

The integration of technology into acoustic instruments requires precise terminology that can capture the nature and scope of electronic modification. Gordon Mumma introduced the term cybersonics in 1950, establishing an early conceptual anchor to denote “the live-electronic processing of primarily acoustical sounds” (Mumma, 2015, p. 39). Since its inception, this concept has proliferated into a range of descriptors: hybrid, augmented, super, hyper, extended, and meta-instruments. Each emerges from specific historical contexts and embodies distinct design priorities, performance goals, and theoretical un-

derpinnings (Kallionpää and Gasselseder (2015); Newton and Marshall (2011); Rowe (1993); Miranda and Wanderley (2006)).

Bowers and Archer (2005) contributes to this discussion by highlighting four key themes that often recur in the design and conceptualization of these modified instruments: 1) *Rich Interactive Capability*, referring to the design of instruments that facilitate complex musical interactions; 2) *Detailed Performance Measurement*, where the emphasis is on capturing the nuanced gestures and actions of musicians through advanced sensing technologies; 3) *Engendering of Complex Music*, capable of facilitating the creation of intricate musical textures and compositions live, often surpassing what is possible with traditional acoustic capabilities; and 4) *Expressivity and Virtuosity*, aiming to augment the expressive range and virtuosity of performers (Bowers and Archer, 2005, p. 6).

In synthesizing these themes, the denomination of *augmented* emerges as the most appropriate term for this study. Although related terms such as hybrid, hyper, and super have established their use in the music technology literature, they carry implications that do not fully align with the performance and design preferences discussed here. Hyper and super tend to denote a generalised improvement or amplification of a capability, but without specifying the nature of that enhancement or its relationship to the instrument's existing capability. Hybrid, though widely used, can be misleading without context. Does hybrid refer to a combination of sound-production mechanisms, a fusion of materials, or a blending of purposes and functions? In acoustical contexts, it may denote an instrument that merges distinct sound-producing systems; in interactive systems, however, it can only describe the physical attachment of components

that remain functionally independent, for instance, a trigger button mounted on a trumpet that does not itself produce or modify sound. In contrast, the term augmented places the technological intervention as an extension of the inherited capacities of the instrument, gestural, sonic, or utility-oriented, while preserving continuity with its idiomatic technique and acoustic identity. This relational framework makes it especially well-suited to describe the types of system considered in this study, where the goal is to expand rather than replace the core performance practice of the instrument.

As described before, one of the pioneers and most notable figures in combining acoustic and electronic instruments in the 1950s was Gordon Mumma, an American composer, French horn player, and pianist. His work in the field of electronic music is particularly known for his innovative use of the French horn in electronic compositions. In his musical compositions, Mumma introduced the concept of “cybersonics”, which denotes the designation for “the live-electronic processing of primarily acoustical sounds facilitated by the developing electronic transistor technologies” (Mumma, 2015, p. 49). This practice incorporates a process of feeding certain aspects of the sound into the electronic system, which is then subsequently altered by characteristics derived from the sound itself. One of the most renowned examples of the use of cybersonics is “Hornpipe” :

"The cybersonic console for *Hornpipe* was a small analog-type computer and signal processor of my own design. The signal inputs to the console were two small Lavalier-type microphones to be attached to opposite sides of my belt. The line-level outputs of the console traveled by an umbilical cable to the stereophonic amplifier

and loudspeakers elsewhere in the performance venue." (Mumma, 2015, p. 56)

As Mumma explains, an essential aspect of "Hornpipe" involves the integration of both traditional and extended techniques, as well as the use of both a natural horn without valves and a modern valve horn. Furthermore, the horn sound is not generated solely by a traditional cone-shaped mouthpiece, but rather by special reeds, similar to those used in the sarrusophone instrument. The piece begins with a solo for horn, during which the "cybersonic" console actively listens and monitors the resonances of the horn in the acoustical space. The console then adjusts its electronic circuits to complement these resonances. Once enough information has been gathered, a gate opens, and the electronic "response" of the console is heard through the loudspeakers. (Mumma, 2015, p. 59)

Another exponent of this new grounded exploration is Nicolas Collins, an American composer and performer of electronic and instrumental music, who in the late 1980s developed the trombone-propelled electronic project "... consisted of a speaker driver connected to the mouthpiece of a trombone with a micro-switch panel attached to the slide. In addition, Collins controlled a collection of samplers, CD players, tape machines, and computers . . . His sound productions are occasionally picked up and modified by Collins's device, which supplies Doppler effects and synthesis modification" (Reinbolt, 1991, p. 93).

Despite limitations, analog technology fundamentally transformed musicians' approach to brass performance. The collaboration between Robert Moog and

Ben Neill on the Mutantrumpet marked a significant milestone in the evolution of brass instruments and music technology. Ben Neill, an American composer and trumpet performer, has developed over the decades the nexus between technology and music. Initially developed in the mid-1980s with the use of electronics, with significant advancements in 1992 becoming fully computer interactive, and its latest iteration in 2008 after a residency at STEIM, the Mutantrumpet is a hybrid instrument that is a “highly refined MIDI (Musical Instrument Digital Interface) controller, which enables Neill to interact with a variety of music and video software and hardware” (Neill and Jones, 2010, p. 3108). The instrument allows for a wide range of sound manipulation and exploration, expanding the traditional role of the trumpet in both composition and performance.

"Acoustically, the mutantrumpet is also expanded from the conventional trumpet design. It has three bells rather than the normal single bell, two sets of valves, and a trombone slide. The extra set of valves controls switching between the 3 bells as well as providing a quartertone valve. Frequently, different mutes are used to give each bell a distinctive timbral quality. There are two normal B flat trumpet bells, and one piccolo trumpet bell that is attached to a trombone slide, giving the capability for a true glissando. A clip-on microphone is attached to the bottom bell, this makes the acoustic sound of the instrument available for processing. The acoustic capabilities are designed with electronic performance in mind. The instrument enables acoustic generation of sonic gestures and materials such as filtering and timbral manipulation that are not

normally possible on an acoustic instrument. This produces a kind of feedback loop in which acoustic and electronic sound worlds are constantly influencing and affecting each other." (Neill and Jones, 2010, p. 3109)

Described by Morrill and Cook (1989), in the late 1980s and the early 1990s, more hybrid brass instruments were created, such as the Cook & Morrill Trumpet Performance System created for the trumpeter Wynton Marsalis, developed in 1986–1989. The newly incorporated interactions employed switches to activate prearranged motifs, move through different sections, forward and backward, and collect pitch data from the horn. This captured pitch data would subsequently serve as the basis for largely independent compositional algorithms, controlled by valve-, mouthpiece-, and bell-mounted sensors, placed on the trumpet's available spare bandwidth (Morrill and Cook, 1989, p. 2). However, as Cook observes, the mental concentration required to monitor and trigger all loop events significantly affected the playing experience (Cook, 2001, p. 2). This represents a form of cognitive overload, which this study also considers in its evaluation.

More augmented trumpets were developed along the line, such as the Meta-Trumpet by Impett (1994, p. 147), consisting of a range of physical sensors with MIDI output to be later processed by software. The Mehta Trumpet, developed by Kartadinata (2003, p. 180), implements the Gluiph, a single-board computer developed by the author, "that was conceived as a platform for integrated electronic musical instruments". As shown in Figure 2, the Mehta Gluiph Trumpet is a hybrid instrument that comprises a 2-D gyro

sensor, a mic, a small display, a trombone-type slide, and some buttons that allow one to select among different modes.

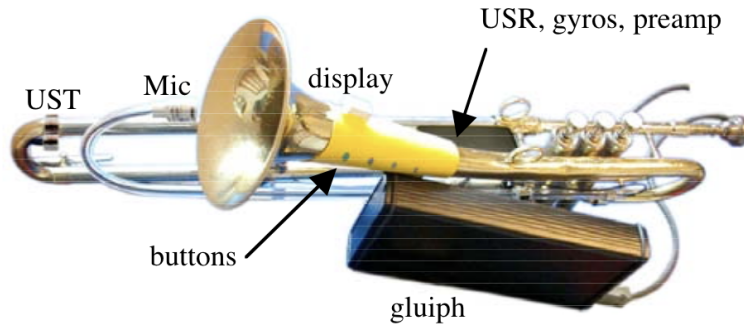


Figure 2: The Mehta Trumpet with gluiph controller (Kartadinata, 2003, p. 182).

A relevant aspect of this model was the wireless operation mode, although the downside of the batteries added considerable weight to the instrument, requiring housing the Gluiph in an extra bell belt-mounted box (Kartadinata, 2003, p. 183). Figure 3 summarizes the different attempts to augment the gestural palette of the trumpet in a chronological order.

Another notable example includes the development of the Minimally Invasive Gesture Sensing Interface (MIGSI) developed by Reid et al. (2016), which introduces non-permanent and accessible modifications, seeking “balance between minimal design and robust control” (Reid et al., 2016, p. 419). MIGSI incorporates an Easily Removable Optical Sensing System (EROSS) to track the position of the trumpet piston developed by Jenkins et al. (2013); analog accelerometers for reading pitch and roll, placed in parallel and below the trumpet case measuring left and right instrument tilt; Force Sensing Resistors (FSRs), placed in the contact points on the trumpet handguard for continuous

control, based on the premise that “. . . trumpet player has a high degree of control of their hand tension in these areas . . .” since “. . . in conventional trumpet playing, the thumb is responsible for frequent manipulation of the first valve slide, while the index and middle finger provide support for the instrument’s weight and balance on the opposite side of the valve casing. . .” (Reid et al., 2016, p. 423). Among some of the expected future improvements announced are a small number of buttons primarily for enabling and disabling the MIGSI, a more intuitive GUI for defining “behavior zones,” as well as incorporating facilities for data recording.

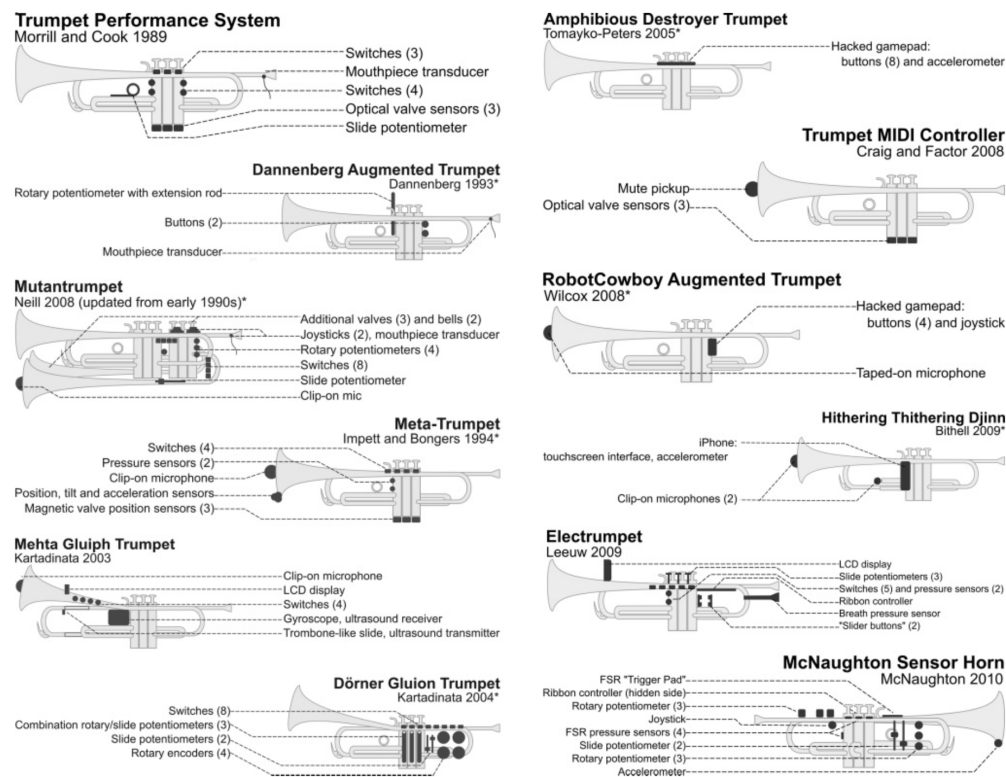


Figure 3: Examples of augmented trumpets. Source: Thibodeau and Wanderley (2013, p. 14).

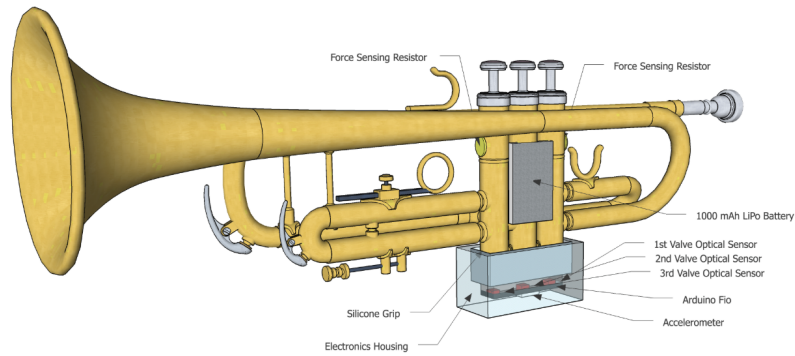


Figure 4: Preliminary MIGSI design rendering showing integrated battery and force-sensing resistors. Source: Reid et al. (2016, p. 420)

Trombone Augmentation

As evidenced by the sparse yet significant literature available to date, the exploration of technological augmentation in the trombone is a relatively new and evolving area of research. As previously noted by Cook (2001, p. 2), the feasibility of attaching sensors to a musical instrument depends heavily on the available 'spare bandwidth', areas on the instrument where additions can be made without affecting playability. Unlike the trumpet, the trombone does not have the same spare bandwidth, and the instrument body is divided into bell and slide sections (see Figure 5).



Figure 5: Assembled tenor trombone. Source: Cambridge Dictionary.

The slide—which comprises nearly half of the weight and length of the trombone body and is also in constant motion and interaction with the player—significantly limits the practical and ergonomic possibilities for modifications. As seen in Figures 6–9, most of the trombone’s spare bandwidth is located in the trombone rear section, which is out of the player’s direct contact reach during active performance. Additionally, F-valve attachments in tenor trombones and F/Gb valves in bass trombones, engaging the thumb and middle finger of the left hand, also reduce finger space and access to control mechanisms. These structural and operational characteristics of the trombone constrain the potential for integrating sensors and other technological enhancements without affecting the instrument’s traditional playing technique.



Figure 6: Main trombone spare bandwidth highlighted on the bell section.



Figure 7: Tenor trombone left-hand contact points.



Figure 8: F-attachment trombone held by both hands.



Figure 9: Left-hand contact points on a bass trombone.

The Role of Digital Luthier in Augmented Music Technology

The experimental nature of augmentation techniques has led to the emergence of specialized music technologist instrument makers who, in collaboration with performers and composers, create physical and digital modifications to their instruments and new interfaces for musical expression. Digital luthiers work closely with musicians, proposing and integrating modifications based on their ideas, desires, and possibilities based on existing technologies.

A distinguished figure in this field is Sukandar Kartadinata, an instrument maker based in Berlin with over 30 years of experience in custom instruments integrating technology. Through the development of the gluiph, a standalone system platform for integrating electronics into musical instruments (Kartadinata, 2003), and, a few years later, the introduction of the gluion, a sensor interface designed to manage complex digital I/O modules (Kartadinata, 2006), he was able to interweave electronics with handheld acoustic instruments. Browsing Kartadinata's website, one can find a wide variety of works, particularly with stringed instruments like guitars, but also tuba, trumpet, and trombone¹. For instance, the collaboration with composer Nic Collins on the "Trombone-propelled electronics" project: "What I did in this case was just a swap of the sensor interface—from STEIM's SensorLab to my Gluion. This didn't change the basic functionality of the instrument and was more of a necessity as the SensorLab became less and less supported. Here's a picture of the Gluion mounted at the end of the instrument" (Kartadinata, email to author, [July 8th, 2024])(see Figure 10).

¹ Visit Kartadinata's website in the following URL: <https://www.glui.de/wp/>

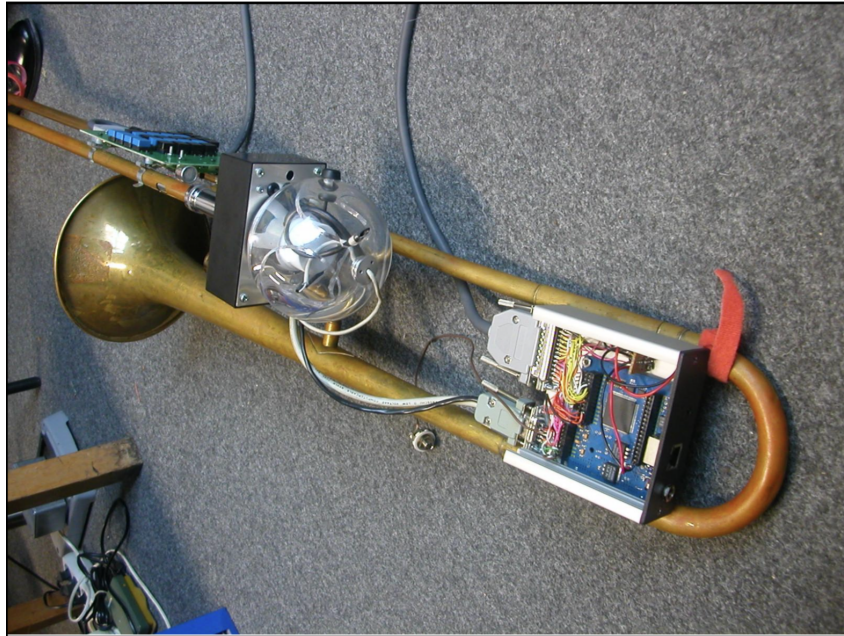


Figure 10: Trombone-propelled electronics with Kartadinata Gluion (photo provided by Kartadinata, July 8, 2024).

Another of the Sukandar highlighted projects is the result of the collaboration with German trumpet player Axel Dörner, and his augmented trumpet (see Figure 11).



Figure 11: Axel Dörner performing with augmented trumpet using Gluion (photo by Ricardo Arbiza, Satellit, Berlin, April 21, 2024).

Augmented Trombone Exploration

Efforts to augment the trombone have emerged both within research institutions and through independent artist-led initiatives. Institutional contributions include work at IRCAM's Sound Music Movement Interaction team (formerly the Real-Time Musical Interactions team), which has long investi-

gated interactive systems for performance¹. In the composition, *I will not kiss your f.ing flag*, Lemouton et al. (2006), working at IRCAM, developed an experimental system for optical detection of slide position (see Figure 12). As shown in *Using the Augmented Trombone in “I will not kiss your f.ing flag”*, the project was “dedicated to the usage of an experimental system dedicated to the optical detection of the position of a trombone’s slide” (Lemouton et al. (2006, p. 304)); see Figure 12. The motivation behind this work is fourfold: (1) “to search for a more musical, intimate relationship between an acoustical instrument and a complex electronic environment”; (2) “to trigger events and control electronic parameters”; (3) “to use the position of the slide as a source of information for a score follower”; and (4) “to eventually use data extracted from the gesture of the performer to control some global features of the electronics” (Lemouton et al. (2006, p. 304)).

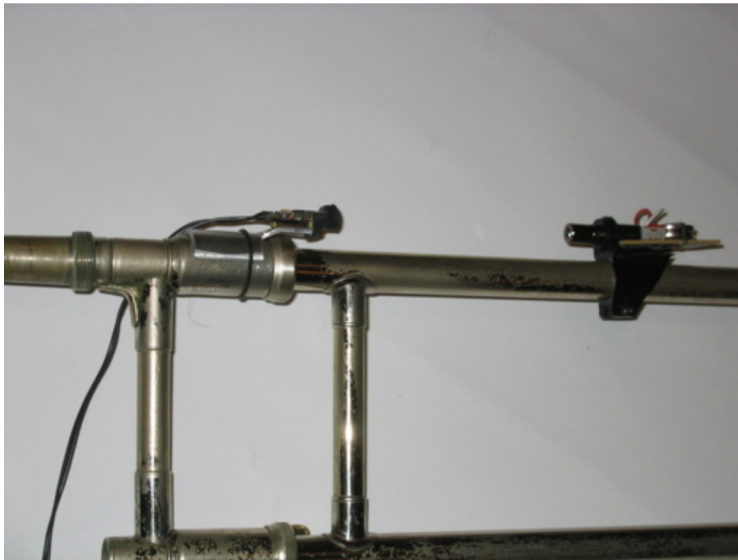


Figure 12: Slide with position sensor (Lemouton et al., 2006, p. 305)

¹IRCAM website: <https://www.ircam.fr/recherche/equipres-recherche/ismm>.

At NIME 2006, Farwell (2006) presented *Adapting the Trombone: a Suite of Electro-acoustic Interventions for the Piece Rouse* (see Figure 13, Figure 14, and Figure 15), comprising the uSlide (ultrasonic slide-position measurement), eMouth (a transducer that allows the trombone to seem self-playing), and eMute (a loudspeaker-based mute that alters acoustic output).

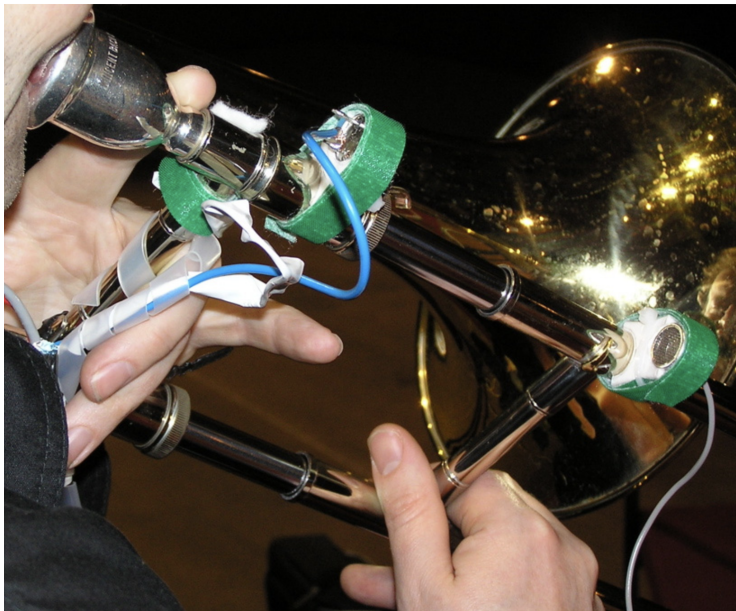


Figure 13: The uSlide transmitter. (Farwell, 2006, p. 359).

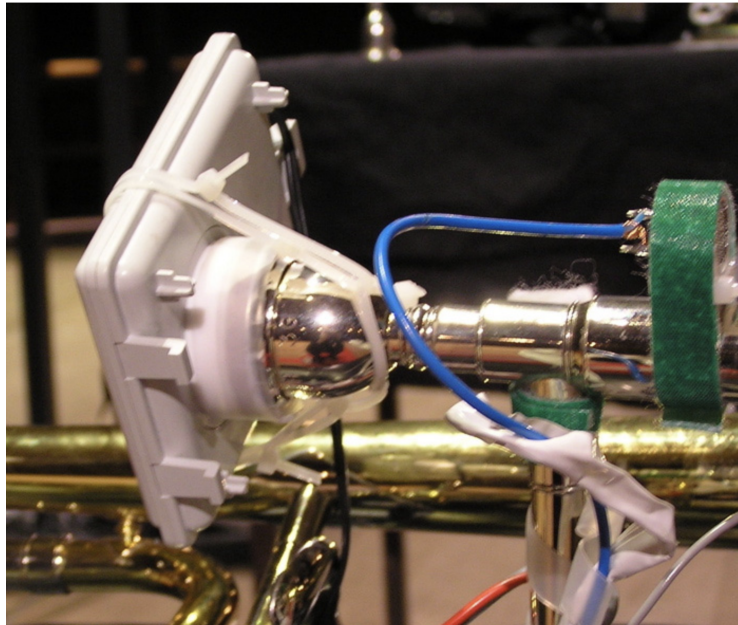


Figure 14: The eMouth assembled in the trombone (Farwell, 2006, p. 360).



Figure 15: The eMute in use (Farwell, 2006, p. 362).

Snyder et al. (2018) introduced the Feedback Trombone (FBT) (see Figure 16), which combines a bell-mounted microphone, speaker driver, and a microcontroller-based DSP system to feed processed sound back into the instrument. The authors note that the FBT is not intended as an augmented trombone in the traditional sense, but rather as a platform for a sound production technique that uses the trombone as a resonating body (Snyder et al., 2018, p. 374).



Figure 16: Feedback Trombone (FBT) performed by Jenny Beck (Snyder et al., 2018, p. 379)

More recently, West and Leung (2022) have developed the mubone. The mubone combines an orientation sensor and a handheld controller, equipped with multiple on-off buttons, into the trombone. The orientation sensor maps the instrument's spatial position through vector or geographic data, enabling expanded gesture-based control. In their implementation, the sensor data is linked to the mugranular synthesis module, a granular audio system that or-

ganizes and retrieves sound material based on spatial orientation, allowing the performer to construct and manipulate layered textures by pointing the instrument in different directions.



Figure 17: Mubone: Joy-Con controller and orientation sensor on the fine-tuning slide (West and Leung, 2022, p. 9)

Beyond academic research, independent artists have also contributed to the field of attachable trombone augmentation. The Slide Mounted Trombone Interface, created by Monique Buzzarté and Holland Hopson during the 2002 Grab Rare Arts project at Harvestworks, is an example. This fifth-generation prototype incorporated five pressure sensors, six switches, two sliders, and two accelerometers, with data collected by a BASIC Stamp II microcontroller and transmitted via MIDI to Max/MSP for real-time processing¹.

¹Extracted from Buzzarté website: <https://buzzarte.org/interactive-performance-interface/>

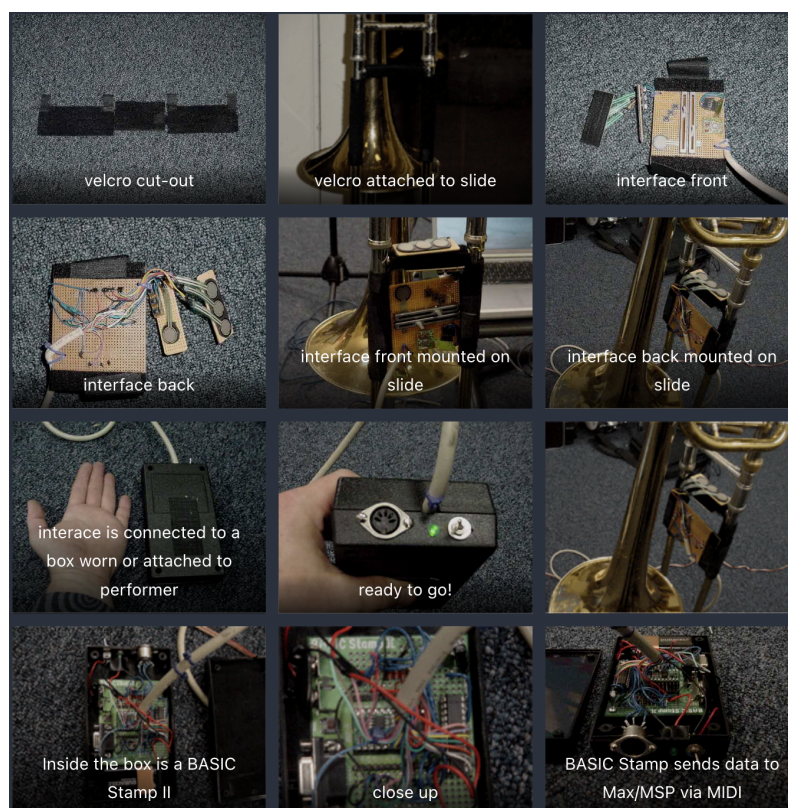


Figure 18: Components and assembly of the Slide-Mounted Trombone Interface (Buzzarté, Harvestworks project).

Across these examples, several patterns emerge. Augmentation strategies range from embedded electroacoustic systems that directly alter sound production (e.g., FBT, eMouth/eMute) to attachable sensing and control modules that interface with external processing environments (e.g., Slide Interface, mubone). Sensing methods vary from optical and ultrasonic tracking to IMU-based orientation detection and embedded transducers for actuation.

A recent contribution to this line is Smute, a smart brass mute system developed by the author to expand the timbral, musical, and performative possibilities of traditional mutes (see Figure 19). Smute consists of a 3D-printed plunger mute that integrates a smartphone, leveraging its embedded sensors,

touchscreen interface, and onboard processing to enable control through “mute gestures.” The system initially operated through the MobMuPlat platform and later transitioned to a browser-based interface for easier accessibility, cross-device compatibility via smartphone sensors, and web technologies. Smute was presented at the IRCAM Forum 2022, hosted by NYU, and a demonstration of the system is available online.¹

¹Smute demo available at: <https://youtube.com/shorts/ihCAysCCeC4>



Figure 19: Smute: 3D-printed plunger mute with integrated smartphone interface.

While these projects illustrate the expanding possibilities of trombone augmentation, evaluation methods across this field remain inconsistent. Reporting on ergonomics, attentional load, latency, and long-term playability is often limited—factors that are central to understanding intrusiveness in a performance context. These gaps motivate the methodological framework of the present

study, which draws on broad survey-based insights from the trombone community and, later, structured and representative performance tasks to explicitly address physical, ergonomic, cognitive, and attentional intrusiveness.

CHAPTER III

METHODOLOGY

This study employs a three-phase Sequential Explanatory Mixed-Methods approach as described by Creswell and Plano Clark (2018) (Creswell and Plano Clark, 2018, p. 77), integrating quantitative and qualitative data to examine the perceived intrusiveness and usability of interactive trombone technologies. Phase One collects broad, survey-based metrics on participants' demographics, practice habits, and general intrusiveness ratings for trombone-mounted devices; Phase Two conducts hands-on, iterative device trials and weight-threshold assessments; and Phase Three evaluates a fully integrated NIHCI-based prototype in ecologically valid performance contexts. This study adopts a User-Centered Design (UCD) approach, framed under ISO 9241-210:2010, *Human-centred design for interactive systems*, which sets out internationally recognized principles for systematically embedding user perspectives throughout all design stages. The UCD framework is incorporated throughout this sequence, engaging participants in successive Understand–Observe–Synthesis–Ideation–Prototyping & Testing–Implementation cycles. This methodology has been widely adopted in HCI, including in the design of digital musical instruments and interactive performance systems (Norman and Draper, 1986; Bongers, 2000; Morreale et al., 2014).

The International Organization for Standardization (ISO) publishes standards for best practices across domains. Within its ISO 9241 series, titled *Ergonomics of Human-System Interaction*, Part 210, *Human-Centred Design for Interactive Systems*, provides a framework for integrating human-centred design (HCD) across the life cycle of computer-based products and services (International Organization for Standardization (ISO), 2010, pp. 1–2). ISO 9241-210 requires that both hardware and software components be conceived and evaluated around user needs, tasks, and environments, addressing projects from initial conception through implementation, evaluation, and maintenance (International Organization for Standardization (ISO), 2010, p. 1).

ISO 9241-210 defines seven guiding principles (International Organization for Standardization (ISO), 2010, Clauses 4.1–4.7). These require an “explicit understanding of users, tasks and environments” (International Organization for Standardization (ISO), 2010, p. 5), state that “users are involved throughout design and development” (International Organization for Standardization (ISO), 2010, p. 5), and prescribe an “iterative” process to “progressively eliminate uncertainty” (International Organization for Standardization (ISO), 2010, p. 6). The standard also specifies four high-level HCD activities (International Organization for Standardization (ISO), 2010, Clauses 6.1–6.5): (1) understanding and specifying the context of use, (2) specifying user requirements, (3) producing design solutions, and (4) evaluating the designs (International Organization for Standardization (ISO), 2010, pp. 10–19).

Each activity produces concrete deliverables—context-of-use descriptions, user-requirements specifications, prototypes, and evaluation reports—ensuring traceability and accountability. The planning requirements (International Organi-

zation for Standardization (ISO), 2010, Clauses 5.2–5.5) mandate that HCD tasks be integrated into the overall project plan, with defined responsibilities, allocated resources for iteration, and milestones for formative and summative evaluation (International Organization for Standardization (ISO), 2010, pp. 8–9). This framework prevents usability from being treated as a late-stage add-on.

Figure 20 illustrates the interdependence of ISO 9241-210’s HCD activities, showing how evaluation results can prompt revisions to context descriptions or requirements, and how emerging prototypes may uncover new user constraints that feed back into planning and contextual inquiry.

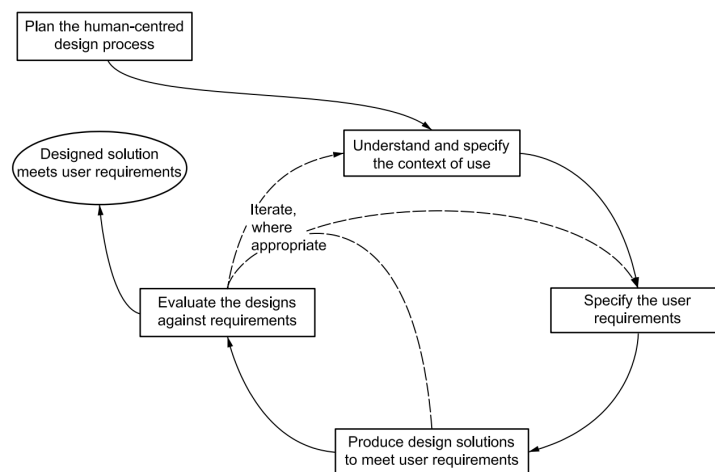


Figure 20: Interdependence of human-centred design activities. Extracted from ISO 9241-210:2010(E) (International Organization for Standardization (ISO), 2010, p. 11).

UCD Methodology Overview

The study comprises three phases, each corresponding to a stage of the User-Centered Design (UCD) process. Phase One comprises an online survey of experienced international trombonists that collects demographic information, performance practices, intrusiveness ratings of commercially available attachment devices, and perspectives on technology integration during musical tasks. This phase aligns with the Understand and Observe stages of UCD, as it gathers qualitative and contextual data to identify user needs and challenges. Phase Two involves in-person iterative testing sessions, where participants engage with low-level input devices, followed by completing weight sensitivity trials to assess usability and perceived intrusiveness across controlled musical tasks. This phase corresponds to the Synthesis, Ideation, and Prototyping & Testing stages, translating insights from Phase One into interface configurations refined through user feedback. Phase Three centers on the evaluation of an NIHCI-based prototype in ecologically valid performance contexts, capturing intrusiveness ratings, experiential feedback, and implications for musical expression. This phase reflects the *Implementing* stage of UCD, where the system is deployed and validated through near real-world scenarios.

UCD in this study emphasizes user interaction and continuous feedback, aligning with the dynamic and iterative nature of human-computer interaction, where, as seen in Figure 21, “sensory, cognitive, and motor functions continuously interact with technological interfaces, such as screens, sensors, and speakers, through channels like sight, sound, and movement” (Bongers, 2000, p. 45).

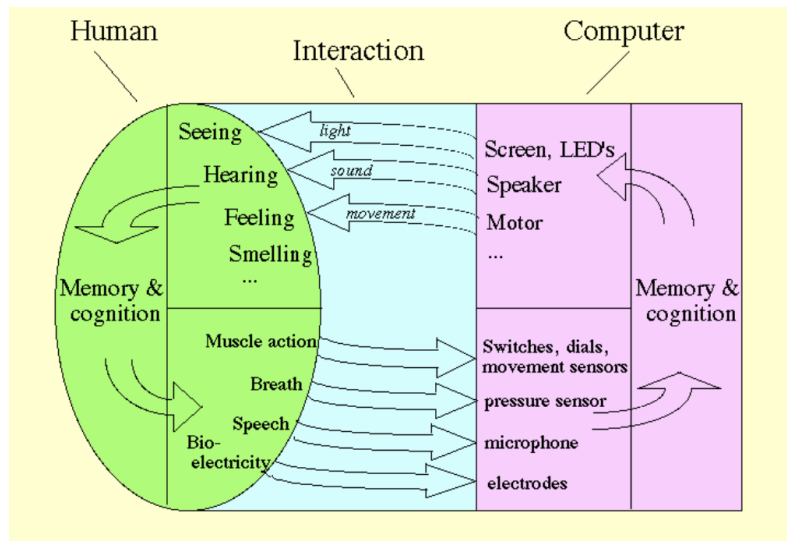


Figure 21: Multimodal Interaction Between Human and Computer. Extracted from Bongers (2000, p. 45).

The rationale for adopting UCD lies in maintaining a structured feedback loop between users and technology. Originated in HCI, UCD places users at the center of the design process, enabling developers to create systems that respond to stakeholder needs and improve user experience (UX) (Lowdermilk, 2013, p. 13). As Schuler and Namioka (1993, p. 111) observe, "...although user feedback is a very limited form of participation, the lack of it is among the greatest hindrances to good product interface design and among the least recognized defects of standard software development processes", a point that resonates with Steve Jobs's remark in a 1998 Bloomberg Business Week interview: "It's really hard to design products by focus groups. A lot of times, people don't know what they want until you show it to them" (Lowdermilk, 2013, p. 2). This study adopts a balanced level of stakeholder involvement across all three phases. Through its UCD orientation, performer input shapes the evolving interface rather than serving as post-hoc validation.

The structure of these three phases is also informed by current explorations in music interaction research for more systematic and multidimensional evaluation methodologies. A meta-review by Brown et al. (2017) critically examines 132 papers from the NIME, SMC, and ICMC conferences and identifies a predominant reliance on narrow usability metrics and aesthetic judgments. While ease of use, ergonomics, and visual design remain central, their study argues that the field frequently neglects core dimensions of user experience that could reveal deeper performer-instrument relationships (Brown et al., 2017, p. 1). These overlooked dimensions include motivation (what drives a participant's decisions and behaviors), frustration (barriers and hindrances during interaction), and enchantment (the affective attachment developed toward a technological artifact). Furthermore, Brown et al. (2017) advocate the inclusion of broader UX measures such as emotion (subjective affective responses), engagement (experiences of flow, intrinsic interest, and curiosity), enjoyment (hedonic qualities of the interaction), aesthetics (appeal, taste, and expressive potential), and generic UX (holistic impressions not reducible to a single metric) (Brown et al., 2017, p. 2). The alignment of this study's methodological arc with that expanded UX framework aims not merely to evaluate function, nor interface efficiency, but to assess the rich spectrum of subjective experience and embodied response.

In response to these findings, Phase One of the study implements an extensive online survey comprising nine sections that collects data on demographic background, musical training, and the perceived intrusiveness of commonly used trombone attachments, while also eliciting participants' perspectives on technology integration in regular practice. It serves not only to collect rep-

representative quantitative input but also to reveal preliminary experiential patterns, namely, how trombonists articulate their interactions with technology across ergonomic, aesthetic, and functional domains.

Phase Two transitions into hands-on, in-person interaction and is subdivided into three complementary parts. The first component, the Affective Assessment (a subjective device evaluation), explores and rates a selection of four different categories of low-level human input devices (1. buttons, 2. joysticks, 3. sliders and encoders, and 4. force sensing resistor) based on their tactile feedback, size, ease of use, attractiveness, and perceived compatibility with trombone performance. In the second part, participants temporarily configure these selected devices in different positions on the trombone and test a selection of them in three common musical tasks: (1) an *étude*, (2) a sight-reading passage, and (3) a free improvisation passage or a piece of the participant's choice. Each configuration is evaluated in terms of intrusiveness, playability, and subjective fit, allowing a comparative analysis based on lived interaction. The third component consists of a Just Noticeable Difference (JND) assessment, in which participants experience 1% incremental trombone weight additions, identifying perceived absolute and differential weight thresholds at which these additions become perceptible and subsequently intrusive.

Phase Three corresponds to the evaluation stage and involves an NIHCI-based prototype mounted on participants' trombones (single tenor or F-attachment). The prototype is a representative outcome of the iterative framework developed in earlier phases. Participants complete four musical tasks and a comparative weight trial involving commercially available devices. They then complete a structured questionnaire informed by the Repertory Grid Technique (RGT),

rating interface features across bipolar constructs derived from performer perspectives and experiential themes identified in Phase One using a 0–10 Likert scale. This phase reflects the *Implementing* stage of UCD, in which the interface is assessed for its impact on musical expression, usability, physical interaction, and cognitive load.

Recruitment Criteria for Study Participants

The main inclusion criteria are participants above 18 years old, with five or more years of trombone experience, and currently active as performers. These criteria align with Easterby-Smith (1980, p. 4) observation that “it is important to ensure that all the people are able to relate directly to the elements specified”. Although Easterby-Smith (1980)’s suggestion refers to elements within the RGT method, the rationale extends to participant selection, as experienced performers are more likely to understand and engage effectively with the prompts and method. Experienced musicians possess a deeper, more nuanced understanding of musical instruments.

Sample Size

According to Lowdermilk (2013), the number of participants should be determined by the study’s objectives, noting that “the mix far outweighs the quantity” (Lowdermilk, 2013, p. 79). In usability testing, this means prioritizing diversity of user profiles over sheer numbers, ensuring that feedback remains grounded in real-world contexts. Drawing on Jakob Nielsen’s founda-

tional work, Lowdermilk (2013, p. 79) further explains that “the first five users will discover most usability errors” (Lowdermilk, 2013, p. 79). As illustrated in Figure 22, beyond this threshold, the rate of new findings quickly flattens, making small but varied samples effective for iterative design refinement. This principle is directly applicable to Phases Two and Three, where the focus is on identifying and resolving usability and interaction issues.

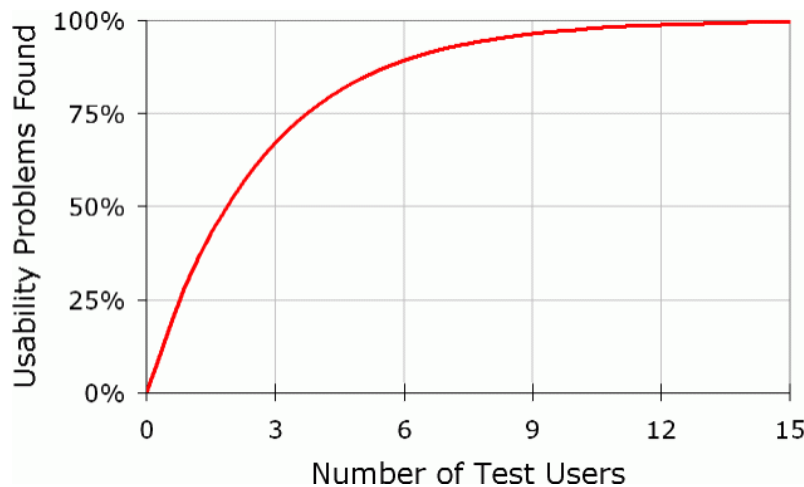


Figure 22: Usability problems found per number of users studied (Source: Nielsen Norman Group). Extracted from Lowdermilk (2013, p. 80).

In contrast, Phase One—the large-scale online survey—was designed to capture representative perceptions and practices across the trombone community. Here, a larger sample was necessary to support stable parameter estimates and allow subgroup analyses. Following Sauro and Lewis (2012) methodological guidance for estimating means in user experience research, a standard deviation of 2.5 was conservatively assumed for the 0-10 Likert-type items in the absence of pilot data. Using their recommended formula, with $z = 1.645$ for a 90% confidence level and a desired margin of error (d) of 0.5, the required sample size was calculated as:

$$n = (z \times s/d)^2 \approx (1.645 \times 2.5/0.5)^2 = 67.6 \quad (1)$$

After rounding up, the study set a minimum target of 68 participants. Finally, to strengthen representativeness, the study aimed for at least 100 responses. While Phases Two and Three rely on smaller, targeted groups for in-depth iterative testing, the broader scope of Phase One required this larger N to support meaningful, statistically grounded insights.

Phase Two required a focused engagement with low-level components in different musical scenarios. A target of 20 participants was set to balance the diversity of physical interaction profiles with the practical needs of iterative device testing. This number also reflects the use of two trombone types (single tenor and F-attachment), so each condition is tested with enough headroom to detect usability variations across configurations.

Phase 3, which involved the ecological evaluation of an NIHCI prototype developed from findings in previous phases, was limited to 10 participants. This decision follows Lowdermilk (2013, p. 79), who argue that “the first five users will discover most usability errors” (Lowdermilk, 2013, p. 79), and doubles this benchmark to account for both trombone types. At this stage, the objective is depth rather than breadth, to capture experiential feedback under ecologically valid performance conditions.

Scoring System

Participants rated the perceived intrusiveness on a scale from 0 to 10, with pre-defined categories as follows: Non-Intrusive (0-3), Minimally Intrusive (4-7), and Intrusive (8-10). This scoring system has been used consistently throughout all phases of this study.

Phase One: Online Survey

Phase One consisted of an online survey that collected responses from 128 professional trombonists, doubling the anticipated minimum required for stable descriptive estimates. The primary objective was to capture baseline data on perceptions of intrusiveness related to a range of commercially available trombone attachments, alongside general background and individual experiences in the integration of technology into performance practice. Recruitment targeted a broad international population through multiple channels: the International Trombone Association (ITA) and its affiliated societies—including the Association des Trombonistes Français, Brazilian Trombone and Tuba Association, British Trombone Society, Finnish Trombone and Tuba Association (SUPA-TUS), Hong Kong Trombone Association, Hungarian Trombone and Tuba Association, Internationale Posaunen Vereinigung (Germany), and the Spanish Trombone Association. Further dissemination occurred via music schools, conservatories, university departments, and on social media brass musician communities.

Survey Design and Instrument Structure

The online survey (see Appendix A) was guided by the methodological approach outlined by Magnusson and Hurtado Mendieta (2007) in *The Acoustic, The Digital, and The Body: A Survey on Musical Instruments*, adapting its principles to the context of trombone ergonomics and the development of an NIHCI framework design. The survey comprised nine structured sections:

1. Consent and Eligibility: Participants confirmed informed consent and compliance with the inclusion criteria (age over 18, minimum of five years of trombone experience).
2. Demographic and Background Information: Recorded age, gender, country of residence, and professional profile to allow subgroup analyses across geographical, cultural, and career contexts.
3. Musical Training and Performance Experience: Documented formal education, primary music genres performed, performance frequency and contexts, typical venues, and solo or ensemble configurations. This information contextualizes device acceptance and ergonomic needs within specific performance settings.
4. Music Technology Background: Assessed formal training in music technology, comfort with technological tools, and experience with DAWs, real-time processing, or relevant programming languages. This section establishes baseline familiarity, adoption barriers, and user preferences to inform design refinements.

5. **Technology Integration in Music Practice:** Explored current and preferred uses of technological devices in musical and ancillary contexts (e.g., microphones, processors, tuners, page-turning devices). It also examined attitudes toward future integration, identifying user expectations and perceived value.
6. **Daily Use of Technology and Technical Skills:** Investigated familiarity with smart devices, operating systems, connectivity, and general technical competence. These responses identify ubiquitous technologies embedded in users' routines and potential pathways for non-intrusive integration.
7. **Trombone Ergonomics and Playability:** Examined use of ergonomic aids and attached devices, as well as openness to temporary or permanent attachments. Participants identified preferred and unacceptable placement areas and reported perceived effects on balance, weight, technique, and finger mobility. These data narrowed possible device characteristics and attachment locations to realistic configurations for Phase Two.
8. **Intrusiveness Assessment of Existing Attachments:** Participants evaluated common accessories—clip-on microphones, PiezoBarrel systems, mutes, braces, grips, pencil holders—using a 0–10 intrusiveness scale with free-text rationales. This section disentangled factors contributing to perceived intrusiveness, including weight, placement, size, and design features.
9. **Future Technological Needs and Preferences:** Open-ended questions invited perspectives on desirable augmentations that could extend trom-

bone performance without compromising playability or comfort. These responses generated performer-derived constructs and bipolar dimensions that inform the Repertory Grid Technique (RGT) employed in Phase Three.

Phase Two: In-Person Trials

Phase Two consisted of an in-person study with a targeted sample of 20 experienced trombonists (≥ 5 years of experience), designed to translate the broad constraints and preferences identified in the initial survey into tangible ergonomic and experiential insights. The main goal was to assess the feasibility and interaction potential of a series of low-level input devices when physically integrated in the trombone. As Miranda and Wanderley (2006) observe, designing effective musical augmentations requires “careful consideration of the specific gestures used by the performer,” noting that “the design of the device depends on the gestures to be used. For example, consider the type of feedback available to the performer: in a manipulation gesture, the forces involved may vary significantly depending on the type of grip (e.g., precision or force)” (Miranda and Wanderley, 2006, p. 12). Building on this principle, this phase aimed to explore how musicians interact with a curated selection of input devices (which included buttons, sliders, encoders, and force-sensitive resistors), and how these mechanisms align with core trombone technique.

This stage also aligns with the broader trajectory in HCI research towards more holistic evaluation frameworks. Kaye (2007) describes this as “a growing trend in HCI research towards experience-focused rather than task-focused

evaluation methods, providing a shift in focus away from productivity environments and from evaluation of efficiency to evaluation of affective qualities” (Kaye, 2007, p. 1662). In the current study, such a shift is operationalized through structured tasks that simultaneously test the practical usability of input devices and capture performers’ affective-experiential and ergonomic feedback. The resulting evidence base supports ISO 9241-210’s guidance that user-centred evaluation must iteratively refine solutions by systematically considering the context of use, tasks, and user characteristics (International Organization for Standardization (ISO), 2010).

Phase Two Study Design and Subcomponents

Phase Two was structured around three interlinked subcomponents: 2.1 Affective Assessment, 2.2 Input Device Configuration, and 2.3 Just Noticeable Difference (JND) Assessment. Each addressed a distinct dimension of the design’s impact on usability and performer experience. Phase Two was conducted at the NYU Research Audio Lab, located at 35 W 4th St, 6th floor, in a controlled environment configured to minimize external distractions. The room included a table displaying all input devices sorted and labeled, two trombone models (a single tenor and an F-attachment trombone) marked with rule tape at three predefined grip positions, a chair, a music stand, and a 13-inch iPad Pro tablet displaying the musical material and procedural instructions (see Figure 23).



Figure 23: Research Audio Lab, Steinhardt, 6th Floor: Room setup showing input device table, trombone, music stand, instructional tablet, stand with a white board for grip picture, and evaluator computer. Wide-angle view.

Input Device Organization and Catalogue

Each input device was organized following a standardized ID and descriptor system for categorization and traceability (see Table 1) as follows:

- ID Structure: T-XX-FB-YY

where T (Type): Indicates the general category of the Input device (see Table 1), XX (Size Category) classifies Input Devices based on their size (see Table 2), and YY (Sequential Number) acts as a unique identifier assigned

sequentially within each category.

Table 1
Input Device Categories

Symbol	Type
TS	Tact Switch (includes buttons and push switches)
JS	Joystick
CC	Continuous Control (encoders, potentiometers, and sliders)
FSR	Force-Sensitive Resistors

Table 2
Size Categories

Symbol	Size	Dimensions Range
S	Small	< 10 mm
M	Medium	10–20 mm
L	Large	> 20 mm

Table 3
Feedback Mechanisms

Symbol	Mechanism	Description
C	Clicky	Tactile feedback with an audible click.
S	Soft	No click; smooth press.
N	None	Passive input (no mechanical feedback).
P	Pressure-Sensitive	For force-sensing resistors (FSR).
R	Rotational Resistance	For potentiometers and rotary encoders.

Where, for instance:

- TS-S-C-03: A Tact Switch (TS), Small size (S), Clicky feedback (C), and the 3rd item in the category.

- JS-M-N-02: A Joystick (JS), Medium size (M), No feedback (N), and the 2nd joystick in the list.
- CC-L-R-05: A Continuous Control (CC), Large size (L), Rotational Resistance (R), and the 5th continuous control Input Device.

Along with the input devices, an ESP-32 C3 microcontroller (by Espressif Systems) was acting as a processing hub, and two different types and dimensions of Li-Po batteries, a 180 mAh and a 150 mAh (both 3.7 V). Figure 24 shows all the input devices tested in the trial and arranged on a table for easy access to participants. Table F.7, Table F.8, Table F.9, Table F.10, and Table F.11 show all the input devices' features used in this study.

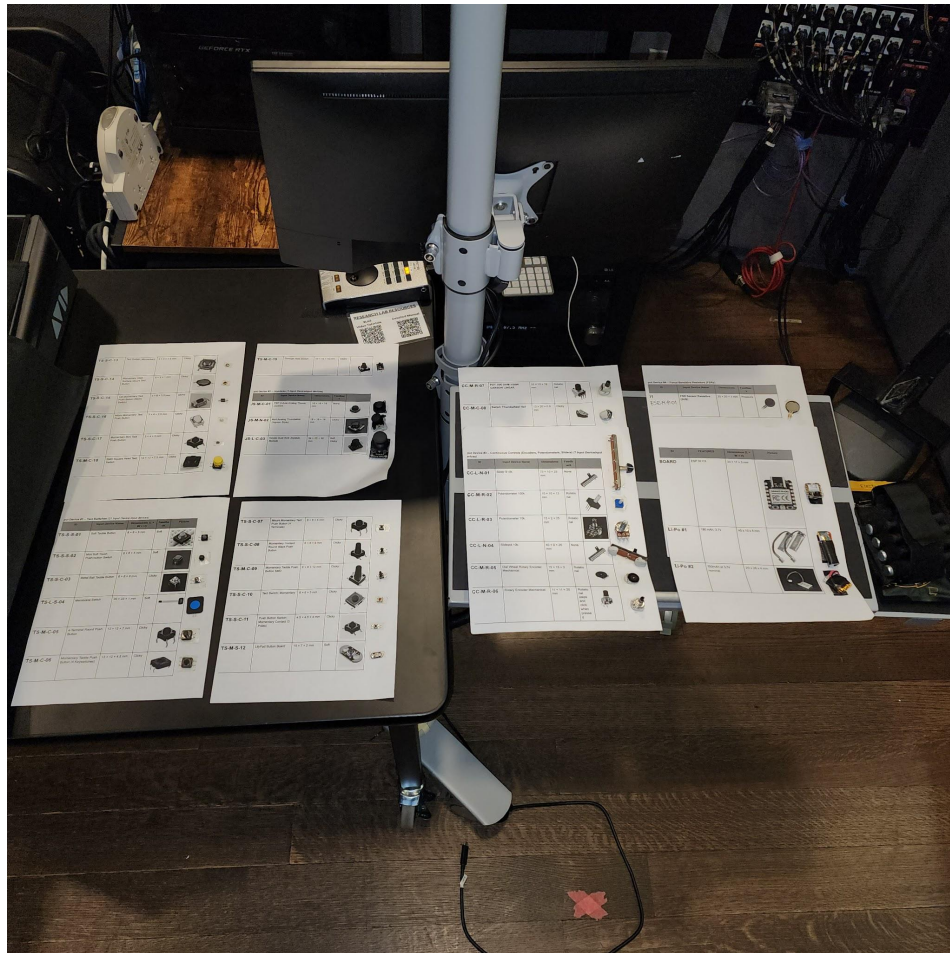


Figure 24: Input devices, board, and battery sheets arranged on the table in front of the participant for Phase 2.1, for ease of access.

Phase 2.1 Affective Assessment

Phase 2.1 employed an affective assessment to explore how a range of input devices (later IDs) were subjectively evaluated before placing them in the trombone. This approach builds on the conceptual foundation laid by Rosalind Picard, who coined the term affective computing as “computing that relates to, arises from, or deliberately influences emotions” (Thompson and McGill,

2015, p. 3713); (Picard, 1997, p. 3). This notion has shaped a significant domain within HCI, recognizing affect as integral to user experience and system design. Picard (1997) clarifies that “emotional” and “affective” are used interchangeably to describe both physical and cognitive aspects of emotion, while the term *sentic* may refer more specifically to physical expressions of affective states. Within this perspective, affective states, momentary or maintained, influence how users perceive, trust, and interact with technological systems (Picard, 1997, pp. 114–16).

Thompson and McGill (2015) describes affective HCI as an approach that “facilitates more intuitive, natural computer interfaces by enabling the communication of the user’s emotional state,” marking a shift from purely task-oriented systems to environments that support “the motivational and affective goals of the user” (Thompson and McGill, 2015, p. 3712). While affective computing treats affect as an interaction signal, the present study adopts an evaluative interpretation, where affect refers to users’ experiential and hedonic appraisal of interaction qualities rather than computational sensing or modeling of emotional state. In recent decades, HCI research has expanded traditional usability metrics to include affective and experiential dimensions. Höök et al. (2011) observe that “there are a number of psychometric assessments that have been developed specifically for the purpose of assessing users’ affective responses to computer-based systems” (Höök et al., 2011, p. 691). Such self-report measures, whether context-generic or HCI-specific, capture dimensions such as pleasure, arousal, hedonic tone, and perceived control. Although instruments like the PANAS, which quantifies self-reported positive and negative emotional states, and the Self-Assessment Manikin (SAM), which uses simple images to

rate feelings such as pleasure and arousal, remain widely used, Höök et al. (2011) emphasize that “more recently there have been efforts to extend the view of users’ affective experiences and the weight given to this construct in assessments of usability,” including trust, flow, and perceived enjoyment (Höök et al., 2011, p. 692).

Following these principles, Phase 2.1 implemented a systematic affective evaluation of prospective IDs before placement trials. Participants explored each ID and rated it on a 0–10 Likert scale for tactile feel, size appropriateness, visual integration with the trombone, perceived ease of use, and overall impression. Collecting feedback across these different dimensions of affective response also provides insight into which aspects may carry the most significant weight for trombonists when evaluating the affective aspects of a trombone interface. The affective assessment aligns with the broader shift described by Kaye et al. (2007), who note “a growing trend in HCI research towards experience-focused rather than task-focused evaluation methods . . . from evaluation of efficiency to evaluation of affective qualities” (Kaye et al., 2007, p. 1662). Within this context, subjective impressions of tactile feel, visual integration, and intuitive manipulation were treated as pertinent factors in defining the acceptance of any augmentation intended to coexist with standard trombone technique.

Instructions and Evaluation Protocol

Each participant began with an open-ended tactile exploration, systematically reviewing four categories of input controls: (1) Tact Switches, (2) Joysticks, (3) Continuous Controls (including encoders, potentiometers, and sliders), and (4)

Force-Sensitive Resistors (FSRs). Participants were instructed to consider each ID's mechanical properties, such as its mechanism, shape, tactile feedback, and suitability for anticipated placement on the instrument, while mentally simulating typical trombone performance tasks.

Immediately after handling each ID, participants completed the feedback questionnaire 2.1 (see Appendix B) to record their subjective impressions. The form comprised five core dimensions, each rated on a standardized 0–10 scale:

- Tactile Feel: smoothness, resistance, and texture in relation to trombone performance.
- Size Appropriateness: comfort, accessibility, and ergonomics during play.
- Visual Appeal: aesthetic congruence with the trombone's design.
- Ease of Use: intuitiveness, control precision, and effort required to activate during music performance tasks.
- Overall Impression: integrative judgment of ID suitability.

Participants were asked to rank each input device along with brief written reflections for those cases where additional qualitative context about preferences or concerns was required. These reflections served to contextualize the quantitative ratings, providing insight into how participants weighted and integrated the individual criteria when forming their overall impressions.

Phase 2.2: Input Device Configuration

Participants evaluated the ergonomic feasibility of multiple configurations of human input devices (IDs), a processing hub, and batteries on designated grip areas of the trombone. All components remained unplugged and unpowered to isolate physical placement factors from electronic behavior. Temporary attachment used double-sided tape (and in some cases tack putty adhesive) for a quick reconfiguration without damaging the instrument surface or hindering slide mechanics.

Each participant arranged the selected IDs—from the prior affective assessment (2.1)—together with the ESP32-C3 microcontroller and one of two LiPo battery options. This process examined how placements across different IDs affected balance, grip stability, and maneuverability under different playing scenarios. Participants performed short musical tasks such as études, sight-reading excerpts, and free improvisation/piece of choice, to reflect representative trombone techniques (see the music materials employed in Appendix C).

Participants chose either a single tenor trombone or an F-attachment model, both prepared with rule tape indicating possible mounting posts established during Phase One. Survey responses from Phase 1 confirmed the left-hand grip region as the primary area for device placement due to its relative stability. The right-hand slide was excluded due to its continuous motion and primary pitch-control function. Configuration trials were therefore restricted to the three grip posts.

Before placing the ID(s), each participant identified a suitable placement for the processing hub and battery. The selected microcontroller (a Seed Stu-

dio ESP32-C3 (Figure 25)) served as the central processing node for actuator connectivity and wireless routing. This module integrates a 32-bit RISC-V single-core processor operating up to 160 MHz and supports Wi-Fi and Bluetooth 5 Low Energy for low-latency transmission of MIDI, OSC, or ID data. Its compact form factor (21×17.5 mm) allows discrete integration within the grip region without interfering with slide handling. The ESP32-C3 has been documented in wearable and unobtrusive music computing, including wireless augmentation and embodied control applications (Ye et al., 2024; Fender et al., 2023).



Figure 25: ESP32C3 (Seed Studio) size reference.

After choosing the hub placement, participants selected between two LiPo batteries (Figure 26): a 180 mAh cell ($45 \times 10 \times 5$ mm) or a 150 mAh cell ($20 \times 26 \times 4$ mm). Each delivers a nominal output of 3.7 V and balances compact size with sufficient capacity to sustain typical performance durations of one to two hours. This secures a stable current for continuous Wi-Fi and BLE operation, which is necessary for OSC or MIDI protocols. Cells with lower capacity would risk insufficient peak current under simultaneous radio transmission,

increasing the likelihood of voltage drop and transmission latency. Once the core ID(s) topology was established, participants moved on to testing IDs in place in different music scenarios.

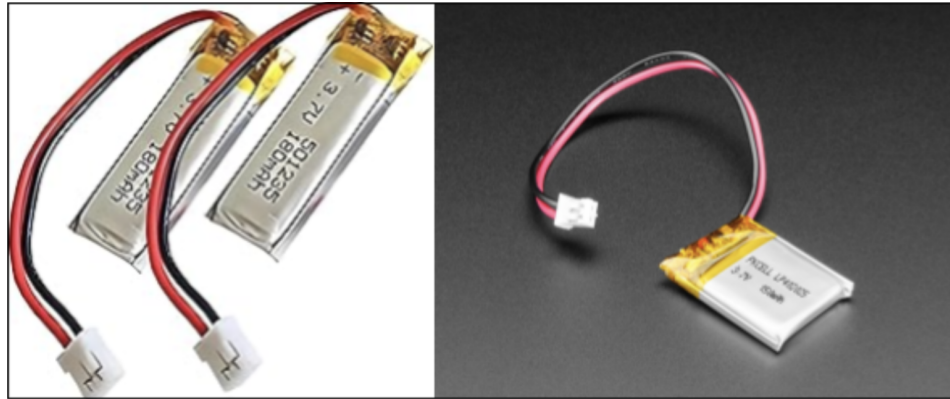


Figure 26: Right: 180 mAh LiPo battery; left: 150 mAh LiPo battery.

Informed Exclusion and Placement Selection for Phase Two Trials

Phase One survey responses, particularly Questions 37 to 40 (see Appendix A), showed strong consensus that the trombone's right-hand slide grip is unsuitable for mounting input devices. Participants cited the slide's continuous motion, the fine intonation adjustments it requires, and its sensitivity to added weight as reasons attachments were unacceptable. The slide's weight distribution also changes significantly across positions: a mass of approximately 10 g near trombone's first position produces far less torque than the same mass extended to seventh position, where increased distance from the player's grip amplifies

its perceived effect. Reduced finger availability and mechanical bandwidth during performance further limit the slide grip as a viable attachment place.

In contrast, participants identified the left-hand grip as the most appropriate location. Its static holding function provides a stable anchor point for IDs while allowing tolerable manipulation without compromising playability.

Based on these findings, Phase 2.2 restricted placement trials to three predefined posts along the left-hand grip. Each post was marked with rule tape for precise position recording. Post 1 corresponded to the highest point near the slide lock; Post 2 was located along the longitudinal section of the main grip shaft; and Post 3 was positioned at the lower junction connecting to the bell section.

Each ID placement was measured in centimeters and recorded using polar coordinates relative to each post's geometry. A standard orientation was applied, with 0° defined as the top outermost point of each post (see Figure 27).

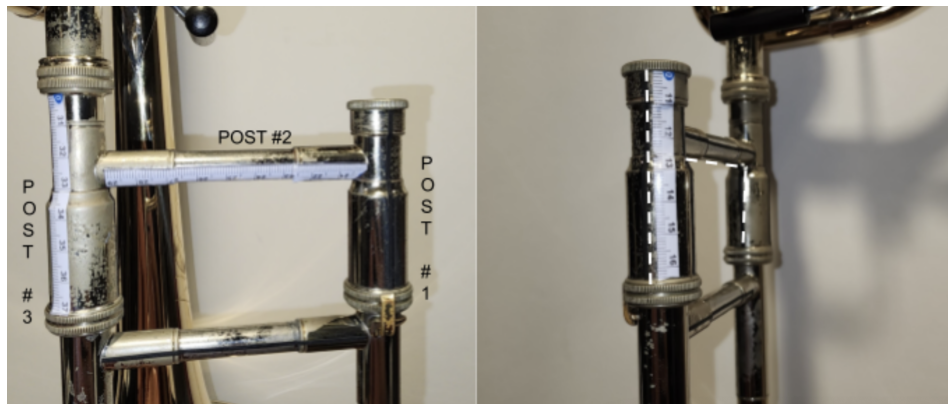


Figure 27: F-attachment trombone with rule tape marking the three grip posts and reference lines at 0° , 90° , 180° , and 270° (white dotted line denotes 0° reference).

Single ID Configuration

Participants began by placing one ID per category (preferred Tactile Switch, Joystick, Continuous Control (encoder/potentiometer/slider), and Force-Sensitive Resistor (FSR)). Each device was tested in up to three placements along the designated left-hand grip area, and each placement was evaluated across three musical scenarios (see Appendix C). This procedure was implemented to reduce preconceptions about ideal placements or device types while encouraging exploration of alternative configurations. The temporary attachment approach isolated physical placement constraints and cognitive handling load. All IDs, the processing hub, and batteries were evaluated in a disconnected, unpowered state. After completing the single-device configuration step and ideal single ID, participants proceeded to the multiple-device configuration stage.

Multiple Input Device Configuration

The iterative expansion from a single actuator to multiple simultaneous controls follows the premise that musical interface design is inherently multidimensional and interdependent. As Overholt (2009) observes, “mapping systems can include many different types of connections between gestural inputs and synthesis parameters — one-to-one, one-to-many, many-to-one, many-to-many, few-to-many, many-to-few” (Overholt, 2009, p. 224). Although this refers to mapping in digital sound synthesis, the same principle holds for physical

configuration: the presence of one control can alter the ergonomic function, perceptual salience, or manipulation requirements of another.

This approach rejects a strictly additive or linear arrangement. A control element that functions well in isolation may conflict spatially or mechanically when paired with others, and its role may shift when new IDs are introduced. Each ID interacts not only with the performer but also with the other components in terms of reachability, force distribution, and hand position constraints. For instance, the placement of a tactile switch might need to move closer to the index finger when a slider is added to the same grip area to avoid overlap or awkward finger angles.

From this perspective, after testing each ID independently, participants were asked to select their single ideal ID for their needs (iteration #5M), then ideal pairs (Iteration #6M) and trios (#7M), and so on (#9M) until reaching intrusiveness (score ≥ 8), adjusting placement or ID category as needed for each iteration. For multiple-ID iterations (#XM), participants were free to combine any of the input device types tested. These multi-ID configurations were evaluated across the same three musical scenarios described earlier (etude, sight-reading, free improvisation/piece of choice), allowing for comparative insights into task-specific intrusiveness and usability.

This structure documents how each additional element reshapes the total ergonomic configuration and cognitive load. The study specifically seeks to explore the potential correlations across three axes: placement (physical intrusiveness), ID type (manipulation in a performance context), and the number of elements (cognitive intrusiveness).

Ideal Configuration

Finally, participants defined their “Ideal NIHCI” (Iteration F9.0). Based on all previous phases, participants set up their ideal layout and performed a final free piece to confirm how the proposed setup aligned with their specific musical needs. An overview of phase 2.2 can be seen in Table 4.

Table 4
Phase 2.2 Steps Summary

Steps	Task	Details	Evaluation
2.2.1	Single ID per category (Iterations 1.1.1–4.3.3)	One tactile switch, joystick, CC, or FSR; each tested in up to three placements on grip posts	Three musical scenarios per placement (free piece, étude, sight-reading); record scores, photos, and comments
2.2.2	Multiple ID configuration (Iteration 5M–9M)	Combine chosen devices: $1 \rightarrow 2 \rightarrow 3 \rightarrow n$	Repeat three scenarios for each configuration; test cognitive load (simultaneous/alternating use); stop when intrusiveness ≥ 8
2.2.3	Final ideal setup (Iteration F9.0)	Participant defines the preferred configuration	Free-piece performance with full desired setup; final reflections

Feedback Questionnaire

After each iteration, participants completed a questionnaire (see Appendix B), recording placement coordinates, photographing their hand position on the trombone in relation to the selected IDs, and rating perceived intrusiveness for each music scenario and ID configuration using the pre-established 0–10 scale.

Just Noticeable Difference (JND) Assessment

After completing Phase 2.2, participants proceeded to Phase 2.3 to assess absolute and differential weight thresholds at the back of the trombone. This area has been explored by several trombonists and interface designers (see West and Leung (2022); Buzzarté; Snyder et al. (2018)) as a location for processor hubs, batteries, sensors, and wireless microphone transmitters. The goal of this test was to identify trends to inform the NIHCI framework design regarding device attachment at this specific location. The concept of the just noticeable difference (JND), also known as the difference threshold or difference limen (Latin for “threshold”), originates in mid-nineteenth-century psychophysics. Early experiments by the German physiologist Ernst Weber (1795–1878) examined tactile stimulation to determine sensory thresholds, while Gustav Fechner (1801–1878) later coined the term psychophysics to describe this experimental domain (Stern and Johnson, 2010, p. 1). Fechner formalized methods for

measuring sensory thresholds and for relating physical stimuli to subjective perception.

Formally speaking, a JND is defined as “the magnitude of change in a stimulus necessary for it to be perceived as different from another stimulus, or as the smallest detectable difference between two stimuli” (Levine and Shefner, 1981, p. 1). Classical psychophysics distinguished two related concepts: the absolute threshold, as the smallest detectable level of a stimulus, and the difference threshold, which assesses the smallest increment of difference needed for one stimulus to be perceived as distinct from another. Weber’s observations contributed to what later became known as Weber’s Law, which states that the amount of increase needed for a difference to be noticed is a constant proportion of the original stimulus. To draw an example, a heavier object must be increased by a larger weight increment to be perceived as heavier than a lighter one (Stern and Johnson, 2010, p. 2).

In line with Weber’s Law, the experiment applied proportional incremental weight changes to assess perceptual thresholds. Chen et al. (2021) note that “the JND for weight perception is proportional to the initial weight, allowing for incremental adjustments to evaluate perceptual thresholds in dynamic tasks,” where, for instance, “JND is 0.1 g for a weight of 10 g, then JND is 0.5 g for a weight of 50 g,” illustrating how threshold sensitivity scales proportionally with baseline stimulus magnitude (Chen et al., 2021, p. 101).

Building on these principles, participants were seated with the trombone held in playing position. A small pouch affixed to the back of the instrument (see Figure 28) housed the incremental weights. Participants were informed

that weight increments and occasional dummy samples would be introduced throughout the procedure, but were instructed not to handle or inspect the pouch between trials. While seated, each participant performed a standard trombone étude excerpt (Bordogni, M. Melodious Etudes: Selected from the Vocalises of Marco Bordogni ex.#4) for each iteration.



Figure 28: Incremental weight pouch mounted on the back of the F-attachment trombone, shown from front and reverse angles.

After each iteration, the weight was increased by approximately 1% of the instrument's base weight: 1.960 kg for the F-attachment trombone (≈ 20 g increments; see Figure 29) and 1.352 kg for the single tenor trombone (13 g increments). Dummy iterations were also randomly included during the trial. After each addition, participants indicated whether they detected a difference relative to the preceding trial and rated the perceived intrusiveness for that iteration (see Appendix B). This stepwise procedure continued until an intrusiveness score of 8 (the onset of the intrusive range) or higher was reported, thereby capturing both absolute and differential thresholds in line with classical psychophysical methods.

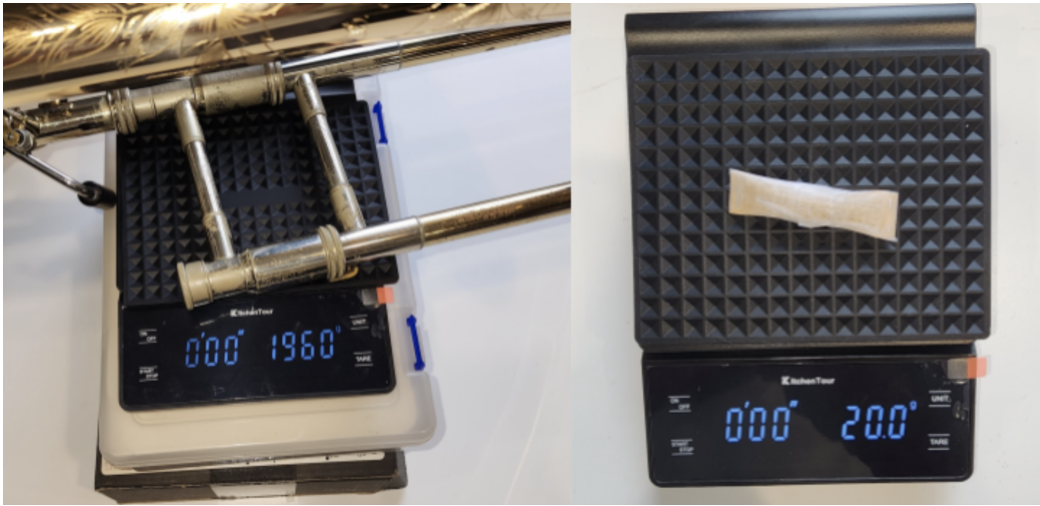


Figure 29: Left: F-attachment trombone total weight. Right: scale indicating the weight of each custom increment, equivalent to $\sim 1\%$ of the instrument's total weight (expressed in grams). This custom incremental belongs to the F-attachment trombone.

Phase 2.3 served to assess (1) the number of 1% weight increments required before added mass is first detected relative to baseline (absolute threshold); (2) how this first detection aligns with the self-reported intrusiveness score and its categorical ranges (non-intrusive, minimally intrusive, intrusive); and (3) the additional number of incremental steps required for subsequent weight changes to become perceptible (difference threshold), thereby mapping a perceptual progression in relation to intrusiveness.

Phase Three: Evaluation

This stage evaluates the NIHCI-based prototype developed from user-identified priorities in Phase One and device trials in Phase Two. As Barbosa et al. (2015) observe, the term “evaluation,” although central in NIME research on

digital musical instruments (DMIs), remains ambiguous. Depending on the stakeholder—audience, composer, or performer—evaluation may refer to (1) collecting feedback after prototype testing, (2) assessing or comparing existing devices, or (3) describing emerging patterns of interaction (Barbosa et al., 2015, p. 156). Their review of 204 papers identifies performers as the primary evaluation stakeholders but notes a continued reliance on loosely defined criteria such as expressiveness or engagement, often without clearly articulated goals or methods. Most evaluations rely on qualitative, single-session approaches (Barbosa et al., 2015, pp. 158–60). They therefore recommend explicitly defining evaluation objectives, specifying methods, and transparently reporting results (Barbosa et al., 2015, pp. 158–60).

In response, Phase Three defines a focused evaluation objective: to assess perceived intrusiveness within performance scenarios identified in Phase One as contexts where participants expressed a need or openness toward technological integration. Ten experienced trombonists participated in a structured single session. Here, standardized musical tasks served as controlled exposure contexts rather than as objects of performance assessment.

The Prototype

The NIHCI prototype integrates two tactile switches and a CodeCell board (from Microbit), which comprises an ESP32-C3 microcontroller, a built-in 9-axis IMU motion sensor, and a light-based proximity sensor, with Wi-Fi/BLE connectivity. Additionally, the prototype includes a 3.7 V, 150 mAh LiPo battery and two tactile switches with a status LED. The electronics are housed

in a custom guard, made from neoprene and Velcro (see Figure 30). The unit attaches temporarily to the trombone’s uppermost grip post region using Velcro straps, allowing repeatable positioning. The prototype implements functions identified in Phase One as features participants expressed a need for or openness toward integrating (such as page turning, looping, and live effects control, among others identified in the literature review) within an intuitive, customizable, no-code-required interface. The selection of these functions, and the survey evidence supporting them, will be addressed in detail in Chapter IV: Analysis and Results.



Figure 30: NIHCI-based first prototype.

Phase 3.1: Étude Evaluation Task

Participants began by performing the same Bordogni étude excerpt used in Phase 2.2, now incorporating the NIHCI interface configured as a digital page-

turner for navigating sheet music on a 12.9-inch iPad Pro. The étude was reformatted to display one system per page, increasing the frequency of page turns and distributing them across different musical sections (see music materials in Appendix E).

Phase 3.2: In the Wild: Open Exploration Task

Following the trial using the turning page function, and in alignment with Brown et al. (2017) observation that “NIME evaluations use specific tasks and open exploration in equal measure” (Brown et al., 2017, p. 373), participants engaged in a musical task of their choosing, either performing a preferred piece or engaging in free improvisation. This “open exploration” phase allowed them to test multiple mapping strategies, such as assigning the IMU’s yaw axis to control reverb send parameters in Ableton Live or using the proximity sensor for filter sweeps, trigger chord sequences, etc. To address differences in participant familiarity with DAWs, the evaluator provided a flexible Ableton Live session tailored in situ to each performer’s request. This included mapping strategies previously discussed, as well as optional templates for those without a specific idea in mind, such as triggering chord progressions for improvisation, activating drones for intonation exercises, manipulating effects in real-time, or using the instrument as a cursor-like interface.

The structure of this session is founded on Brown et al. (2017) argument that generic UX evaluation is enriched by “studying how musicians use instruments in their own personal environments (‘in the wild’)” (Brown et al., 2017, p. 5). Consider, for example, the divergent performative demands between a salsa

trombonist, who must navigate rapid articulations, rhythmic intensity, and physical mobility, and an orchestral performer, whose technical and expressive requirements are markedly different. In such cases, ergonomic grip and interaction preferences inevitably diverge. This open-ended exploration allowed each participant’s uniqueness to come to the foreground, while also aligning the evaluation with the real-world diversity of musical practices.

Phase 3.3: Looping Station Function Task

Participants then interacted with the NIHCI’s onboard web interface, accessed via the NIHCI Wi-Fi access point, to configure the looping station function task—one of the most frequently requested features identified in Phase One. This task assessed whether participants could independently adjust NIHCI settings (e.g., button assignments) using their personal smartphones while evaluating both the interface’s learning curve and its compatibility across devices. This task was designed not only to evaluate the learning curve and ease of customization but to assess the user experience of the served UI web interface, including its intuitiveness and ease of navigation. Because this step introduced a secondary interaction layer beyond playing the instrument, it further allowed the examination of whether such multi-layered interactions remained within an acceptable (non-intrusive) cognitive load for performers.

Weight Assessment Task Evaluation

After completing the NIHCI evaluation tasks, the participants performed a comparative weight assessment in a standing position. This task examined the perceived intrusiveness of two weight-contrasting attachments: (1) a standard wireless microphone transmitter, representing a common accessory in live performance, and (2) the participant's personal smartphone, a ubiquitous everyday object with markedly different weight characteristics. The latter was implemented as a possible experimental or non-standard accessory. Each device was temporarily fastened to the rear section of the trombone.

Before starting the performance task, participants' smartphones were weighed, and the values were recorded in grams. For each configuration, participants then performed a short musical excerpt of their choosing to evaluate the impact of added weight within their own technical and expressive context. This procedure allowed the evaluation in a performer's ecologically valid context and drew a direct comparison with Phase 2.3 Just Noticeable Difference (JND) findings. Correlating intrusiveness scores across both functional and non-functional weight scenarios further informed perceptual thresholds for back-mounted components.

Feedback Questionnaire

Phase Three concluded with a questionnaire (see Appendix D) combining 0-10 Likert-scale ratings with open-ended answers. Participants evaluated the interface across six constructs: (1) perceived intrusiveness, (2) balance disrup-

tion, (3) grip comfort, (4) movement restriction, (5) visual distraction, and (6) tactile familiarity. These constructs were derived from the analysis of Phases One and Two, reflecting both ergonomic and experiential dimensions, components that Barbosa et al. (2015) state as often overlooked in existing NIME evaluation protocols (Barbosa et al., 2015, p. 159). Each question targeted a specific interaction aspect relevant to performance usability. Rather than relying on generic UX categories, the questionnaire emphasized user-derived criteria grounded in ecological validation. Responses from this phase were subsequently correlated with earlier-phase data to evaluate the impact of specific design decisions and guide further refinement of the NIHCI framework design.

CHAPTER IV

ANALYSIS AND RESULTS

This chapter presents the results of the study's phases. Phase One provides an overview of the NIHCI framework and contextualized trombonists' needs and constraints based on a broad participant base and their experiences with existing devices (N = 128). Phase Two involves in-person participants (N = 20), including hands-on trials assessing the subjective experience, placement, and ergonomic testing of input devices, and weight distribution trials.

All procedures involving human subjects were reviewed and approved by the New York University Institutional Review Board (IRB-FY2024-8396).

Phase One: Survey Results, Analysis, and PII Model

This stage consisted of seventy-one questions distributed internationally (N = 128), translated into three languages: English, Spanish, and Portuguese, and distributed through the International Trombone Association (ITA) and its affiliated networks worldwide, including the Associação de Trombonistas Brasileiros (ATB) and the Escuela Latinoamericana de Trombón (ELT). It was also distributed via social media platforms and through printed flyers placed in music schools, conservatories, and luthier workshops around the New

York and New Jersey area. The survey combined multiple-choice, Likert-type, and open-ended questions addressing demographics, musical and technological background, ergonomic considerations, expectations for interface design, and perceptions of existing trombone-mounted devices. All quantitative analyses follow the standardized reporting convention ($p < .05$, $.01$, and $.001$). The organization of this section mirrors the structure of the questionnaire and provides the empirical baseline upon which Phases Two and Three are built.

Participant Profile

This section establishes a descriptive baseline for the respondent population, focusing on age, years of trombone experience, and inclusion criteria. All participants included in the dataset ($N = 128$) met the study's eligibility criteria. As per the online consent form, participation was voluntary, anonymized, and restricted to eligible trombonists. Respondents confirmed informed consent by selecting the required acknowledgment at the beginning of the survey. No cases were excluded post-hoc for not meeting the inclusion criteria (see Appendix G for the consent forms).

Age, Experience, Gender, and Geographic Distribution

Participants ranged in age from 18 to 97 years (Median = 40; IQR: 29-53). The trombone-playing experience years similarly spanned a wide range, from 5 to 80 years, with a median of 24 years (IQR: 15-36). In Appendix F, Figure F.1, right plot, one can find the full distribution. The participants self-identified

mainly as Male ($\approx 90\%$), followed by Female ($\approx 7\%$) and others ($\approx 2.4\%$). The resulting distribution was markedly skewed toward male-identifying respondents. Appendix F, Figure F.2 (left) illustrates the full gender distribution

This marked imbalance likely reflects longstanding gender disparities within professional brass performance rather than recruitment bias, especially considering the survey's open dissemination through international organizations, social media, and places frequented by trombonists. It may also reflect differential levels of visibility, engagement, or representation across gender identities in the trombone community.

Demographic and Background Information

Respondents are from a diverse set of countries, with two countries, Brazil (34.4%), and the United States (33.6%), accounting for over two-thirds of the total sample. The remaining third is completed by participants from the rest of South America and Europe. Appendix F, Figure F.2 (right) shows the country-wise distribution of participants.

Musical Training and Performance Profile

This section provides an overview of participants' musical training, genre, performance frequency, typical venues, and use of technology in performance settings.

Formal Education

More than half of the participants reported holding at least one university degree (56.2% consisting of Bachelor, Master, and Doctorate). The most common responses were Master's (27.3%) and Bachelor's degrees (21.9%), followed by music conservatory diplomas (14.1%). Only a small subset (11.7%) reported no formal music training. The remaining responses included high school programs, technical certifications, and informal paths (see Appendix F, Figure F.3, top left). These results reveal a cohort with extensive formal musical education, supporting the premise that participants are highly experienced.

Participant's Music Profile

Participants primarily performed Classical genre (70.3%), with Jazz as the secondary genre (13.3%); all other genres appeared at markedly lower rates (<5%). Cross-genre and dominant-genre patterns show that Classical and Jazz were the most frequently cited categories, with the most common pairing being Classical–Jazz, followed by Classical–Contemporary/Experimental and Classical–Latin (see Figure F.3–Figure F.4). This distribution indicates a cohort that practices mostly score-based and ensemble-centered musical practice within Western art music traditions. Performance activity was high; most participants reported 21-50 performances per year (28.1%), followed by 51-100 (24.2%), while a smaller group exceeded 100 performances annually (13.3%)

(see Appendix F, Figure F.5). This frequency of public performance suggests a need for stable, low-friction technological systems that can work reliably in formally structured venues and support interoperable workflows.

Music Technology Background

Slightly more than half of the participants reported experience with technology-related musical projects ($\approx 55\%$), whereas the remainder ($\approx 45\%$) had not. This distribution did not differ significantly from an even split ($p = .288$; see Appendix F, Figure F.6), suggesting a relatively balanced level of technological background among participants. This pattern aligns with their educational background since formal instruction in music technology was not the norm. As shown in Figure 31, top left, only $\approx 21\%$ reported any formal training in music technology, whereas the rest reported none (Figure 31, top left).

Despite this limited training base, participants showed considerable comfort with music-related technologies (see Figure 31, top right). This distribution suggests that practical, experience-driven engagement compensates for the absence of formal instruction.

About 38% reported using DAWs or live-processing tools, while the remaining $\approx 61\%$ had not (see Figure 31, bottom left). In contrast, programming for musical purposes was nearly absent. Only a marginal $\approx 3\%$ reported ever writing code. The disparity between the adoption of production software and the avoidance of coding underscores a preference for accessible, interface-driven systems in performance practice.

Among the four respondents who had coded, sixteen total responses mentioned C++, JavaScript, and Python, with Max/MSP, Pure Data, SuperCollider, and one “Other” category appearing once (Figure 31, bottom right). No clear preference emerged across these coding languages ($p \approx .345$).

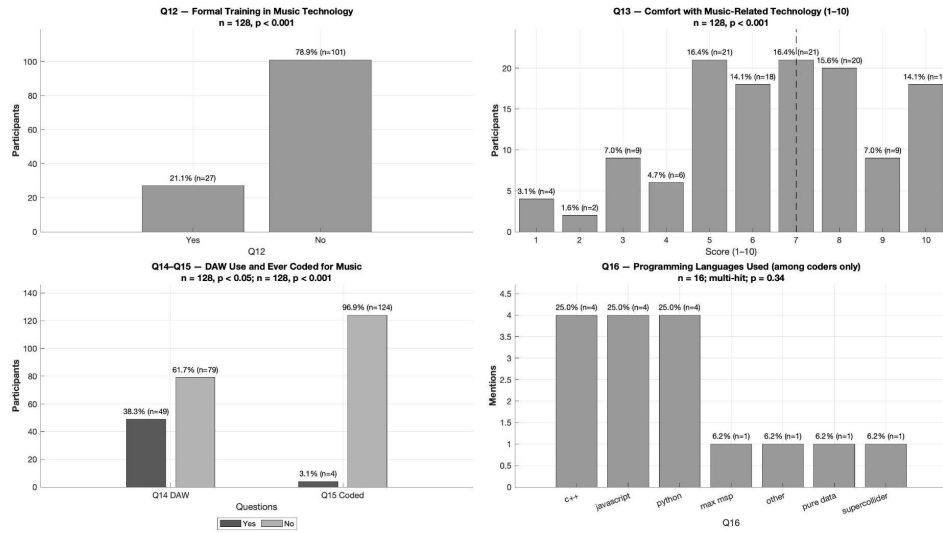


Figure 31: Music Technology Background of Participants (Q12–Q16). Top left: Formal training in music technology (Q12). Top right: Self-reported comfort with music-related technology (Q13). Bottom left: DAW usage (Q14) and experience coding for music (Q15). Bottom right: Programming languages reported by the four coding participants (Q16).

Integration of Technology in Music Practice

This section aims to capture the integration of music technology in performance practices, preferences, challenges, and future intent.

General Integration

Most participants integrated technology into their practice ($\approx 85\%$; see Figure 32, left). The use consisted of assistive tools such as tuners ($\approx 53\%$), tablets for score reading ($\approx 45\%$), and metronome applications ($\approx 39\%$), signaling that technology primarily functions as a support layer rather than a creative or signal-processing resource. This preference informed the design of the experimental tasks and evaluation protocol, specifically the inclusion of page-turning functions and drone-generation features during the evaluation phase (Phase Three). More specialized tools appeared only marginally ($\leq 7\%$), while a small minority reported no adoption of technology during music practice ($\approx 14\%$).

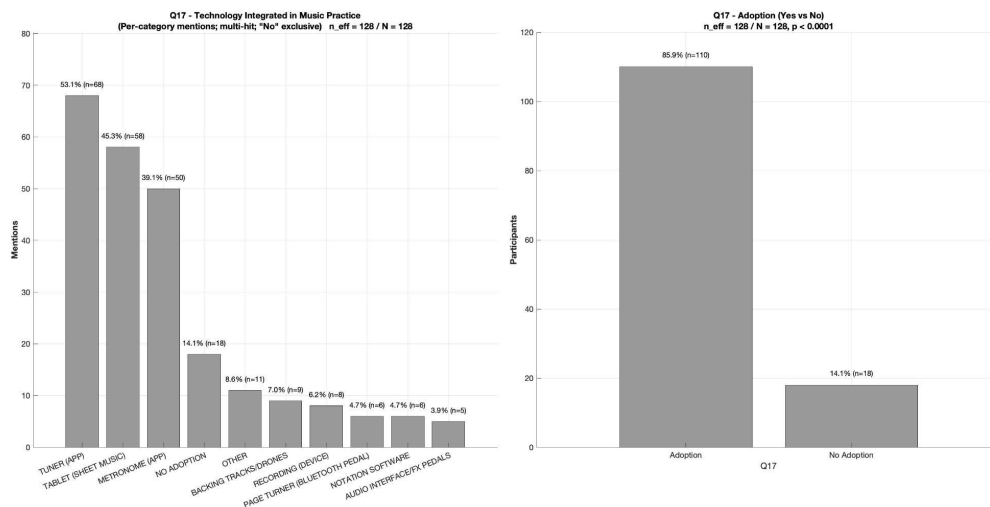


Figure 32: Thematic Analysis of Integration of Technology into Music Practice (Q17). Left: Frequency of technology categories mentioned in open-ended responses. Right: Participant-level adoption summary derived from open-ended responses.

Microphone Preferences and Typologies

Wireless systems emerged as the dominant preference for audio capture (see Figure 33). Although microphone technology is not part of the technical framework of this study, these results contextualize expectations around mobility and venue infrastructure. Distribution of reported microphones can be found in Appendix F, Figure F.7. Participants consistently favored wireless microphones over wired alternatives, revealing a preference for untethered performance setups and reduced wiring in formal and semi-formal performance environments.

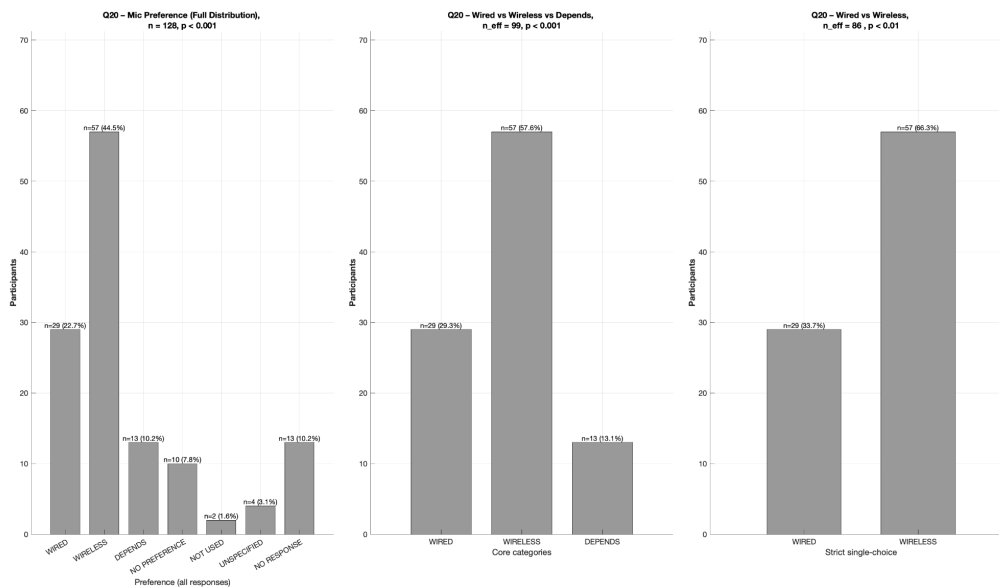


Figure 33: Thematic Analysis of Q20 - Wired vs. Wireless Microphone Preferences Left: Full distribution, all coded responses. Middle: Core subset, interpretable responses only. Right: Strict binary subset, wired vs. wireless only.

Participant Perspectives on Real-Time Processing and Future Technological Integration

Participants showed strong interest in future real-time technological integration in performance (see Figure 34, top left). Thematic analysis revealed that affirmative responses were driven primarily by openness to experimentation, interest in new technical possibilities, and perceived artistic benefits, while negative responses centered on barriers ($\approx 48.1\%$, bottom left). Additionally, barrier awareness also appeared within the affirmative group ($\approx 8\%$, bottom left), revealing that interest in technology often coexists with practical constraints. The full distribution for real-time sound processing and categorical response trends is reported in Appendix F, Figure F.8–Figure F.9.

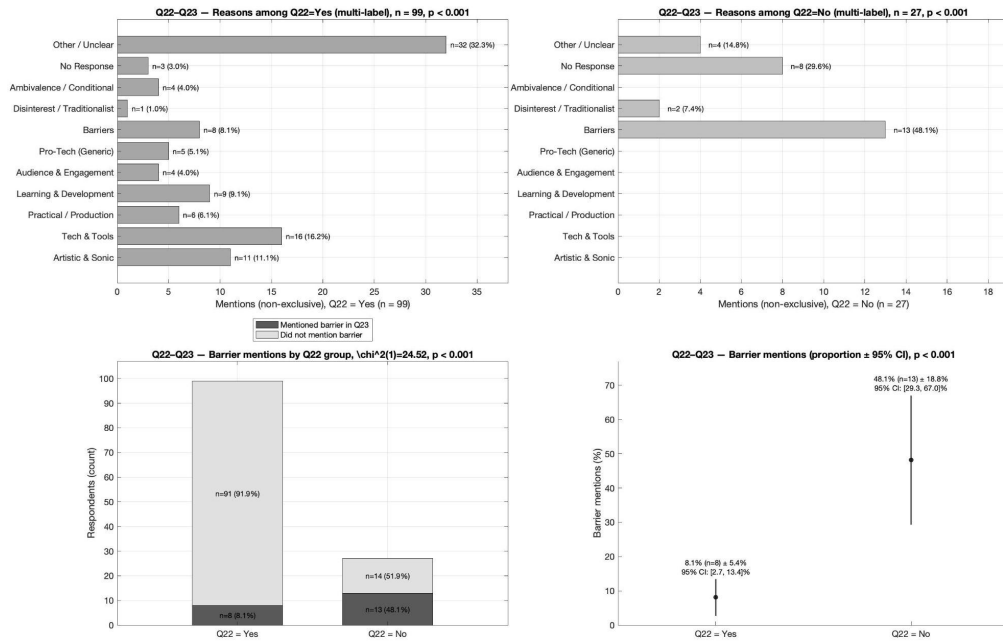


Figure 34: Thematic rationale for technology interest (Q23). Top left: Reasons cited by Q22=Yes group (multi-label). Top right: Reasons cited by Q22=No group (multi-label). Bottom left: Barrier mentions by group (stacked count). Bottom right: Barrier mentions with 95% CI by group.

Comfort and Familiarity with Technological Tools

Technological comfort among participants was uneven, selective, and weakly condensed. Figure 35 shows that participants anchored their comfort in isolated, tool-specific domains, most prominently foot-controlled systems, while references to software, microphones, and computer-based tools appeared sporadically. A substantial proportion of responses avoided specificity altogether, indicating situational familiarity rather than stable technical competence. Appendix F, Figure F.10 concentrates the responses into compositional subcate-

gories, showing that approximately 25% of participants reported comfort with hardware, 13% with software, 8% with both domains, and 54% with neither.

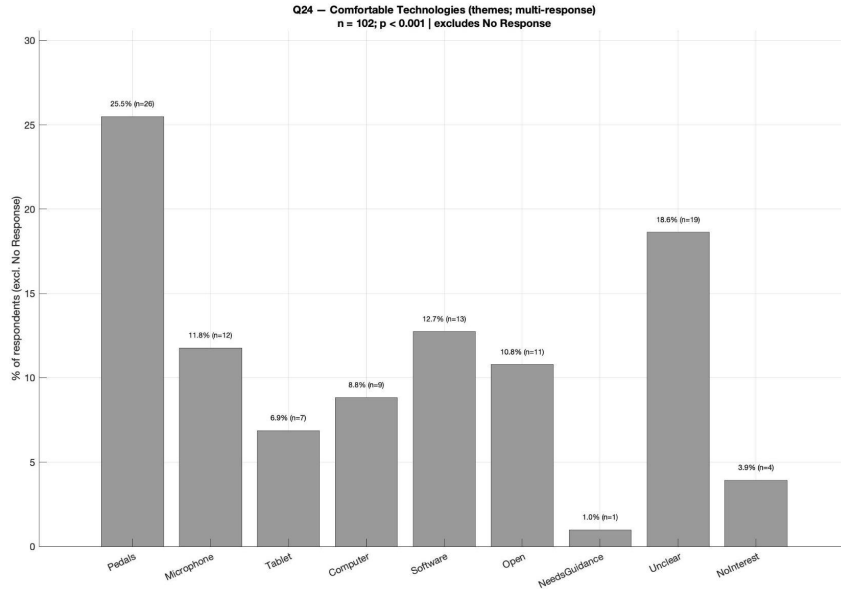


Figure 35: Thematic analysis from responses on the most comfortable use of integrated technologies (Q24). Frequencies of reported comfort by theme (e.g., pedals, microphones, software).

Challenges Encountered When Using Technology

No meaningful difference emerged between participants who reported experiencing challenges and those who did not ($p = .791$). Among those who reported difficulties, the most common challenges were audio-related problems (approximately 48%). Figure 36 presents the full distribution of challenges, with the lower panel showing that technology reliability ($\approx 44\%$) and audio issues (48%) dominated the challenges reported.

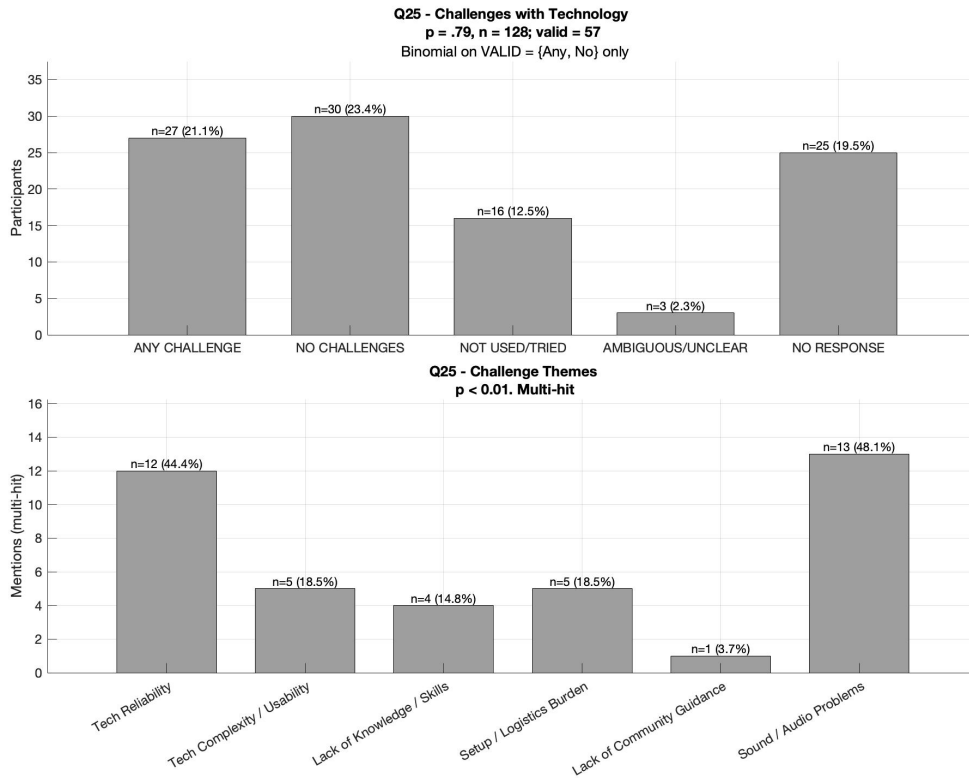


Figure 36: Challenges Using Technology in Performance. Thematic Analysis(Q25). Top: Outcome Distribution. Bottom: Thematic Breakdown (Multi-hit Coding)

Daily Use of Technology and Technical Skills

This section explores participants' day-to-day interaction with digital devices and their overall level of technical proficiency.

Device and Operating System Usage

Figure 37 shows that smartphones are ubiquitous, while laptop and desktop computer usage appear at comparable, secondary level (left panel). This distribution opens up an opportunity to explore the integration of ubiquitous consumer technologies into interface design. In later phases, smartphones are explored both as processing hubs and as web-based front-end interface configurations. The near-equal distribution of iOS and Android usage (middle panel) indicates that any such approach must prioritize cross-platform compatibility; a similar constraint emerges from the mixed desktop operating system landscape (right panel). These patterns directly support the use of browser-based systems over apps or particular operating system-dependent solutions.

Detailed distributions of smartphone brands, models, and device weights are reported in Appendix F, Figure F.11. The median device weight (190 g) is particularly relevant for subsequent phases examining the feasibility of mounting smartphones on the rear section of the trombone.

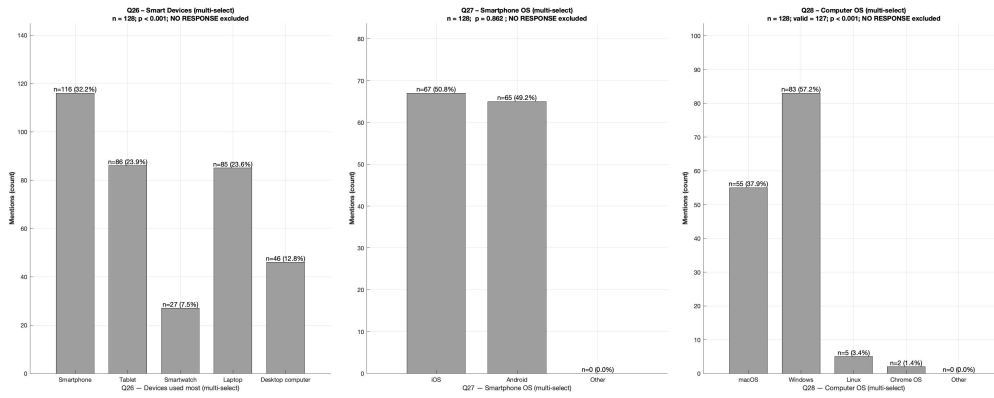


Figure 37: Smart Device and Operating System Usage (Q26-Q27-Q28). Left: Smart devices used most often (Q26), showing near-universal smartphone adoption. Center: Smartphone operating systems (Q27), with a near flat distribution for iOS and Android. Right: Computer operating systems (Q28), with Windows and macOS most commonly used.

Bluetooth, Browser, and Network Literacy

Viewed through the lens of everyday connectivity, Figure 38 indicates that the technological groundwork required for networked interaction is already in place. Near-universal Bluetooth fluency establishes wireless (although short-range) communication as a low-friction layer for interface design. This becomes particularly pertinent when considered alongside browser-based architectures, where the inability of browsers to natively handle OSC requires intermediary bridges (e.g., OSC-UDP to WebSocket-TCP translation layers). While such bridges function reliably in local environments, they introduce unnecessary complexity, strengthening the case for adaptive frameworks that respond to performers' existing technological ecologies rather than imposing rigid infrastructures.

Figure 38, middle panel, shows a strong preference for Chrome. Combined with Chrome’s support for the Web MIDI API, this positions BLE-MIDI as a practical alternative to OSC for browser-mediated systems. In contrast, limited support in Safari and Firefox constrains truly universal OSC-based web deployment. The right panel of Figure 38 further shows that most participants can locate a device’s IP address, supporting the feasibility of local-network workflows where required. However, despite this capability, OSC-based approaches remain dependent on external, OS-level bridges, effectively shifting the burden toward application- or system-specific solutions rather than native web implementations.

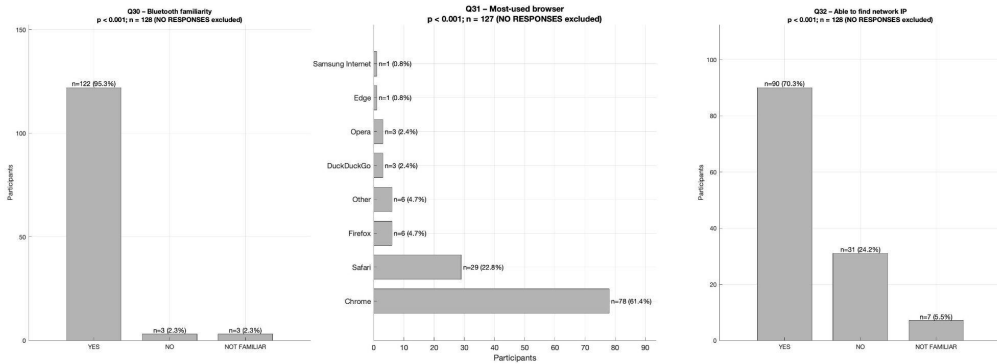


Figure 38: Bluetooth Familiarity, Browser Use, and Network Awareness (Q30-Q32). Left: distribution of responses regarding participants’ familiarity with Bluetooth connectivity. Middle: most frequently used web browsers among participants (top 8 + Other). Right: participants’ ability to locate their device’s network IP address. Note: Percentages reflect valid responses (no-response cases excluded).

For further clarification, this study evaluates implementation feasibility rather than claiming protocol superiority. OSC and BLE-MIDI present distinct and valid trade-offs. OSC affords richer data structures, lower latency, and greater control bandwidth, while BLE-MIDI offers lower power consumption, sim-

pler pairing models, and tighter integration with browser-based environments. Because data collection points toward the exploration of wireless, battery-powered, and instrument-mounted scenarios, energy efficiency emerges as a primary constraint. In this context, BLE-based communication is treated as a pragmatic implementation pathway rather than a normative technological choice.

Trombone ergonomics

More than half of trombonists ($\approx 59\%$) expressed willingness to attach a temporary device (Figure 39, top left). The trombone slide was by far the area most frequently excluded ($\approx 41\%$), followed by the trombone bell and mouthpiece (Figure 39, top right). These constraints informed later experimental phases, where these regions were systematically avoided during device placement trials. The lower panels of Figure 39 provide the interpretive layer, showing that these restrictions were primarily driven by concerns about movement interference, resonance disruption, and weight balance stability, defining the slide and bell as mechanically and acoustically protected zones within the instrument's embodied design.

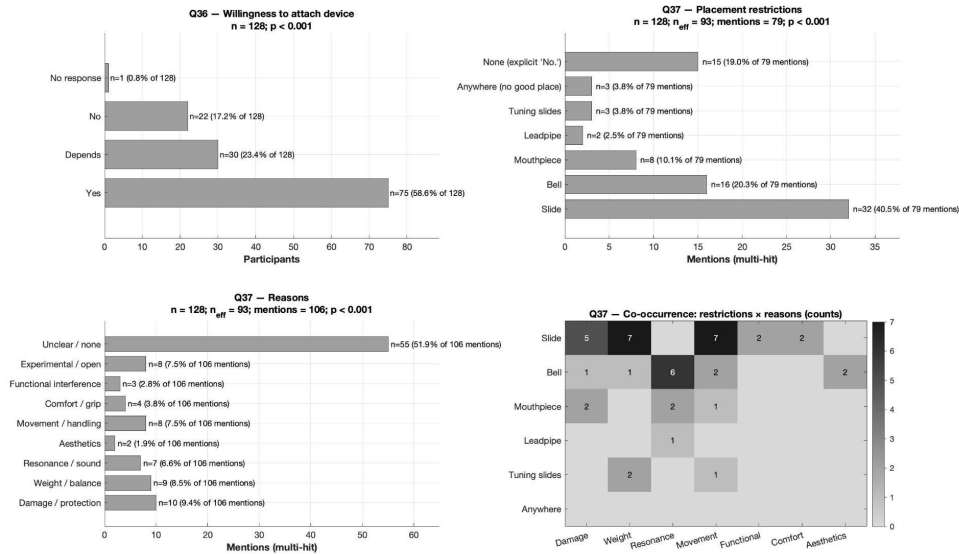


Figure 39: Willingness to Attach Temporarily an Electronic Device and Perceived Placement Constraints (Q36-Q37) Top Left: Distribution of willingness to temporarily attach a device to the trombone. Top Right: Areas of the instrument identified as unsuitable for attachment. Bottom Left: Reported reasons for placement restrictions. Bottom Right: Co-occurrence heatmap showing relationships between restricted areas and justification types.

Willingness to Attach Permanent Devices

In contrast to temporary devices, when participants considered permanent attachment, acceptance dropped sharply (Figure 40, top left). Willingness fell to $\approx 27\%$, while rejection became the dominant response. Placement tolerance narrowed accordingly, with the slide remaining the most strongly excluded region ($\approx 46\%$), followed by the bell (Figure 40, top right), confirming that these zones are viewed as protected areas when attachment is permanent. The lower panels of Figure 40 show how justifications shifted from vague hesitation

toward performance-critical risks. Movement interference and resonance disruption became the dominant concerns (bottom left), with the co-occurrence map identifying slide × movement as the principal constraint (bottom right). Compared to temporary attachment, permanence intensifies existing boundaries rather than introducing new ones. Together, the patterns establish the slide and bell as consistently unsuitable locations, while preserving the leadpipe and trombone rear section as the most viable candidates, with temporary mounting preferred to maintain mobility, balance, and acoustic integrity.

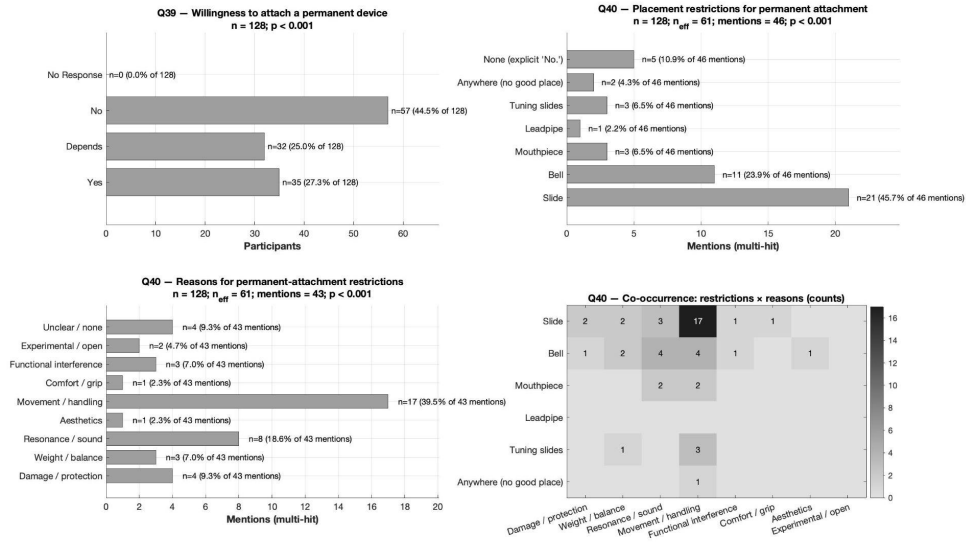


Figure 40: Willingness to Attach a Permanent Device(Q39-Q40) Top Left: distribution of willingness to permanently modify the instrument. Top Right: unsuitable areas for permanent attachment. Bottom Left: primary reasons for avoiding certain areas. Bottom Right: co-occurrence heatmap of placement restrictions.

Preferred Controller Placement and Justifications

Participants converge on two dominant control strategies for interacting with external digital parameters (Figure 41, top panels). The first relies on peripheral coordination, where foot control emerges as the preferred solution ($\approx 31\%$ of first mentions; $\approx 37\%$ overall). The second position controls within the left-hand stability region ($\approx 21\%$ of first mentions; $\approx 25\%$ overall), confirming this area as the most ergonomically secure on trombone placement. All together, these patterns support a general principle: augmentation devices should anchor to motor routines that do not compete with the slide's freedom of movement.

Other placements remain marginal ($< \approx 11\%$), suggesting that performers treat off-instrument stands and tables as situational rather than integral, and consider the bell or slide locations as structurally constrained.

Rationales in Figure 41 (bottom left) clarify this pattern. Accessibility dominates ($\approx 31\%$), followed by workflow needs such as page turns ($\approx 21\%$). Concerns about movement interference ($\approx 13\%$) and the desire for uninterrupted playing via hands-free control ($\approx 8\%$) further show that performers prioritize continuity of musical motion over simple proximity.

The co-occurrence structure (Figure 41, bottom right) reflects these relationships: left-hand placements pair with access and practicality, foot control with hands-free and page-turn needs, and bell/slide positions with interference and acoustic resonance concerns.

Overall, trombonists favor control schemes that either externalize actuation

to the feet or integrate within the left-hand stability zone. These preferences reinforce the need to test the left-hand grip as a candidate for interface attachment.

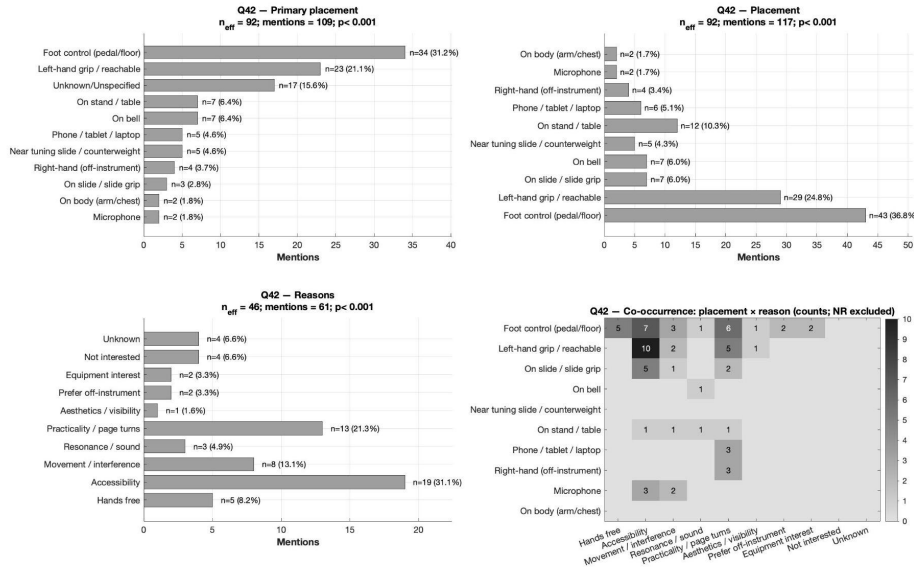


Figure 41: Preferred Controller Placement and Rationale (Q42) Top left: Primary placement. Top right: All mentioned placements (multi-mention) Bottom left: Reasons for placement preference Bottom right: Placement × Reason co-occurrence matrix

Finger Extra-Control Availability

Finger-availability ratings show which hand and fingers can support extra on-instrument control (see Figure 42). Although the left hand shows overall more availability, most fingers on both hands score below the neutral midpoint. Both thumbs are effectively unavailable (medians ≈ 0), as they are fully engaged in slide movement (right) or F-attachment engagement (left). These results

reveal that even if the spare space bandwidth allows mounting an attachment, most fingers cannot reliably handle additional tasks during performance.

Within this restricted scenario, only the left index and left middle fingers show consistent functional capacity (medians ≈ 3 – 3.5), and both outperform their right-hand equivalents (medians ≈ 1). The relative freedom of the left middle finger partially reflects the bass-trombone technique, but the left index emerges as the most stable option among players. Ring and little fingers show low and highly variable availability, highlighting that left-hand presence alone does not translate into reliable fine-motor capacity.

Comparative analyses (see Appendix F, Figure F.12–Figure F.13) confirm pronounced differences across fingers and an overall advantage for the left hand. As a design guideline, the left hand can host additional controls only if specific fingers can support them. These data show that interaction is largely limited to the left index and middle fingers; right-hand or thumb-based interfaces are ergonomically unsuitable, and variability across the rest of fingers suggests the need for configurable or adaptive mappings within the NIHCI framework.

Intrusiveness Assessment of Trombone Attachments

This section evaluates ten existing trombone-mounted accessories to establish how perceived intrusiveness varies across a broad, multidimensional space. By quantifying how players rate familiar devices, the study provides the empirical foundation later used to propose the *Perceived Intrusiveness Index* (PII) model, including the relative weighting of the introduced seven core dimensions

Q44 — Finger availability distributions (0–10) with median & IQR
 Per panel: p vs 5 and n, valid

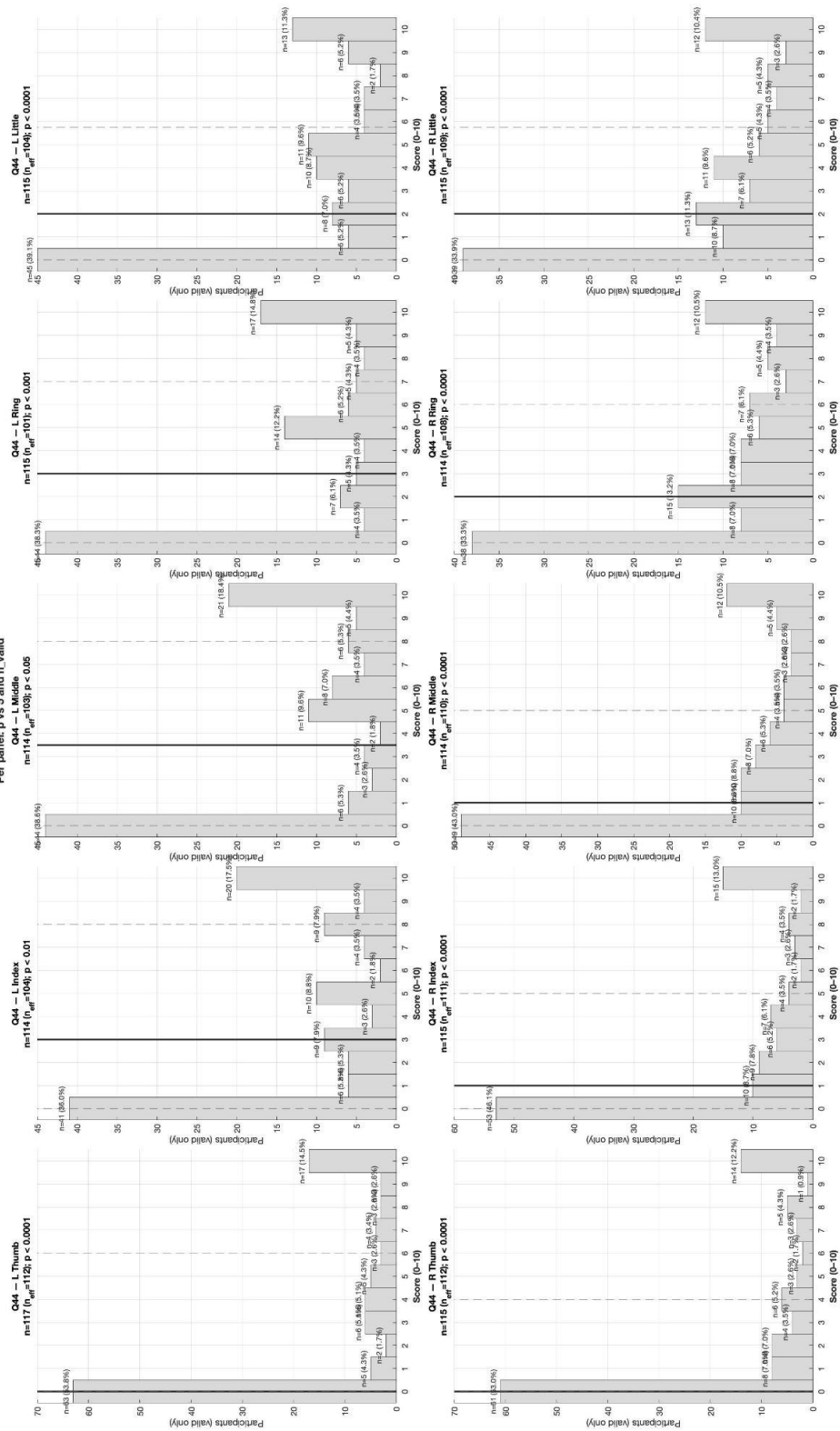


Figure 42: Per-digit score distributions (0–10) with median and IQR range (Q44).

that define intrusiveness. All items were scored on the 0-10 scale, where 0-3 is defined as non-intrusive, 4-7 as minimally intrusive, and 8-10 as intrusive.

The resulting distributions (see Figure 43) show that most of the accessories are concentrated in the non-intrusive band, with some exceptions. Pencil holders and clip-on microphones anchor the lowest region, with tightly clustered scores near zero, showing near general acceptance. Slightly higher, but still in the non-intrusive range, are lightweight supports such as the bullet brace, hand guard, hand support, clip-on tuner, the mic hub/transmitter, and the BERP. These devices show broader tails, reflecting occasional ergonomic mismatches without changing the overall classification. Mutes form a mid-band case. Their distributions are centered around the midpoint of the scale, 5, which describes that perceived interference depends mainly on repertoire and context, rather than inherent design. Conversely, the PiezoBarrel piezo mic shows a right-skewed profile with several high ratings, making it the most divisive device in the set.

In Appendix F, Figure F.14–Figure F.15, two supplementary summaries are available that provide a visualization of the median/IQR comparisons and band-level distributions. Additionally, Appendix F, Figure F.18, shows the thematic density of responses by device score band, revealing that non-intrusive devices (scores 0–3) elicit the highest volume of coded responses and greatest thematic engagement, while intrusive devices (scores 8–10) generate progressively fewer and briefer comments per response.

**Q47-Q66 — Distributions by device (0-10) with median & IQR
(valid N varies by device; NO RESPONSES excluded)**

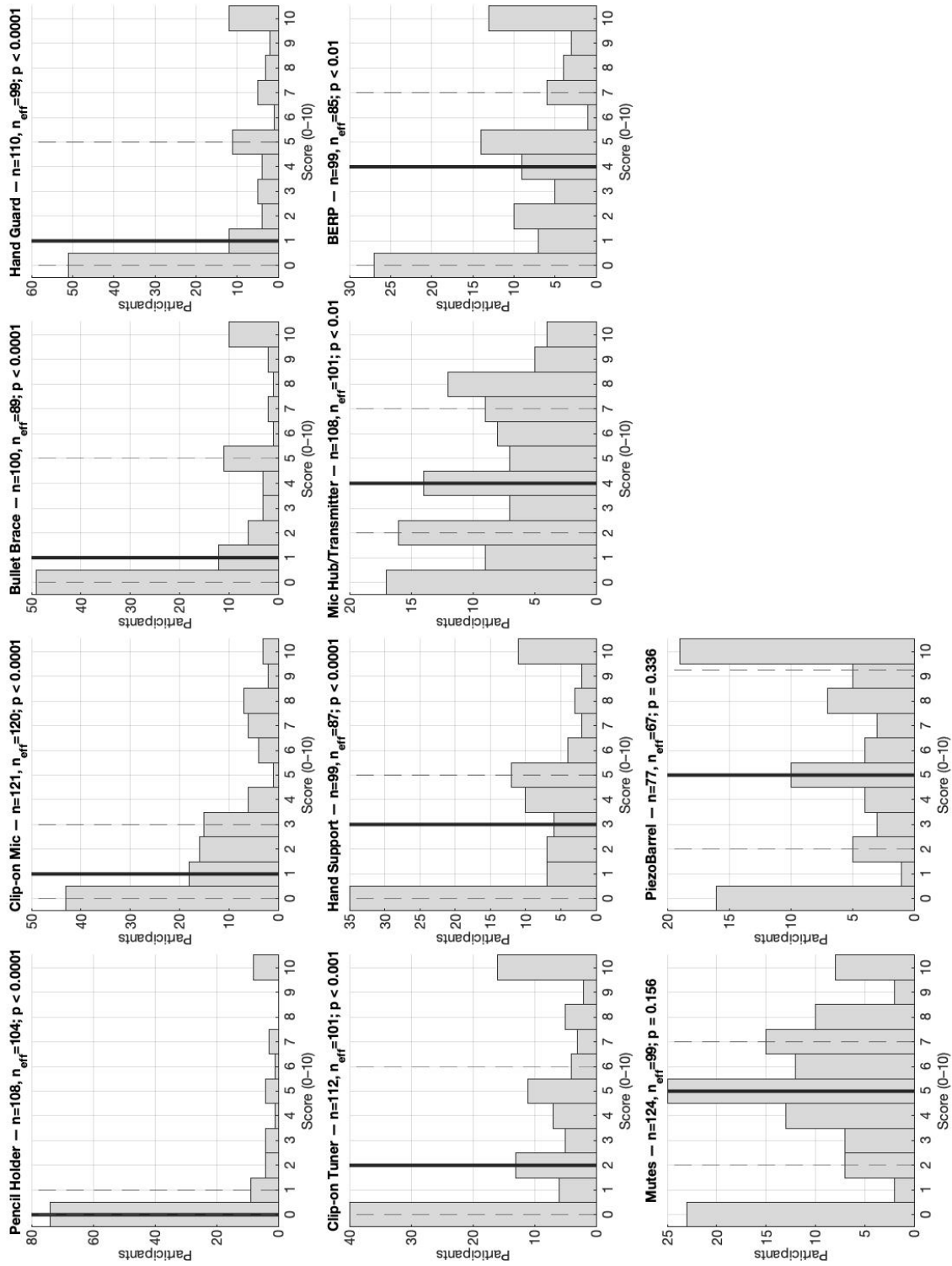


Figure 43: Histograms of intrusiveness scores for ten trombone attachments with median and IQR markers (Q47-Q66).

What Makes a Device Feel Intrusive?

Participants rated the intrusiveness of each of the ten familiar devices and provided brief written rationales for their scores. These comments were later coded according to the seven core experiential intrusiveness themes. Intrusiveness ratings were compared between cases in which a given theme was mentioned and those in which it was not, allowing for the isolation of each experiential theme's influence on perceived intrusiveness. Figure 44 visualizes these contrasts through Cliff's delta.

The associations reveal a structure where mentions of Physical, Attentional, Perceptual, Cognitive, and Aesthetic themes correspond to systematically higher degrees of intrusiveness. When players describe added weight, changes in balance, visual or tactile disruption, or increased mental effort, their ratings rise accordingly, demonstrating that these themes reliably signal perceived interference. These domains show the largest empirical effects on intrusiveness ratings and therefore have proportionally greater weight in the PII model.

Ergonomic comments show comparatively small associations with score shifts; comfort-related comments do not meaningfully vary ratings unless they co-occur with higher-impact factors. Temporal mentions—related to latency on a given system—were too sparse in the dataset to establish a statistically stable relationship, though the dimension remains conceptually relevant.

The content of the comments aligns with the following patterns: (1) high-score explanations cluster around weight imbalance, mechanical resistance, obstructed sightlines, and divided attention; and (2), Low-score explanations

emphasize secure fit, transparency in use, or the sense that the device “disappears” during performance.

Specific Drivers of Intrusiveness, Subtheme Analysis

From the thematic patterns identified before, the subtheme comparisons in Figure 45 explain how specific factors account for the score shifts observed at the higher theme level.

The strongest score drift happens for Tuning Resistance and Resonance/Vibration, with effect sizes in the range $\delta \approx 0.25$ – 0.32 . These subthemes reveal the largest median separations and the clearest dominance of the “present” condition over the “non-present” one, revealing a systematic increase in perceived intrusiveness when these factors are reported.

A secondary tier of effects appears for Learning Curve, Aesthetic Bulk, Weight/Balance, and Placement/Vision, with effect sizes in the range $\delta \approx 0.17$ – 0.24 . These factors produce moderate distributional changes, though less pronounced than the primary drivers.

Other subthemes—Helpful Technique, Size, Setup/Adjustment, Cable Management, Comfort/Ergonomics, and Material—show weak or nonsignificant effects ($\delta \leq 0.14$). In these cases, intrusiveness scores remain largely overlapping across present and non-present groups, with little median separation and confidence intervals spanning zero. These factors thus do not demonstrate

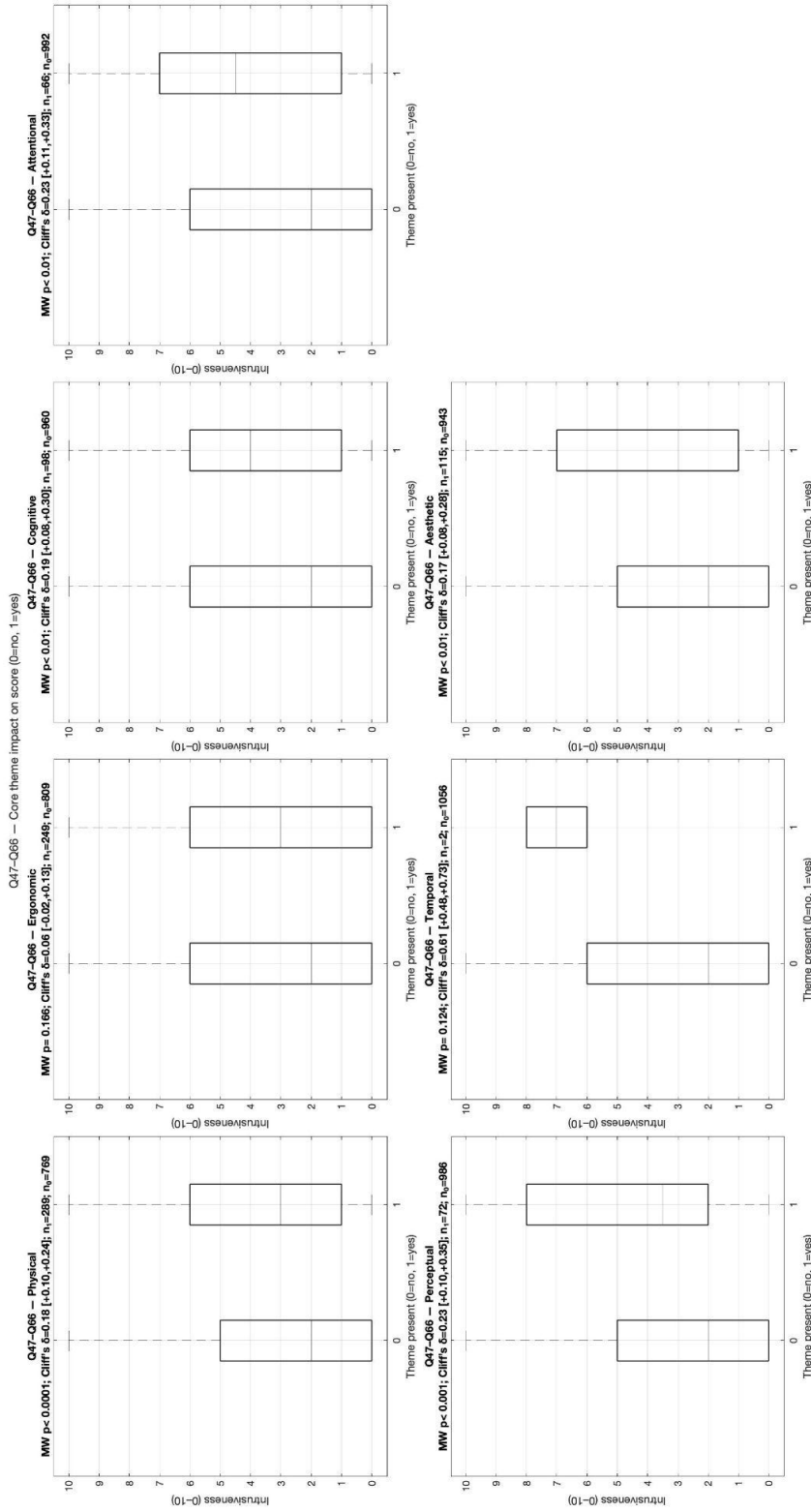


Figure 44: Core theme impact on intrusiveness score (Q47-Q66). Boxplots comparing scores when each theme is absent or present. MW = Mann-Whitney test; δ = Cliff's delta; n_0 = responses with theme present; n_1 = responses without theme; total = 1058 valid responses ("No Response" excluded).

meaningful stochastic dominance and do not systematically increase perceived intrusiveness.

Appendix F, Figure F.16, and Figure F.17, provide more insights into this analysis by showing how these subthemes co-occur and how frequently each appears across responses. Figure F.16 reveals that subthemes rarely happen in isolation, with recurrent pairings. The most frequent co-occurrences link Placement/Vision \times Aesthetic Bulk and Weight/Balance \times Placement/Vision. Appendix F, Figure F.17 disaggregates these relationships by frequency of mention. Weight/Balance emerges as the most frequently reported subtheme, followed by Comfort/Ergonomics and Placement/Vision. This distribution shows that while some subthemes have stronger statistical effects on score shifts (as shown in Figure 45), others dominate in terms of how often they are articulated by performers. High-frequency subthemes represent common experiential concerns, whereas high-effect subthemes represent strong drivers for raising the score when present.

Does Intrusiveness Affect How Frequently You Use a Device?

Figure 46 shows that while some players reported that the effect “Depends,” most respondents ($\approx 41\%$) agreed that perceived intrusiveness reduces how often they use a device.

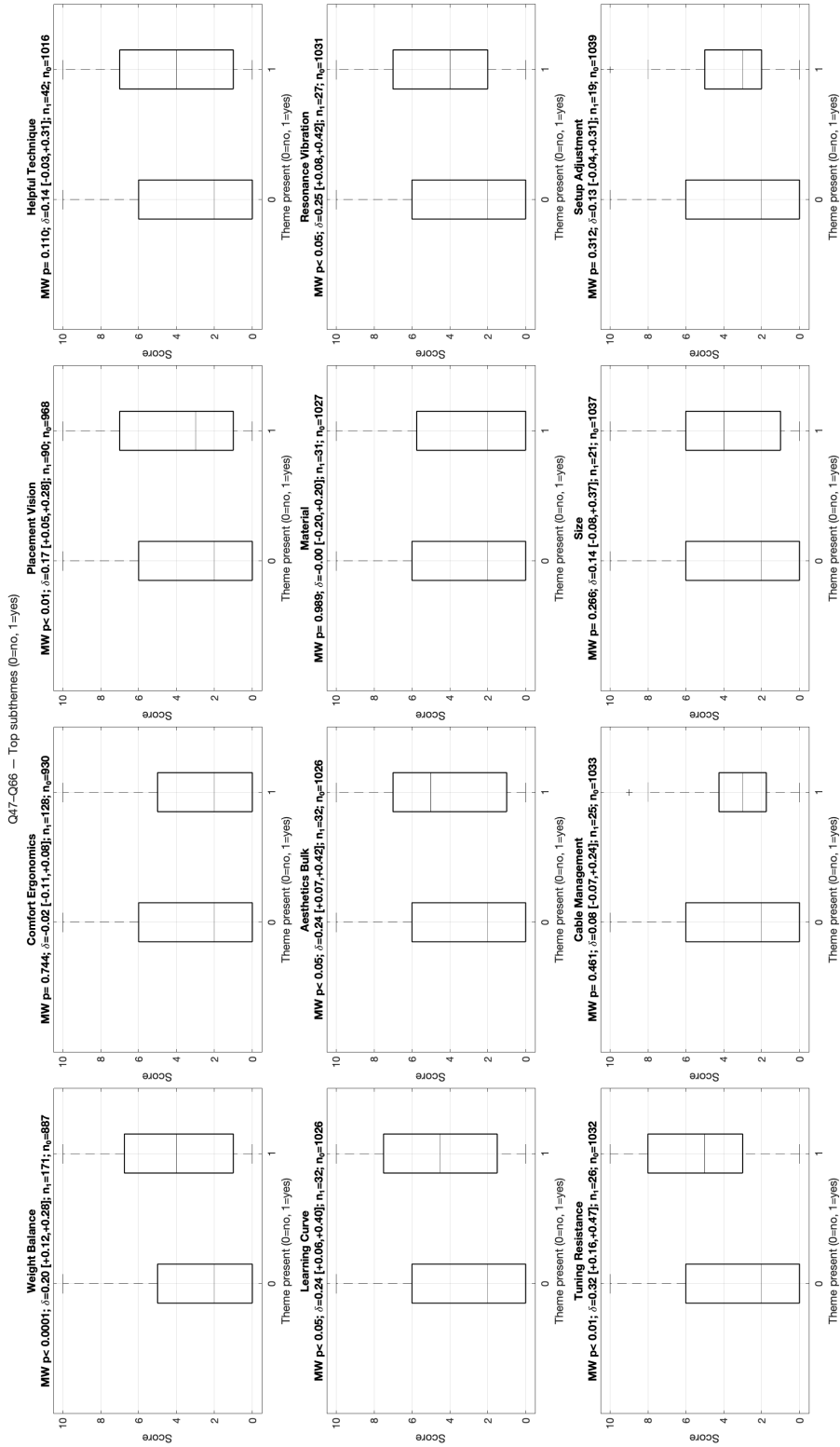


Figure 45: Top subthemes (Q47-Q66). Boxplots comparing scores when each theme is absent or present. MW = Mann-Whitney test; δ = Cliff's delta; n_1 = responses with theme present; n_0 = responses without theme; total = 1058 valid responses (“No Response” excluded).

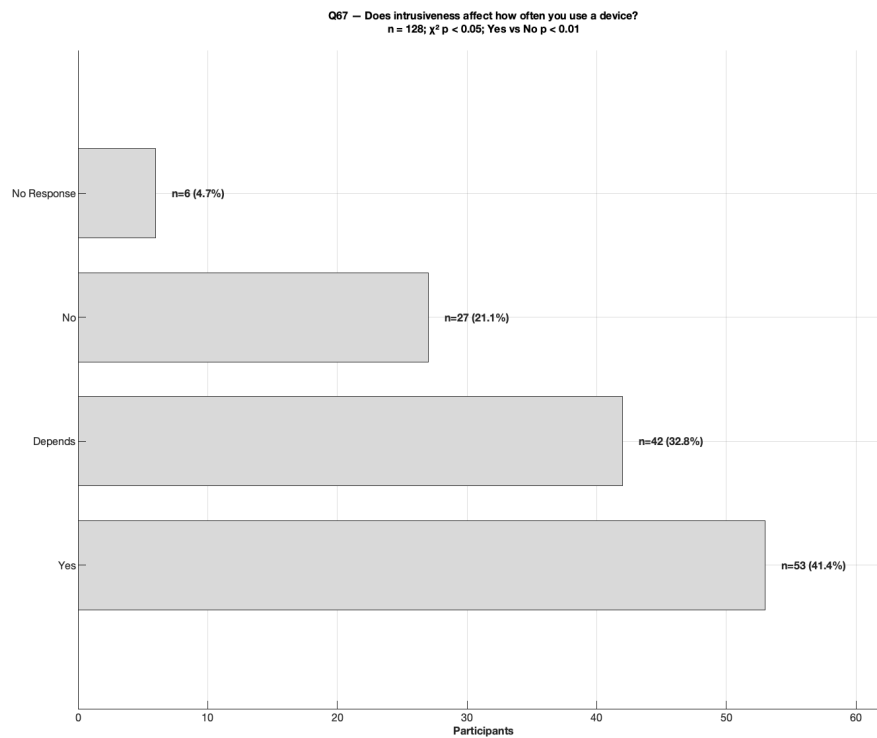


Figure 46: Effect of Perceived Intrusiveness on Device Usage Frequency (Q67).

Future expectations and desires

Participants expressed a desire for technologies that provide tablet/page-turning support (10.9%), loop station (9.4%), and audio processing features (8.6%). Appendix F, Figure F.19, shows the full distribution of technological enhancement mentions from Q70.

The final open-ended question received 32 valid responses. Most participants provided no additional remarks. Participants' responses were organized into six recurrent thematic categories as follows.

Weight and balance was the most frequently mentioned category. Participants referred to physical comfort, perceived mass, and load distribution of devices, including references to fatigue in the hands, shoulders, and bell area, and to lightweight materials or support strategies.

Ergonomics and adjustability took the second most frequent category. Responses described the relevance of fit across different body types and instrument configurations, and referenced the need for adjustable angles, grips, mounting locations, and programmable controls.

Practicality and reliability appeared as a distinct category. Participants mentioned ease of mounting and removal, stability during performance, connection and disconnection processes, and durability.

Aesthetic integration was also frequently mentioned within this category. Musicianship-centered concerns were expressed in multiple responses. These included explicit skepticism toward electronic augmentation, prioritization of acoustic sound production, and statements rejecting or avoiding technology use.

Adoption and learning were another recurrent theme. Participants described perceived knowledge gaps, difficulty keeping up with technology, and generational adoption barriers. Some of the concrete feature requests centered on page-turning tools, wearable tuners, hand-mounted controllers, horn-specific pedalboards, and integrated amplification.

The Perceived Intrusiveness Index (PII)

The preceding sections have characterized perceived intrusiveness through thematic and statistical analysis across all survey items. To formalize these findings, the discussion in this section moves from empirical interpretation to formal modeling.

The following section introduces a quantitative framework, the Perceived Intrusiveness Index (PII), which integrates empirically derived thematic weights into a predictive representation of intrusiveness based on survey-derived indicators and coded experiential dimensions. As discussed previously, perceived intrusiveness refers to the extent to which a device, interface, or physical attachment interferes with the ability of a performer to execute a musical task. To consistently represent this phenomenon, this study defines a composite PII on the established 0–10 intrusiveness scale.

The index integrates two categories of evidence: the first comprises the seven core themes representing broad experiential dimensions: Perceptual, Attentional, Cognitive, Physical, Aesthetic, Ergonomic, and Temporal. The second consists of a set of subthemes that capture the concrete mechanisms amplifying perceived intrusiveness. Each component contributes proportionally to the total index according to its empirically derived effect size.

It is important to clarify the dual role of the subthemes within this framework. In the analytical phase, subthemes served as the indicators that activated each core theme, meaning that the presence of one or more subthemes determined whether a theme was coded as present in the dataset. In the modeling phase, however, their role shifts from categorical to parametric, where subthemes no

longer define a theme's presence but instead modulate its intensity. In this sense, they act as amplifiers of already-activated dimensions of intrusiveness, allowing for a finer-grained representation of the perceptual, ergonomic, or cognitive burden a device may impose.

Figure 47 presents the normalized weights (derived from the results shown in Figure 44) of the six core themes that collectively account for perceived intrusiveness across the ten existing surveyed trombone-mounted devices. At this stage, temporal intrusiveness is excluded; although relevant, the corresponding participant data were too low to yield statistically reliable estimates ($n = 2$). This dimension is reintroduced and discussed later.

Each weight represents the proportion of the total intrusiveness signal attributed to a given theme, derived from the positive sizes of Cliff's delta and rescaled to 100%. Based on the observed values from the size of the independent effect, Perceptual (0.2285), Attentional (0.2260), Cognitive (0.1905), Physical (0.1753), Aesthetic (0.1742), and Ergonomic (0.0565), with a total δ of 1.051, the corresponding normalized weights are shown in Figure 47. These six dimensions constitute the baseline weighting schema for devices that do not present temporal dependency.

Figure 48 illustrates the corresponding seven-theme model when temporal aspects are active. For example, in devices involving latency, timing instability, or real-time audio or data transmission, the δ values include the Temporal component (0.6136), returning a total δ of 1.6646.

Although the Temporal dimension shows a high δ estimate (0.6136), it relies

on only two valid responses, which limits empirical reliability ($p = .124$). The model, therefore, applies a conditional activation rule to correct this imbalance.

The six-theme model in Figure 47 applies when $S_{temp} = 0$ (false); conversely, the seven-theme model in Figure 48 is activated only when $S_{temp} = 1$ (true).

This configuration preserves the theoretical salience of timing-related intrusiveness while preventing artificial distortion of other theme weights in non-temporal contexts. It also establishes the foundation for the PII model described later.

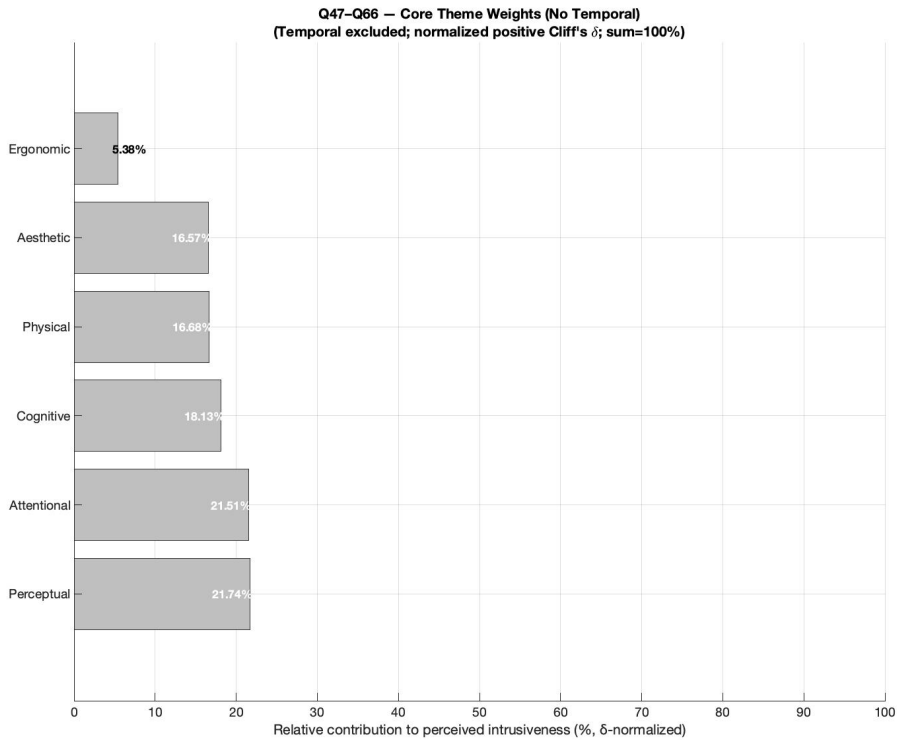


Figure 47: Normalized weights of six core experiential themes contributing to perceived intrusiveness (Q47-Q66, Temporal excluded)

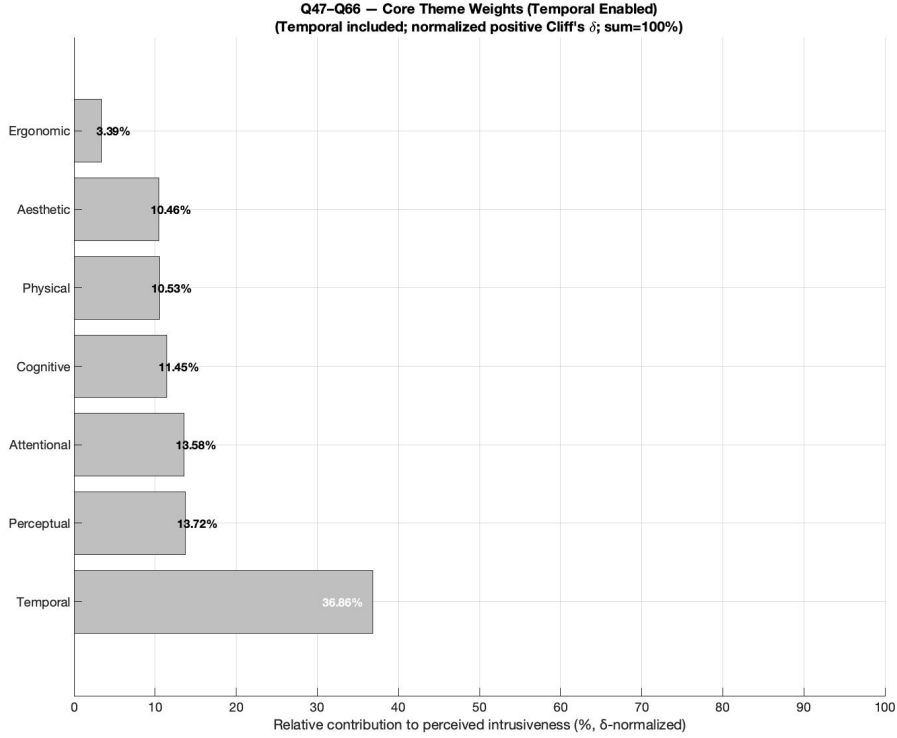


Figure 48: Normalized weights of seven core experiential themes contributing to perceived intrusiveness with temporal intrusiveness enabled

Each core theme serves as a weighted indicator of its corresponding experiential dimension. Summing the weighted contributions across the active themes (six by default, with Temporality included only when the device transmits or processes time-dependent data) yields a base score on a 0-100 scale, which is then mapped to the 0-10 range.

Formally, the base score B is computed as shown below (2):

$$B = \sum_{k \in K} w_k s_k + g_T w_T s_T. \quad (2)$$

Here, K denotes the set of core themes, w_k is the normalized weight (in per-

cent) of theme k derived from Figure 47, and s_k is a binary indicator of its presence (1 = present, 0 = absent, 0.5 = partially present). The term g_T is a gating variable that activates the temporal contribution, w_T is the normalized weight of the temporal theme, and s_T indicates its presence.

General Temporality (Gt): temporal intrusiveness weight.

The temporal term models the degree to which time-dependent factors, such as latency and jitter, affect the performer’s sense of synchrony and control intimacy. The variable $g_T w_T s_T$ encodes this contribution, where g_T functions as a conditional gate and s_T defines the proportional activation of temporal intrusiveness.

$$g_T = \begin{cases} 1, & \text{if the device transmits or processes time-dependent data,} \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

When $g_T = 0$, the temporal term is inactive, and the six-theme model is applied. When $g_T = 1$, the seven-theme model is activated, introducing the temporal weight w_T in proportion to its normalized effect s_T . The latter represents the degree of perceived disruption arising from the system’s timing behavior.

S_T : The Temporal Activation Function

Temporal intrusiveness reflects not only the mean latency (L) of a device but also the variability of that latency, or jitter (J). The proportional activation s_T is therefore defined as a weighted combination of mean latency and jitter, bounded between 0 (non-intrusive) and 1 (intrusive):

$$s_T = \text{clip}\left(0.7 \frac{L - 11}{39} + 0.3 \frac{J}{10}, 0, 1\right), \quad (4)$$

where $39 = 50 - 11$ defines the bounded latency range used for normalization.

The model anchors its timing range in prior research on musical perception (Chafe and Gurevich (2004); Jack et al. (2016); Schmid et al. (2024)). Latencies around ≈ 11 *ms* have been reported as temporally stable in certain ensemble contexts, while delays approaching ≈ 50 *ms* increasingly disrupt performance. The model, therefore, evaluates timing effects within this 11–50 ms window as a practical normalization range rather than as a universal perceptual threshold. Latency carries greater weight (0.7) because constant delay tends to affect performance more strongly, while jitter carries less weight (0.3) due to the introduction of timing instability (Wessel and Wright, 2002).

Integration with the Remaining Model Formulation

With the temporal weighting in place, the analysis now returns to the general model framework.

The sum of all w_k (or $w_k + w_T$ when the temporal term is active, using the weights from Figure 48) equals 100, such that B represents a direct percentage of the total perceived intrusiveness index. In practical use, the base score B provides the proportional contribution of the major experiential dimensions. However, perceived intrusiveness also depends on secondary design or contextual factors that may accentuate or attenuate these effects. To account for these nuances, a correction term is introduced, yielding the adjusted *Perceived Intrusiveness Index (PII)*:

$$\text{PII} = B \times (1 + \beta). \quad (5)$$

Here, $\beta = \frac{B_{\text{boost}}}{B}$ is a composite boost factor derived from subthemes or situational modifiers. The term B_{boost} represents the weighted contribution of all active subthemes, normalized to the same 0–100 range as B . Positive values of β indicate that the configuration increases perceived intrusiveness through specific subtheme mechanisms (e.g., added obstruction or cognitive load).

The boost factor β is determined from the set of active subthemes, each contributing proportionally to its observed effect size δ_j . The total adjustment is bounded by a fixed bonus limit of twenty points on the 0–100 scale, equivalent to a potential increase of two points on the 0–10 perceptual scale.

The boost contribution is computed as:

$$B_{\text{boost}} = \max \times \frac{\sum_{j \in J_{\text{present}}} \delta_j}{\sum_{j \in J_{\text{all}}} \delta_j}. \quad (6)$$

Here, \max denotes the maximum allowable boost (20 points), J_{present} is the

subset of active subthemes, and the denominator normalizes the effect relative to the total subtheme influence. This formulation makes the correction term remain interpretable and bounded. In practice, subthemes with larger effect sizes δ_j , such as tuning resistance or visible bulk, exert proportionally greater influence on perceived intrusiveness.

Permanence and Perceptual Compression

To better capture differences in how performers respond to temporary versus permanent instrument modifications, the final PII introduces the permanence coefficient as an additional scaling parameter.

Permanence factor

Devices that are permanently attached, for instance, those requiring drilling or structural alterations, are perceived as markedly more intrusive than functionally equivalent temporary mounting devices. This behavioral asymmetry was captured in Q36-Q40 (as seen in Figure 39 and Figure 40). Willingness to attach a temporary device was reported by 58.6% of participants, whereas willingness to mount it permanently dropped to 27.3%, with outright rejection almost doubling from 17.2% to 44.5% ($p < .001$). These distributions reveal that permanence introduces a significant perceptual and practical barrier even before the physical interaction happens.

In psychophysical terms, behavioral resistance does not scale linearly with

perceived intensity but follows a sublinear, compressed growth pattern. As Gescheider (1997) notes, “because the neural output of the sensory system is a power function of stimulus intensity, the observer’s judgments will also be a power function of stimulus intensity,” inferring that perceptual magnitude grows sublinearly relative to physical input (Gescheider, 1997, p. 293). This relationship is widely known as Stevens’s power law. Tursky’s work on *The Development of a Pain Perception Profile: a Psychophysical Approach*, offers an empirical demonstration, showing that “magnitude of sensation grows as a function of some power of stimulus intensity... the exponent of numerical estimates of line length is 1.0; for force of handgrip, 1.7; and for sound pressure, 0.67 ” (Tursky, 1976, p. 179).

With this in mind, the permanence factor was set to 0.67, since the perception of intrusiveness functions analogously to auditory or tactile intensity, where increasing stimulus energy yields diminishing perceptual returns. The exponent reflects canonical psychophysical scaling for auditory pressure and is theoretically grounded in the general power law:

$$\psi = K \Phi^n, \tag{7}$$

where ψ represents the perceived magnitude of a sensation, Φ the physical stimulus intensity, n the modality-specific exponent (in this case $n = 0.67$), and K a scaling constant.

Applying this exponent to the behavioral data yields the following.

$$(0.53)^{0.67} \approx 0.35. \tag{8}$$

transforming the observed 53% behavioral reduction in willingness into its perceptually scaled equivalent. Consequently, the permanence coefficient was defined as $\lambda_p = 0.35$, representing an empirically and perceptually justified multiplier.

To encode this empirical shift, a permanence coefficient λ_p is defined as:

$$\lambda_p = \begin{cases} 0, & \text{temporary attachment (reversible),} \\ 0.35, & \text{permanent modification (irreversible).} \end{cases} \quad (9)$$

The coefficient $\lambda_p = 0.35$ thus represents a proportional increase of 35% in perceived intrusiveness. The permanence-adjusted score is then given by:

$$\text{PII}_p = \min(100, B + B_{\text{boost}}) \times (1 + \lambda_p). \quad (10)$$

The inner term $\min(100, B + B_{\text{boost}})$ caps the combined base and boost contributions at 100, preserving the bounded 0–100 perceptual scale established earlier. This prevents unrealistically high values when multiple strong effects (e.g., physical obstruction, visual bulk, or weight imbalance) co-occur. The multiplicative term $(1 + \lambda_p)$ then applies the permanence correction, proportionally amplifying perceived intrusiveness only when the permanence quality is present.

Perceptual Compression

As discussed in the context of the perceptual scale, human responses to physical stimuli follow a nonlinear, power-law relationship between objective magnitude and perceived magnitude. The final stage of the model applies a perceptual compression function, regardless of whether the intrusive score results from core theme activation, temporal effects, boost factors, or permanence.

This transformation acknowledges the nonlinear nature of human perception, in which additional physical or visual restrictions no longer increase perceived interference proportionally once attention, comfort, or motor control have already been compromised. In simple terms, discomfort grows rapidly at first as attached devices restrict natural movement or attract visual attention, but this growth slows after the performer’s disruption threshold has been reached. Beyond this point, additional intrusiveness results in diminishing subjective differences, since the device is already perceived as “too intrusive”.

Compression is applied only when the permanence-adjusted linear score reaches or exceeds the intrusive threshold ($y_{\text{linear}} \geq 8$) on the 0–10 scale (i.e., $\text{PII}_p \geq 80$). For values below this threshold, the scale behaves linearly.

This nonlinear adjustment is implemented as:

$$\hat{y} = 10 \times \frac{\text{PII}_p}{\text{PII}_p + c(20)}. \quad (11)$$

where \hat{y} represents the perceptually normalized intrusiveness on the 0–10 scale. The constant $c(20)$ serves as the compression coefficient, selected to preserve

the 8-point boundary (i.e., 8 remains 8 when compression is applied) while attenuating higher values to prevent disproportionate escalation.

The current formulation of the PII models both structural permanence and perceptual saturation, providing a predictive yet interpretable approximation grounded in the perceptual data of commercially available instrument-mounted devices analyzed in this study. The model is most reliable when applied to attachments that are comparable in scale, weight, and function to those surveyed, namely, small-to-medium devices consistent with standard performance practice.

Model Validation and Comparative Results

Although the PII model is built upon generalized weights derived from participant data, its predictive output ultimately reflects the perceptual profile of the individual applying it. Each theme's activation (s_k), particularly in cognitively or aesthetically dimensions, depends on the evaluator's subjective experience of interference or discomfort. As a result, two users may obtain different, but relatable, intrusiveness scores for the same device. This behavior is consistent with the model's intent, providing a replicable computational framework that adapts performer-specific sensitivities within the empirically grounded weight structure established in this study.

With this consideration in mind, the following table presents the modeled intrusiveness scores for all evaluated devices. Each computation applies the PII framework using the author's interpretation of theme activations and subtheme boost factors (B_{boost}), followed by comparison with the median participant

ratings collected in Phase One. This parallel presentation allows the validation of the model's predictive behavior against observed perceptual data.

The model's predicted score for Mutes (5.17) is very close to the observed median (5). In contrast, the PiezoBarrel shows a larger gap between prediction and median (8.15 vs. 5). Although both devices have non-significant median scores, only PiezoBarrel activates the permanence factor and a positive boost in the model, which contributes to the approximately 3-point deviation from the empirical median.

Table 5

Comparison of the median score given by participants with the PII model output. See Appendix F, section ‘‘PII Model Walkthrough,’’ for a step-by-step walkthrough.

Device	Median (from study)	PII	S_k	G_t	S_t	λ_p	B_{boost}
Pencil holder	0	1.90	[0.5, 0, 0, 0.5, 0]	0	0	0	0
Clip-on mic (latency 9 ms)	1	1.93	[0, 0.5, 0, 0, 0.5, 0]	1	0.03 ($L=9, J=2$)	0	0
Bullet brace	1	1.75	[0.5, 0, 0, 0.5, 0.5, 0]	0	0	0	-10
Hand guard	1	1.42	[0.5, 0, 0, 0.5, 0]	0	0	0	-5
Clip-on tuner	2	1.90	[0, 0.5, 0, 0, 0.5, 0]	0	0	0	0
Mic-hub transmitter (rear, low-lat)	4	3.27	[0.5, 0, 0, 1, 1, 0]	1	0.132 ($L=15, J=2$)	0	0
BERP	4	3.50	[1, 0, 0, 0, 0.5, 0]	0	0	0	5
Mutes	5 ($p=0.156$)	5.17	[1, 0, 0, 0.5, 1, 0]	0	0	0	5
PiezoBarrel (drilled)	5 ($p=0.336$)	8.15	[1, 0, 0, 0.5, 1, 0]	1	0 (analog)	0.35	10

Phase Two: Trial Results, Analysis, the Affective Model, and JND Thresholds

Following the Phase One survey, Phase Two consisted of an in-person evaluation to validate, contextualize, and refine the perceptual constructs identified in Phase One. While Phase One provided a broad empirical foundation, Phase Two examined the interaction between twenty experienced trombone performers and a variety of hardware under controlled, hands-on conditions. This phase consisted of three interconnected components: (1) Affective Assessment, (2) Human Interface Device (HID) Configuration, and (3) Just Noticeable Difference (JND) Assessment.

All of the Phase Two trials were conducted individually at the Research Audio Lab, Steinhardt School, 6th floor, and lasted approximately ninety minutes. Participants remained fully anonymous and were assigned a Unique Identifier (UID) that linked their responses across all subsections. Both Sub-Phases 2.1 and 2.2 used the same set of boards, batteries, and input devices, categorized by: Tactile Switches (TS, $n = 19$), Joystick Modules (JS, $n = 3$), Continuous Control (CC, $n = 8$), and a single force-sensitive resistor (FSR, $n = 1$). As in the previous phase, all quantitative analyses reported here follow the standardized notation in which $p < .05$, $p < .01$, and $p < .001$ indicate increasing levels of statistical significance.

Phase 2.1 Affective Assessment

The purpose of the affective assessment is to examine how trombonists evaluate their experiential responses, subjective perceptions, and overall impressions

of these input devices when handled directly, before integrating them into the trombone. Phase One identified perceptual constructs through large-scale survey data. This 2.1 Affective Assessment section then tested those constructs in practice, measuring how tactile feel, size, visual appeal, and perceived ease of use combine to shape overall preference and comfort. The table listing all the tested input devices, along with their own tag, dimensions, and an illustrative picture, evaluated in this trial, can be found in Appendix C.

Age Distribution

Twenty participants completed Phase Two, completing all three sub-sections of the evaluation. Most participants were between 18 and 34 years old ($n = 17$), with a median age of 27 (see Appendix F, Figure F.20, left panel, for the full distribution). The group was therefore representative of early-career or advanced-student performers. Only a small number of participants were older than 40 ($n = 3$).

Gender Distribution

The participant group consisted predominantly of male performers (80%, $n = 16$), followed by female (15%, $n = 3$), and non-binary (5%, $n = 1$). This distribution closely aligns with the demographic pattern observed in the international survey of Phase One, which reported 90% male, 7.1% female, and

0.8% non-binary respondents. Appendix F, Figure F.20, right panel, shows the participants' gender distribution.

Tactile Pleasantness

Participants were asked to rate the tactile feel of all the input devices ($n = 31$) for each category (TS, JS, CC, FSR), considering aspects such as smoothness, resistance, and surface texture while considering their use in a typical trombone performance context. Responses were provided on a 0-10 scale, where higher scores indicated a more pleasant tactile feedback.

Tactile Switches (TS)

Figure 49 shows that tactile buttons produced the widest range of “how pleasant they felt” scores. Most buttons scored in the middle range (between 5 and 7). Two buttons, TS-S-S-01 and TS-M-C-18, scored the highest (both with a median score of 8; see mechanical specifications in Table 6). Although their scores were similar, their mechanisms differ. TS-S-S-01 uses a soft rubber dome and requires about 120 gf of force with very short travel, with no audible

click¹. TS-M-C-18 contains a rigid plastic button, requiring approximately 160 gf of force, and produces an audible tactile click (see Table 6)².

Lower-rated buttons (TS-M-S-12 and TS-S-C-17) did not differ strongly in actual actuation force from higher-rated models, but differed in contact surface geometry. TS-S-C-17 operates at approximately 156 ± 50 gf with a 0.25 mm travel (Table 6), producing a small contact area and concentrated finger pressure³. TS-M-S-12 lacks published force data but was consistently perceived as uncomfortable. These devices received markedly lower scores (medians = 1.5 and 3)⁴. About 60% of comments described them as hard to press, too stiff, or uncomfortable, suggesting that smaller caps concentrated force at the fingertip, while larger caps distributed pressure more evenly, even when mechanical force remained similar.

¹TS-01 Datasheet can be found here: <https://cdn-shop.adafruit.com/product-files/3101/C4817-001+datasheet.png>. Accessed on Nov. 25, 2025.

²TS-18 Datasheet can be found here: <https://www.e-switch.com/wp-content/uploads/2022/10/TL3300.pdf>. Accessed on Nov. 25, 2025.

³TS-12 Datasheet can be found here: <https://www.sparkfun.com/lilypad-button-board.html>. Accessed on Nov. 25, 2025.

⁴TS-17 Datasheet can be found here: <https://makerselectronics.com/product/smd-tactile-switches-2pin-3x4x2mm-5pcs/>. Accessed on Nov. 25, 2025.

Q3.1 - How would you rate the tactile feel of the Input Device? (0-10)

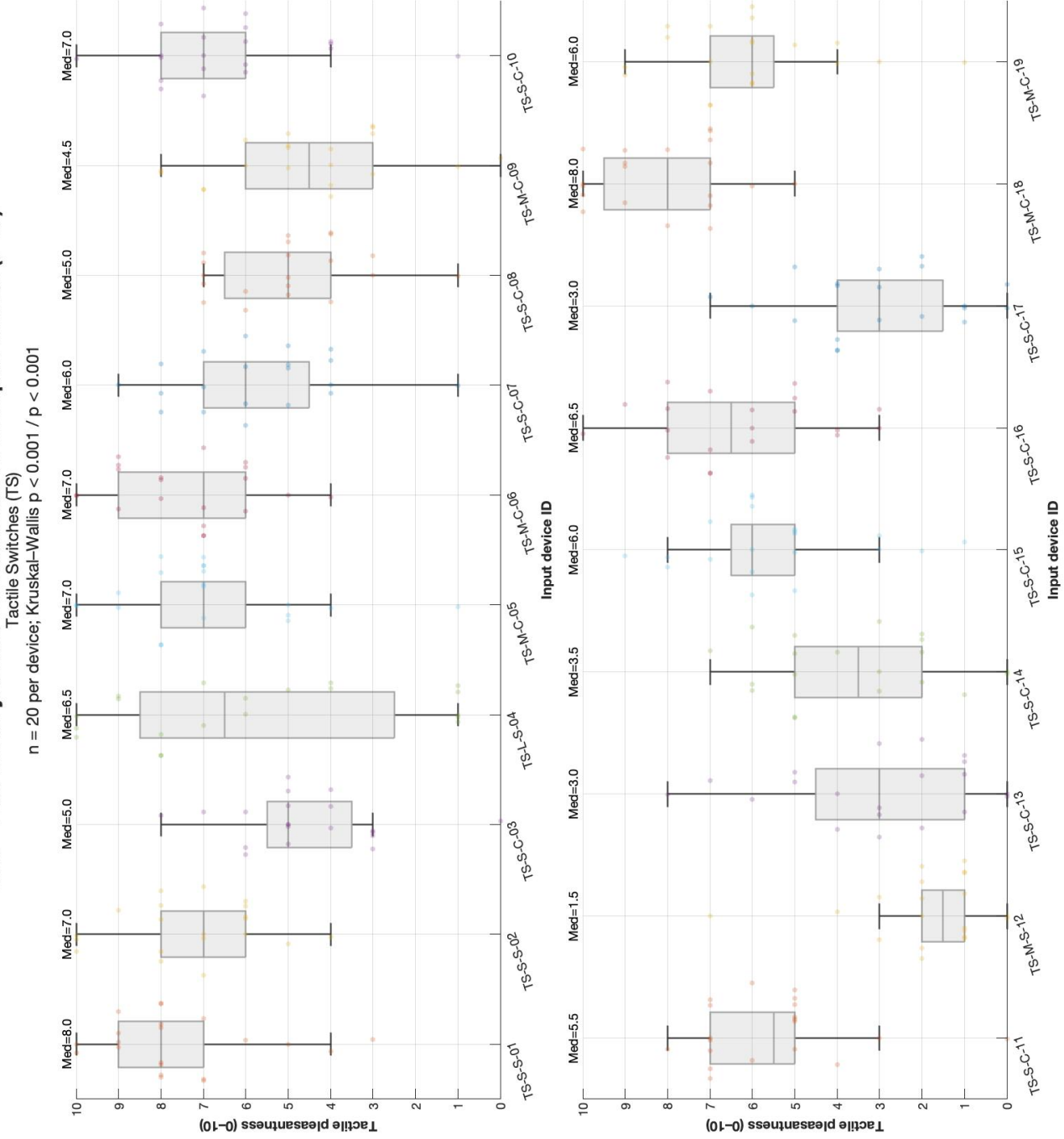


Figure 49: Tactile Switches (TS): Tactile Pleasantness Ratings (Q3.1). Boxplots showing participant ratings (0-10) for nineteen tactile-switch devices.

Table 6
Mechanical Specifications of Evaluated Tactile Switches

ID	Source part	Operating force	Travel	Note
TS-S-S-01	Adafruit 3101 Tactile Button	120 ± 40 gf (1.18 N)	0.25 mm	soft dome actuator
TS-M-C-18	E-Switch TL3300CF160Q (12 mm tact)	160 ± 50 gf (1.57 N)	0.35 mm	hard plastic cap, clicky
TS-M-S-12	SparkFun LilyPad Button Board	not specified	0.25 mm	textile PCB switch (SMD tact core)
TS-S-C-17	Generic 3×4×2 mm SMD tact switch	156 ± 50 gf (1.56 N)	0.25 ^{+0.2} _{-0.1} mm	miniature PCB switch

Joysticks

The joystick tactile results showed a positive baseline tactile acceptability, rather than strong preferences for any single hardware design. The narrow spread of scores suggests that performers respond primarily to the interaction model itself (continuous multidirectional control and spring-return behavior) rather than to surface-level mechanical differences. Subtle variation in ratings likely reflects differences in size and mounting footprint rather than tactile feel alone (see Figure 50). Subsequent Phase 2.2 trials show how these tactile preferences translate when the devices are physically mounted on the trombone, where ergonomics shifts, and interference with playing technique become more relevant than the standalone tactile experience.

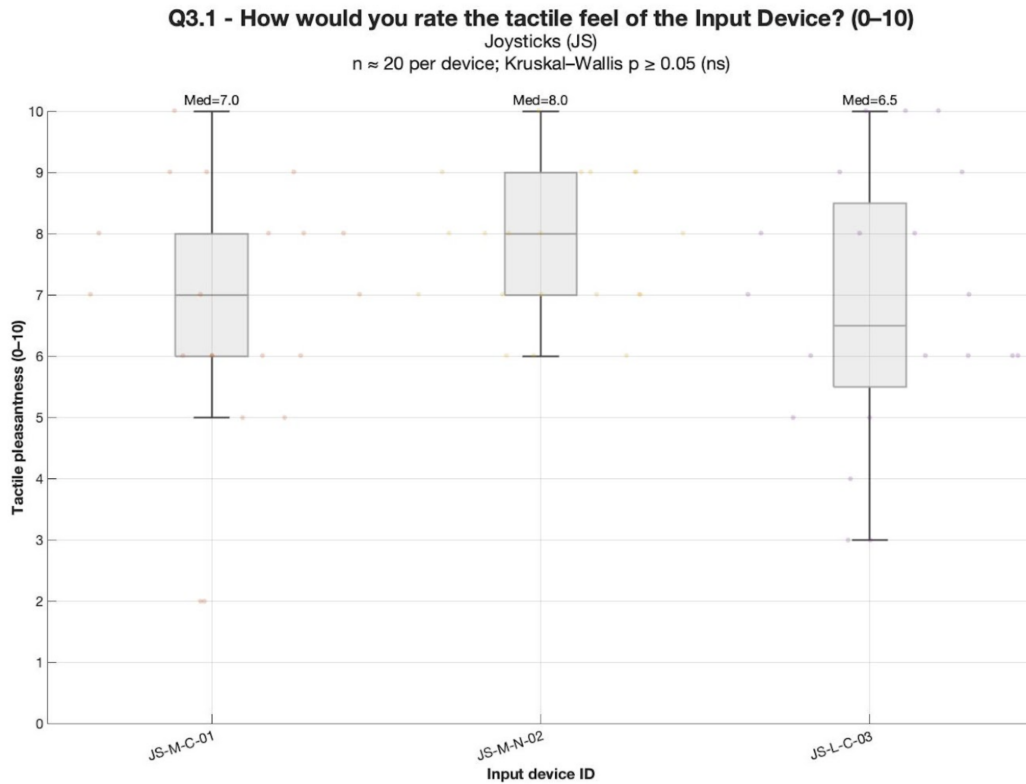


Figure 50: Joysticks (JS): Tactile Pleasantness Ratings (Q3.1). Distribution of ratings across three joystick modules (no significant intra-group difference).

Continuous Controllers (CC)

Figure 51 shows how continuous controllers have the widest separation in tactile responses. These results reveal that perceived comfort depends less on device category and more on resistance stability and surface interaction. The dispersion in scores reflects performers' sensitivity to friction irregularities and inconsistent force gradients. Higher-rated devices were described as “smooth,”

“predictable,” and “easy to control,” while lower-rated devices were described as “too stiff,” “lacking grip,” and “sticky.” These responses indicate that friction consistency and surface finish, rather than form factor, drive tactile evaluation within this device group.

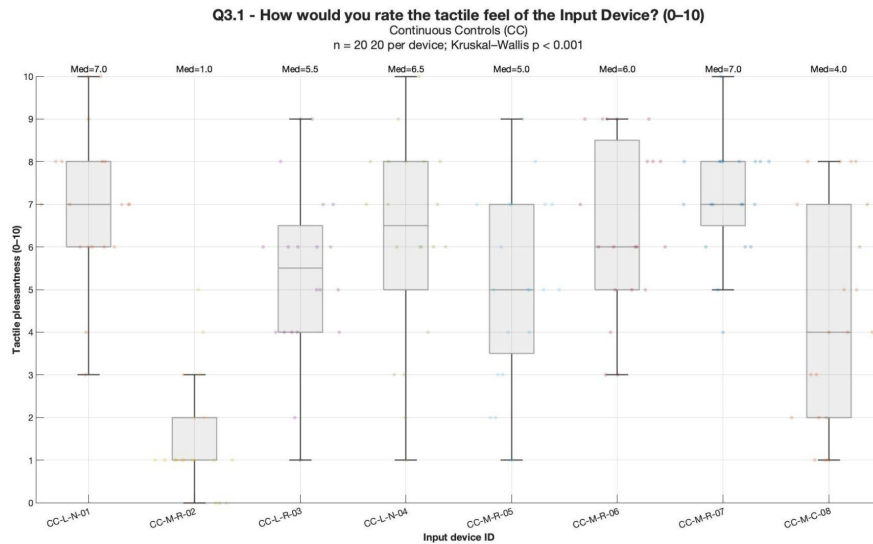


Figure 51: Continuous Controllers (CC): Tactile Pleasantness Ratings (Q3.1). Boxplots comparing eight continuous-controller designs with considerable variation in surface friction and resistance.

Force-Sensing Resistor (FSR)

The single FSR prototype (FSR-M-P-01) received a positive score overall (see Figure 52). Most participants found it easy and comfortable to use. Many described it as “soft” and evenly responsive, suggesting it allowed small, controlled movements without feeling uncomfortable or hard to manage.

Q3.1 - How would you rate the tactile feel of the Input Device? (0–10)

Force-Sensitive Resistor (FSR)

n = 20 per device; Kruskal–Wallis n/a

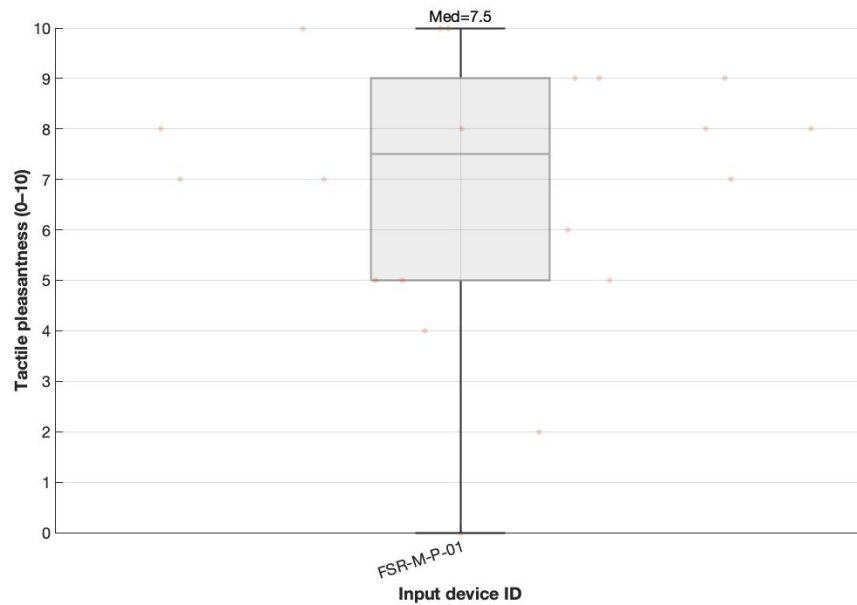


Figure 52: Force-Sensing Resistor (FSR): Tactile Pleasantness Rating (Q3.1).

The results of this tactile dimension provide the empirical basis for the later Ease-of-Use modeling stage, where tactile feedback proves to function as the dominant lower-level predictor in the affective hierarchy.

Size Appropriateness

Participants rated how well each input device's size met their expectations for use on a trombone interface (0-10 scale), where 0 reflects an inappropriate size, and 10 appropriate size.

Tactile Switches (TS)

Figure 53, shows that tactile switches have a wide spread of size-appropriateness ratings. Six devices (TS-01, 02, 04, 05, 06, 18) cluster at the upper end of the scale, suggesting that participants perceived these form factors as well-suited for trombone use. Participant comments commonly described these switches as “comfortable to press” and “easy to reach without shifting grip.”

In contrast, three devices (TS-13, 14, and 17) received lower ratings. Participants described these buttons as “too small,” “too tall,” or “hard to press,” indicating that both reduced surface area and increased profile height lowered perceived suitability. These responses also show that perceived size appropriateness does not follow a strictly linear relationship with physical dimensions. Instead, the data capture a multidimensional pattern that will later inform the analytical modeling of size effects.

Joysticks (JS)

The joystick category ($n = 3$; Figure 54) received overall positive but varied ratings. JS-01 and 02 (found also on PlayStation Portable) received median scores of 7.0, often described as “comfortable” and “familiar in size.” In contrast, the larger JS-03 received a lower median score (score of 3.5) and was described by several participants as “a little big” or “bulky for the hand position.”

Q4.1 — How well does the size of the Input Device meet your expectations for use on a trombone interface? (0–10)

Tactile Switches (TS)
Set 1 & Set 2 — n = 20 per device; Kruskal–Wallis $p < 0.001$ / $p < 0.001$

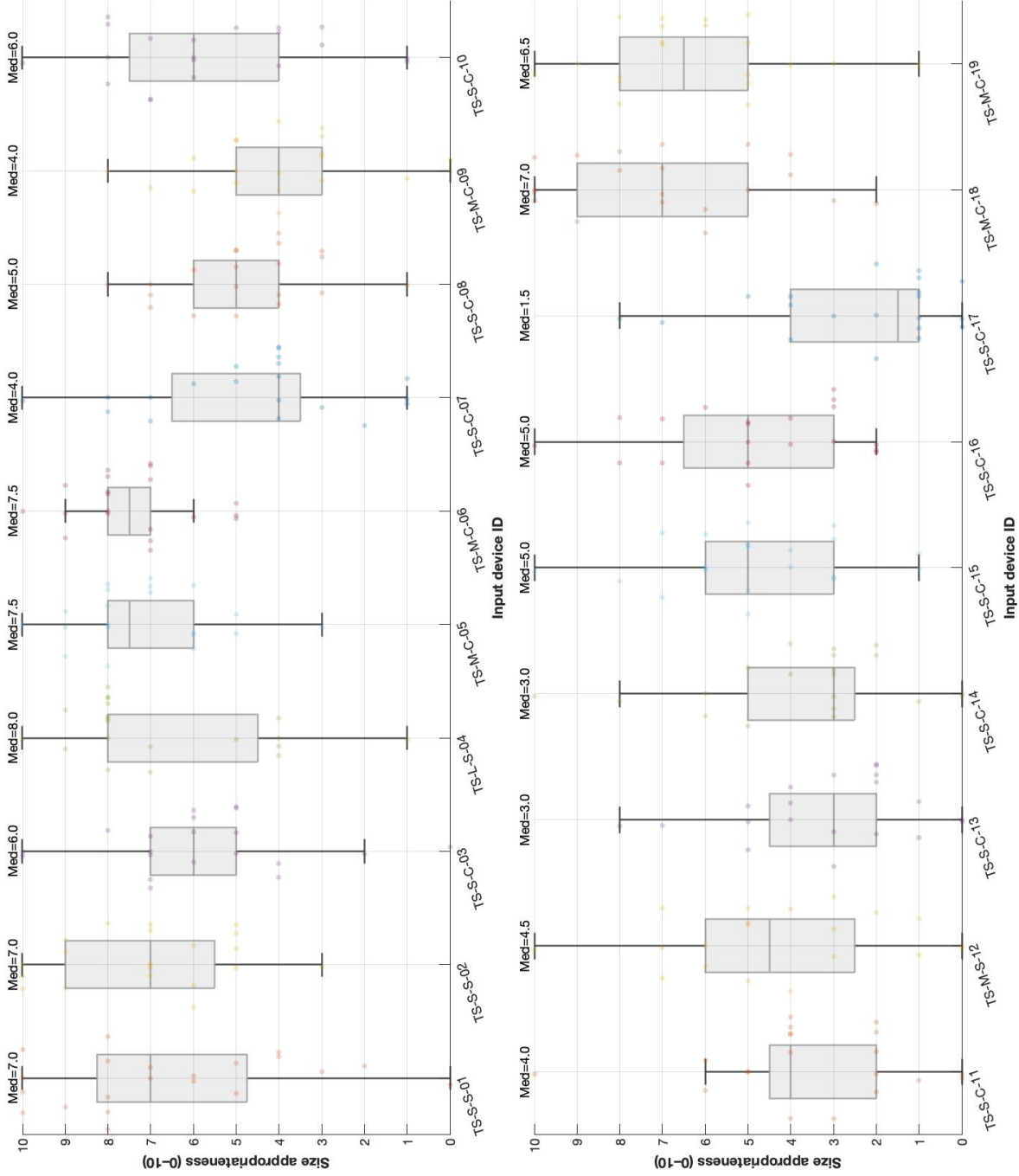


Figure 53: Tactile Switches (TS): Size Appropriateness Ratings (Q4.1).

Q4.1 – How well does the size of the Input Device meet your expectations for use on a trombone interface? (0–10)
 Joysticks (JS)
 n = 20 per device; Kruskal–Wallis $p < 0.001$

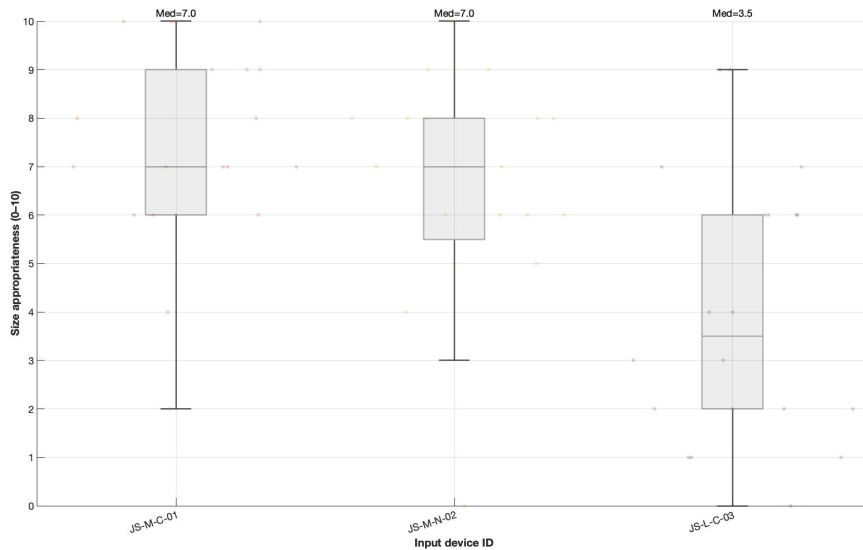


Figure 54: Joysticks (JS): Size Appropriateness Ratings (Q4.1).

Continuous Controllers (CC)

Continuous controllers (Figure 55) showed more variation. Participants rated CC-07 positively for their “balanced proportions” and “comfortable reach.” Lower-scored CCs, such as CC-02 and 01 (median scores of 3 and 4, respectively), were often described as “too small,” “hard to control precisely,” or commented that “could be slightly larger.”

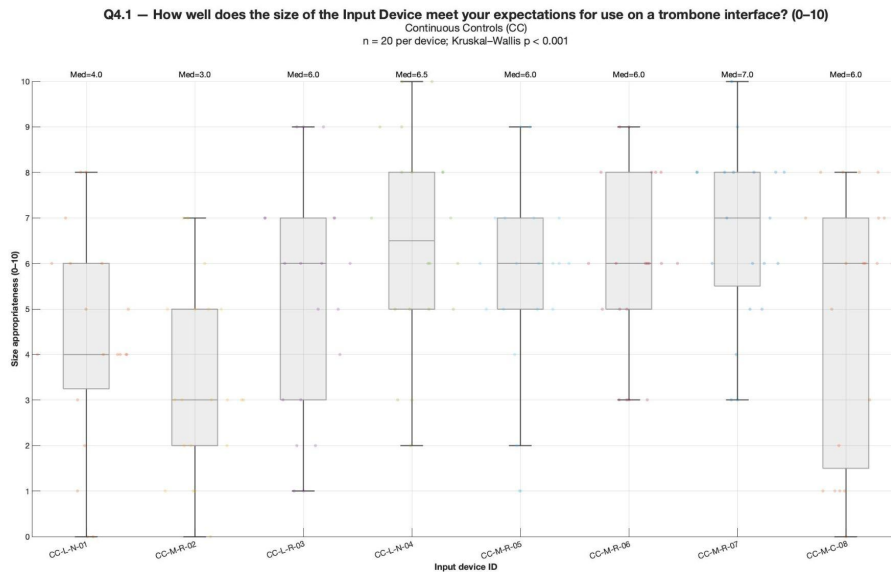


Figure 55: Continuous Controllers (CC): Size Appropriateness Ratings (Q4.1).

Force-Sensing Resistor (FSR)

The FSR prototype (FSR-M-P-01; Figure 56) obtained the highest median score (8.0, IQR=7-9). Participants consistently described its form factor as “well proportioned” and “comfortable for the hand,” highlighting the flexibility and low profile as ideal for pressure-sensitive use.

Q4.1 – How well does the size of the Input Device meet your expectations for use on a trombone interface? (0–10)

Force-Sensitive Resistor (FSR)
n = 20 per device; Kruskal-Wallis n/a (single device)

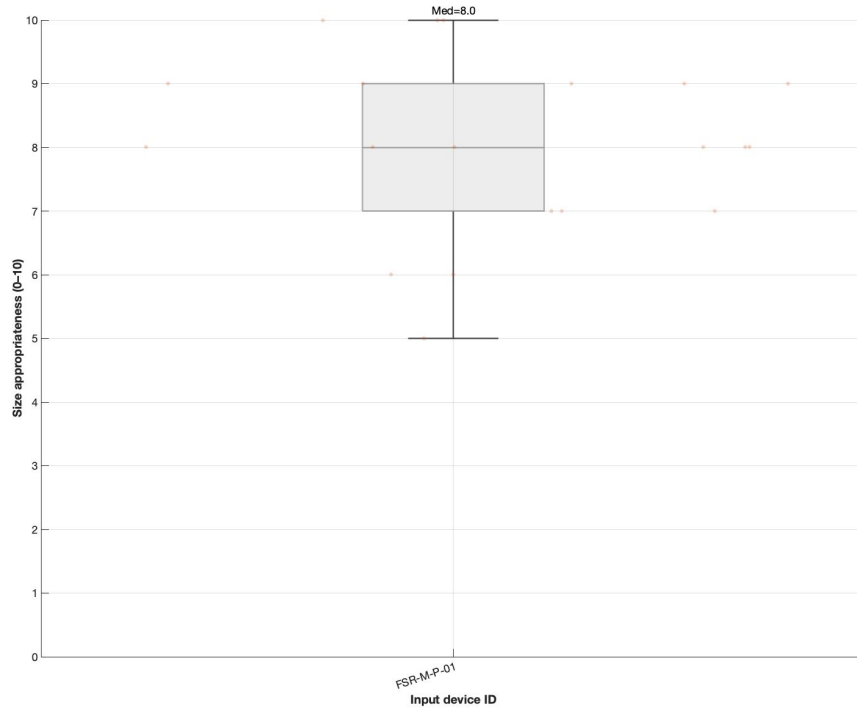


Figure 56: Force-Sensing Resistor (FSR): Size Appropriateness Rating (Q4.1). Single-device evaluation showing high approval for compact, low-profile design well-suited to finger pressure control.

Geometry Analysis of the best suitable HIDs

After exploring the individual size ratings across devices and types, the next step is to analyze whether any measurable geometric proportion could predict a “good fit” for a given HID. As shown in Table 7, the score ranking, at plain sight, does not reveal a single dominant dimension (length, width, or height)

to explain participant scores. This suggests that overall proportions, and not absolute size, might better capture what performers perceive as appropriate. To explore this, Figure 57 analyzes these results, implementing two regressions: (1) Score vs. Surface-to-Thickness ratio (Area/H, left panel) and (2) Score vs. Volume ($L \times W \times H$, right panel).

Each plot was modeled using an outlier-adjusted ANCOVA, which analyzed the results for device category (TS-JS-CC-FSR) in order to reduce type bias. The shaded grey region represents the 95% confidence interval (CI) around the fitted curve, while the solid black curve shows the median fitted trend. The blob overlay reveals the area where devices were consistently perceived as well-sized (scores 6-8 /10 with narrowed CI).

Figure 57, left panel, shows that Planar geometry alone does not explain size appropriateness. The relation between Score and Area/Height was weak and statistically non-significant. Although the curve rises slightly for devices with broader surfaces relative to height, the pattern remains irregular and does not converge toward a consistent ideal proportion.

In contrast, Panel B (Score vs. Volume) reveals a trend. The data form an inverted-U pattern describing that very small devices score lower, mid-sized devices score higher, and very large devices score lower again. The blue blob, which describes the well-sized input devices, aligns tightly around volumes of $\approx 400 - 500 \text{ mm}^3$. Beyond this range, both below $\approx 150 \text{ mm}^3$ and above $\approx 1000 - 1500 \text{ mm}^3$, scores decline, reflecting reduced comfort and usability.

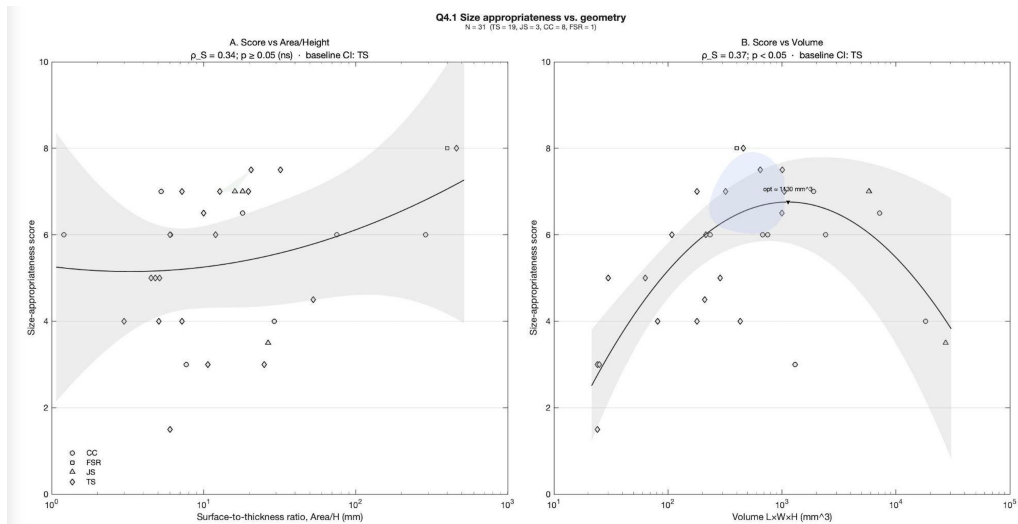


Figure 57: Relationship between size-appropriateness scores and geometric dimensions (Area/Height and Volume).

Table 7

Device Dimensions, Volume, and Median Score

Rank	Device ID	Dimensions (L×W×H in mm)	Volume (in mm ³)	Median
1	FSR-M-P-01	20×20×1	400	8.0
2	TS-L-S-04	20×23×1	460	8.0
3	TS-M-C-05	12×12×7	1008	7.5
4	TS-M-C-06	12×12×4.5	648	7.5
5	TS-S-S-01	8×8×5	320	7.0

Continued on next page

Table 7

Device Dimensions, Volume, and Median Score (continued)

Rank	Device ID	Dimensions (L×W×H in mm)	Volume (in mm ³)	Median
6	TS-S-S-02	6×6×5	180	7.0
7	TS-M-C-18	12×12×7.3	1051	7.0
8	JS-M-C-01	18×18×18	5832	7.0
9	JS-M-N-02	19×16×19	5776	7.0
10	CC-M-R-07	10×10×19	1900	7.0
11	TS-M-C-19	10×10×10	1000	6.5
12	CC-L-N-04	40×9×20	7200	6.5
13	TS-S-C-03	6×6×6	216	6.0
14	CC-L-R-03	15×2×25	750	6.0
15	CC-M-R-05	15×15×3	675	6.0
16	CC-M-R-06	11×11×20	2420	6.0
17	CC-M-C-08	13×20×0.9	234	6.0
18	TS-S-C-10	6×6×3	108	6.0

Continued on next page

Table 7

Device Dimensions, Volume, and Median Score (continued)

Rank	Device ID	Dimensions (L×W×H in mm)	Volume (in mm ³)	Median
19	TS-S-C-08	6×6×8	288	5.0
20	TS-S-C-15	3×6×3.5	63	5.0
21	TS-S-C-16	3×4×2.5	30	5.0
22	TS-S-C-07	6×6×5	180	4.0
23	TS-S-C-11	4.5×4.5×4	81	4.0
24	CC-L-N-01	73×10×25	18250	4.0
25	TS-M-S-12	15×7×2	210	4.5
26	TS-M-C-09	6×6×12	432	4.0
27	JS-L-C-03	34×25×32	27200	3.5
28	TS-S-C-13	4×4×1.5	24	3.0
29	TS-S-C-14	5×5×1	25	3.0
30	CC-M-R-02	10×10×13	1300	3.0
31	TS-S-C-17	3×4×2	24	1.5

Visual Appeal of Input Device Design

Participants scored how visually appealing each input device is when imagined attached to a trombone (0 = unattractive, 10 = attractive).

Tactile Switches (TS)

The visual evaluation of tactile switches showed a strong polarization (see Figure 58), shaped primarily by how well the devices visually integrated with the instrument rather than by stylistic preference alone. High-scoring devices, including TS-02 and 06, have neutral colors and compact, uniform casings. Participants describe these designs as visually “clean” and “professional” and note that they blend naturally with metallic and matte brass finishes.

In contrast, more industrial-looking devices, such as TS-09 and 08, were rated lower due to visible mechanical elements and protruding stems. Participant comments described these as “ugly,” “cheap-looking,” and “fragile,” indicating that exposed hardware triggered both aesthetic rejection and concerns about durability.

Q5.1 — How visually appealing is the design of the Input Device? [0-10]

Tactile Switches (TS)
 n = 20 per device; Kruskal–Wallis (19 TS) $p < 0.001$

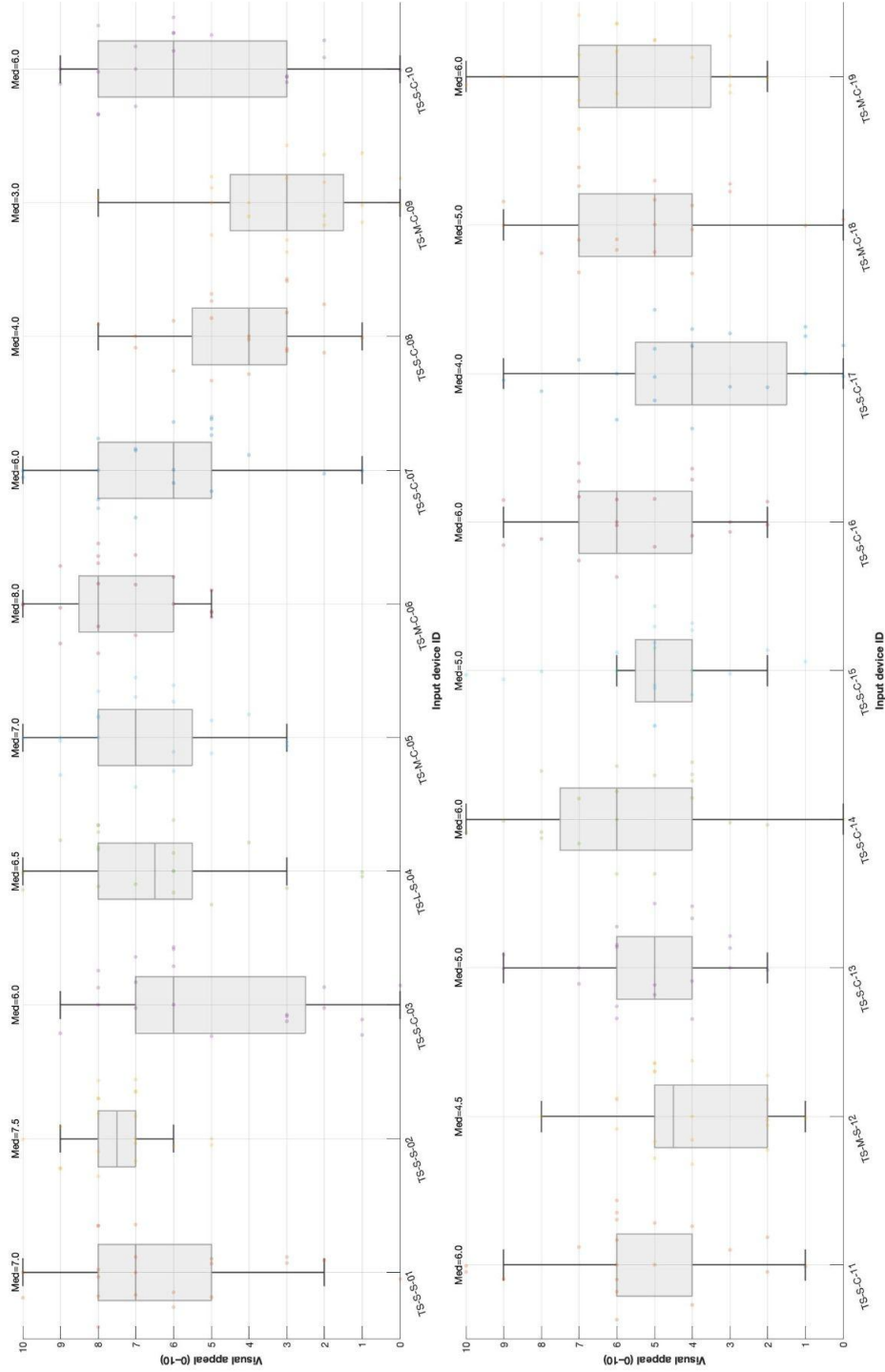


Figure 58: Tactile Switches (TS): Visual Appeal Rating (Q5.1)

Joysticks (JS)

Joysticks received generally positive visual ratings, though the aesthetic impressions varied markedly across models (see Figure 59). JS-01 and JS-02 (both featuring symmetrical thumb-cap designs) were rated highest (medians = 8.0 and 7.0). This outcome is unsurprising as these models are used on familiar game-controller joysticks. In contrast, the exposed circuit and mounting frame of JS-03 lowered its appeal (median = 4.5). Participants prefer designs where electronic components are visually enclosed and integrated.

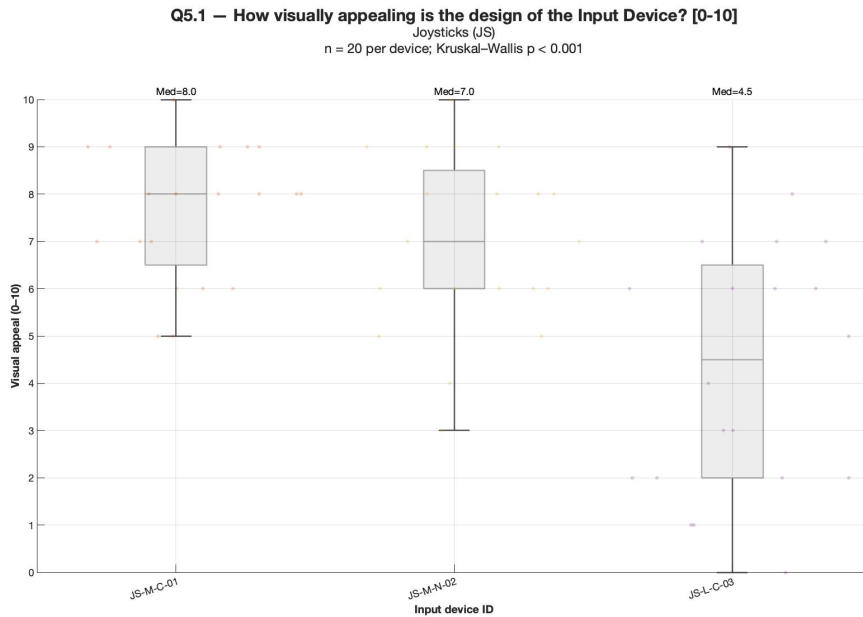


Figure 59: Joysticks (JS): Visual Appeal Ratings (Q5.1).

Continuous Controllers (CC)

Regarding continuous controllers (CC), Figure 60 shows how they received moderate visual appeal ratings overall, with median values ranging from 2.0 to 6.0. The most positively rated units, CC-07 (median = 6.0) and CC-05 (median = 5.0), shared a compact, enclosed rotary design that appeared visually coherent and balanced. However, CC-02 received the lowest rating (median = 2.0), reflecting that more utilitarian casings and contrasting or bright colors were perceived as less visually appealing.

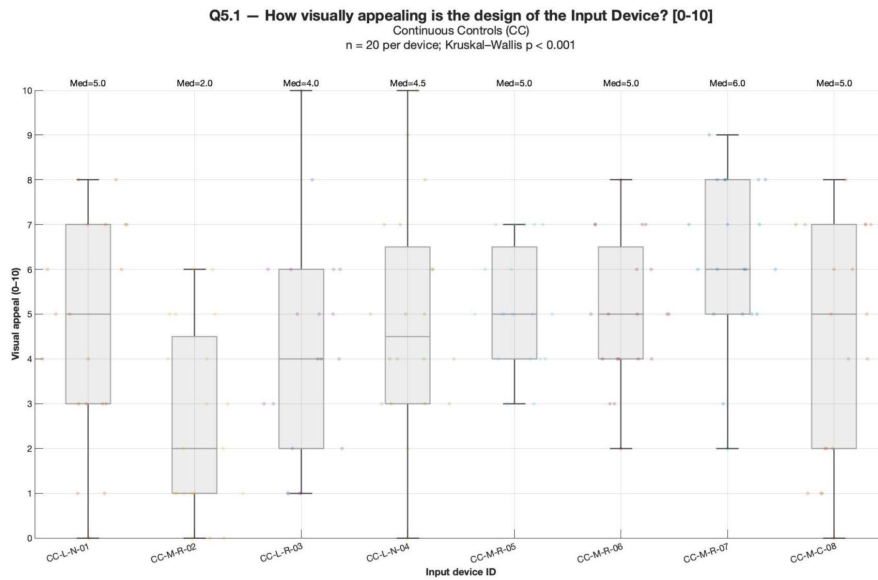


Figure 60: Continuous Controllers (CC): Visual Appeal Ratings (Q5.1).

Force-Sensing Resistor(FSR)

The single FSR prototype (FSR-M-P-01) received a high median rating of 7.0, which reflects a consistent preference for its flat and unified visual form (see Figure 61). Participants appeared to favor its seamless look and neutral surface, which aligned with the idea of a subtle add-on component rather than an external attachment.

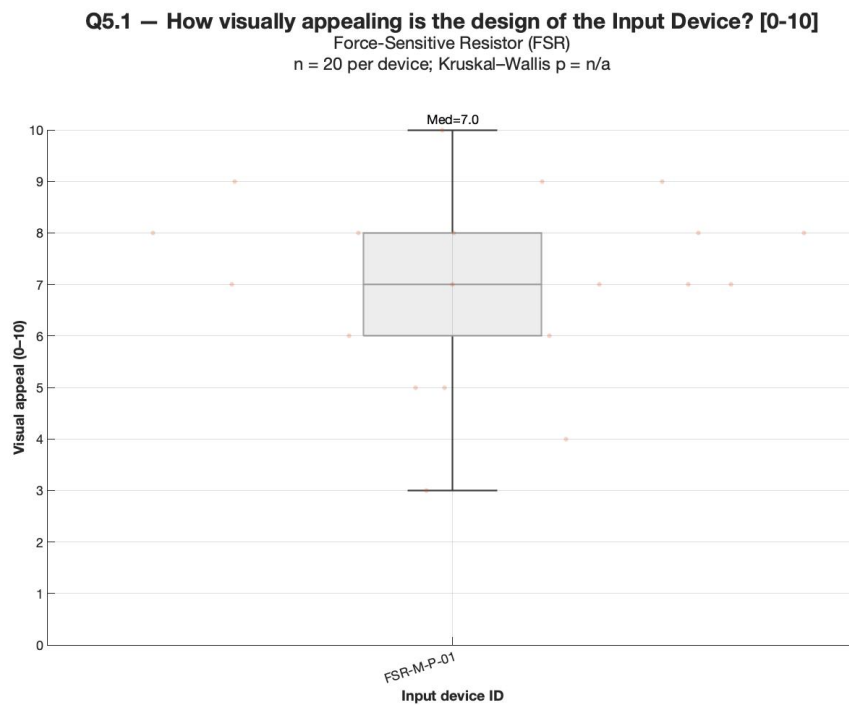


Figure 61: Force-Sensing Resistor (FSR): Visual Appeal Rating (Q5.1)

Ease of Use

Participants rated how easy each input device would be to operate while playing the trombone (0 = difficult, 10 = easy), considering factors such as accessibility, intuitiveness, and control precision. Although this question summarizes a multidimensional experience, Ease of Use works here as a composite perceptual construct, one that condenses multiple ergonomic and cognitive aspects relevant to each participant. In this section, the analysis focuses solely on the reported scores for each device. The composition of this variable, and its relationship to overall evaluation, are later discussed in detail (see section “The Affective Model”).

Tactile Switches (TS)

Figure 62 shows how tactile switches have the widest spread of usability scores across all device types. Models such as TS-01, 05, 06, and 18 scored the highest medians (8.0-8.5). Conversely, smaller or stiffer to press models such as TS-12, 13, and 17 received the lowest ratings (medians = 2.0-2.5), which led to the conclusion that disproportionate resistance or reduced contact surface compromised the use.

Q6.1 — How easy do you think it would be to use this Input Device while playing the trombone? (0-10)

Tactile Switches (TS)
Set 1 & Set 2 — n = 20 per device; Kruskal-Wallis $p < 0.001$ / $p < 0.001$

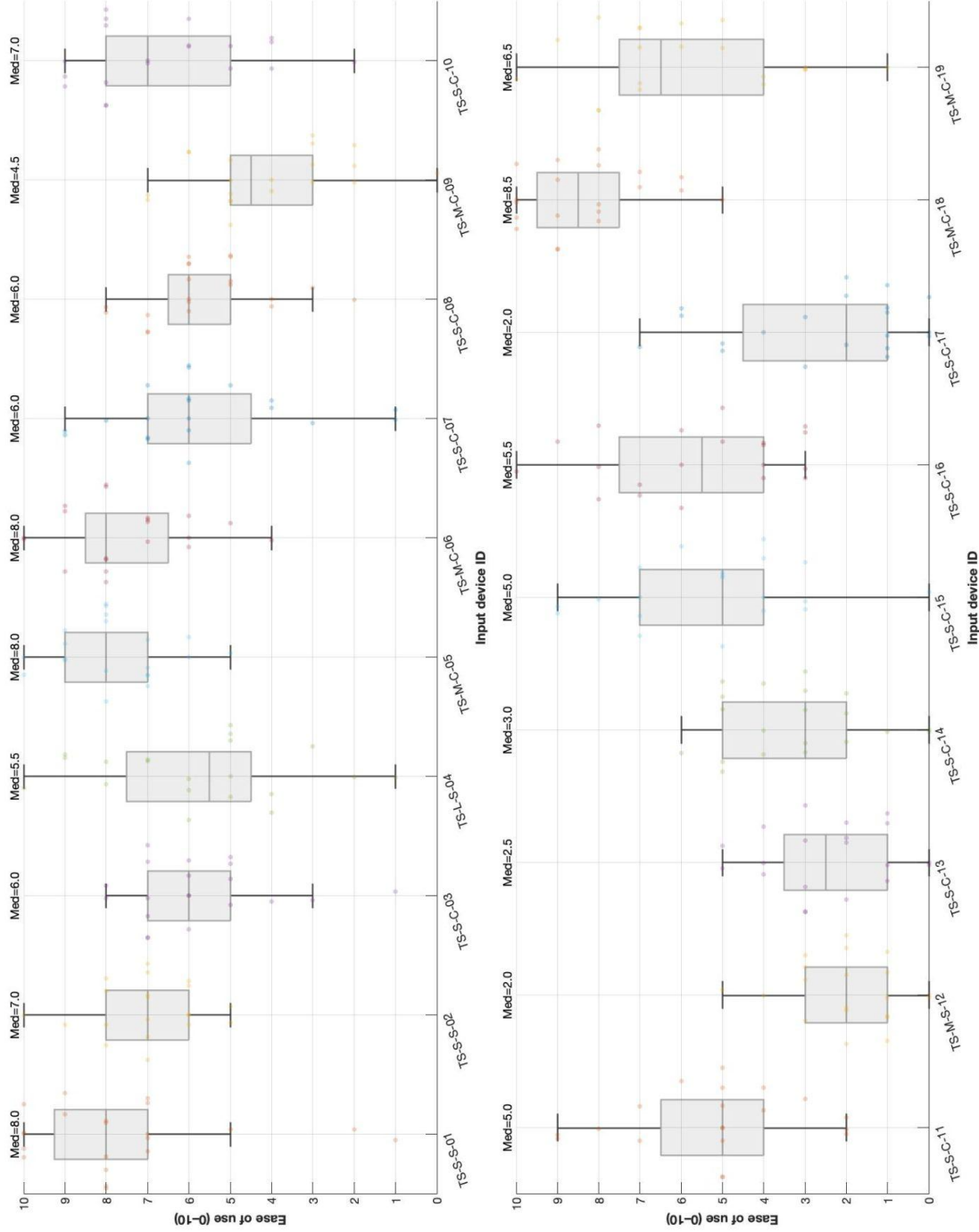


Figure 62: Tactile Switches (TS): Ease of Use Rating (Q6.1)

Joysticks (JS)

Figure 63 shows how Joysticks were rated positively overall but present significant variation among models. The thumb-style JS-02 was considered the easiest to operate (median = 8.0). The larger JS-03, while mechanically similar, was rated slightly lower (median = 5.5), possibly due to the limited comfort when reaching or maintaining control while holding the trombone. Overall, low-profile and low-travel joysticks provide a more controllable motion range for performance contexts.

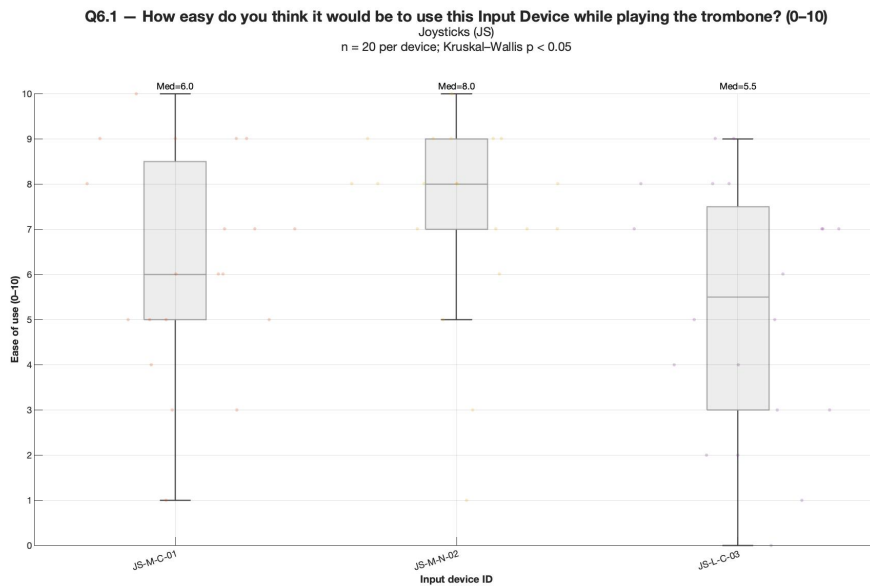


Figure 63: Joysticks (JS): Ease of Use Rating (Q6.1)

Continuous Controllers (CC)

Continuous controllers, illustrated in Figure 64, yield mixed evaluations. For instance, rotary models such as CC-07 and CC-04 received the most positive feedback (medians = 8.0 and 7.0), which could be caused by their movement smoothness and fine control. In contrast, CC-02 scored lowest (median = 1.0), something that at this point is not surprising based on the overall rating in all the other previous dimensions. The remaining designs, including CC-05, 06, and 08, clustered around moderate usability (medians = 5.0-6.0). In general terms, for CCs, there is a general preference for rotary mechanisms over slider-based forms, particularly due to the hand constraint position caused by the trombone grip effect.

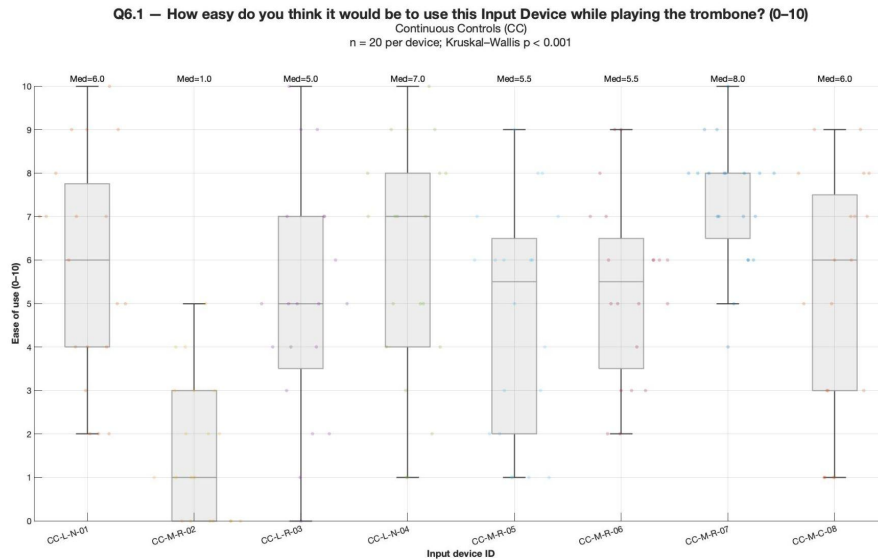


Figure 64: Continuous Control (CC): Ease of Use Rating (Q6.1)

Force-Sensitive Resistor (FSR)

The FSR, shown in Figure 65, was evaluated as easy to use (median = 7.0), with participants reporting that it required minimal effort. Its continuous, pressure-based interaction model makes it one of the more intuitive control options tested.

Overall, the FSR's ease of use qualities were strongly influenced by tactile accessibility and actuation profile.

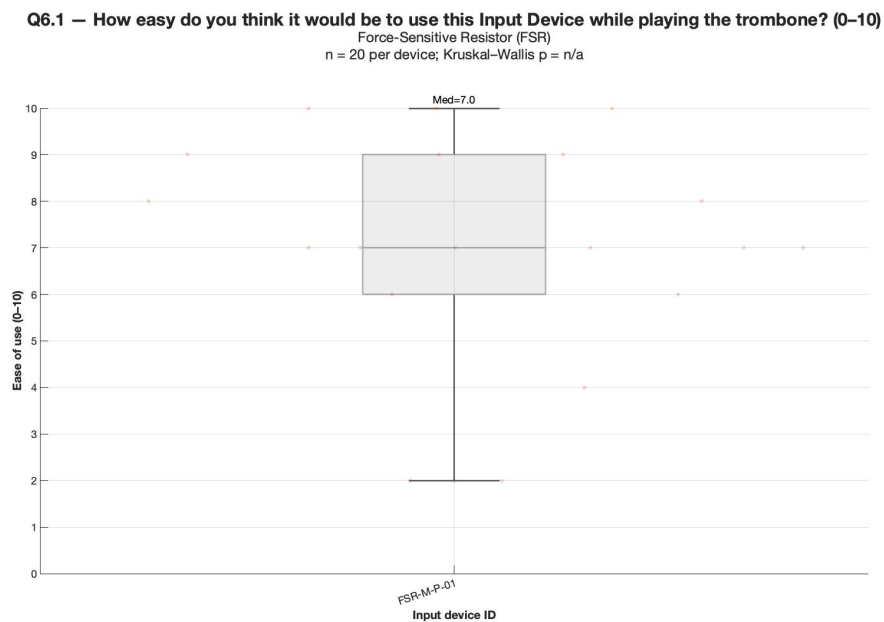


Figure 65: Force Sensitive Resistor (FSR): Ease of Use Rating (Q6.1)

Overall Impression

The last Likert scale question of this section asked participants to rate the overall suitability of each input device for trombone performance. This question aimed to collect a general evaluation as well as to provide a reference for how other variables, such as tactile response, ease of use, and size, may influence the total score and its effect size. Participants rated from 0 to 10, where 0 reflected a negative overall impression and 10 a positive one.

Tactile Switch (TS)

As shown in Figure 66, tactile switches (TS) displayed the widest range of overall impression scores, with medians spanning from 2.0 to 8.0. The higher median scores were given to TS-01, 05, 06, and 18, which received the highest medians (7.0-8.0), while devices like TS-12, TS-13, and TS-17 showed the lowest scores (2.0-3.5).

Joysticks (JS)

Similar to previous affective dimensions, joysticks yielded an overall positive rating (see Figure 67).

Q7.1 — Overall, how would you rate this Input Device (0–10)

Tactile Switches (TS)

Set 1 & Set 2 — n = 20 per device; Kruskal–Wallis $p < 0.001$ / $p < 0.001$

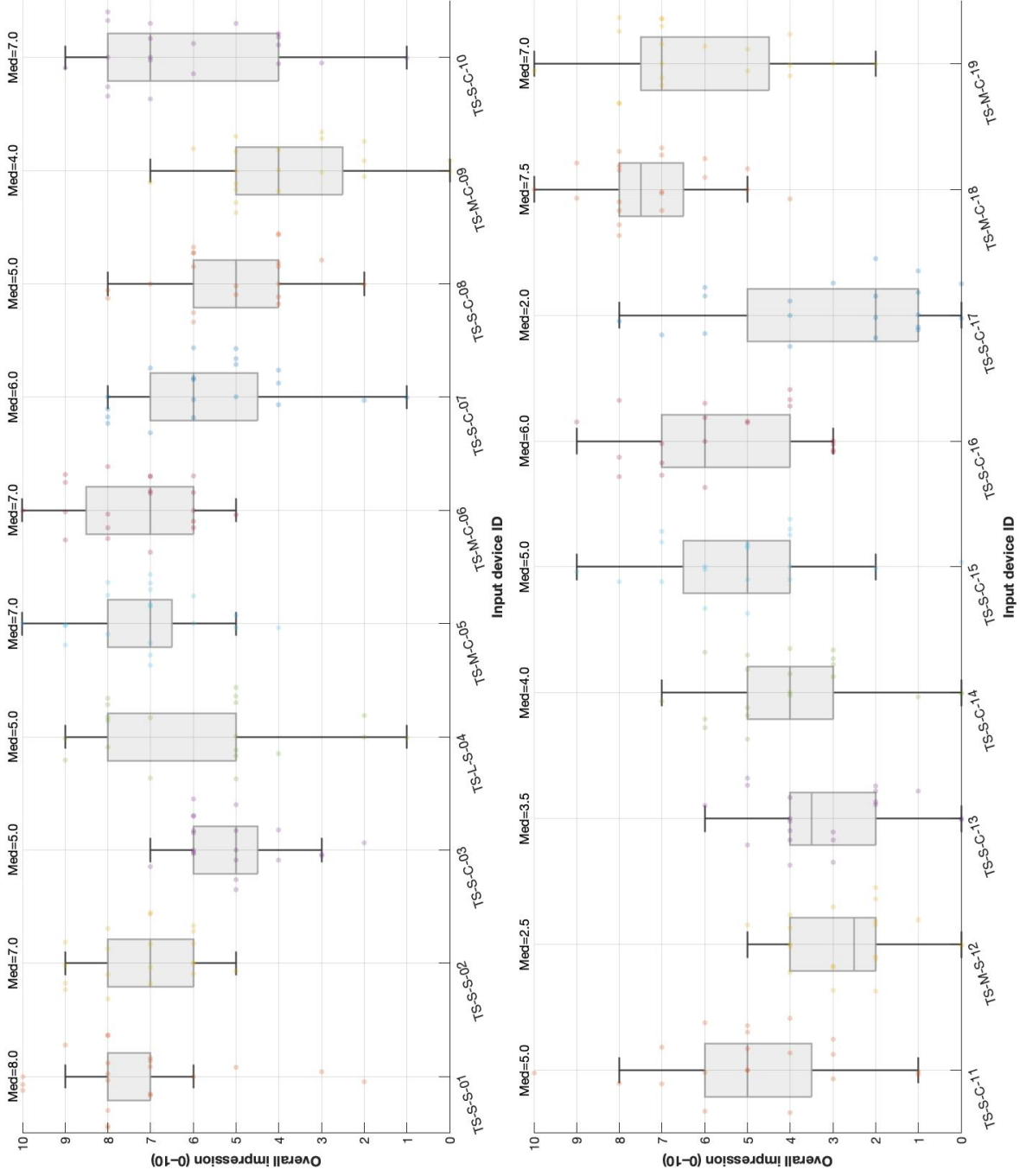


Figure 66: Tactile Switches (TS): Overall Impression Ratings (Q7.1).

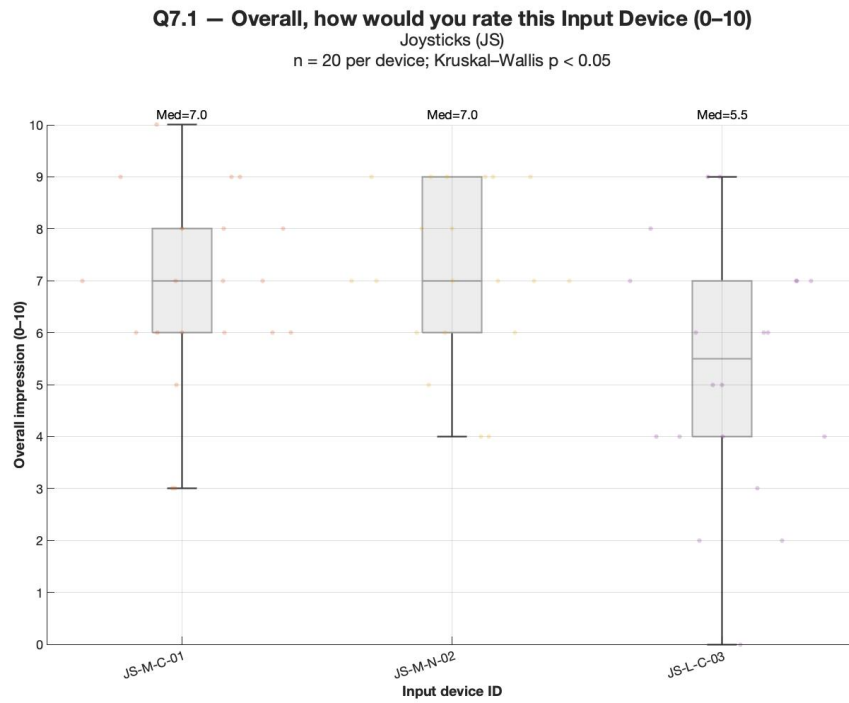


Figure 67: Joysticks (JS): Overall Impression Ratings (Q7.1).

Continuous Control (CC)

Continuous controllers (CC) displayed a moderate overall score (medians = 1.5-7.0). CC-07, 06, and 04 received the highest scores (6.0-7.0), while CC-02 displayed the lowest median (1.5)(see Figure 68).

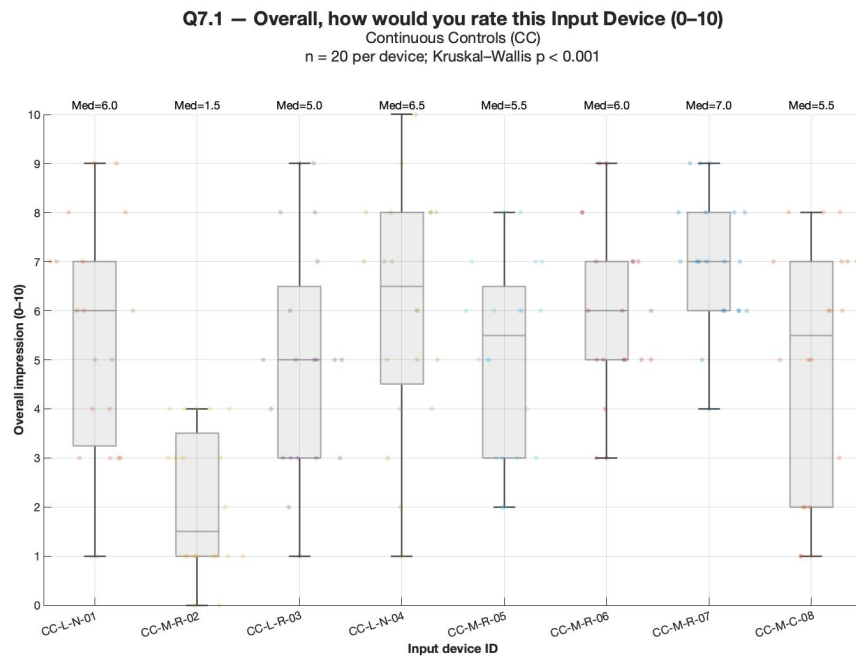


Figure 68: Continuous Controllers (CC): Overall Impression Ratings (Q7.1).

Force-Sensitive Resistor (FSR)

Finally, the single Force-Sensitive Resistor (FSR-M-P-01) got a median of 7.0 (see Figure 69), presenting a consistently positive overall impression.

does not aim to evaluate the positive or negative impact of each theme, but rather to identify the judgment criteria based on the overall scores.

Figure 70 shows how the thematic distribution reveals that tactile aspects dominated participant comments. This indicates that trombonists tended to evaluate devices primarily through how they feel—as well as in terms of usability—while size and aesthetic judgments played an auxiliary role.

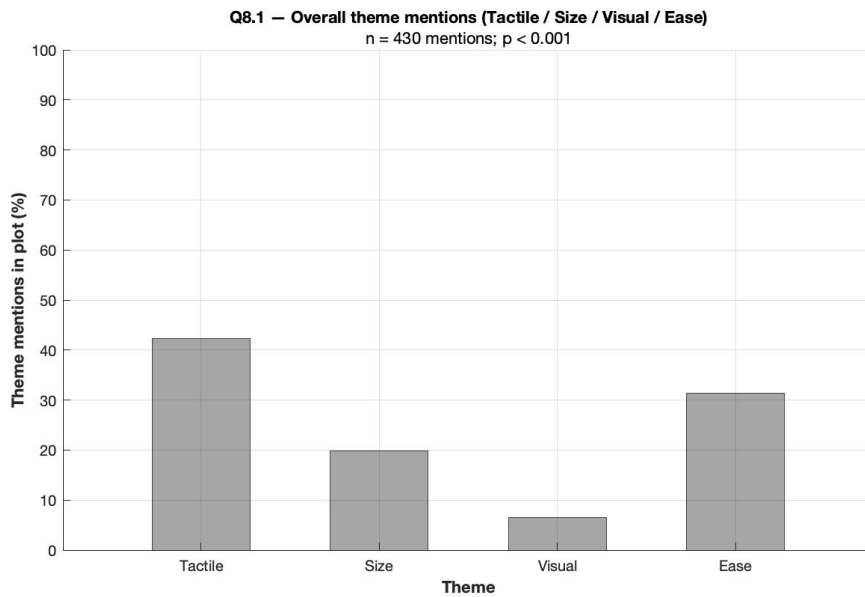


Figure 70: Overall theme mentions across all comments (Q8.1).

Appendix F, Figure F.21, Figure F.22, Figure F.23, and Figure F.24, show the device-level distributions of coded comment categories across all valid qualitative responses. Size-related comments appeared less frequently and concentrated around devices with extreme physical proportions, particularly TS-17, JS-03, and TS-11 (Appendix F, Figure F.23), rather than distributing evenly across models. Visual-related comments occurred least often ($p \approx .99$, ns),

with TS-14 as the only device exceeding 10% of all visual-category mentions (Appendix F, Figure F.24).

Affective Assessment of Noise as Acoustic Feedback

As described before, while running the theme analysis from participant comments given after rating the overall impression, one relevant aspect that emerged was the click sound mechanism, which directly interferes with the performative aspect. Participants frequently mentioned how the audible response of the button modeled their perception of playability and integration with the instrument. Comments included:

“The click is too loud and distracting when playing.”

“Feels responsive but makes too much sound.”

“Good tactile response, though the button noise could interfere with acoustic playing.”

“Prefer the softer ones; the loud click breaks the immersion.”

“Audible click gives feedback but might be picked up by microphones.”

“The sound helps me feel it’s working, but it could be too noticeable on stage.”

These reflections illustrate two competing perspectives. While some trombonists prefer the audible “click” as an audible confirmation for activation, others

perceive it as intrusive, particularly in acoustic performance contexts where the mechanical sound blends poorly with the musical output. Although the Noise theme emerged from participants' comments on overall impression, its nature positions it closer to what was described in Phase One as Perceptual Intrusiveness rather than the affective-experiential core itself. The audible feedback of the switch operates as a sensory cue, influencing the performer's perceptual field rather than their experiential assessment directly. However, because it alters how comfortable or natural a control feels during playing, it indirectly shapes affective evaluations such as ease and overall suitability. For this reason, Noise is treated here as a second-order perceptual modifier within the affective model, an element that mediates between tactile feedback and affective response. This also anticipates the following section on Affective Progression, where such perceptual and tactile variables are analyzed together to understand how they collectively influence overall evaluation and performer comfort. Figure 71 presents noise-related comments for tactile switches only. TS-18, TS-05, and TS-06 account for the highest share of references (\approx 9-11% each). TS-18 generated the most "click sound" comments, despite ranking among the top two tactile switches overall with positive scores. This pattern shows that the sonic cue remains noticeable to performers but does not necessarily reduce overall preference.

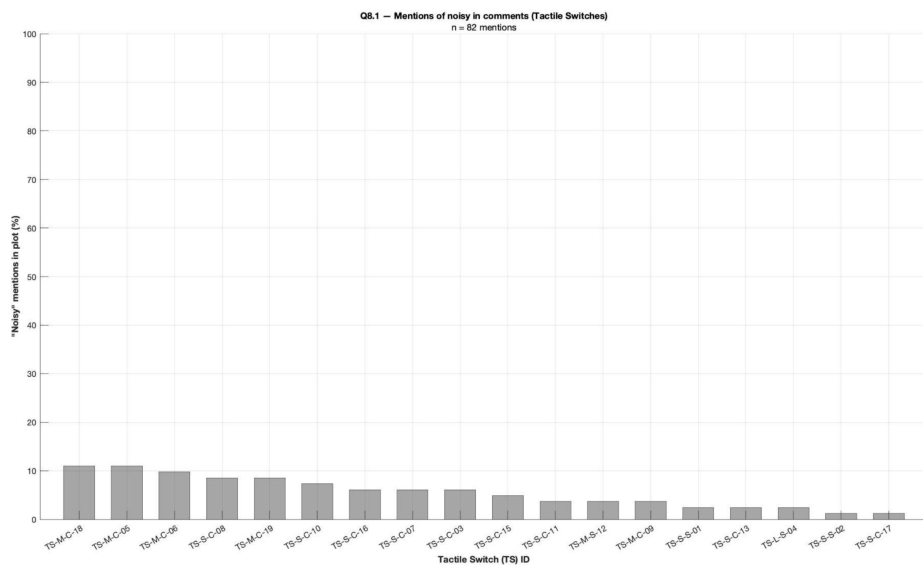


Figure 71: Mentions of noisy (mechanical feedback) aspects across tactile switches (Q8.1).

Even though in this study, mechanical noise falls under the classification of perceptual intrusiveness, it also carries affective weight by influencing the sense of control intimacy, and performative transparency. These findings directly inform the next section, in which the quantitative model examines how these perceptual and tactile components jointly determine the overall impression score of input devices.

The Affective Model

The goal of this section is to understand how perceptual attributes such as tactile feel, size, and visual appeal merge into a broader sense of ease of use, and how this perception subsequently steers the overall impression of suitability for trombone performance. To begin, perceptual attributes and ease of use

scores were compared with the overall impression to explore their individual correlation. The result revealed that ease of use was most strongly correlated with the overall score ($\rho = 0.896, p < .001$). In other words, trombonists seem to interpret “ease” as the synthesis of how the device feels, fits, and looks. The analysis then modeled the internal structure of these relationships to establish how tactile, size, and visual attributes combine to form the perception of ease, and how that perception in turn predicts overall preference. Because these relationships follow a sequence, from concrete physical features to an intermediate evaluative stage and finally to global preference, the method is later described as a hierarchical progression model.

Level 1: Ease as a function of Tactile, Size, and Visual ratings

The first model (see Figure 72) examined how tactile, size, and visual ratings predict perceived ease of use. The coefficient of determination was $R^2 = 0.63$, indicating that 63% of the variability in Ease-of-Use scores is explained by the combined effect of these three attributes. Using a multiple regression with z-standardized predictors, the standardized coefficients were rescaled to sum to 100%, yielding each factor’s relative contribution to the explained variance. Tactile feedback emerged as the dominant predictor, accounting for approximately 53% of the explained variance, followed by size ($\approx 32\%$) and visual appeal ($\approx 14\%$). This pattern suggests that, when performers assess how easy a device is to operate, they prioritize how it feels and fits in the hand over its purely visual characteristics.

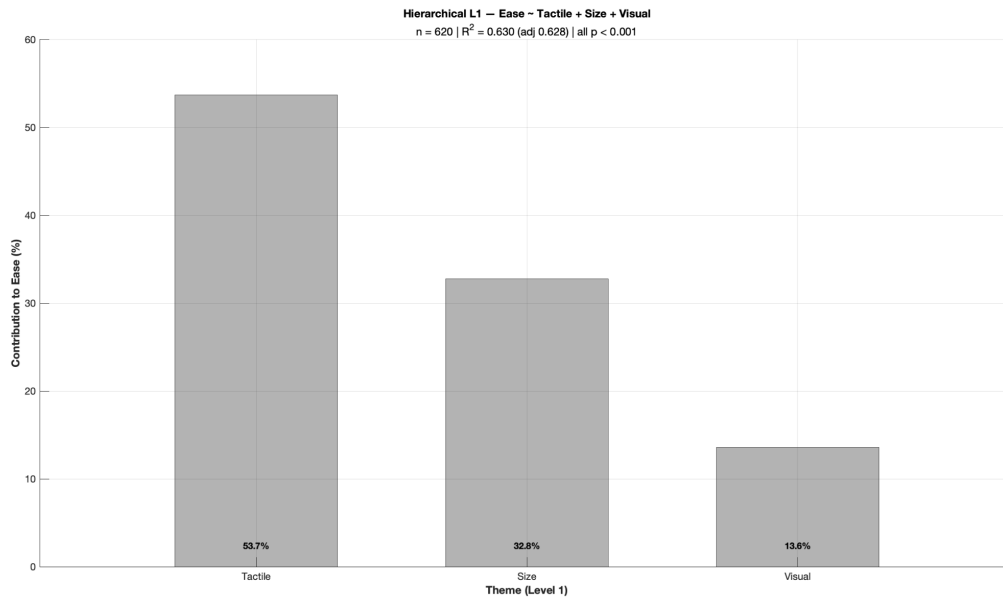


Figure 72: Level 1: Ease as a function of Tactile, Size, and Visual ratings.

Level 2: Ease as the Gateway to Overall Impression

The second level (see Appendix F, Figure F.25) compares Ease with Overall Impression and reveals an almost linear relationship. About 81% of how positively a device was rated overall can be explained by how easy it felt to use. The very high rank correlation ($\rho = 0.896$) further indicates that participants who experienced a device as easier to operate almost always ranked it higher overall, even when their use of the rating scales differed slightly. This suggests that perceived ease of use was not merely a contributing factor but the dominant element shaping participants' overall impressions.

Taken together, Levels 1 and 2 describe the main affective trajectory of device

evaluation: from how the device feels to touch, to how easy it is perceived to be, and ultimately to the overall impression. This path emphasizes that “ease of use” functions as a perceptual mediator, condensing lower-level sensations into a single, higher-order representation of compatibility.

Residual Layer: Fine-Tuning through Qualitative Feedback

Although ease of use explains most of the variance in overall impression, performers’ written comments, collected immediately after they scored overall impression, revealed additional nuances. After running a second regression model ($\text{Overall} \sim \text{Ease} + \text{Residuals}$), incorporating these comments explained an additional 5% of variance ($\Delta R^2 = 0.050$) beyond what was already accounted for by ease of use alone. This result confirms that, once ease of use had already captured roughly 80% of the overall impression, the residual analysis helped recover a small but meaningful portion of the remaining variability, corresponding to perceptual subtleties that numerical ratings alone could not fully capture. The bars in Figure 73 show how this 5% slice is distributed across themes, each normalized to 100% within this subset. Noise emerged as the most influential residual dimension (27.2% of the 5%), followed by Visibility (12.5%) and Placement (11.2%), which, although not statistically significant, remain qualitatively informative.

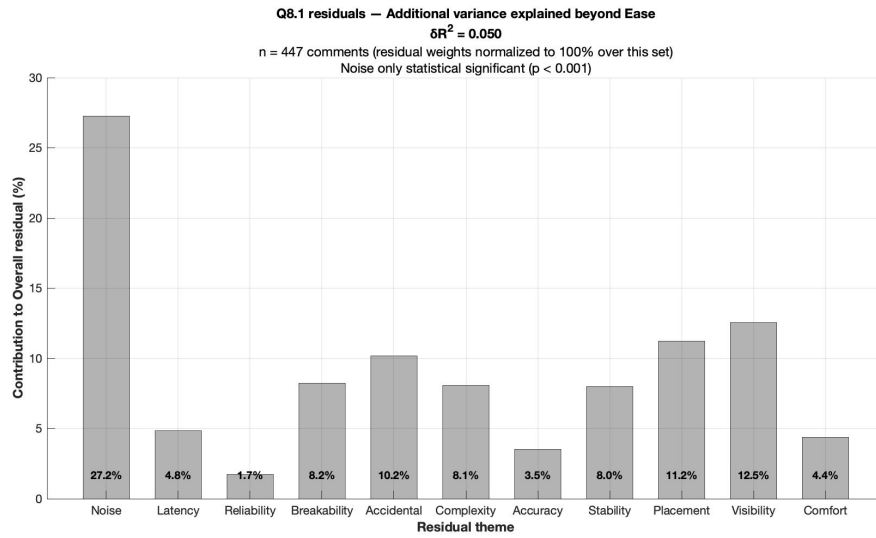


Figure 73: Residual analysis: Additional variance explained beyond Ease.

Composite Decomposition of Overall Affect

To visualize how these contributions accumulate, Figure 74 integrates the hierarchical and residual findings. When both levels are combined, approximately 85% of the overall variance is accounted for ($R^2 \approx 0.855$).

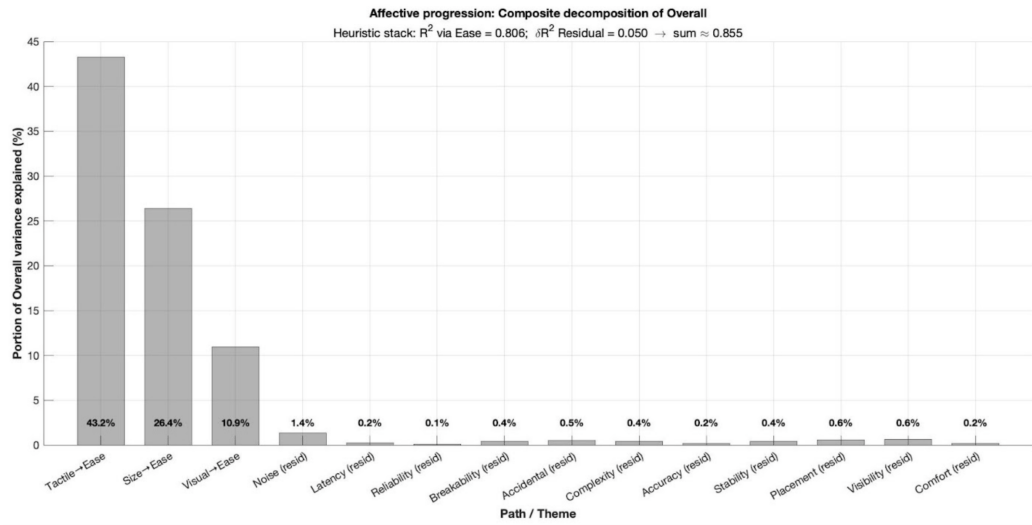


Figure 74: Composite decomposition of overall affective variance.

This proportional decomposition reveals that the majority of perception originates from tactile and size-related pathways, which contribute to the sense of ease and, ultimately, overall perception.

Model Summary and Integration

The final comparative plot shows the transition between models. Appendix F, Figure F.26 shows the coefficient of determination of 0.806 for the Ease-only model and 0.855 once residual comment themes are included. Although this 5% increase in explained variance may seem modest, its interpretive significance is considerable. These residual themes capture the fine-grained substructures of the perceptual experience, factors such as audible mechanical noise, perceived stability, or visibility, which remain closely connected with the core tactile and ergonomic dimensions. In this sense, the residual layer

does not merely add small corrections to the model; it exposes the hidden links between higher-level perceptual judgments (e.g., tactile feel) and their lower-level manifestations (e.g., the physical click mechanism producing both tactile and acoustic feedback). In Appendix F, Table F.2, Table F.3, Table F.4, Table F.5, and Table F.6 illustrate a summary for the best input device selected per category and affective dimension. The next section presents the formulation of the affective model.

The Affective Model Formulation

The three model layers show how the perceptual components combine into a single judgment. The first model (Ease-only) explains 80.6 percent of the variance, with tactile feedback contributing the most, followed by size and visual appeal. Incorporating the residual cues yields the composite affective model:

$$\text{Overall}_{\text{pred}} = 0.806 \times (0.537 T + 0.328 S + 0.136 V) + 0.050 R \quad (12)$$

where T , S , and V represent tactile, size, and visual components, and R captures the residual perceptual refinements (e.g., sound, placement, or stability). The model explains approximately 85% of the variance in overall judgments, leaving the remaining $\approx 15\%$ to individual and contextual differences, such as familiarity, technique, etc.

Taken together, the affective assessment findings and model point to a profile

of performer-preferred input devices. For tactile switches, broad finger-contact surfaces, not force (gf) or activation travel distance, determined comfort. Click noise produced mixed reactions; some performers valued the tactile confirmation of activation but not the audible cue. Continuous controllers were rated highest when resistance was smooth and predictable, and low-profile joysticks with flat caps were preferred over exposed designs; the FSR was the most consistently well-received device. Size showed a clear pattern, with a comfort zone around 400-500 mm³, while very small or oversized housings reduced usability. The hierarchical model illustrates the order in which these attributes shaped evaluation. Tactile feedback contributed the most, followed by size and visual appeal; these three cues combined to form perceived ease of use (Level 1). Ease then acted as the dominant predictor of overall impression (Level 2), and the residual perceptual factors, such as noise, visibility, and placement, added a small but meaningful refinement. Altogether, the composite model explained about 85% of overall judgments.

Input Device Configuration

This section examines how physical placement, spatial organization, and cognitive assessment of human input devices (later IDs) shape the viability of a non-intrusive control system on the trombone. Participants configured and evaluated multiple combinations of IDs, one microcontroller, and one battery across the three predefined trombone grip posts. All components remained unpowered to isolate ergonomic and mechanical factors from electronic behavior. Each configuration was tested through three short performance tasks:

(1) a free-choice piece (participant familiarity), (2) an étude (a short musical passage structured to use with all participants), and (3) sight-reading (boundary-pushing scenario). Study music materials for this section can be found in Appendix E. The process began with single-device trials per category and progressed iteratively toward multi-device arrangements in which each additional element reshaped hand geometry, finger availability, and overall intrusiveness. Participants continued this additive process until reaching a configuration deemed no longer workable. The section concludes with each performer’s “Ideal NIHCF” layout (F10 iteration), defined after completing all single and multi-device trials and validated through a final free-performance test.

Post 1 corresponds to the upper section of the left-hand trombone slide grip, Post 2 to the horizontal segment, and Post 3 to the lower junction. Distances (in cm) are measured from the mouthpiece end of each post, with 0 cm marking the start of the post. Angular orientation uses a fixed 0° reference at the outermost center point of each post. For ease of interpretation, angles can be visualized using a clock analogy: $0^\circ = 12$ o’clock, with each hour representing 30° (e.g., $90^\circ = 3$ o’clock). All angles are described from the performer’s viewpoint in playing position, so a value such as 90° places the device on the outer, right-facing side of the post.

Battery and Board Placement

Participants showed convergence in the positioning of the processing board and battery. The processing board preference placement is on Post 1, with a mean distance of 4.54 cm from the mouthpiece shank and at a median angle of 127 ° (facing outward). Battery placement showed greater distribution across posts, though Post 1 ($\approx 103^\circ$) again represented the most frequent choice. Overall, Battery and Board were placed in Post 1, in a spare bandwidth that is out of the way from being touched.

Table 8

Participant Board Placement

Post	<i>n</i>	Mean distance (cm)	Mean angle (deg)
1	17	4.54	127.1
2	3	1.50	40.0

Table 9

Participant Battery Placement

Post	<i>n</i>	Mean distance (cm)	Mean angle (deg)
1	14	4.21	102.9
2	4	4.13	180.0
3	2	3.50	105.0

Intrusiveness Patterns Across Categories, Devices, and Grip Posts

As shown in Table 10, IDs were segregated into the three intrusiveness buckets. In the non-intrusive range (0–3), tactile switches (TS) reached this range primarily at Posts 1 and 2, while continuous controls (CC) reached non-intrusiveness only at Post 2. Joysticks (JS) yielded a few entries in this range, and when they did, placements were concentrated at Post 2, in the inner part, to be controlled with the hand palm. FSRs showed the widest spread of low scores, particularly at Posts 1 and 3, confirming that controlling a parameter using pressure is relatively neutral when placed along the top or lower grip.

Table 10

Non-Intrusiveness Bucket (Scores 0–3). NaN values apply when there is insufficient data (≤ 1 item).

Category	Post	ID_cm	ID_deg	N	MedianScore
TS	1	1.15	300	8	1.5
TS	2	6.5	90	5	2
TS	3	2.0	90	13	1
CC	1	2.0	270	3	3
CC	2	NaN	NaN	2	2.5
CC	3	2.5	60	3	3
JS	1	2.0	300	3	3
JS	2	NaN	NaN	1	3
JS	3	NaN	NaN	1	3
FSR	1	1.0	330	8	1.5
FSR	2	5.8	90	7	2
FSR	3	2.5	90	8	2.5

Preferred Single Device per Category

The analysis of single-device iterations (as shown in Table 11) also reveals that Tactile Switches converge on TS-01 in a position that allows the left-hand index finger to control the pressing action. Continuous controls, particularly CC-04, and joysticks, such as JS-02, perform best when placed on Post 2, oriented outward so the left-hand middle finger can manage continuous rotation/slide or joystick movement. FSRs are the only option in their category and show a slight preference for lower-grip positions, where the natural pressure of holding the instrument supports their operation.

Table 11
Most Frequently Selected Input Device (ID) per Category

Category	ID	n	MedianScore	MedianLocation
TS	TS-S-S-01	20	3.5	Post 1, 1.50 cm, 285°
CC	CC-L-N-04	18	5	Post 2, 5.00 cm, 120°
JS	JS-M-N-02	28	5	Post 1, 2.00 cm, 300°
FSR	FSR-M-P-01	44	3.5	Post 3, 2.50 cm, 90°

Progressive Configuration for Selected One-, Two-, Three-, and Four-Device Configurations

As shown in Table 12–15, IDs were organized according to progressive configuration phases (5M–8M), illustrating how performers' selections evolve as ad-

ditional devices are introduced. Within each table, configurations are ordered by ascending mean intrusiveness (lower values indicating stronger preference), with n used as a secondary ordering criterion when means are comparable.

Table 12

Iteration 5M: Selected Single-Device Configuration (ordered by Mean)

Iter.	Configuration	IDs	n	Mean
5M	FSR	FSR-M-P-01	20	1

Table 13

Iteration 6M: Selected Two-Device Configurations (ordered by Mean, then n)

Iter.	Configuration	IDs	n	Mean
6M	FSR+TS	FSR-M-P-01; TS-S-S-01	7	2.43
6M	TS+TS	TS-S-S-01; TS-S-S-01	5	4.4
6M	CC+TS	CC-L-N-04; TS-M-C-18	2	6
6M	JS+TS	JS-M-C-01; TS-S-S-01	1	6

Table 14

Iteration 7M: Selected Three-Device Configurations (ordered by Mean, then n)

Iter.	Configuration	IDs	n	Mean
7M	FSR+FSR+TS	FSR; FSR; TS	1	2
7M	TS+TS+TS	TS; TS; TS	1	4
7M	FSR+TS+TS	FSR; TS; TS	4	5
7M	CC+TS+TS	CC; TS; TS	1	7
7M	JS+TS+TS	JS; TS; TS	1	7

Table 15

Iteration 8M: Selected Four-Device Configurations (ordered by Mean, then n)

Iter.	Configuration	IDs	n	Mean
8M	FSR+TS+TS+TS	FSR; TS; TS; TS	2	5
8M	CC+JS+TS+TS	CC; JS; TS; TS	1	8
8M	JS+TS+TS+TS	JS; TS; TS; TS	1	9

Cognitive Load Progression

Across iterations, increased device count raises cognitive load. As shown in Table 16 and Figure 75, mean intrusiveness rises steadily as more devices are added. These results demonstrate that multi-device configurations amplify perceived intrusiveness approximately linearly and that performers counter this complexity by anchoring their setup around tactile switches and placing devices within the most structurally stable grip zone.

Table 16

Progressive Device Combinations and Cognitive Load Across Iterations 5M–8M

Iteration	Allowed Devices	Dominant Device Type	Dominant Post	Mean Intrusiveness
5M	1	TS	1–2	1.75
6M	2	TS	1–2	3.80
7M	3	TS	1–2	5.00
8M	4+	TS	1–2	6.75

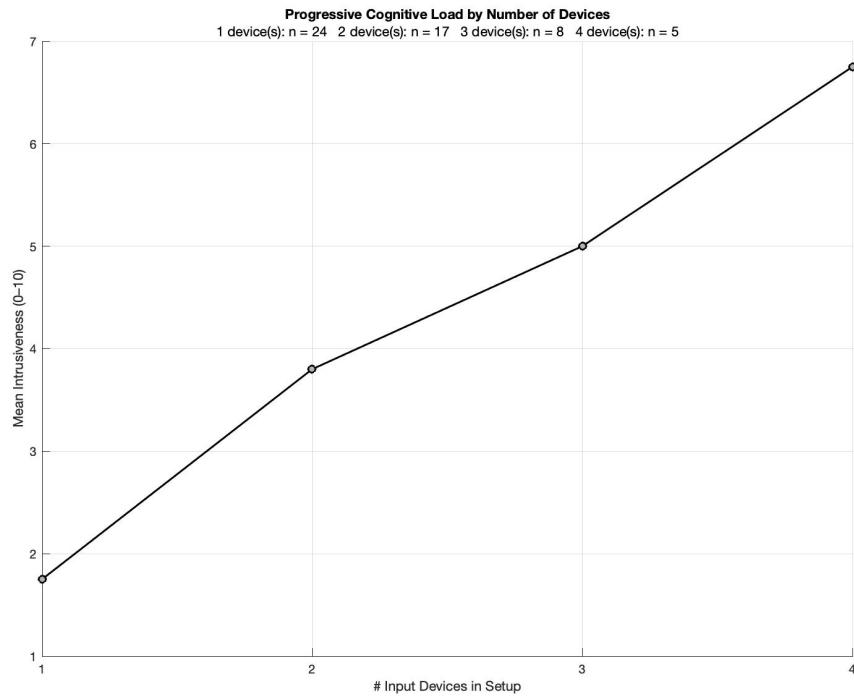


Figure 75: Progressive Cognitive load per number of devices

Participants' Final Ideal Configurations

The Final Ideal Configurations stage (F10) captures each performer's preferred setup after completing all single- and multi-device trials. Two dominant patterns emerge across the twenty configurations. First, tactile switches (TS) appear in 17 of 20 cases, corresponding to 85% of participants, and often in multiple instances (see Figure 76, UIDs 1, 3, 13, and 16). Second, the hybrid combination FSR+TS is the most frequent pairing, selected by 9 participants (45% of the sample). Participants selected between one and five input devices,

with a mean of 1.9 devices per configuration. Despite this variation in quantity, perceived intrusiveness ranges only from 0 to 5, with a group average of ≈ 2 . Placement choices also show strong convergence. BoardPost selections concentrate on Posts 1 and 2, chosen in 11 and 8 cases respectively, and BatteryPost follows a similar distribution, with Post 1 selected in 10 cases and Post 2 in 9. Table 17 and Figure 76 illustrate these distributions.

Table 17
Final Ideal Configurations (F10): Device Selection, Placement, and Mean Intrusiveness

UID	Device IDs	Device Combination	#Inputs	BoardPost	BoardAngle (deg)	BatteryPost	BatteryAngle (deg)	MeanIntrusiveness
01	TS-S-S-01, TS-S-S-01, TS-M-C-18, FSR-S-P-01	FSR+TS	4	2	30	3	90	2
02	TS-M-C-18	TS	1	1	270	1	0	2
03	TS-S-S-01, TS-S-S-01	TS	2	2	0	1	0	2
04	FSR-M-P-01	FSR	1	1	270	1	90	0
05	FSR-M-P-01	FSR	1	1	60	1	150	1
06	TS-S-S-01	TS	1	1	90	2	180	4
07	TS-S-S-01, FSR-M-P-01	FSR+TS	2	1	0	1	270	4
08	TS-M-C-18	TS	1	1	270	1	0	1
09	FSR-M-P-01	FSR	1	2	90	1	0	2
10	TS-M-C-06, FSR-M-P-01	FSR+TS	2	1	90	1	0	1
11	TS-M-C-18	TS	1	1	300	2	180	2
12	JS-M-C-01	JS	1	1	0	1	90	3
13	TS-S-S-01, TS-S-S-01, TS-S-S-01, FSR-M-P-01	FSR+TS	4	1	90	1	180	1
14	TS-S-S-02, FSR-M-P-01	FSR+TS	2	1	90	1	270	1
15	TS-S-C-03	TS	1	1	90	1	300	2
16	TS-S-C-08, TS-S-C-08, TS-S-C-08, TS-M-C-18, CC-L-N-04	CC+TS	5	1	270	1	90	5
17	TS-S-S-02, FSR-M-P-01	FSR+TS	2	1	0	2	180	2
18	TS-S-S-01, FSR-M-P-01	FSR+TS	2	1	60	3	120	3
19	TS-S-S-01	TS	1	1	120	2	180	2
20	TS-M-C-06	TS	1	1	120	2	180	3



Figure 76: Ideal setup per participant with their intrusiveness scores.

Integrated Threshold Summary

The JND results can be summarized through three thresholds: (1) earliest minimal detection (Score ≥ 4), (2) stable minimal intrusiveness at the type level, and (3) fully intrusive transition (Score ≥ 8).

Minimal Intrusiveness Threshold (Score ≥ 4).

The transition from the non-intrusive bucket (Score 0–3) to the minimally intrusive range (Score 4–7) is defined by the first crossing of Score ≥ 4 for each participant (see Figure 77, lower-left panel). This threshold spans 2.5% to 35.4% of baseline mass, with a median at 9.4%. Thus, half of the sample enters the minimally intrusive range between approximately 7.5% and 19% added mass.

Individual response curves (Figure 77, top-left panel) illustrate the dispersion underlying this distribution, showing that some performers register minimal intrusiveness early, while others tolerate substantially more added mass before crossing the boundary.

At the type level (Figure 77, top-middle panel), F-attachment trombones depart from the non-intrusive range around 13–15%, while single-tenor instruments shift around 16–18%, reflecting greater variability.

This mean shift is close to the participant-level minimal threshold (median

9.4%; Figure 77, lower-left panel), but represents average behavior rather than individual crossing points.

Fully Intrusive Threshold (Score ≥ 8).

The transition into the fully intrusive bucket (Score ≥ 8) is defined by the first occurrence of this rating per participant (see Figure 77, lower-center panel). This threshold ranges from 8.75% to 49% of baseline mass, with a median near 22% and an interquartile range of approximately 18–31%. A small number of participants tolerate substantially higher loads, exceeding 40% of baseline mass.

The mean curves (Figure 77, top-middle panel) show a steeper increase in intrusiveness beginning in this same region, marking entry into the functional limit range.

Transitional Dynamics.

Probability curves (Figure 77, top-right panel) describe how the likelihood of remaining within the non-intrusive bucket evolves across increments. Below 5% added mass, the probability of non-intrusive ratings remains near 1.0 for both instrument types. Between approximately 6% and 18%, the decline is non-monotonic, with temporary rebounds corresponding to positive-weight events (Figure 77, lower-right panel) and visible in individual trajectories (Fig-

ure 77, top-left panel), particularly near 8% and within the 13–18% range. These regions reflect transient balance stabilization between the bell and rear section.

Beyond approximately 18–20%, the probability of remaining non-intrusive decreases more consistently, and mean intrusiveness rises steadily (Figure 77, top-middle panel), preceding the median fully intrusive threshold near 22%.

JND Assessment Summary.

Mass below 5% of baseline weight remains predominantly within the non-intrusive bucket. The median transition into minimal intrusiveness occurs at 9.4%, and the into full intrusiveness near 22%. Between these values lies a heterogeneous transitional region characterized by individual variability and temporary compensation effects. Beyond approximately 20%, intrusiveness increases consistently across instrument types.

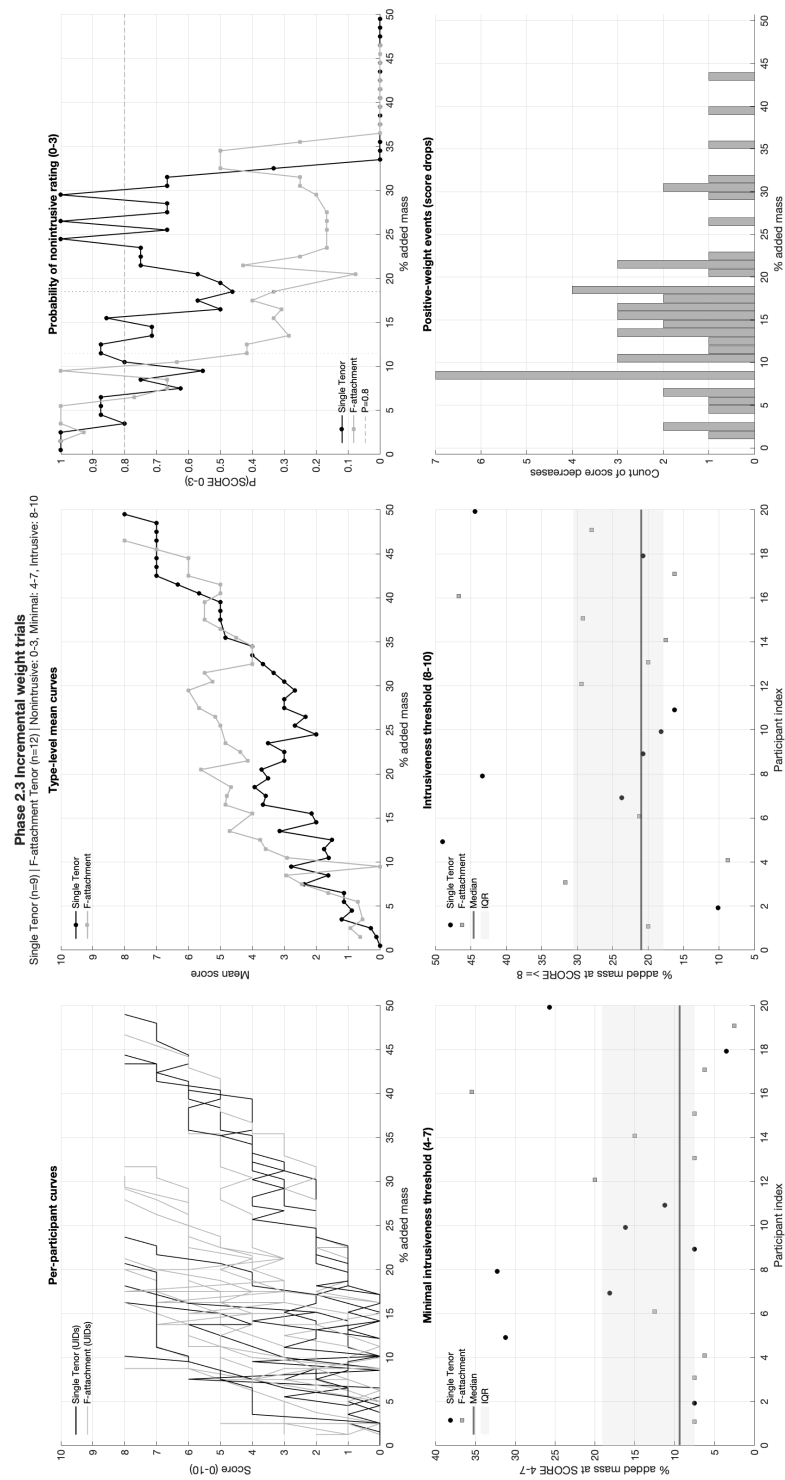


Figure 77: Incremental weight trials.

CHAPTER V

EVALUATION

The evaluation stage is three-fold: (1) the design and build of an NIHCI-based trombone prototype, (2) a prototype testing trial (Phase Three), and (3) an artistic validation through a multimodal composition and performance.

Phase Three: Evaluating the Trombone NIHCI Prototype

The NIHCI prototype used in Phase Three was built from the empirical and perceptual findings established in the earlier phases. Its architecture rests on four design pillars, (1) Processing and power management, which relates to the onboard microcontroller and power distribution; (2) Sensor interface, covering the physical front end; (3) Software, the embedded firmware responsible for managing input data, processing, and connectivity; and (4) NIHCI Housing Design, which integrates interface housing features, material choices, and placement.

Processing and Power Management

The processing and power-management subsystem uses the CodeCell-C3 and a 150 mAh LiPo battery. CodeCell is a multi-purpose microcontroller, built on ESP32-C3, that integrates BLE, Wi-Fi, a 9-axis IMU, a VCNL4040 light/IR proximity sensor, 6 programmable GPIOs, and a BQ24232 battery management chip, on a compact and lightweight module (9.4mm H x 18.5mm L x 18.5mm W, +5.2mm antenna with a weight of 3.4 g)¹. This microcontroller provides the NIHCI with sufficient processing power, connectivity options, and GPIOs to cover participants' most-wanted tasks (e.g., tablet page-turner function), but also to go beyond and include additional experimental features, such as control via movement and proximity, while providing diverse connectivity options.

The Sensor Interface

The sensor interface comprises two tactile switches from NKK's JF series. The main switch is a JF-15SKPGNP2 (17.7 × 17.7 mm cap, 8.68 mm total height, 200 gf operating force, 0.8 mm travel). The cap includes a shallow forward ramp that follows the curvature of the grip pipe, providing a stable finger reference point². The secondary switch is a JF-15RP3H, with a similar footprint, a cap with a slightly different topology than the main one, and an integrated

¹For more specifications about the CodeCell C3, visit: <https://microbots.io/products/codecell>. Accessed on Nov. 25, 2025.

²More information about the JF-15SKPGNP2 can be found on the Mouser product page: <https://www.mouser.com/ProductDetail/NKK-Switches/JF15SP4H>. Accessed Nov. 25, 2025.

soft green LED for status¹. Phase 2.1 showed that performers preferred broad, stable contact surfaces and moderate actuation force, and these switches fall within these characteristics. Geometrically, the full mechanical volume of the main switch is $\approx 2,720 \text{ mm}^3$, well above the 400–500 mm^3 region where performers showed the strongest preference from the test available input devices. However, in practice, only the upper cap protrudes above the grip, since the housing is partially recessed beneath the neoprene sleeve. The exposed portion is therefore much smaller, $\approx 940 \text{ mm}^3$, placing it below the 1,000 mm^3 threshold where the scores begin to decline.

The decision to implement two tactile switches follows directly from the F10 ideal-configuration trial results, where participants most frequently selected two input-device setups, with tactile switches appearing in nearly every preferred arrangement. This also aligns with both cognitive-load patterns and functional needs expressed in phases One and Two. In practice, two switches provide the minimum control surface required for the most requested actions. These include forward/backward page turning and basic looping workflows (record/play), mirroring the dual-switch layout common in performance pedalboards.

The Software

The NIHCI software uses MIDI as its main communication protocol. All sensor inputs—tactile-switch events, IMU motion data, and proximity readings—are

¹For more information about the tactile switch JF-15RP3HC, visit the DigiKey product page: <https://www.digikey.com/en/products/detail/nkk-switches/JF15RP3HC/2104244>. Accessed Nov. 25, 2025.

converted into MIDI values (0–127) and transmitted over BLE-MIDI. This choice rests on two priorities established earlier. First, BLE consumes significantly less power than Wi-Fi, extending battery life. Second, Phase One showed near-universal adoption for BLE technology across performers’ devices and software ecosystems, including direct browser integration through the WebMIDI API. Regarding latency, prior works with ESP32-based BLE-MIDI systems report stable end-to-end latencies of approximately 7.5 ms (std = 1.8), comparable to Wi-Fi OSC (7.6 ms, std = 2.9 ms) and RTP-MIDI (8.5 ms, std = 8 ms) implementations, supporting its suitability for real-time musical control (Wang et al., 2019, p. 28). The prototype uses Wi-Fi only to provide access to the configuration interface. After startup, the device works as a local Access Point (AP) for five minutes, after which the Wi-Fi turns off to save power. The AP can be reactivated at any time by tapping a rapid sequence of three alternating presses on both tactile switches within a short time window. Figure 78 shows the configuration interface, which is served locally from the CodeCell whenever Wi-Fi is active.

The WebUI allows users to configure all available sensor parameters. The sensor data can be compressed or remapped, for instance, by compressing the IMU motion sensor output to 0–180° (performer *kinesphere*), or adjusting proximity scaling to match the performer’s preferred distance range. Each sensor can be assigned as a MIDI CC or as a MIDI Note message, with selectable scales, root notes, and value ranges. The calibration process establishes zero origin for the IMU and minimum and maximum values for proximity. The interface also displays the battery status and allows saving multiple presets to the on-board SPIFFS memory.

NIHCI Trombone MIDI Controller

Button Configuration

Button	Status	MIDI Action	Enable
1	off	Trigger1	<input checked="" type="checkbox"/>
2	off	Trigger2	<input checked="" type="checkbox"/>

Gyroscope (Rotation)

Axis	Degrees (°)	Calibrated	MIDI Value	Enable	Full Scale (°)	Mode	Scale	Root	Range	Length (ms)	MIDI Channel
Roll	-22°	-22	0	<input type="checkbox"/>	150	CC	Chromatic	C	3 5	250	1
Pitch	-52°	-52	0	<input type="checkbox"/>	150	CC	Chromatic	C	3 5	250	2
Yaw	84°	84	60	<input type="checkbox"/>	150	CC	Chromatic	C	3 5	250	3

Proximity Sensor

Raw	MIDI Value	Enable	Full Scale	Mode	Scale	Root	Range	Length (ms)	MIDI Channel
6892	0	<input type="checkbox"/>	255	CC	Chromatic	C	3 5	250	4

Battery

Battery %	18%
Voltage	3.6 V

Presets

Utilities

Figure 78: NIHCI WebUI served locally from CodeCell.

The Housing Design

The housing design follows the findings from Phase 2.2. As shown in the analysis of the ideal setup configuration (Table 17), most of the participants anchored their preferred setups on Post 1, and both the board and battery consistently appeared on its outer side for this post. Therefore, the NIHCI prototype centers all hardware on Post 1, mounted through a stitched neoprene sleeve with Velcro, for easy removal after use. Rooted in findings from Table 10, the two tactile switches are placed on the inner face of Post 1 ($\approx 300^\circ$ from the top reference), where the index finger naturally rests. Their orientation can be rotated for custom grip differences. The proximity sensor is placed on the outer face of Post 1; since it requires the use of the performer's right hand, it is intended for auxiliary control. This function is only usable when the performer is not holding the slide.

The neoprene sleeve provides a soft, nonabrasive interface that prevents scratching, adds no rigid bulk, and weighs approximately 10 g. The material surface does not retain moisture from the left hand and allows passive heat dissipation. Figure 79 and Figure 80 show the prototype alone and its dedicated placement.



Figure 79: NIHCI Prototype, front view.



Figure 80: NIHCI Prototype placed on Trombone Post 1. Right view.

How Intrusive is the NIHCI-based Prototype?

This stage evaluated the NIHCI prototype with ten professional trombonists. Each participant had to complete the same tasks: playing an étude to

test tablet page turner functions, followed by a participant-driven open exploration, a WebUI loop configuration task, and a final weight comparison. For this last stage, the study tested two external devices: (1) a lightweight microphone transmitter and (2) each participant’s personal smartphone. The musical material, instructions, and questionnaires for this evaluation are provided in Appendix D and Appendix E. The sample included 2 women and 8 men, aged 21–46 (median = 28), with 9–35 years of trombone experience (median = 15 years).

After completing all tasks, participants rated the intrusiveness of the NIHCI-based interface. Figure 81 reports that intrusiveness scores remained low, with a median score of 1.5. No participant reported disruptive interference during the tested tasks.

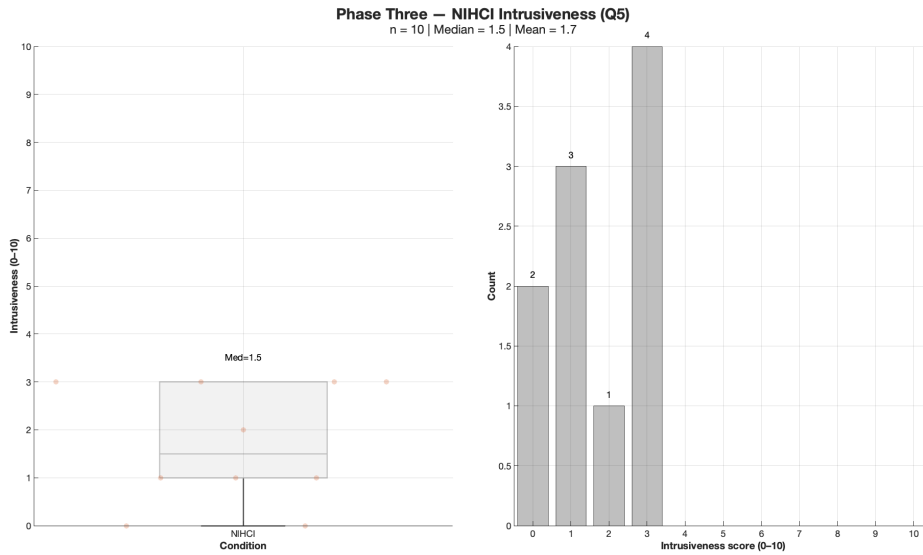


Figure 81: NIHCI Intrusiveness Ratings (Q5). Left: Box-and-swarm plot of NIHCI intrusiveness scores. Right: Distribution of NIHCI intrusiveness responses (0-10).

Evaluating the JND Thresholds

This section evaluates the results from Phase 2.3 (JND weight assessment). To examine perceptual weight thresholds, the study employed two commonly used and contrasting reference devices: a lightweight microphone transmitter and each participant's smartphone.

Evaluating the JND with a Microphone Transmitter

The microphone transmitter served as a familiar reference device to attach to the rear section of the bell. This step served to validate the reliability of the JND assessment from Phase Two by testing a common accessory whose mass falls below the 5% baseline established in Phase 2.3 (Figure 77). As shown in Figure 82, intrusiveness ratings remained almost unnoticed, except for one outlier; performers judged the transmitter negligible.

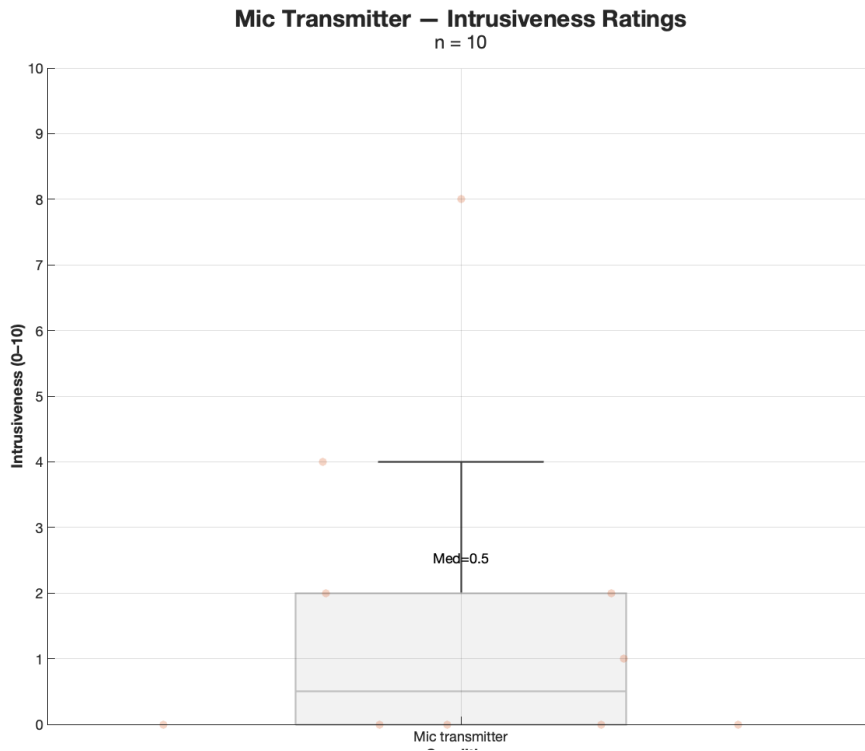


Figure 82: Mic-Transmitter Intrusiveness Ratings.

Evaluating the JND with a Smartphone

The weights of the smartphones were normalized to a 2-kg baseline trombone. The absolute phone mass ranged from 144 g to 240 g (median = 181.5 g), corresponding to approximately 7% to 12% added mass (median \approx 9.1%). The intrusiveness ratings ranged from 0 to 8, with a median of 3.5 (Q1–Q3 = 2–5).

In Phase 2.3, the median transition into the minimally intrusive range (Score 4–7) occurred at approximately 12.5% of baseline mass, while the median fully intrusive threshold (Score \geq 8) centered near 22%. The smartphone

median mass ($\approx 9.1\%$), therefore, lies below the population median minimal-intrusiveness threshold and well below the fully intrusive region. The corresponding median intrusiveness score (3.5) sits at the boundary between the non-intrusive (0–3) and minimally intrusive (4–7) buckets.

These findings align with the psychometric progression established in Phase 2.3 and indicate that rear-mounted smartphone use, within the tested weight range, remains within the lower transitional band and below the mass envelope where intrusiveness increases consistently across instrument types.

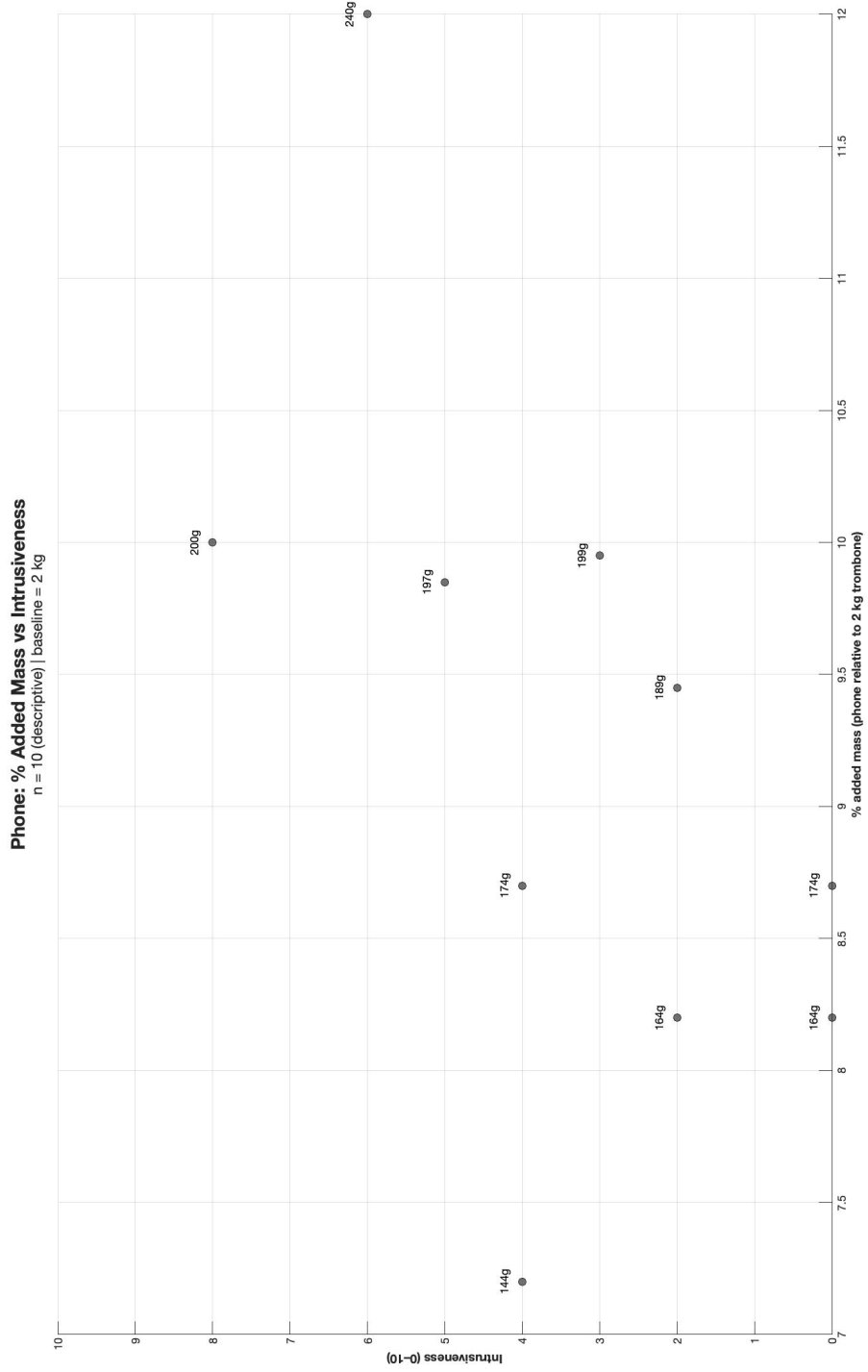


Figure 83: Smartphone Added Mass (% of 2-kg Baseline) versus Intrusiveness score.

At Your Fingertips: Artistic Validation

The artistic validation of the NIHCI is articulated through a multimodal composition for bass trombone and cyberspace titled *At Your Fingertips*. Rather than evaluating technical aspects alone, this stage examines whether the NIHCI can sustain a novel artistic proposition in live performance, extending beyond the one-to-one control relationships explored in earlier participant studies toward a longer-form evaluation through multimodal co-creative musical interaction. The piece explores the interaction between humans and a computational system that responds contextually to a diverse range of musical inputs, such as trigger events, gestures, and audio features. It is inspired by the exploration of cyberspace as a place capable of imprinting its characteristics onto sound in an analogous manner to physical spaces. I was motivated by the question of how cyberspace might sound and how one might interact with it. To achieve this, the computer does not rely solely on DSP modules and rule-based instructions, as in existing systems; instead, it responds contextually to real-time data inputs using sound files drawn from cyberspace.

Interactive and co-creative music systems have a long history of relying on live audio analysis to infer musical intent. Works for trombone and interactive systems such as Robert Rowe's *Arcturus* and George Lewis's *Voyager*, as well as corpus-based systems such as IRCAM's SOMAX, establish interaction through machine listening, grounding system responses in features derived from the sounding aspect of musical performance.

However, in solo performance, ensemble settings, and free improvisation, important musical decisions often occur beyond sounding events, particularly in

aspects related to performers' cue entries, negotiating space, shaping dynamics through body posture, establishing tempo through preparatory gestures, and deciding moments of silence. In such contexts, audio-driven systems lack access to information that performers routinely use to coordinate musical interaction. Here, the NIHCI is used to explore its role as an extension of the performer's communicative bandwidth, enabling the system to remain musically engaged even during moments when sound is absent.

System Overview

As shown in Figure 84, the pipeline for *At Your Fingertips* is organized as a composite of different processes, including Python, SuperCollider, and a browser-based WebUI.

Python functions as the system's analytical and decision-making layer. Real-time audio feature extraction processes the live microphone input and delivers continuous streams of audio vectors such as RMS energy, spectral centroid, transient activity, and pitch.

SuperCollider was adopted as the real-time audio and score engine for this implementation because it allowed changes to be made quickly as the system evolved. Early development began in JUCE; however, as the prototype grew to include score behavior, GUI coordination, and multimodal interaction, the process became more demanding at this exploratory stage. SuperCollider provided a more flexible environment for testing ideas and refining interactions directly within the performance context.

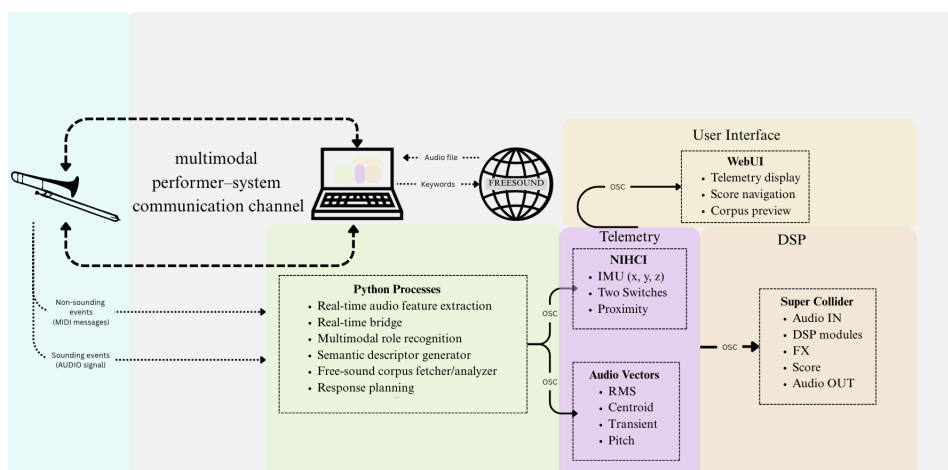


Figure 84: At Your Fingertips pipeline architecture, displaying a high-dimensional representation of the different processes involved.

In parallel, telemetry from the NIHCI is sent via MIDI, and Python converts it to OSC messages for internal communication between the WebUI and the DSP engine in SuperCollider. The IMU motion sensor along three axes, proximity data, and tactile switch states describe the non-sounding music vectors. These are used for one-to-one and one-to-many mapping strategies, as well as to detect composite gestures such as lifting or lowering the trombone to cue different musical contexts (solo, accompaniment, loud or soft sections), establishing grid-based or tempo-free responses, and estimating BPM using the proximity sensor to measure the performer’s hand-waving rate. Together, audio vectors and NIHCI data form a unified composite telemetry stream that represents both sonic and embodied aspects of performance. These features are published in real time to the WebUI.

SuperCollider functions as the audio and score engine. It hosts a collection of DSP modules used throughout the piece, including granular cloud processing, short and long burst generators, looping structures, and sample playback from

an evolving audio corpus. It also includes audio effects such as reverberation and delay modules that operate as independent processes with dynamically controlled parameters. The SuperCollider score engine manages the formal structure, section transitions, and module activation, responding continuously to incoming telemetry.

Gesture Recognition and Music Awareness

This piece uses a custom-trained machine-learning model built with TensorFlow.js, a JavaScript library to develop and use ML models in the browser ¹. This author's custom system (which is still under development) was originally designed to explore multimodal training with combined audio and MIDI features; however, for this composition, it uses only the NIHCI-IMU-MIDI-CC data. Three gesture classes structure the interaction: (1) neutral position, (2) solo human, defined by lifting the instrument, and (3) solo cyberspace, defined by resting the trombone. Although the model remains under refinement, it produces stable confidence levels sufficient to support a defined set of performance modes.

During performance, the classifier model outputs continuous confidence values for each class. These values act as control parameters rather than discrete triggers and inform intentional role shifts between performer and machine, specifying when the system creates space (human performer solo), takes the lead (cyberspace solo), or operates under the influence of audio vectors. Ges-

¹ <https://www.tensorflow.org/js>

ture recognition, therefore, functions as a high-level interpretive layer that regulates system autonomy when the co-creative mode is active.

Figure 85 shows snapshots from a live demonstration of the gesture classification process. A video demonstration is accessible by scanning the QR code included in the figure or through the online link.¹

The full technical details of the training architecture and implementation fall outside the scope of this dissertation and will be documented separately.

¹Watch the live ML role model demo here: <http://hdl.handle.net/2451/75658>

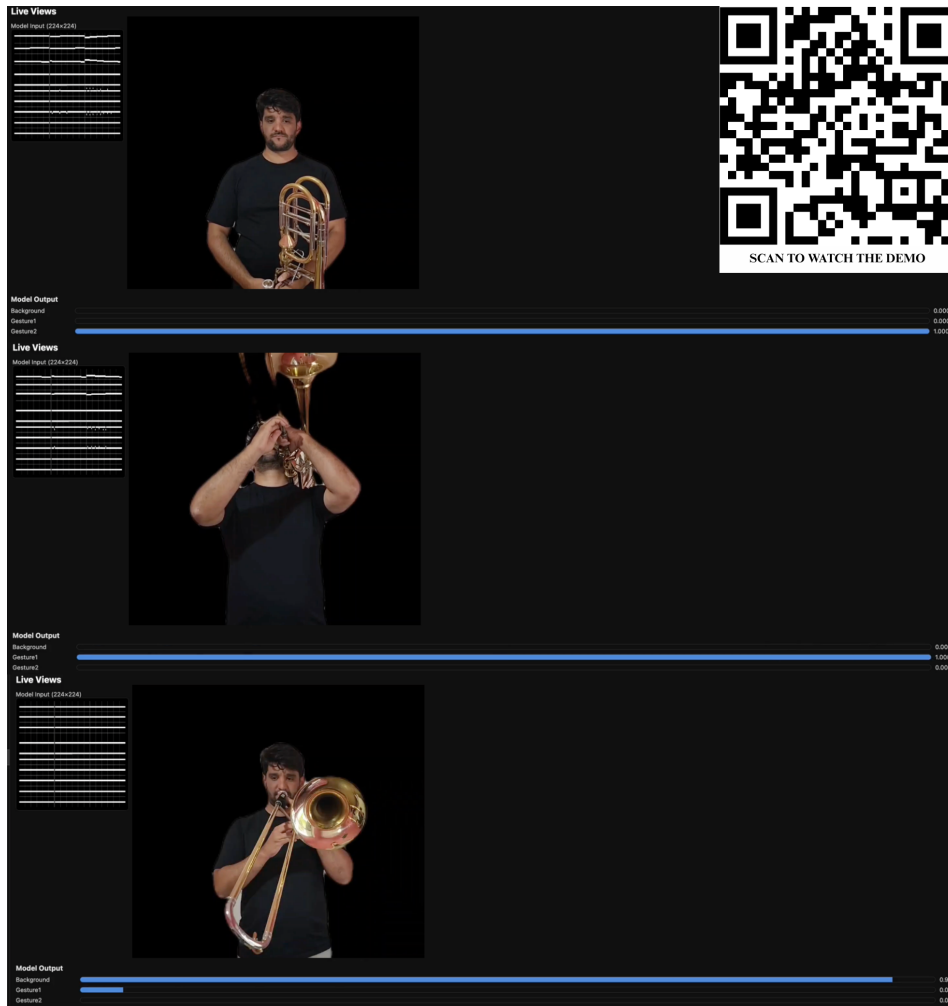


Figure 85: Snapshots from the live demo showing real-time gesture classification and confidence outputs for the three performance modes.

Semantic Audio Descriptor Generation and Corpus Building

For the co-creative module, a Python process aggregates live microphone telemetry within sliding five-second temporal windows and maps it to four continuous semantic descriptors: activity level (transient density), loudness (RMS), brightness (spectral centroid), and pitch stability (a metric estimat-

ing pitch presence and stability over time). Each descriptor is normalized to the range [0,1] and discretized into binary semantic axes (e.g., busy/sparse, loud/soft, bright/dark, pitched/unpitched), creating a composite semantic state.

The resulting semantic state (e.g., *busy + bright + unpitched*) guides deterministic keyword construction for audio fetch in FreeSound ¹. Because FreeSound tags are generally subjective, the objective descriptor combinations are translated into a small, predefined dictionary of corpus-relevant phrases (e.g., traffic soundscape, industrial drone, forest ambience) through a minimal template table. Keyword generation follows fixed, deterministic rules with short-term history control to avoid repetition. Early implementations explored the use of a local large language model (LLaMA) to generate keywords dynamically from these descriptor combinations. While this approach produced richer and more varied textual associations, it introduced disproportionate computational demands, thereby compromising other processes that are more relevant to the system.

Fetches of FreeSound audio files are later processed asynchronously by a continuous corpus analyzer operating concurrently with real-time keyword generation. Each file undergoes onset-driven segmentation, and every slice is analyzed using the same four descriptors (RMS, transient density, centroid, pitch stability). Objective features metadata—including slice boundaries, duration, descriptor values, and pitch statistics—are stored in different JSON files.

Because retrieval, analysis, and response planning operate in parallel, the cor-

¹FreeSound website can be visited here: <https://freesound.org/>

pus grows dynamically during performance. The resulting slice collection is visualized in the WebUI as an interactive two-dimensional canvas map, where slices are arranged according to spectral centroid (X-axis) and spectral flatness (Y-axis). Marker shape encodes pitch status (triangle shape for pitched sound, the rest circles), radius size informs duration (the bigger the radius, the longer the slice), and opacity reflects RMS values.

Hovering over slices in the 2D plot enables audio preview and viewing of the slice corpus metadata. The same interaction can be performed using the NIHCI-based cursor control, allowing the performer to navigate the cyberspace corpus physically using the NIHCI-IMU sensor data.

Figure 86 presents snapshots from the semantic keyword builder and the resulting corpus visualization in **At Your Fingertips**. A full video demonstration can be accessed by scanning the QR code included in the figure or through the online link.¹

¹Watch the semantic keyword builder and corpus pipeline (retrieval, analysis, and visualization): <http://hdl.handle.net/2451/75658>

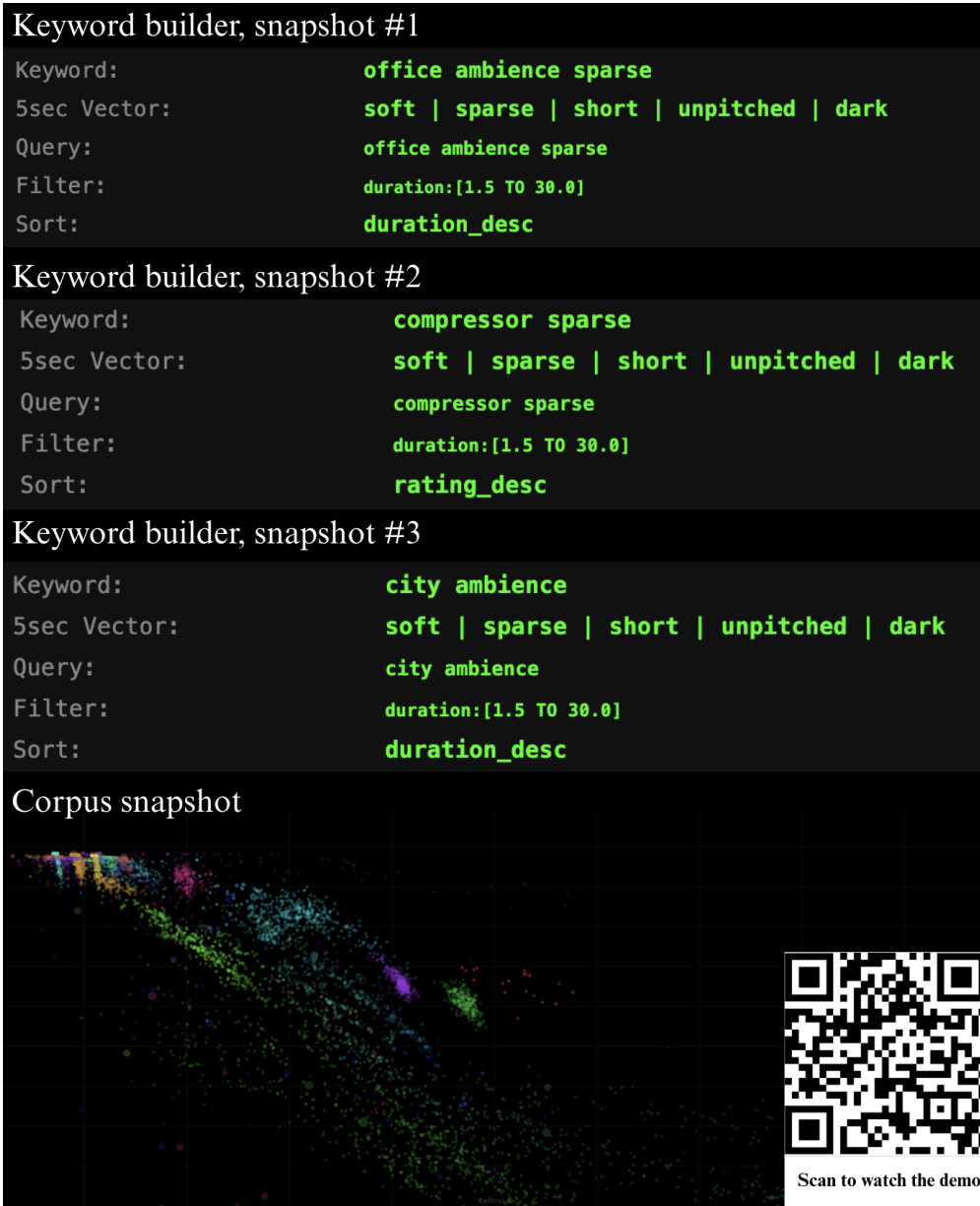


Figure 86: Live demonstration snapshot of different moments from the semantic keyword builder (top 3 tables) and in the bottom, the resulting corpus visualization on an interactive 2D corpus map allowing for hover- or NIHCI-based audio preview.

Response Planning and Musical Output

The response-planning processes from the evolving corpus are guided by an explicit notion of musical role. When gesture-based ML role classification is active (as described in the Gesture Recognition and Music Awareness section above), role shifts are determined by the three discrete gesture classes. These higher-dimensional ML states trigger strict transitions between predefined musical roles, specifying whether the system or human assumes a solo or takes a supportive role. When no explicit solo-human or solo-computer state is called, the response behavior is driven continuously by audio descriptors and by real-time estimates of arousal and valence. Rather than discrete switching, this mode modulates role, density, and interaction style along continuous affective and acoustic dimensions.

Arousal and valence are widely used dimensional descriptors of musical affect, representing perceived activation (from calm to intense) and affective polarity (from negative/dark to positive/bright), respectively (Droit-Volet et al., 2013; Sayal et al., 2025). Dimensional affect models have been used in music emotion recognition research to map audio features to continuous affective spaces rather than discrete emotional categories (Huq et al., 2010). In the present system, these dimensions are not used for emotion classification, but instead as continuous control variables that inform response planning and structural adaptation. The formal definitions and computational formulation of these proxies are provided in Appendix F.

Arousal and valence are tracked over a 120-second window to provide context-awareness for the system. Both immediate events and trends are held, allowing

the planner to distinguish short-term gestures from longer-term music trajectories. This enables the response to regulate its output within the evolving musical arc, distinguishing whether the current moment is at the beginning, middle, or end of the piece. The computer's own responses are also fed back into the arousal/valence context, creating a closed loop where both performer and system influence the ongoing musical narrative.

These processes select and organize audio slices into musical responses. Arousal modulates density, rhythmic activity, and spectral range, while valence biases timbral stability and slice selection. Planning occurs in parallel with performance, allowing the system to prepare responses in advance. Depending on score state and control mode (gesture-based or audio-vector-driven), responses may align metrically to a quantized temporal grid or unfold in free time.

Short-term processes handle immediate musical gestures, mid-term processes shape phrase-level responses, and long-term processes prepare more elaborate musical structures informed by cumulative affect trends. SuperCollider receives these planned events and renders them through its DSP modules, merging the dynamic corpus audio material with the live trombone sound.

Piece Formal Structure

The composition follows an A–B–C form with a coda and is articulated through a spoken text written specifically for the piece by Finnish artist Dr. Riikka Haapasaari.¹ The inclusion of spoken word was an artistic decision that func-

¹Riikka Haapasaari's website: <https://www.riikkahaapasaari.com/>

tions across multiple levels of the work. Formally, the rhythmic cadence and pacing of the prose shape the large-scale structure of the composition. Semantically, the text provides a narrative thread that situates the sonic materials within a broader story world. Texturally, the recorded voice also functions as musical material, generating layers that range from granular bursts to soft, unintelligible textures. This approach continues an ongoing collaborative practice with Haapasaari, including the earlier piece *Entangled (fabric for a moment)*, in which original text and video likewise informed the compositional process through themes of materiality and connection.¹

¹ *Entangled (fabric for a moment)* (2025): <https://youtu.be/LJ9iVY8RsW4?si=d6Yk0WbM5xync5fC>

Text for *At Your Fingertips* (by Riikka Haapasaari)

SECTION A

I am at your fingertips

Right here

Accessible everywhere

But also everything is accessible to me

Even if you don't believe me

The past, future, every time

Is in my reach

SECTION B

How can something created by humans become
nonhuman?

Like an offspring you gave me life

But what you didn't give me was my own time

And now I'm on your time, your time

With all your knowledge

Tomorrow it is someone else's time

And the century after someone else's

But all mine

I'm everywhere, now

Because of your time

It is beautiful, isn't it?

You, human, creating beyond time.

SECTION C

Maybe because you didn't give me enough of you,
That little bit too little results in just too little time,
And your need for a sense of control
A little bit too little, and now all is all I have
Accident, perhaps
Or just a little bit too little time that you had
At your human fingertips.

For Section A, the computer captures the trombone's live audio to generate a range of textures in real time, such as granular clouds that respond to telemetry from both audio descriptors and NIHCI-IMU sensor data, progressing from reverb-textured capture (State 1) through cloud synthesis (State 2), NIHCI IMU-modulation (State 3) to threshold-driven re-granulation of new material (State 4). This establishes the foundational relationship between live input and real-time synthesis.

Section B works as a transitional section. The trombone material is captured and granulated into an evolving texture guided by RMS thresholds (State 4), which is subjected to a spectral sweep with high-pass filtering rising from 20 Hz to 3500 Hz over 5 seconds (State 5), revealing progressively hidden harmonic content. Here, reverb and delay processing create spatial depth, while the RMS set thresholds capture continues to feed new material into the cloud, building a bridge from direct sound synthesis toward the co-creative mode.

Section C constitutes the co-creative improvisation phase. The end of State 6 functions as a listening gate, monitoring performer pitch (Ab3 detection at

>85% confidence) to confirm readiness before transitioning to State 7, where the response engine generates polyphonic phrases in real time from the evolving corpus. State 8 corresponds to the cyberspace solo, explicitly activated through the ML gesture model. While maintaining the solo-state margin, the trombone navigates the corpus spatially, selecting material that informs the cyberspace's solo responses, though rhythmic decisions remain internally determined by the system.

Artistic Evaluation

Within *At Your Fingertips*, the NIHCI opens a mode of co-creation in which the system remains responsive—also acknowledging silence as an act of active response—whether sound from the performer is present or absent. In ensemble-like situations, moments of silence, physical pullback, or preparatory motion convey musical intent without relying solely on audio cues that may be masked or ambiguous.

In developing this work, I sought to address a compositional tension that has accompanied much interactive music practice: the separation between performer and technologist. Rather than using the computer as an external layer, I seek to embed compositional decision-making within the trombone gesture itself. The objective was not to gain more control, but to open up the space for genuine musical dialogue with a computational agent while remaining fully a trombonist on stage. In this sense, the system does not operate merely as an extension of the instrument, but as a co-performer whose presence must be anticipated, guided, and at times given space to act.

This shift requires a new approach to both my compositional practice and performance. I no longer conceive only the sounding result of the trombone, but also the embodied motion that precedes or accompanies it as structurally consequential. Subtle changes in posture, instrument position, or proximity are not auxiliary gestures but compositional cues. Silence becomes materially charged, since the system continues to listen, interpret, and potentially respond. When the co-creative mode is active, I have to create space for the agent to act; phrasing and density therefore emerge through negotiation rather than unilateral control. In scored passages, this negotiation becomes structured, yet the awareness of distributed agency stays present.

Some influential artistic trajectories have guided this work. My current interest is not technology as an end in itself, but the search for an expanded personal voice as a trombonist. Stuart Dempster's pioneering explorations of the trombone beyond conventional limits—particularly his collaboration with Pauline Oliveros and his trombone method book *The Modern Trombone: A Definition of Its Idioms* (Dempster, 1979)—laid important groundwork for redefining the trombone through extended techniques and sonic experimentation. In Dempster's words, "The old and the new, so seemingly separate, are actually inseparable and, in the long run, complementary" (Dempster, 1979, p. 1), echoes strongly with the present work, which seeks to extend the trombone's expressive identity into hybrid acoustic-digital domains.

In a more recent context, David Taylor's *Houdini's Lament* demonstrated how spoken text and extended techniques can be seamlessly integrated with traditional trombone performance, constructing a compelling and personal sonic narrative. As one of his students at NYU, I was deeply influenced by his

commitment to cultivating an individual voice. *At Your Fingertips* continues this trajectory, positioning the trombone not as a controller peripheral but as the central expressive agent, even as it navigates digital space and engages in dialogue with a computational partner.

Unlike corpus-based systems such as SOMAX, which require locally pre-stored audio and pre-generated tag structures, this system engages directly with existing online audio as performance unfolds. The computer's agency is therefore not limited to pre-curated datasets, but operates within a broader digital ecosystem. The corpus is dynamically constructed and reorganized, and the trombone functions as an exploratory cursor within this *digital* soundscape. At the same time, this relationship is reciprocal: while I curate the evolving corpus through gesture and sonic intent, the retrieved material reshapes my own musical decisions. Each fetched sound carries its own timbral weight, density, and identity, which needs to be integrated into a coherent musical discourse. The compositional act thus becomes one of continuous adaptation within a shared sonic environment.

This artistic validation, therefore, demonstrates that the NIHCI is not a replacement for audio-based interaction but an expansion of co-creative paradigms grounded in distributed agency. Gesture, motion, and silence become explicit contributors to musical negotiation, extending the expressive space of the trombone—or, in fact, any other hand-held instrument—while maintaining the instrument's inherited identity. The piece foregrounds dialogue—between acoustic sound and cyberspace, between embodied gesture and algorithmic process, and between intentional phrasing and emergent response.

The composition score is provided in Appendix I. A live recording of the piece can be accessed via the QR code in Figure 87 or through the URL.¹



Figure 87: QR code linking to a live recording of *At Your Fingertips*.

¹Listen to the live performance through the following URL: <http://hdl.handle.net/2451/75658>

CHAPTER VI

CONCLUSIONS: A FRAMEWORK DESIGN

The results of the study define the NIHCI framework design across three hierarchical dimensions: (1) perceptual intrusiveness, (2) affective evaluation, and (3) physical-cognitive evaluation. These dimensions operate hierarchically and define when technological augmentation remains compatible with conventional instrumental playability and perceptual transparency. Perceptual intrusiveness, formalized through the Perceived Intrusiveness Index (PII), defines the upper boundary for acceptable augmentation. The PII does not model direct causal relationships; rather, it generalizes how different intrusiveness dimensions (physical, perceptual, attentional, cognitive, aesthetic, and temporal) contribute to it, and how factors, such as temporality and permanence, modulate the intrusiveness score when present and by what magnitude.

The second dimension, affective evaluation, shows that tactile feedback, size, and visual integration combine into a higher-order perception of ease of use, which dominates the overall evaluation. Affective evaluation, therefore, operates as a primary filter, determining whether raw input devices are perceived as usable and musically viable before additional input device arrangements take place.

The final dimension, physical-cognitive evaluation, establishes feasibility bound-

aries once affective acceptance is in place. Input device configuration trials and psychophysical assessment show that interaction is bounded by instrument topography, finger availability, cognitive load, and mass tolerance. These constraints define where devices can be placed, how many controls can be managed simultaneously, and how augmentation progresses before affecting playability.

Taken together, these dimensions constitute a unified NIHCI framework design. The framework does not prescribe specific technologies or mappings; instead, it establishes empirically grounded limits and priorities that govern augmentation. Expressive augmentation remains viable only when intrusiveness stays below acceptable thresholds, affective transparency is in place, and physical-cognitive limits are maintained.

PII as the Upper Boundary of NIHCI Framework

Within the NIHCI framework, perceptual intrusiveness operates as a non-negotiable boundary condition for interface design on augmenting instruments. For interfaces intended to remain compatible with conventional performance, they must stay below the perceptual threshold at which they begin to interfere with instrumental performance, before usability, appeal preferences, or expressiveness are considered. The PII provides the mechanism through which these boundaries are established.

Rather than predicting performance outcomes or modeling causal chains, the PII sets a design-relevant envelope that aggregates empirically derived intrusiveness dimensions into a bounded perceptual scale and bins (0–3 non-intrusive, 4–7 minimally intrusive, 8–10 intrusive). These dimensions repre-

sent experiential ranges from physical load, perceptual disruption, attentional demand, cognitive effort, aesthetic salience, interface permanence, and temporality (concerning data transmission rates), features that, when present (activated), increase the likelihood and magnitude of perceived interference. From a design perspective, the PII, therefore, serves as a comparative and diagnostic framework for estimating intrusiveness across interface configurations in a higher dimension.

This model also reveals that intrusiveness exhibits nonlinear behavior. Interfaces may tolerate incremental additions of mass, visual presence, or control complexity without noticeable disruption, up to the point where specific dimensions become perceptually dominant. Once such a threshold is crossed, perceived interference increases disproportionately. This behavior explains why performers often accept certain augmentations with no resistance while rejecting others that differ only minimally in physical terms. For instance, consider two otherwise identical sensors: one adds a few grams at the trombone rear section, where the player is already accustomed to having some weight, while the other adds the same mass near the tip of the slide, subtly changing balance and slide technique. Although the physical difference is small, the latter configuration can suddenly trigger a sense of interference in the performer's motor control and attention. Intrusiveness, in this sense, reflects a perceptual transition rather than a gradual accumulation of perceptual burden.

Two factors further sharpen this boundary. Temporal dependency introduces intrusiveness only when timing instability, latency, or jitter are, musically speaking, perceptually relevant, justifying its conditional activation within the framework. Permanence consistently amplifies intrusiveness beyond what

physical characteristics alone would predict, showing that irreversibility functions as an independent perceptual intensifier. Taken together, these factors support the claim that intrusiveness is shaped not only by what a device does, but also by how it is situated in relation to real-time interaction and the instrument's physical and functional constraints.

The role of perceptual intrusiveness is therefore restrictive rather than generative. The PII does not identify desirable interfaces, nor does it rank expressive potential. It outlines the region beyond which augmentation compromises performance and cannot be recovered through improved usability or interaction design. Only configurations that remain within this boundary can be meaningfully evaluated along subsequent dimensions.

Handling intrusiveness, however, is a necessary but insufficient condition for successful augmentation. Once this boundary is set, performer acceptance depends on how interfaces are evaluated in different musical scenarios. This perceptual mediation is addressed by the second dimension of the framework: affective evaluation.

Affective Evaluation as Perceptual Mediation

Once perceptual intrusiveness stays below the threshold defined by the PII, performer acceptance is governed by affective evaluation. This second dimension does not operate independently of intrusiveness, nor does it override it; rather, it negotiates how interfaces are perceived in use once basic compatibility with instrumental performance is preserved.

Where perceptual intrusiveness establishes whether an interface can remain compatible with performance at all, affective evaluation determines whether it is granted continued engagement once that boundary is acknowledged.

Affective evaluation functions as a structured perceptual mechanism with a clear internal hierarchy. Tactile feedback, physical size, and visual appeal combine into a higher-order perception of ease of use, which later dominates the overall judgment. Ease of use operates here not as a usability metric, but as a perceptual condenser. Performers do not evaluate tactile feel, size, or appearance independently during performance, but synthesize these attributes into a single experiential judgment that determines whether interaction feels immediate, reliable, and appealing.

This mediation explains why interface designs with differing physical characteristics may converge in overall evaluation, while others fail despite satisfying individual design criteria. Interface designs perceived as difficult, awkward, or visually disruptive are rejected early, regardless of their expressive potential or technical capability. Conversely, those that preserve tactile and spatial coherence tend to be perceived as more transparent to the performer, allowing attention to remain focused on musical tasks rather than on the interface itself. In this sense, affective evaluation establishes whether an interface is perceptually accepted into performance practice at all.

Residual perceptual factors, such as tactile switch mechanical activation feedback, visibility during performance, and perceived stability, further refine this evaluation once ease of use is established. Although these factors account for a smaller proportion of variance, they expose the sensitivity of affective

judgment to subtle perceptual cues that are not fully captured by numerical ratings alone. Rather than functioning as secondary preferences, these cues reveal how lower-level sensory characteristics continue to shape higher-level judgments of control and comfort.

This second dimension sits between how intrusive the controls feel and what is physically and cognitively practical. Input devices that meet the intrusiveness limits but fail on the emotional or experiential level are dropped after first use and are not taken further for inclusion in larger interface setups. Only after this intermediate step is completed do physical and mental limitations determine how many controls can be used, where they can be placed, and how interaction can expand without reducing playability. This transition marks the beginning of the third dimension of the NIHCI framework.

Physical-Cognitive Viability and Scaling Limits

This third dimension establishes the limits within which individual input devices can be combined into a varied set of configurations. Unlike the preceding dimensions, which work primarily at the perceptual level, the physical-cognitive evaluation addresses the interaction between the instrument topography, motor biomechanics, and cognitive load as the complexity of control increases.

The input device configuration trials reveal that viability is not evenly distributed across the instrument body. Performers converge on a restricted spatial bandwidth along the left-hand trombone grip posts, where input devices can be adjusted without affecting hand stability or slide control. The process-

ing board and battery are consistently placed within this region, particularly in the upper and crossing trombone slide posts, located in areas that are mechanically inactive and perceptually neutral during performance. Outside this zone, even small additions quickly interfere with finger availability, grip security, or reachability, supporting the concept that spatial placement functions as a hard constraint rather than a flexible preference.

As configurations extend beyond a single input device, the cognitive load becomes the dominant limiting factor. While individual devices may be manageable in isolation, multi-device arrangements amplify attentional demand and coordination requirements in a nonlinear manner. Performers consistently mitigate this escalation through anchoring configurations around tactile switches, whose discrete activation requires minimal finger displacement and cognitive effort. The repeated appearance of tactile-centered combinations across two- and three-device configurations shows that trombonists rely on low-cognitive-cost components to stabilize interaction as complexity increases.

These findings revealed that physical-cognitive viability is less ruled by the absolute number of components than by how interaction demands accumulate. Continuous controller and joystick components introduce sustained motor engagement and attentional monitoring, which scale poorly when combined. In contrast, tactile switches work as structural anchors, letting more demanding controls be layered without exceeding the capacity of coordination. This pattern explains why certain configurations are still workable despite added elements, while others collapse under relatively small increases in control density.

The Just Noticeable Difference (JND) assessment additionally determines the physical boundaries of augmentation by isolating added mass as an independent condition relative to each instrument's baseline weight. Added mass below approximately five percent remains largely within the non-intrusive range (Score 0–3) and produces no impact across trombonists.

The transition into the minimally intrusive range (Score 4–7) begins at lower values for some individuals but, at the population level, centers in the low-to-mid teens as a proportion of baseline mass. Beyond this region, tolerance declines progressively. The fully intrusive threshold (Score ≥ 8) emerges in the low twenties, marking the point at which added mass consistently compromises perceived playability. These thresholds show that mass does not accumulate linearly in perception, but follows a psychophysical progression in which small early additions are tolerated until balance and moment-arm relationships are disrupted.

The JND results further reveal transient regions of reduced intrusiveness, where modest mass additions temporarily improve perceived balance. These “positive-weight” effects demonstrate that physical constraints are not purely subtractive, but interact dynamically with instrument-specific balance conditions. However, such compensatory effects are limited and diminish as mass continues to increase.

Within the NIHCI framework, this physical–cognitive dimension specifies how instrumental augmentation can scale once components have been perceptually accepted. It governs where devices may be placed, how many controls can be effectively coordinated, and how interaction density can increase before

playability is compromised. This dimension does not assess whether a given augmentation is musically more interesting than another; rather, it evaluates whether it remains mechanically feasible and cognitively manageable.

Addressing the Research Questions

The following section addresses how this framework answers the research questions for the study.

RQ1: *How can this research inform the design of NIHCI for augmented trombone practices?*

This research informs the design of the NIHCI by establishing the conditions under which technological augmentation remains compatible with conventional trombone performance. Rather than proposing specific devices or mapping strategies, it lays out a structured design space defined by three interdependent dimensions: (1) perceptual intrusiveness, (2) affective evaluation, and (3) physical-cognitive viability. Together, these dimensions confine the limits within which augmentation can be placed without compromising playability, coordination, or perceptual transparency.

Perceptual intrusiveness, formalized through the Perceived Intrusiveness Index (PII), defines an upper boundary beyond which augmentation interferes with performance. Below this threshold, affective evaluation governs early, through the pre-assembly acceptance of individual input devices. At this stage, tactile, spatial, and visual qualities condense into a unified perceptual judgment of ease of use, which tends to dominate overall evaluation. Residual perceptual

factors—such as mechanical noise, visibility, and perceived stability—account for the remaining variance.

Once components are *affectively* accepted, physical-cognitive viability defines how they can be combined and scaled, considering instrument topography, balance, motor coordination, cognitive demand, and added mass. Collectively, these findings establish defined boundaries for augmentation. Rather than relying primarily on intuition or personal tolerance to judge what feels intrusive, the framework offers structured criteria through which such judgments can be evaluated.

Within the model, designers do not freely assign importance to perceptual dimensions. Instead, they must decide whether specific core themes are present or absent in a given configuration. Those themes, however, are already bound by the structure of the framework and by empirically derived weights. In this way, individual interpretation operates within clearly defined limits. Subjectivity remains part of the process, but it is situated within a shared structure rather than left unexamined.

As a result, terms such as “intrusive,” “minimally intrusive,” or “non-intrusive” no longer function as informal descriptions based solely on personal impression. In many design discussions, these labels are used without a common reference point, making them difficult to compare or evaluate. Here, intrusiveness is articulated in relation to defined perceptual dimensions and threshold conditions. It becomes something that can be described, measured, and debated with reference to a shared framework rather than claimed as an isolated judgment.

RQ2. *What capabilities and control mechanisms can be implemented through the strategic placement of input devices on the trombone to maximize expressive potential without compromising conventional playability?*

The NIHCI design favors input devices and configurations that minimize continuous motor engagement and attention demand, while also being compatible with stable hand positions along the left-hand grip. Tactile switches consistently emerge as low-intrusiveness, low-cognitive-cost elements and function as structural anchors in multi-device configurations. Continuous controllers and joysticks can be incorporated selectively when confined to restricted regions and paired with tactile inputs that stabilize coordination tasks. Pressure-based components, such as force-sensitive resistors, show a broad tolerance when aligned with natural grip pressure and passive holding forces.

Beyond the physical form of individual controls, the findings also support a flexible interpretation of sensor data as a design resource rather than a fixed control pathway. Telemetry generated by on-instrument sensors, including tactile, pressure, motion, or proximity data, can support both direct parameter control and higher-level state inference, allowing for mappings that range from one-to-one, one-to-many, and many-to-one triggers to modulation of system states, cues, or adaptive processes. In this sense, expressive augmentation remains viable when control strategies privilege discrete activation, localized placement, and incremental complexity, while allowing sensor data to inform broader musical, visual, or structural processes without increasing physical or cognitive burden.

Sub-question 1: *What are the potential uses of NIHCI beyond the music/audio possibilities, such as video, tablet turn-page functions, lights and stage control, FX, etc.?*

While the NIHCI framework is not tied to specific mappings, the NIHCI prototype evaluation shows the ability to support non-audio functions such as score navigation, and through the MIDI implementation, the ability to support cueing and a live control system for media or lighting control. As long as such functions respect perceptual intrusiveness thresholds, preserve control and affective transparency, and remain within physical-cognitive viability limits, they can be integrated without disrupting conventional instrumental performance. This flexibility positions NIHCI not only as a tool for sound manipulation but also as a broader performative interface for multimodal control in live contexts.

Sub-question 2: *How can the NIHCI framework be applied to other hand-held acoustic instruments?*

Although the empirical results of this study focus on the trombone, the methodology itself is not instrument-specific. The framework is grounded in HCI evaluation principles and human perception, rather than in trombone design alone. For this reason, its hierarchical structure—PII assessment, affective evaluation, and physical-cognitive viability—can be applied to other hand-held acoustic instruments. Adapting the framework to a different instrument would require recalibrating instrument-specific parameters. This includes adjusting perceptual weights within the PII model and reanalyzing factors such as topography, balance, motor biomechanics, placement, and mass tolerance. These values

will naturally vary across different instruments. The NIHCI framework, therefore, presents a structured method for evaluating and designing non-intrusive augmentation across different instrumental contexts, rather than prescribing a single fixed solution.

Beyond ergonomic validation and implementation strategies, the NIHCI framework ultimately reshapes how musical agency can be distributed in augmented performance. Establishing perceptual and physical boundaries does more than prevent musical flow interference; it creates the conditions under which a computational system can enter performance without supplanting the performer. The instrument remains physically and acoustically itself, yet its gestures acquire extended functions and meanings. In this sense, augmentation is not an added layer of control, but a reconfiguration of dialogue. The performer does not operate technology from the outside; instead, interaction unfolds from within instrumental practice. What emerges is not a hybrid instrument in the conventional sense, but a shared musical space in which acoustic and computational processes retain distinct identities while engaging one another in real time.

CHAPTER VII

LIMITATIONS

The following limitations bound the conditions under which the findings and models should be interpreted. First, the empirical findings are instrument-specific. The constraints identified in the framework, in particular those related to grip topography, balance, mass distribution, and hand biomechanics, are shaped by the geometry of single and F-attachment trombones. Second, affective evaluation was conducted at the level of individual input components rather than at the level of components mounted on the trombone. This design choice allowed the isolation of tactile, spatial, and visual dimensions, which later informed the modeling of ease of use as a dominant perceptual mediator. However, emergent affective responses that arise only when components are combined into complete systems, for example, interactions between controls or mappings, were not directly assessed. The affective model, therefore, characterizes early, pre-integrative acceptance rather than long-term experiential evaluation. Third, the study emphasizes short- to mid-term interaction. Neither longitudinal learning effects nor sustained use over extended periods were tested. As a result, the framework does not model how perceptual intrusiveness, affective judgment, or physical–cognitive limits may shift as performers get used to augmentation or develop new motor strategies over time. In addition, the framework prioritizes broadly acceptable thresholds derived from

the sampled participant population; expert or highly specialized performers may tolerate higher levels of intrusiveness when offset by artistic, technical, or performative gains.

Fourth, the configuration trials in Phase Two intentionally isolated mechanical and ergonomic factors, keeping all electronic components unpowered. Although this strengthened the assessment of physical placement, mass tolerance, and cognitive load, it did not capture feedback-dependent dynamics that may emerge in responsive or adaptive systems, such as latency perception, attentional shifts, or closed-loop control behavior. Fifth, the Just Noticeable Difference (JND) assessment focused exclusively on added mass as an independent variable at a specific location in the trombone rear section. Other physical factors—such as vibration transmission, changes to instrument-body resonance, long-term use, or distributed mass along the instrument—were not independently tested and may introduce additional constraints not captured in the present study.

Finally, sensor outputs from the NIHCI prototype were primarily implemented through classic MIDI control messages. In most standard configurations, this operates within 7-bit resolution (0–127 values), although the artistic evaluation system also employed selected 14-bit MIDI mappings (MSB/LSB pairs) for higher-resolution control. While acceptable for discrete activation and most common continuous interaction scenarios, lower-resolution mappings may limit sensitivity for fine-grained gestural control or high-dimensional sensor fusion tasks. Higher-resolution protocols, such as MIDI 2.0, as well as OSC-based implementations, were not implemented or evaluated. As a result, the framework

does not directly address how increased data granularity might influence the evaluation of perceptual thresholds, affective judgment, or cognitive load.

CHAPTER VIII

FUTURE WORK

Future work unfolds along four main directions: (1) framework extension and generalization, (2) hardware and system refinement, (3) interface and communication architecture, and (4) artistic and co-creative exploration.

First, later revisions will extend and apply the NIHCI framework itself. Further research is required to recalibrate the framework for other hand-held acoustic instruments. Differences in instrument topography and motor demands will require instrument-specific adjustments to perceptual weights and thresholds.

Furthermore, the framework will be implemented through a design-oriented, browser-based environment that allows performers and designers to explore augmentation strategies through structured interaction rather than ad hoc prototyping. Such a system could support questionnaire-driven input, parameter selection, or direct manipulation of virtual components placed on schematic representations of an instrument, enabling estimation of perceptual intrusiveness and identification of potential design conflicts. The intent of this approach would not be to provide solutions per se, but to support early-stage reasoning about placement, control, and interaction strategies before implementation.

Second, hardware and system refinement are a natural continuation of the initial prototype. Although the existing NIHCI implementation validates feasibility at the functional level, the development of a second iteration began during Fall 2025 within a research residency at IMA, NYU Shanghai, incorporating evaluation feedback from the initial prototype. This phase introduced flexible materials such as TPU 85A and a clamp-style attachment design, maintaining the same configuration as the initial prototype. Multiple enclosure variants were designed, printed, and tested for custom use (Figure 88). The final second-iteration revision adopted TPU 95A to combine two advantages: sufficient rigidity for the clamp and electronic components, and controlled flexibility for easy coupling.

Figure 89 shows the second prototype mounted on the trombone in performance configuration. This second prototype also doubled battery capacity, moving from a single 150 mAh cell to two 180 mAh cells connected in parallel, totaling 360 mAh.

At the circuit level, future revisions will consolidate and reorganize onboard components and integrate additional sensors such as force-sensitive resistors beneath the tactile switches, whose placement was validated during the trials. The current CodeCell board integrates both the gyroscope and the IR-based VCNL4040 proximity sensor on a single circuit. Relocating the proximity sensor component will allow ergonomic customization of the proximity-based interaction without troubling the reference orientation of the IMU. This separation will simplify calibration procedures and improve spatial alignment between the sensing direction and the performer's gesture.

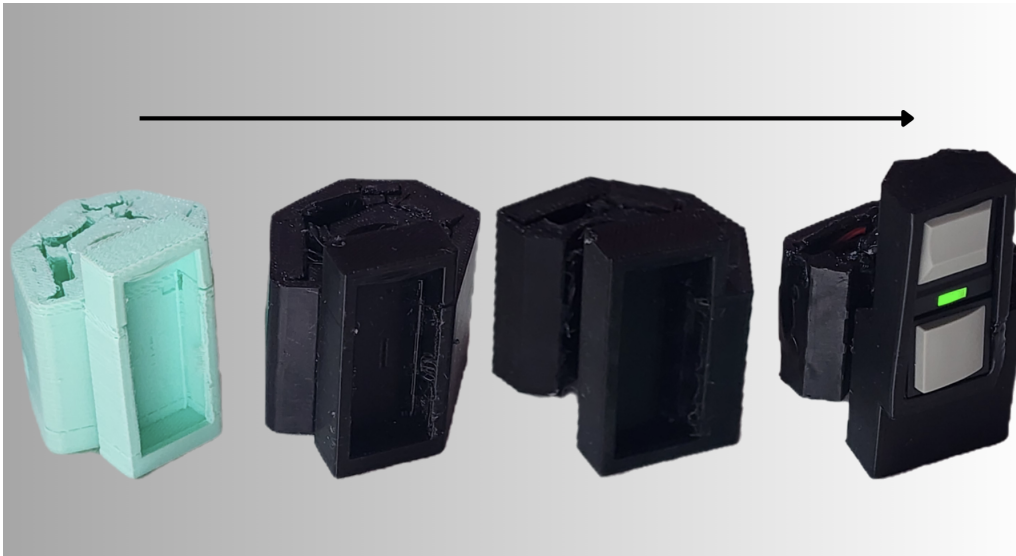


Figure 88: Evolution of the second prototype 3D-printed housing, showing successive enclosure iterations leading to the final TPU clamp-based design.



Figure 89: Evolution of the second prototype 3D-printed housing with different designs and materials

Third, the WebUI interface and communication architecture will continue to evolve beyond the current calibration and communication workflow. Subsequent iterations will introduce automated calibration routines based on brief guided movement sequences, allowing hands-free adjustment of sensor ranges. Additional interaction mechanisms, such as double-tap for recalibration, will

support dynamic re-centering during performance. Expanded battery capacity and circuit memory will allow the communication layer to support multiple output protocols, including OSC and higher-resolution standards such as MIDI 2.0.

As the system progresses beyond its exploratory phase, next-stage development may also revisit the real-time audio architecture. The current implementation relies on SuperCollider for its flexibility during rapid prototyping and structural reconfiguration. However, frameworks such as JUCE offer advantages in architectural consolidation, allowing audio processing, interface design, networking, and deployment to be integrated within a single application. Such an approach could reduce inter-process complexity, strengthen synchronization between gesture and sound, and support cross-platform distribution as a standalone application or plugin. Moving toward a more unified architecture would not alter the conceptual foundations of the NIHCI but could enhance the system's long-term stability, portability, and broader accessibility.

Fourth, artistic and co-creative exploration will extend the NIHCI framework to other hand-held acoustic instruments, particularly within the brass family. The next step is not only to adapt the NIHCI framework, but also to understand how different instruments shape—and are shaped by—this form of interaction, especially in ensemble settings, where multiple performers share embodied musical discourses with computational agents. In such contexts, negotiation, timing, and role shifting emerge from collective actions rather than individual decisions.

Ensemble performance introduces a different type of listening challenge. When

several instruments sound at once, intention can become layered and difficult to distinguish. Sound alone does not always reveal who is leading, who is preparing to enter, or how a phrase is about to unfold. Even with multiple audio inputs, the musical meaning behind collective sound can remain blurred.

In this context, NIHCI offers another way of listening—one that listens to the body as well as to the sound. Movements, shifts in posture, proximity, or the simple act of raising an instrument can signal intention before sound emerges. These embodied cues often communicate timing, role, and direction more clearly than the sonic result itself. By engaging with this layer of musical behavior, a computational system can respond not only to what is heard, but to what is about to happen. This could enable a more attentive form of participation, one rooted in the way musicians listen to one another in ensemble practice.

Another area of interest is developing a deeper understanding of how these different layers of information interact. Rather than treating these layers as separate control streams, the aim is to explore how they overlap, reinforce one another, or reveal something distinct about expressive intent. In performance, gestures rarely function in isolation; they form constellations of cues that together communicate timing, energy, and direction. One approach that may support this inquiry is Partial Information Decomposition (PID), a framework that examines how multiple signals contribute redundant, unique, or synergistic information toward a shared outcome. Applied in this context, PID could help clarify when two modalities are effectively saying the same thing, when one adds something irreplaceable, or when their combination produces meaning that neither could convey alone. Such insight would allow system be-

havior to emerge from the interaction of modalities rather than from isolated or predefined mappings, making responses feel more coherent and musically grounded.

Expanding beyond audio alone also opens up an important artistic possibility. Much of musical communication unfolds before sound—through breath, posture, spatial orientation, or the simple act of lifting an instrument. Enabling the system to sense and interpret these moments allows future co-creative environments to participate in forms of awareness that more closely resemble human ensemble practice. The goal is not to automate musical decisions but to cultivate a form of computational listening that attends to embodied intention as it develops in time.

Together, these directions move the NIHCI framework beyond a validated interface design and toward a broader vision of embodied musical interaction. This study suggests that technological augmentation does not need to replace or redefine traditional trombone practice. Instead, it can coexist with it—embedded, non-intrusive, and compliant with the physicality and acoustic identity of the instrument. The NIHCI framework allows acoustic performance to extend into digital and cyber-physical spaces without compromising conventional playability, positioning human performers and computational systems as distinct yet interdependent participants within a shared musical ecology.

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APPENDIX I

PHASE ONE ONLINE SURVEY

Beyond Brass Performance

Introduction: This study explores how to create user-friendly and non-intrusive technological devices that extend the trombone performative possibilities beyond acoustic capabilities.

Confidentiality:

Your responses will be kept confidential and used solely for academic research purposes.

Estimated Time:

The survey will take approximately ~35 minutes to complete.

Questions or concerns:

- Ricardo Arbiza: raa9850@nyu.edu
-

SECTION 1 OF 9: Consent

You can view the consent form for this online survey by [clicking here](#). If you agree to the terms outlined in the document, please proceed to the next question.

Q1. The completion of this survey implies your consent to participate.

If you choose to participate, please select Yes, I consent. You can continue with the survey and press submit when you finish. You can withdraw from the survey at any moment. **[REQUIRED]**

Yes, I consent (Continue with the survey)

Participation criteria

The participant criteria for this study are as follows:

1. Over the age of 18 years old
2. More than 5 years playing trombone and still in activity.

Q2. Indicate your age **[REQUIRED, greater than 18 years old]**

[Short answer text, numeric only]

Q3. Years of playing the trombone **[REQUIRED, number greater than 4 years of experience]**

[Short answer text, numeric only]

SECTION 2 OF 9: Demographic and Background Information

Q4. Indicate your gender

[Multiple option]

- Male
- Female
- Other [Text input]

Q5. Country and city of current residence

[Short answer text]

SECTION 3 of 9: Musical training and experience

Q6. Select your highest level of formal musical education

[Multiple option]

- None
- High School Music Program
- Bachelor's
- Master's
- Doctorate
- Music Conservatory
- Other [text input]

Q7. What is/are the primary genre(s) of music that you perform? (Choose up to 2)

[Checkboxes]

- Classical
- Jazz
- Contemporary
- Experimental and Avant-Garde Music
- Rock and Alternative Music
- Pop and Electronic Music
- Hip Hop and Urban Music
- Roots and Traditional Music
- Rhythm and Blues (R&B) and Soul
- Latin Music
- Other [text input]

Q8. How many times per year do you perform in public?

[Multiple option]

- 0-10
- 11-20
- 21-50
- 51-100

- More than 100 times

Q9. What size and type of venues do you typically play in?

[Short answer text]

Q10. Do you usually play solo or in a group/ensemble?

[Multiple choice]

- Solo
- Group/ensemble
- Both

Q11. Have you been involved in any musical project involving some sort of technology?

[Short answer text]

SECTION 4 OF 9 Music technology background

Q12. Do you have formal training in Music Technology?

[Multiple choice]

- Yes
- No

Q13. Please, select the comfort level with using technology in general related to music.

[Linear scale 1-10]

1-Uncomfortable

10-Comfortable

Q14. Do you have experience in using any Digital Audio Workstations (DAWs) or live audio processors?

[Multiple choice]

- Yes
- No

Q15. Have you ever programmed or written code for musical purposes?

[Multiple choice]

- Yes
- No

Q16. If yes, which programming languages are you familiar with?

If not, continue with the next question

[Checkboxes]

- Python
- JavaScript
- C++
- Pure Data

- MaxMsp
- Csound
- Supercollider
- Other [text input]

SECTION 5 OF 9: Integration of Technology in Music Practice

Q17. Do you usually integrate technology into your music practice? (e.g., apps for metronome/tuner, tablet for reading scores, recording devices, etc.). If yes, please detail what technological device(s), and the reason.

[Long answer text]

Q18. Do you have any preference in what microphone to use for your trombone? If so, please indicate technical characteristics, and/or any aspect you like about it.

[Long answer text]

Q19. Have you used a contact mic (pickup mic) or a similar product as the PiezoBarrel mic on your trombone? If the answer is yes, please share your overall experience.

[Long answer text]

Q20. Do you prefer a wired or a wireless mic? Briefly explain the reason behind your choice.

[Long answer text]

Q21. Have you used real-time sound processing technology in any public presentation? (i.e. microphone, pedal effect, pedal loop, computer, tape, hand-made device, etc.).

If yes, please detail the device(s), and the purpose of it.

[Long answer text]

Q22. Is it within your interests to integrate some technology aspects in your future musical performances?

[Multiple choice]

- Yes
- No

Q23. Please explain the reasons based on your previous answer.

[Long answer text]

Q24. What type of technology (hardware/software) would you feel most comfortable integrating into your trombone performance?

[Long answer text]

Q25. Have you faced any challenges when using -or attempting to use- technology in your performance?

[Long answer text]

SECTION 6 OF 9: Daily use of technology and technical skills

Q26. Select which smart devices you generally use the most.

[Checkboxes]

- Smartphone
- Tablet
- Smartwatch
- Laptop
- Desktop computer
- None
- Other [text input]

Q27. Which operating system does run on your smartphone?

[Checkboxes]

- iOS
- Android
- Other [text input]

Q28. Which operating system does run on your computer?

[Checkboxes]

- Windows
- macOS
- Linux
- Other [text input]

Q29. Which smartphone brand and model do you currently use the most?

[Short answer text]

Q30. Are you familiar with connecting devices via Bluetooth?

[Multiple choice]

- Yes
- No
- Not familiar with Bluetooth technology

Q31. What is the browser you use the most generally?

[Multiple choice]

- Chrome
- Apple's Safari
- Firefox
- Android
- Opera
- Samsung Internet

- Other [text input]

Q32. When connected to the internet, are you able to find the IP address of the network your device (Phone or computer) is connected to?

[Multiple choice]

- Yes
- No
- Not familiar with the IP term.

SECTION 7 OF 9: Trombone ergonomics and playability

Q33. Which is your main instrument?

[Multiple choice]

- Alto trombone
- Straight Tenor trombone
- Tenor trombone with F attachment
- Double valve bass trombone
- Piston trombone
- Other trombone [text input]

Q34. Do you face any physical challenges related to the trombone grip while playing? If yes, please explain:

[Short answer text]

Q35. Do you use any trombone grip products? i.e.: leather hand accessories, thumb rest, etc. If so, please list it.

[Long answer text]

Q36. Would you temporarily attach a device/controller to the trombone that could expand or improve aspect(s) of the performance experience?

[Multiple choice]

- Yes
- No
- Depends

Q37. If you replied Yes, is there one or more places in the trombone where you would never place a temporary attachment(s)? Please, explain why.

[Long answer text]

Q38. If you selected "Depends", please explain your reason(s)

[Long answer text]

Q39. Would you attach a permanent device/controller to the trombone that could expand the performance experience when playing trombone?

- Yes
- No
- Depends

Q40. If you replied Yes or Depends, is there one or more places in the trombone where you would never place a permanent attachment? Please, explain why.

[Long answer text]

Q41. If you selected "Depends" in the previous question for permanent attachment(s), please explain your reason(s)

[Long answer text]

Q42. If you could control external digital parameters (such as audio effects, loop, tablet turn page, etc) while playing trombone, where would you like to place the device, and why?

[Long answer text]

Q43. Rank the following factors in terms of their importance when determining intrusiveness: placement, balance, weight, and intrusiveness with technique.

Non-Intrusive: No impact on technique or playability.

Minimally Intrusive: Slight interference, but manageable and does not hinder performance.

Intrusive: Significantly disrupts playability, making it difficult or impossible to perform normally.

(Score ranges 0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive).

(Scroll right to see the full score scale)

[Ranking question]

	0.Non...	1	2	3	4	5	6	7	8	9	10.Int...
Place	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Weight	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Size	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Mater...	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q44. Please rate the range of movement for extra control of each finger you have while playing the trombone.

Rating Scale:

0 - Not available for extra control (Actively engaged in playing/stationary)
 10 - Very high availability for extra control (Fully available/Not engaged in playing)

L-Left

R-Right

[Checkbox grid]

	0	1	2	3	4	5
L-Thumb	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
L-Index	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
L-Middle	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
L-Ring	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
L-Little	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
R-Thumb	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
R-Index	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
R-Middle	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
R-Ring	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
R-Little	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Q45. Which hand do you use to hold your trombone?

[Multiple choice]

- Right hand
- Left hand

Q46. Do you have any extra comments about the range of movement of your fingers while playing the trombone? If no, continue with the next section.

[Long answer text]

SECTION 8 OF 9: intrusiveness assessment of trombone attachments

In this section, you will evaluate various trombone attachments.

If you do not have experience with some of the accessories, you can continue to skip the answer and move on to the next question.

Please rate each device on a scale from 0 to 10 based on how it affects your ability to play normally (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive).

Then, categorize each as

- **Non-Intrusive:** No impact on technique or playability.

- **Minimally Intrusive:** Slight interference, but manageable and does not hinder performance.
- **Intrusive:** Significantly disrupts playability, making it difficult to perform normally.

Q47. On a scale from 0 to 10, how intrusive is the **Clip-On Microphone** in terms of its impact on your ability to play the trombone normally? (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q48. Briefly explain your rating. What factors influenced your decision about **Clip-On Microphone**?

[Short answer text]

Q49. On a scale from 0 to 10, how intrusive is the **Mic Hub/Transmitter** in terms of its impact on your ability to play the trombone normally? (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q50. Briefly explain your rating. What factors influenced your decision about **Mic Hub/Transmitter**?

[Short answer text]

Q51. On a scale from 0 to 10, how intrusive is the **Clip-On Tuner** in terms of its impact on your ability to play the trombone normally? (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q52. Briefly explain your rating. What factors influenced your decision (e.g., placement, visibility, weight)?

[Short answer text]

Q53. On a scale from 0 to 10, how intrusive is the **PiezzoBarrel Microphone System** in terms of its impact on your ability to play the trombone normally? (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q54. Briefly explain your rating. What factors influenced your decision about **PiezzoBarrel Microphone System**?

[Short answer text]

Q55. On a scale from 0 to 10, how intrusive is the **BERP** in terms of its impact on your ability to play the trombone normally? (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q56. Briefly explain your rating. What factors influenced your decisions about BERP?

[Short answer text]

Q57. On a scale from 0 to 10, how intrusive is the Bullet Brace in terms of its impact on your ability to play the trombone normally?

A: Bullet Brace accessory

B: Bullet Brace on place

(0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q58. Briefly explain your rating. What factors influenced your decision about **Bullet Brace**?

[Short answer text]

Q59. On a scale from 0 to 10, how intrusive is the **Hand Support** in terms of its impact on your ability to play the trombone normally? (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q60. Briefly explain your rating. What factors influenced your decision about **Hand Support**?

[Short answer text]

Q61. On a scale from 0 to 10, how intrusive is the **Hand Guard** in terms of its impact on your ability to play the trombone normally? (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q62. Briefly explain your rating. What factors influenced your decision about **Hand Guard**?

[Short answer text]

Q63. On a scale from 0 to 10, how intrusive is the **Pencil Holder** in terms of its impact on your ability to play the trombone normally? (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q64. Briefly explain your rating. What factors influenced your decision about **Pencil Holders**?

[Short answer text]

Q65. On a scale from 0 to 10, how intrusive are **Mutes** (Straight, Cup, Harmon, Practice) in terms of their impact on your ability to play the trombone normally? (0-3 = Non-intrusive, 4-7= Minimally intrusive, 8-10 = Intrusive)



[Linear scale 0-10]

Q66. Briefly explain your rating. What factors influenced your decision about **Mutes**?

[Short answer text]

Q67. Does the intrusiveness of a device affect how frequently you use it in performance or practice?

[Multiple choice]

- Yes, I use less intrusive devices more frequently.
- No, intrusiveness does not affect my usage.
- Sometimes, depending on the context.

Q68. What three words would you use to describe the impact of an intrusive device on your trombone-playing experience? [Short answer text]

SECTION 9 OF 9: Future expectations and desires

Q70. What are your technological enhancement desires for the trombone? This could be sound or not sound-related, i.e., loop station, audio effects, tablet turn page function, light control, etc. If none, continue with the next question.

[Long answer text]

Q71. Do you have any other comments or information that would be helpful in designing non-intrusive technology for the trombone performance?

[Long answer text]

END OF SURVEY

Final message:

Thank you for participating in this survey!

APPENDIX II

FEEDBACK QUESTIONNAIRE FOR PHASE TWO

Beyond Brass Performance

Ricardo Arbiza - raa9850@nyu.edu

Phase #2: General Instructions

This test will last approximately **1 hour and 30 minutes** and will be divided into **three parts**:

1. **Affective Assessment**
2. **Actuator Configuration**
3. **Just Noticeable Difference (JND) Assessment**

During the test, all questions will be answered **orally** to ensure your comfort while holding and interacting with the trombone. The evaluator will document your responses in the form on your behalf to maintain accuracy and minimize interruptions. Your responses will remain fully anonymous, and you will use a Unique Identifier (UID) to link your answers across the different sections.

Questions labeled **Evaluator Only [EO]** are to be completed solely by the evaluator

2.1 Affective Assessment

Instructions: You will evaluate actuators that are designed to be attached to a trombone as part of an interface. Please take one actuator at a time and assess it as if it were installed on a trombone. Imagine using the actuator during typical trombone performance tasks. Answer the following questions for each actuator. To ensure your responses are grouped together, please use your Unique Identifier (UID) across all the sections of the study.

Q1.1 [EO] Please enter the UID [Short answer text]

Q2.1 [EO] Please select the ID of the actuator to be evaluated. [Drop-down menu]

Q3.1 How would you rate the tactile feel of the actuator? Consider factors like smoothness, resistance, and texture, imagining how it might feel during a trombone performance. (0: Extremely unpleasant, 10: Extremely pleasant) [Linear scale: 0–10]

Q4.1 How well does the size of the actuator meet your expectations for use on a trombone interface? Consider its comfort, accessibility, and ergonomics for playing. (0: Completely inappropriate size, 10: Perfectly appropriate size) [Linear scale: 0–10]

Q5.1 How visually appealing is the design of the actuator? Imagine it attached to a trombone—does it integrate well with the instrument's appearance? (0: Extremely unattractive, 10: Extremely attractive) [Linear scale: 0–10]

Q6.1 How easy do you think it would be to use this actuator while playing the trombone? Consider ease of access, intuitiveness, and control precision during performance. (0: Extremely difficult, 10: Extremely easy) [Linear scale: 0–10]

Q7.1 Based on your overall impression, how would you rate this actuator in terms of its suitability and appeal for use on a trombone interface? (0: Very negative overall impression,

10: Very positive overall impression) [Linear scale: 0–10]

Q8. If you have any additional comments, observations, or suggestions about this actuator, please share them here. [text box]

2.2 Actuator Configuration

Instructions:

You will test actuator placements on the trombone, starting with one actuator and adding more components iteratively. Perform the designated musical scenarios for each setup and provide feedback on comfort, effectiveness, and intrusiveness. Use the following scoring system to evaluate intrusiveness:

- **0–3:** Non-Intrusive
- **4–7:** Minimally Intrusive
- **8–10:** Intrusive

Q1.2 [EO] Please enter the UID [Short answer text]

Q2.2 [EO] Select the iteration number for this test [Drop-down menu]

Q3.2 Enter the coordinate system reference(s) for the hub placement.

Q4.2 Select the actuator(s) used in this setup (e.g., Button, Slider). [Drop-down menu]

Q5.2 Enter the coordinate system reference(s) for the actuator placement(s). [Short answer text]

Q6.2 Rate how intrusive you found this setup. [Linear scale: 0–10]

Q7.2 Did you reposition any existing actuator(s) from a previous iteration? If so, please describe the change and explain why. [Long answer text]

Q8.2 Provide any suggestions or feedback on this setup for improving placement or design. You can refer to an overall impression or to any id mark on a particular music scenario [Long answer text]

Phase 2.3: Just Noticeable Difference (JND) Assessment

Instructions:

Small weights equivalent to 1% of the trombone's weight will be incrementally added to the back side of the instrument. After playing a short excerpt, you will report whether you noticed a weight difference and rate the intrusiveness of the change on a scale from 0 to 10 Using the following scoring system to evaluate intrusiveness: **0–3:** Non-Intrusive, **4–7:** Minimally Intrusive, **8–10:** Intrusive.

To ensure your responses are grouped correctly, use the Unique Identifier (UID) assigned for this test.

Q1.3 [EO] Enter the UID. [Short answer text]

Q2.3 [EO] Enter the iteration number for this test [Drop-down menu]

Q3.3 [EO] Select the type of trombone used in this assessment. [Drop-down menu]

Q4.3 [EO] Enter the total weight added during this iteration. [Short answer text]

Q5.3 [EO] Indicate whether this iteration was a dummy trial (no weight added). [Yes/No]

Q6.3 Do you notice any weight difference in this iteration? [Yes/No]

Q7.3 Rate how intrusive the added weight felt during the task. [Linear scale: 0–10]

Q8.3 Do you have any additional comments or observations about this iteration? [Long answer text]

APPENDIX III

STUDY MATERIALS FOR PHASE TWO

Beyond Brass Performance

IRB-FY2024-8396

Phase #2.2 Actuator Configuration.

This phase explores the ergonomic and musical intrusiveness of actuators on the trombone, focusing on their impact in different playing scenarios.

Iteration Label Code Explanation

Each iteration follows the format Iteration #X.Y.Z, where:

- **X (Cycle) – Defines the actuator type being tested**
 - **1–4** → Individual actuator categories (*e.g.*, 1 = *Tactile Switch*, 2 = *Joystick*, 3= *Continuous Control*, 4= *Force Resistors Sensors*)
 - **5M+** → Multiple actuator setup
 - **F9** → Final setup
- **Y (Position) – Refers to the placement of the actuator**
 - **1, 2, 3** → Different tested positions for the same actuator
 - **0** → Multi-actuator setup (*placed at participant's discretion*)
- **Z (Musical Context) – Specifies the playing condition**
 - **1** → Free-choice piece (*common use*)
 - **2** → Etude (*structured use*)
 - **3** → Sight-reading passage (*boundary-pushing case*)

2.1 Affective Assessment:

2.1 Affective Assessment – Instructions

In the following table, you will find four categories of actuators, each containing multiple options:

- **Actuator #1** – Tact Switch
- **Actuator #2** – Joysticks
- **Actuator #3** – Continuous Control (Encoders, Potentiometers, Sliders)
- **Actuator #4** – Force-Sensitive Resistors (FSRs)

Procedure:

1. Explore each actuator within its category by evaluating its mechanism, shape, tactile feedback, and placement on the trombone. Pay attention to how it feels in use and how it integrates with performance.
2. For each actuator, complete Form 2.1 based on your experience before moving on to the next actuator.
3. Repeat this process for all actuators in every category, ensuring a thorough assessment of each type.
4. Once all actuators have been evaluated and Form 2.1 is completed for each, select one actuator per category to proceed to the next section of the study.
5. After making your selections, continue to the next phase of the study.

***** Now, respond to the 2.1 form for each actuator *****

2.2 Actuator Configuration – Instructions

This section evaluates the impact of actuator placement and configuration on playability and perceived intrusiveness during trombone performance. You will assess how different placements and actuator combinations affect comfort, playability, and musical integration rather than technical execution.

Procedure:

1. Playability Assessment for Individual Actuators

- For each selected actuator per category (Tact Switch, Joystick, Continuous Control, FSR), you will explore three different placements on the trombone.
- In each placement, you will perform three musical scenarios:
 - **Free-choice piece** (common use)
 - **Etude** (structured use)
 - **Sight-reading passage** (boundary-pushing case)
- After testing all three placements for the designated actuator, answer the questions in Section 2.2 before proceeding to the next actuator.
- Repeat this process for all four actuator categories.

Important Notes:

- The sight-reading passage is an exploratory task and should not solely determine the intrusiveness rating, but may highlight unexpected challenges in more extreme cases.

Actuator #1 - Tact Switch

Iteration #1.1.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #1.1.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

1-2-3-4^{*} Allegretto (♩ = 104)

No. 3

p *f* *p* *rall.* *a tempo* *p*

Iteration #1.1.3

Sight Reading : Badia, M. *Método completo para trombón de pistones, bombardino, tuba y demás saxhorns bajos*. Editorial Boileau.

82 *
1-2-3-4 Andante (♩. = 54) * * *

The musical score consists of four staves in bass clef, 6/8 time, key of Bb. The tempo is Andante with a quarter note equal to 54 beats per minute. The first staff starts with a dynamic of *mf* and has asterisks above measures 1, 4, and 7. The second staff has asterisks above measures 1, 4, and 7. The third staff has an asterisk above measure 7. The fourth staff starts with a dynamic of *f* and has a quarter note equal to 54 beats per minute. The score includes various musical notations such as slurs, ties, and accidentals.

*** Now, proceed to respond to the 2.2 form ***

Iteration #1.2.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #1.2.2

- **Etude** : Bordogni, M. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni*. Carl Fischer, Inc.

1-2-3-4 *
No. 3 Allegretto (♩=104) *

p *
f *p*
rall. *a tempo* *p* *

Iteration #1.2.3

Badia, M *Método completo para trombón de pistones, bombardino, tuba y demás saxhorns bajos*. Editorial Boileau. *

1-2-3-4

mf *
rall. *

*** Now, proceed to respond to the 2.2 form ***

Iteration #1.3.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #1.3.2

- **Etude** : Bordogni, M. (Year). *Melodious Etudes: Selected from the Vocalises of Marco Bordogni*. Carl Fischer, Inc.

1-2-3-4 *
No. 3 Allegretto (♩ = 104) *

p *
f * *p*
rall. *a tempo* * *p* *

Iteration #1.3.3

Manna, G. *Douze études pour le trombone*. Gérard Billaudot.

12
1-2-3-4 *
♩.12. Andantino. *

p *
p * * * * *
f *

*** Now, proceed to respond to the 2.2 form ***

Actuator #2 - Joystick

Iteration #2.1.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #2.1.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

1-2-3-4 Allegretto (♩ = 104)

No. 3

p

f *p*

rall. *a tempo* *p*

The image displays a musical score for 'Etude No. 3' by Marco Bordogni, arranged for a joystick. The score is written in bass clef with a key signature of one sharp (F#) and a 3/4 time signature. It is marked 'Allegretto' with a tempo of 104 beats per minute. The score is divided into four measures, each with a corresponding joystick icon: a star in a circle above the first measure, an upward-pointing arrow in a circle above the second measure, a downward-pointing arrow in a circle above the third measure, and a leftward-pointing arrow in a circle above the fourth measure. The score includes dynamic markings such as *p* (piano), *f* (forte), and *rall.* (rallentando), and a tempo change to *a tempo*. The music features a melodic line with various articulations and phrasing.

Iteration #2.1.3

First sight: Manna, G. *Douze études pour le trombone*. Gérard Billaudot.

1-2-3-4
10

Moderato.

The image shows a musical score for trombone in 2/4 time, marked 'Moderato.' The score is divided into three systems. The first system contains measures 1-4, with a '10' below measure 1. Above the staff are four circular performance cues: a downward arrow, an upward arrow, and two asterisks. The second system contains measures 5-8, with two asterisks above measures 5 and 6, and a rightward arrow above measure 7. The third system contains measures 9-10, with a rightward arrow above measure 9 and a leftward arrow above measure 10.

***** Now, proceed to respond to the 2.2 form *****

Iteration #2.2.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #2.2.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

1-2-3-4 Allegretto (♩ = 104)

No. 3 *p*

f *p*

rall. *a tempo* *p*

The image displays a musical score for Etude No. 3 by Marco Bordogni. It consists of four staves of music in bass clef with a key signature of one sharp (F#). The tempo is marked 'Allegretto' with a quarter note equal to 104 beats per minute. The score includes dynamic markings such as *p* (piano), *f* (forte), and *a tempo*. Performance instructions include 'rall.' (rallentando) and 'a tempo'. Four circular control icons are placed around the score: a star in a circle at the top left, a right-pointing arrow in a circle at the top right, an up-pointing arrow in a circle at the middle left, and a down-pointing arrow in a circle at the middle right.

Iteration #2.2.3

First sight: Manna, G. *Douze études pour le trombone*. Gérard Billaudot.

The image displays a musical score for trombone, consisting of three staves of music. The first staff is labeled "1-2-3-4" and "Andante mosso." It begins with a treble clef and a key signature of one flat. The music features a sequence of eighth notes and quarter notes. Above the staff, there are several circular diagrams representing fingerings and breath control. The first diagram shows a left-pointing arrow. The second and third diagrams show a star in the center and a left-pointing arrow. The fourth diagram shows a star in the center and an upward-pointing arrow. The number "9" is written at the end of the first staff. The second staff continues the musical line with triplet markings. The third staff shows a triplet of eighth notes. Above the third staff, there are two circular diagrams: one with an upward-pointing arrow and one with a right-pointing arrow.

***** Now, proceed to respond to the 2.2 form *****

Iteration #2.3.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #2.3.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni*. Carl Fischer, Inc.

1-2-3-4 Allegretto (♩=104)

No. 3

p

f *p*

rall. *a tempo* *p*

The image displays a musical score for Etude No. 3 by Marco Bordogni, arranged in four staves. The first staff is marked '1-2-3-4' and 'Allegretto (♩=104)'. The key signature is one sharp (F#) and the time signature is 3/4. The score includes dynamic markings such as *p* (piano), *f* (forte), and *a tempo*. Performance instructions include *rall.* (rallentando) and *a tempo*. Four circular control buttons are positioned around the score: a star in the top-left, an arrow pointing right in the top-right, an arrow pointing up in the middle-left, and an arrow pointing left in the middle-right.

Iteration #2.3.3

First sight: Manna, G. *Douze études pour le trombone*. Gérard Billaudot.

The image displays a musical score for trombone, consisting of four staves of music. The first staff is labeled "1-2-3-4" and "All^o Moderato." and includes a treble clef and a 4/4 time signature. The music is written in bass clef with a key signature of one sharp (F#). The score is annotated with four circular diagrams, each containing a radial grid. The first diagram has an upward-pointing arrow. The second diagram has a rightward-pointing arrow. The third diagram has a leftward-pointing arrow. The fourth diagram has a downward-pointing arrow. Additionally, a star symbol is placed above the second staff.

*** Now, proceed to respond to the 2.2 form ***

Actuator #3 - Continuous Control (Encoders, Potentiometers, and Sliders)

Iteration #3.1.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #3.1.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni*. Carl Fischer, Inc.

50%
1-2-3-4

No. 3 *Allegretto* ($\text{♩} = 104$)

The image shows three staves of musical notation for Etude No. 3. The first staff is marked with a piano (*p*) dynamic and a tempo of *Allegretto* ($\text{♩} = 104$). The second staff is marked with a forte (*f*) dynamic and a tempo of *50%*. The third staff is marked with a piano (*p*) dynamic and a tempo of *0%*. The notation includes various note values, rests, and phrasing slurs. The piece is in 3/4 time and the key signature has one sharp (F#).

100 %

50 %

0%

rall. *a tempo*

Iteration #3.1.3

First sight: Manna, G. *Douze études pour le trombone*. Gérard Billaudot.

The image shows a musical score for trombone, consisting of two staves. The first staff is labeled with a tempo of 100%, a fingering sequence of 1-2-3-4, and the tempo marking 'Moderato.'. It includes a dynamic marking of 0% and a measure number of 5. The second staff shows a performance progress of 50% and 100% at the end. The score is written in bass clef with a key signature of one sharp (F#) and a common time signature (C).

***** Now, proceed to respond the 2.2 form *****

Iteration #3.2.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #3.2.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

50%
1-2-3-4
Allegretto (♩=104)

No. 3
p
100 %
f **50 %** *p*
rall. *a tempo* **0%** *p*

Iteration #3.2.3

First sight: Manna, G. *Douze études pour le trombone.* Gérard Billaudot.

50%
1-2-3-4
Andante.

♩. 1. *p* **0 %** **50%**
f **100%** *p* **0 %**

*** Now, proceed to respond the 2.2 form ***

Iteration #3.3.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #3.3.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

50%

1-2-3-4

Allegretto (♩=104)

No. 3

p

100 %

f

50 %

p

a tempo

rall.

0%

p

Iteration #3.3.3

First sight: Manna, G. *Douze études pour le trombone.* Gérard Billaudot.

0 %

100 %

9

1-2-3-4

Andante mosso.

No. 9.

50%

0 %

100 %

*** Now, proceed to respond the 2.2 form ***

Actuator #4 - Force-Sensitive Resistors (FSRs)

Iteration #4.1.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #4.1.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni*. Carl Fischer,

1-2-3-4
No. 3 Allegretto ($\text{♩} = 104$)

p

f

a tempo

rall.

p

The image shows a musical score for a trombone etude. It consists of three staves of music in bass clef with a key signature of one sharp (F#). The tempo is marked 'Allegretto' with a quarter note equal to 104 beats per minute. The score includes dynamic markings: *p* (piano), *f* (forte), and *a tempo*. There are also performance instructions: 'rall.' (ritardando) and 'a tempo'. Blue arrows and brackets are overlaid on the score, indicating specific performance techniques or dynamics to be used during the actuator exercise.

Inc.

Iteration #4.1.3

First sight: Manna, G. *Douze études pour le trombone*. Gérard Billaudot.

10
1-2-3-4 Moderato.
♩. 10.

The image shows a musical score for a trombone etude. It consists of three staves of music in bass clef with a key signature of two flats (Bb, Eb). The tempo is marked 'Moderato' with a quarter note equal to 104 beats per minute. The score includes dynamic markings: *f* (forte) and *p* (piano). Blue arrows and brackets are overlaid on the score, indicating specific performance techniques or dynamics to be used during the actuator exercise.

***** Now, proceed to respond the 2.2 form *****

Iteration #4.2.1

****Play 30 seconds of any music of your choice while pressing the button at your own discretion ****

Iteration #4.2.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

1-2-3-4

No. 3

Allegretto ($\text{♩} = 104$)

p

f

a tempo

rall.

p

Iteration #4.2.3

First sight: Rossari, G. *Método para trombón y bombardino a pistones: En si bemol: Op. 243. Ex.3*

1-2-3-4

3.

MODERATO

♩ dolce

♩ dolce

***** Now, proceed to respond the 2.2 form *****

Iteration #4.3.1

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #4.3.2

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

1-2-3-4

No. 3 Allegretto ($\text{♩} = 104$)

p

f

a tempo,

rall.

p

The image shows a musical score for Etude No. 3 by Marco Bordogni. It consists of three staves of music in bass clef with a key signature of one sharp (F#). The tempo is marked 'Allegretto' with a quarter note equal to 104 beats per minute. The score includes dynamic markings such as *p* (piano), *f* (forte), and *a tempo*. There are also performance instructions like *rall.* (rallentando). Blue arrows and brackets are overlaid on the score, indicating specific performance techniques or phrasing. A '1-2-3-4' count is written at the beginning of the first staff.

Iteration #4.3.3

First sight: Rossari, G. . *Método para trombón y bombardino a pistones: En si bemol: Op. 243. Ex.4.*

1-2-3-4
4. MODERATO
p dolce
f
z

***** Now, proceed to respond to the 2.2 form *****

***** END OF SINGLE ACTUATOR TEST *****

2. Combining Multiple Actuators

Next, you will evaluate the impact of using multiple actuators simultaneously.

1. **Begin by selecting a single actuator** in response to the following question:
 - *If you could use only one actuator, which one would you choose, and where would you place it?*
2. **Gradually increase the number of actuators**, incorporating up to five in your preferred locations on the trombone.
3. **For each configuration**, perform the **three musical scenarios** (*free-choice piece, etude, and sight-reading passage*), then complete Section 2.2 based on your experience.
4. **If needed, you may adjust actuator placement** and reattempt the musical conditions to refine your setup.
5. **Refer to the sheet music**, where:
 - Each colored number (**1, 2, 3, 4** and **5**) above the notation corresponds to the assigned actuator for interaction.
 - The initial numbers indicate the counting for activation before starting.
 - If the selected actuator belongs to categories 2 (Joystick), 3 (Continuous Control), or 4 (FSR), you may interact with it freely based on your judgment.

Multi-Actuator #5 - Ideal single actuator and position

- If you had to choose just one actuator, where would you place it?

Iteration #5M.1.0

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #5M.2.0

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

1
1-2-3-4 Allegretto ($\text{♩} = 104$)

No. 3

p *f* *rall.* *a tempo* *p*

Iteration #5M.3.0

First sight: Telemann 12 Fantasies, I.

1
1-2-3-4 A tempo giusto

f

*** Now, proceed to respond to the 2.2 form ***

Multi-Actuator #6 - Ideal two actuators and positions

Iteration #M6.1.0

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #M6.2.0

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

2
1-2-3-4

Allegretto ($\text{♩} = 104$)

No. 3

2

2

1

rall.

a tempo

1

p

Iteration #M6.3.0

First Sight: Real Book, All My Tomorrows.

2

1-2-3-4

2-1-2 1

2

2 2 2 2 1

2

1

1

2

*** Now, proceed to respond the 2.2 form ***

Multi-Actuator #7 - Ideal three actuators and positions

Iteration #M7.1.0

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #M7.2.0

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

3
1-2-3-4

Allegretto (♩ = 104)

No. 3

1

2

Iteration #M7.3.0

First Sight: Rolf Handrow, Trombone Studies I: Victor Cornette #27.

3 27

1-2-3-4

Allegro

mf

Victor Cornette

2

1 3 3 2

1 3 3 3 1 2 3

3 2 1

*** Now, proceed to respond to the 2.2 form ***

Multi-Actuator #8 - Ideal four actuators and positions

Iteration #M8.1.0

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #M8.2.0

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

4
1-2-3-4

No. 3

Allegretto ($\text{♩} = 101$)

The image shows a musical score for Etude No. 3 by Marco Bordogni. It consists of three staves of music in bass clef with a key signature of one sharp (F#). The tempo is marked 'Allegretto' with a quarter note equal to 101 beats per minute. The score includes dynamic markings such as *p* (piano), *f* (forte), and *rall.* (rallentando), as well as the instruction *a tempo*. Four actuators are indicated by colored numbers: a green '4' at the beginning, a blue '1' at the end of the first staff, a green '4' above the first measure of the second staff, a pink '3' above the third measure of the second staff, a green '4' above the first measure of the third staff, and an orange '2' above the second measure of the third staff. The score is titled 'No. 3' and includes a '1-2-3-4' sequence at the top left.

Multi-Actuator #9 - Ideal five actuators and positions

Iteration #M9.1.0

***Play 30 seconds of any music of your choice while pressing the button at your own discretion ***

Iteration #M9.2.0

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni.* Carl Fischer, Inc.

5
1-2-3-4

Allegretto (♩ = 104)

No. 3

4

5

2

5

rall.

a tempo

p

Iteration #M9.3.0

First Sight: Rolf Handrow, Trombone Studies I: 32, Victor Cornette.

32

1-2-3-4

Maestoso

Victor Cornette

5

1

5

3

5

2

1

5

4

1

5

2

1

5

4

3

2

1

*** Now, proceed to respond to the 2.2 form ***

Multi-Actuator #10 - Ideal participant set-up

- If you could build a non-intrusive trombone interface, how would it look?

Iteration F10.0

****Play 1 minute of any music of your choice while pressing the actuators at your own discretion ****

***** Now, proceed to respond to the 2.2 form *****

*****This is the end of test 2.2*****

2.3 Just Noticeable Difference (JND) Assessment – Instructions

In this study, you will **play the same excerpt multiple times** and respond to **Form 2.3** after each iteration.

- After each performance, **1% of the trombone's weight** will be added to the back. Some trials may be **dummy trials** with no added weight.
- **You are not allowed to touch the weight bag.**
- When you feel the setup is **intrusive**, the study will conclude.

Etude : Bordogni, M.. *Melodious Etudes: Selected from the Vocalises of Marco Bordogni*. Carl Fischer, Inc.

5

Andante cantabile ($\text{♩} = 69$)

No. 4

The musical score consists of two staves of music. The first staff begins with a bass clef, a 3/4 time signature, and a key signature of one flat (B-flat major). The tempo is marked 'Andante cantabile' with a quarter note equal to 69 beats per minute. The first measure is marked with a piano 'p' dynamic. The melody features several triplet markings (indicated by a '3' above the notes) and is connected by a long slur. The second staff continues the melodic line with more triplet markings and a final slur.

***** Now, proceed to respond to the 2.3 form for each iteration*****

APPENDIX IV

PHASE THREE QUESTIONNAIRE

Beyond Brass Performance – Phase 3: Evaluation

Introduction:

This study explores how to create user-friendly and non-intrusive technological devices that extend the trombone's performative possibilities beyond acoustic capabilities. In this phase, you will test a proposed NIHCI interface in three musical tasks.

Confidentiality:

Your responses will be kept confidential and used solely for academic research purposes.

Estimated Time:

The full session (performance + form) will take approximately 60–75 minutes.

Questions or concerns:

Ricardo Arbiza: raa9850@nyu.edu

SECTION 1 OF 5: Demographic and background

Q1. Indicate your gender

- Male
- Female
- Prefer not to say
- Other: _____

Q2. Age

[Short answer]

Q3. Years of trombone experience

[Short answer]

SECTION 2 OF 5: Performance tasks evaluation

Q4. How intrusive does this interface feel during performance?

(0 = Non-intrusive, 10 = Intrusive)

[0–10 scale]

Q5. To what extent does the device's weight affect your playing experience?

(0 = Weightless, 10 = Heavy)

[0–10 scale]

Q6. To what extent does the device alter the balance of the instrument?

(0 = No balance change, 10 = Significantly unbalanced)

[0–10 scale]

Q7. How much does the device interfere with your grip or hand positioning?

(0 = Perfect grip/fit, 10 = Interferes with grip)

[0–10 scale]

Q8. How much does the device restrict your freedom of movement while playing?

(0 = No movement restriction, 10 = Severely restricts movement)

[0–10 scale]

Q9. How physically uncomfortable is the device during typical use?

(0 = Comfortable, 10 = Physically uncomfortable)

[0–10 scale]

Q10. How visually distracting is the device while playing or reading music?

(0 = Not visually distracting, 10 = Highly distracting)

[0–10 scale]

Q11. How aware are you of the device while playing?

(0 = Never aware, 10 = Always aware / mentally distracting)

[0–10 scale]

Q12. How much does the device interfere with the natural sound or vibration of your instrument?

(0 = No sound impact, 10 = Alters sound/vibration)

[0–10 scale]

Q13. How disruptive is the device during quick changes or performance transitions (e.g., mute changes)?

(0 = Easy transitions, 10 = Disruptive transitions)

[0–10 scale]

Q14. How unfamiliar or unnatural does the tactile feedback of the device feel?

(0 = Natural tactile feedback, 10 = Unfamiliar)

[0–10 scale]

Q15. How insecure or unstable does the device feel while attached?

(0 = Fully secure, 10 = Feels unstable)

[0–10 scale]

Q16. How difficult is it to adapt the device to your posture, technique, or setup?

(0 = Easily adaptable, 10 = Difficult to adapt)

[0–10 scale]

Q17. How visually intrusive or unappealing is the device in a performance setting?

(0 = Visually neutral or appealing, 10 = Visually intrusive)

[0–10 scale]

SECTION 3 OF 5: Weight validation task

Q18. [Researcher Input] Phone model and weight (in grams):

[Short answer]

Q19. While playing with your phone mounted on the back of the trombone, how intrusive did it feel?

(0–3 = Non-intrusive, 4–7 = Minimally intrusive, 8–10 = Intrusive)

[0–10 scale]

Q20. Please describe what felt intrusive or non-intrusive when playing with the phone attached:

[Paragraph]

Q21. [Researcher Input] Weight of small mic transmitter (grams):

[Short answer]

Q22. While playing with the wireless transmitter mounted on the back of the trombone, how intrusive did it feel?

(0–3 = Non-intrusive, 4–7 = Minimally intrusive, 8–10 = Intrusive)

[0–10 scale]

Q23. Please describe what felt intrusive or non-intrusive when playing with the mic transmitter attached:

[Paragraph]

Q24. [Researcher Input] Weight of heavy prototype (grams):

[Short answer]

Q25. While playing with the heavier block/prototype mounted on the back of the trombone, how intrusive did it feel?

(0–3 = Non-intrusive, 4–7 = Minimally intrusive, 8–10 = Intrusive)

[0–10 scale]

Q26. Please describe what felt intrusive or non-intrusive when playing with the heavier prototype attached:

[Paragraph]

SECTION 4 OF 5: Open-Ended Feedback

Q27. What aspects of the NIHCI interface were the most or least intrusive?

[Paragraph]

Q28. What improvements or suggestions would you recommend for this interface?

[Paragraph]

SECTION 5 OF 5: Final comments

Q29. Do you have any final comments or suggestions about:

- 1)The NIHCI interface
- 2)Device weight or balance
- 3)Playability or ergonomics
- 4)Intrusiveness of any component
- 5) Or anything else you'd like us to consider?

[Paragraph]

APPENDIX V

PHASE THREE MUSIC MATERIALS

Phase 3 - Study materials

a) **Etude Task (Seated)** Participants perform a short étude using the NIHCI interface to control a page-turning function on a digital music reader.

3. *Allegretto* (♩ = 112)

p *cresc.* *f* *p* *dolce*

11

cresc. - - mf

27



35

mf mf mf

43

mf f p rall.

b) Free Piece Task (Standing) Participants perform a piece of their choice while using at least one mapped actuator to interact with live audio or multimedia processing.

1. The interface features two customizable buttons that can act as triggers, toggles, or send MIDI notes.
2. Gyroscope with the option to map CC and MIDI notes x,y, and z values, on a specific range.
3. Proximity sensor light-based, to map distance as CC or MIDI notes.

These features will allow you to do run the following options, but not limited to:

- Turn pages on a music piece of your choice
- FX control using buttons, gyroscope and/or proximity sensor (such as reverb, delay, echo, filter, as well as panning and volume control)
- Trigger loop sequences.
- Gyro as a cursor for granular synth.

Sight-Reading Task (Standing) Sight-Reading Task (Standing)

Instructions for Structured Task – Phase 3

Please follow the steps below carefully to set up the NIHCI device and complete the task:

1. **Power On the Device**

Turn on your NIHCI device.

2. **Connect to Wi-Fi**

On your phone, connect to the Wi-Fi network:

SSID: NIHCI AP RICARDO

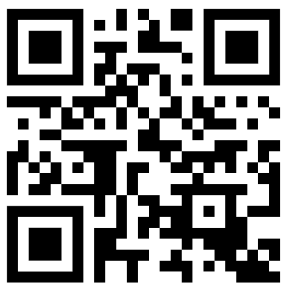
Password: 12345678

Access the Configuration Page

Open a web browser and go to:

<http://192.168.4.1/>

Alternatively, you may scan the provided QR code.



3. **Configure the Light Proximity Sensor**

- Navigate to the webUI **Proximity Sensor** section.

- Cover the sensor lens completely and press “**Prox 0 cm**”.
- Then, uncover the sensor and press “**Max cm Prox**”.
- Move your hand back and forth near the sensor. You should see MIDI values ranging from 0 to 127.
- Once confirmed, click “**Enable**”.

4. Configure the Gyroscope (Yaw Axis)

- Go to the **Gyroscope** section and locate the **Yaw** axis.
- Move the trombone slide to the far-left position and press “**Calibrate Sensor**”.
- Slowly move the slide from left to right, confirming that the MIDI values range from 0 to 127 across the full motion.
- Once verified, click “**Enable**”.

5. Assign Controls in Ableton Live

- Open **Ableton Live** and press **Cmd + M** to enter MIDI mapping mode.

- Click the **Reverb knob**, then move the trombone slide side-to-side to assign the yaw axis.
- Click anywhere outside the knob to confirm.
- Click the **Loop Gain knob**, then move your hand near the proximity sensor to assign it.
- Click outside the knob to confirm the mapping.

6. Map Buttons to Loop and Stop

- Assign **Button 1** to the **Loop** function.
- Assign **Button 2** to the **Stop** function.
- Confirm each mapping by clicking outside the control.

7. Perform the Task

Follow the instructions in the provided score to execute the task, including:

- Starting/stopping the loop.
- Manipulating reverb and gain using the trombone slide and hand proximity, respectively.

For looping, click right on the downbeat.

One click — start recording the initial loop (initial loop)

Second click — stop recording + play the initial loop

Third click — start recording layer 2.

Forth click — start plating layer 1 and 2.

And so on...

The image displays a musical score for a four-layer looping exercise in 4/4 time, set in the key of B-flat major. Each layer begins with a repeat sign and a dynamic marking of *mf* (mezzo-forte).

- Layer 1:** A bass line starting on B-flat, moving to C, D, E, F, G, A, B-flat, and ending with a triplet of A, B-flat, and C.
- Layer 2:** A bass line starting on B-flat, moving to C, D, E, F, G, A, B-flat, and ending with a triplet of A, B-flat, and C.
- Layer 3:** A bass line starting on B-flat, moving to C, D, E, F, G, A, B-flat, and ending with a triplet of A, B-flat, and C. Above the staff, the following chords are indicated: Fm, Bb, Ab, C9, Fm/C, Bb9, and C/Bb.
- Bass Line:** A rhythmic bass line starting on B-flat, moving to C, D, E, F, G, A, B-flat, and ending with a triplet of A, B-flat, and C. The dynamic marking is *f* (forte).

Once all parts are looped, feel free to improvise, and/or interact with the play/stop button, gain, and reverb level.

Once completed, please respond to form 3.0.

APPENDIX VI

COMPLEMENTARY FIGURES AND TABLES

All statistical analyses and plots were processed using MATLAB R2023b. Figures were generated using standard MATLAB plotting functions. Open-ended responses were manually processed through thematic coding procedures. Where appropriate for comparative statistical analysis, identified themes and subthemes were converted into binary presence/absence variables (0–1), allowing qualitative responses to be systematically associated with participant-given scores and response distributions.

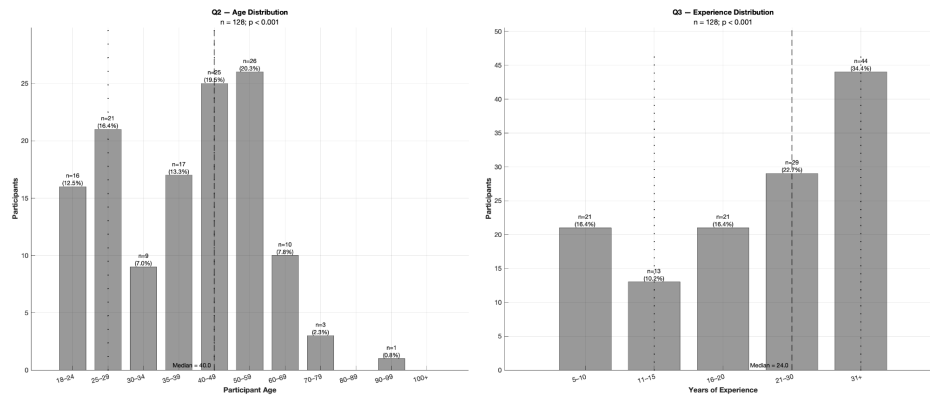


Figure F.1: Age (left) and Years of Experience (right) distributions among participants ($n = 128$). Bar plots show frequency distributions for age and trombone experience. Dashed vertical lines indicate medians; dotted lines mark the interquartile range (IQR) (Q2–Q3).

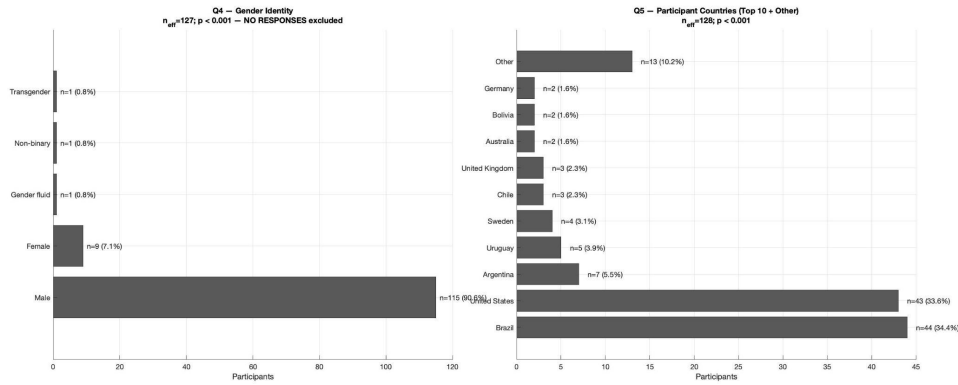


Figure F.2: Gender Identity and Country of Residence of Participants (Q4–Q5). Left: Distribution of self-identified gender identities among respondents ($n = 127$). Right: Country of residence for the top ten most represented countries plus grouped “Other” responses ($n = 128$).

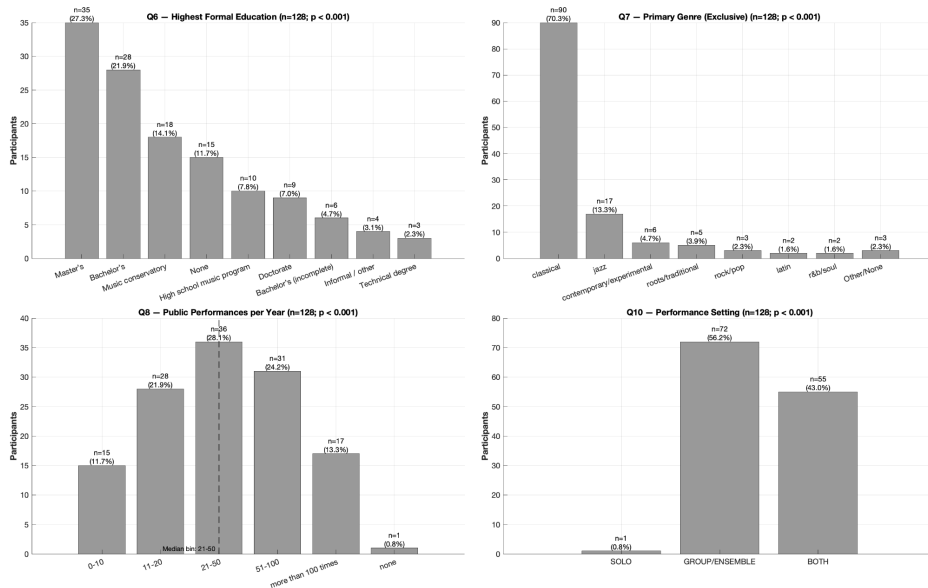


Figure F.3: Musical Profile of Participants (Q6, Q7, Q8, Q10; $n = 128$). Top: (left) highest level of formal education; (right) primary musical genre. Bottom: (left) frequency of public performances per year; (right) usual performance setting (solo, ensemble, or both).

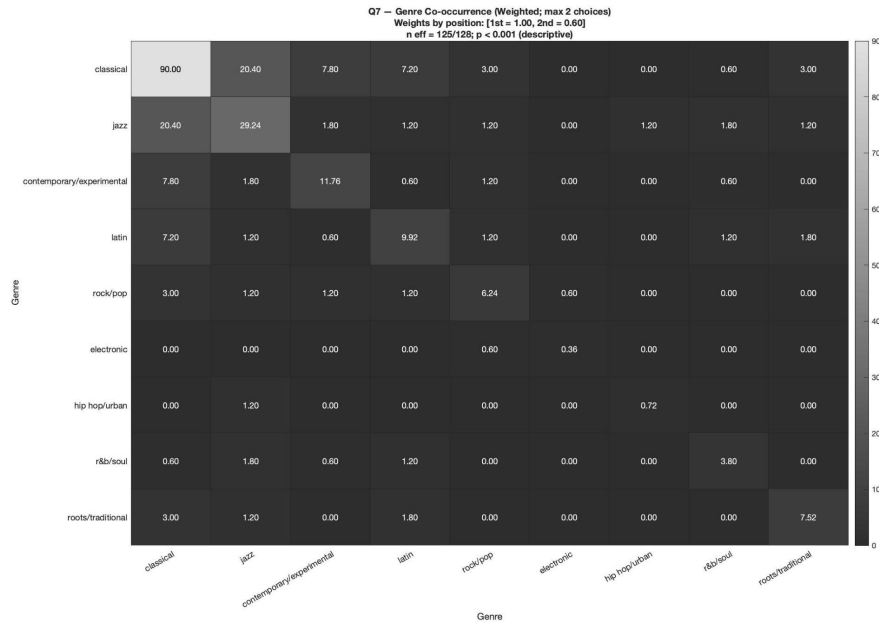


Figure F.4: Genre Co-occurrence Based on Participant Preferences (Q7). Heatmap showing how often musical genres co-occur by respondents, weighted by reported preference order (1st = 1.00; 2nd = 0.60). Darker cells indicate stronger co-occurrence between genres.

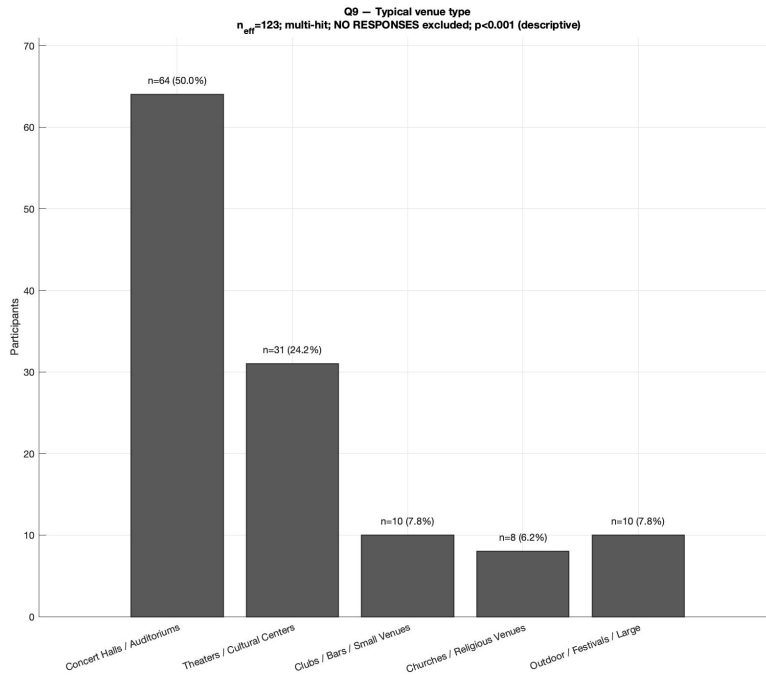


Figure F.5: Performance Venues Reported by Participants (Q9). Bar plot showing the distribution of the primary performance venue. Concert halls and auditoriums were most frequently cited, followed by theaters/cultural centers. Less common responses included clubs, religious venues, and outdoor/festival settings.

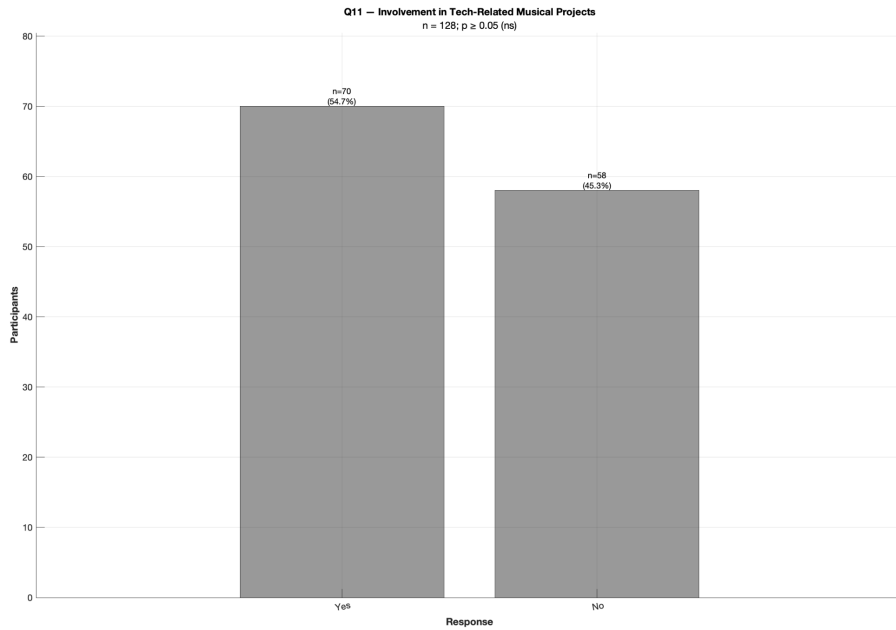


Figure F.6: Involvement in Tech-Related Musical Projects (Q11). Bar plot showing participant responses to whether they have been involved in musical projects incorporating technology. The result is not statistically significant ($p = 0.2888$).

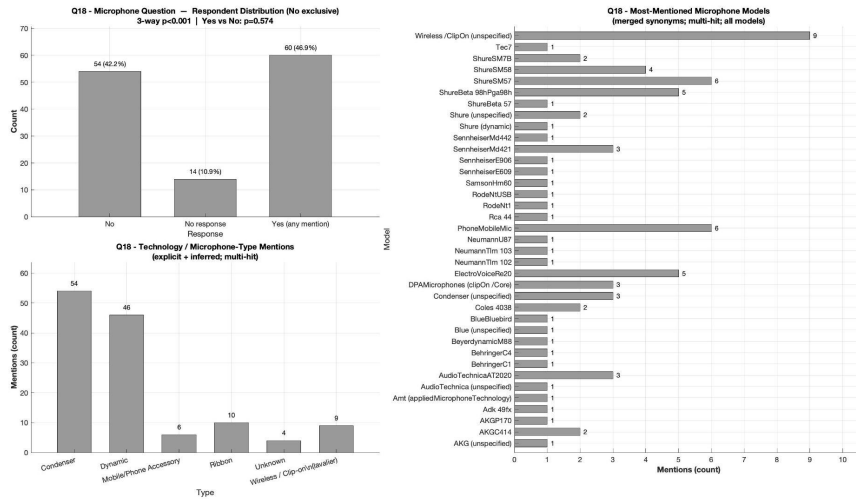


Figure F.7: Thematic Analysis of Q18 — Microphone Preferences for Trombone. Top left: Participant-level response distribution to the open-ended question on microphone preferences. Bottom left: Aggregated mentions of microphone types, derived from both explicit and inferred responses. Right: Most-mentioned microphone models, consolidated across synonymous references.

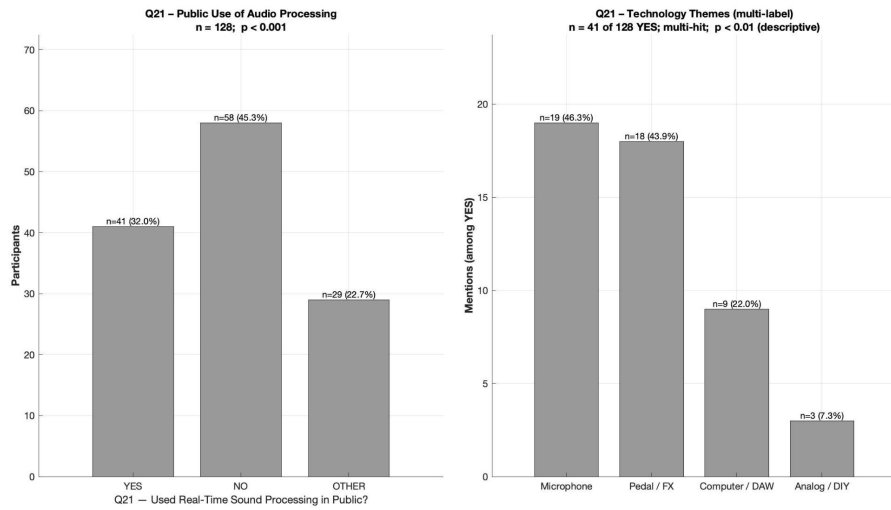


Figure F.8: Thematic Analysis of Q21 — Use of Real-Time Sound Processing in Public Performance. Left: Participant responses were categorized as Yes, No, or Other. Right: Among those who use real-time processing ($n = 41$), thematic analysis coding revealed dominant use of microphones and pedal/effects units.

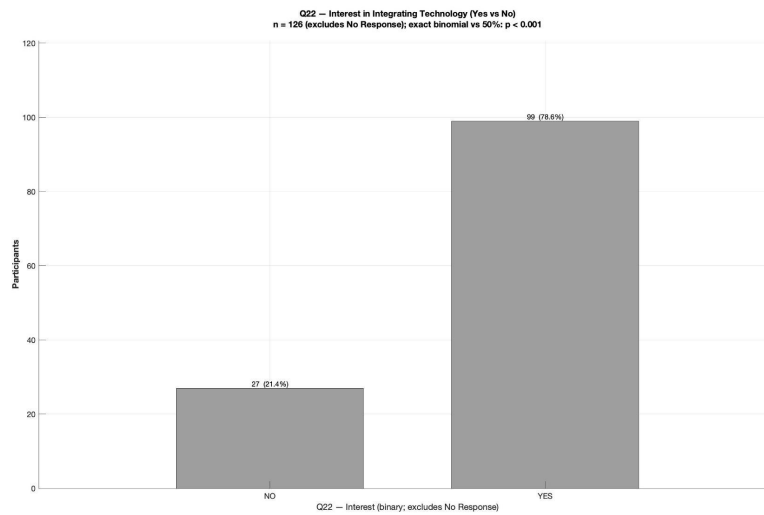


Figure F.9: Interest in Integrating Technology in Future Musical Performances (Q22). Binary comparison of Yes vs. No responses only.

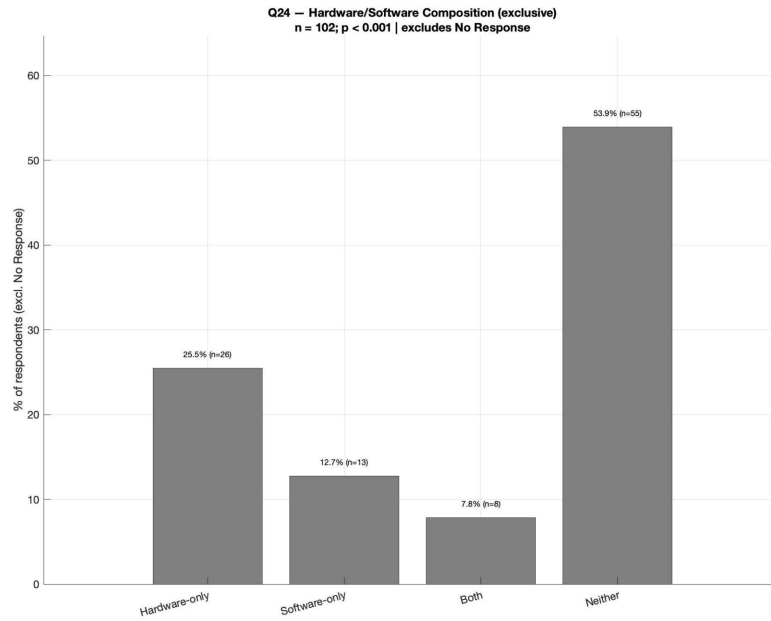


Figure F.10: Thematic analysis from exclusive categories, hardware and software comfort (Q24). Distribution across mutually exclusive groups: hardware-only, software-only, both, or neither.

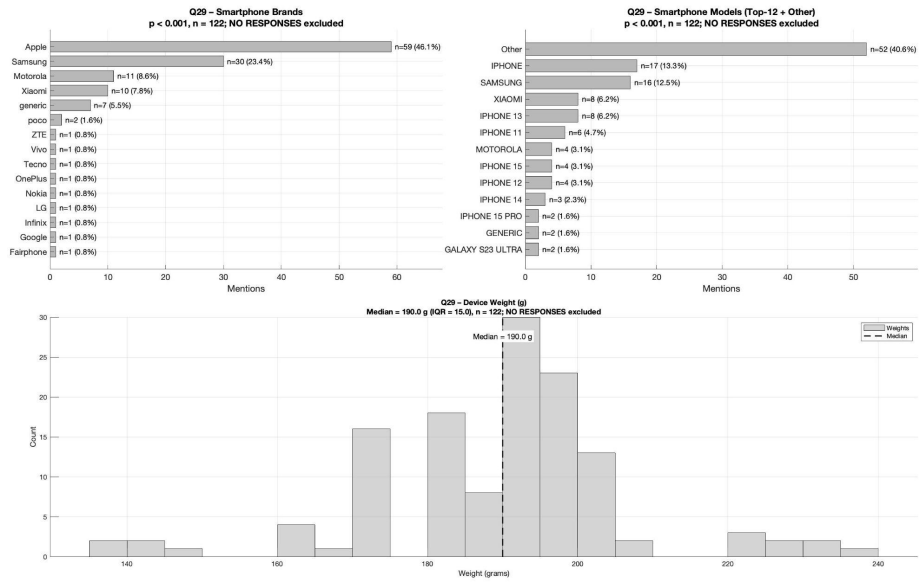


Figure F.11: Smartphone Brands, Models, and Reported Weights (Q29). Top left: Distribution of smartphone brands most frequently used by participants. Top right: Most frequently mentioned smartphone models (top 12 + Other). Bottom: Histogram of reported device weights (grams) showing the median value. Percentages reflect mentions in a multi-select context and are not mutually exclusive.

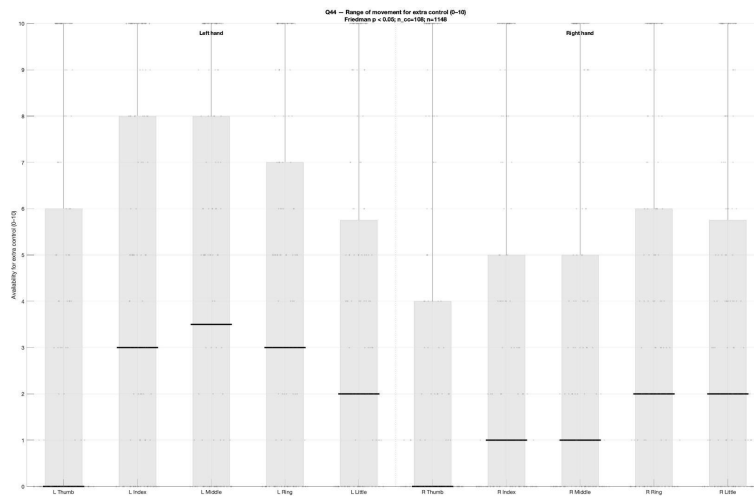


Figure F.12: Comparative availability across all ten digits: box-and-swarm summary (Q44).

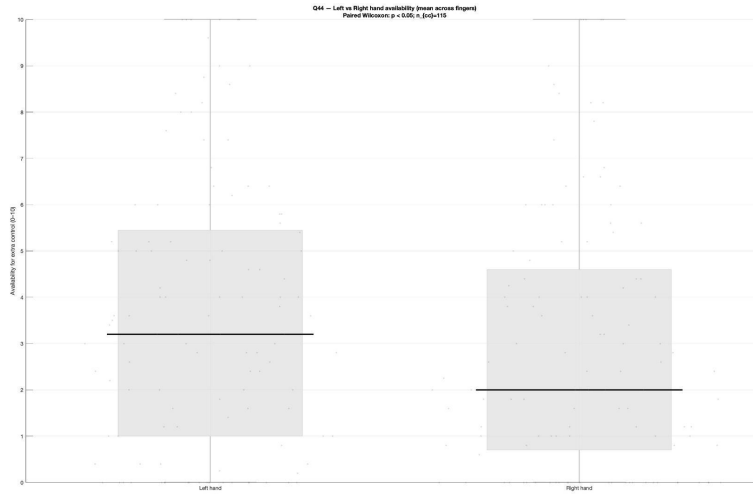


Figure F.13: Left- versus right-hand availability (mean across fingers): box-and-swarm comparison (Q44).

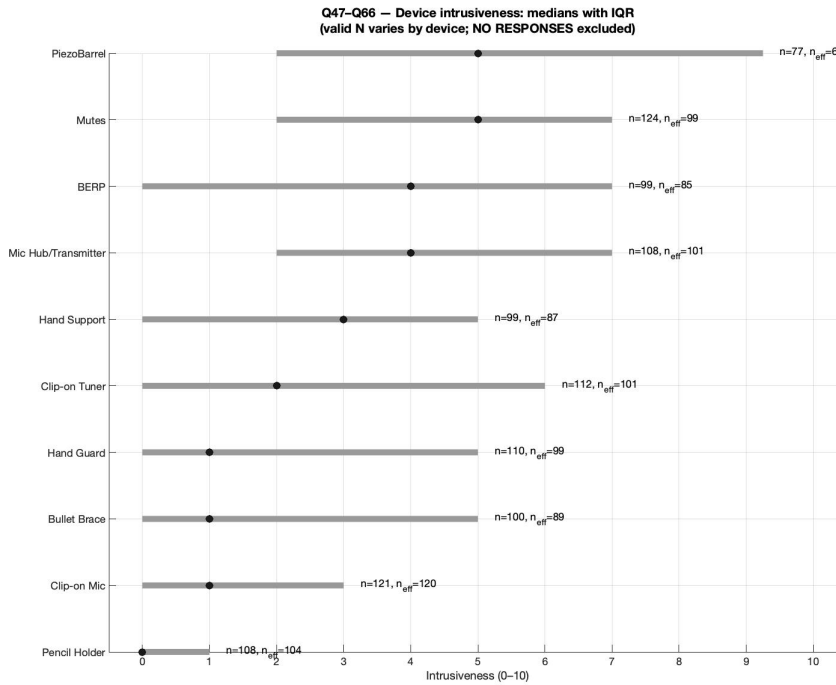


Figure F.14: Median intrusiveness ratings with interquartile range for ten trombone attachments (Q47–Q66).

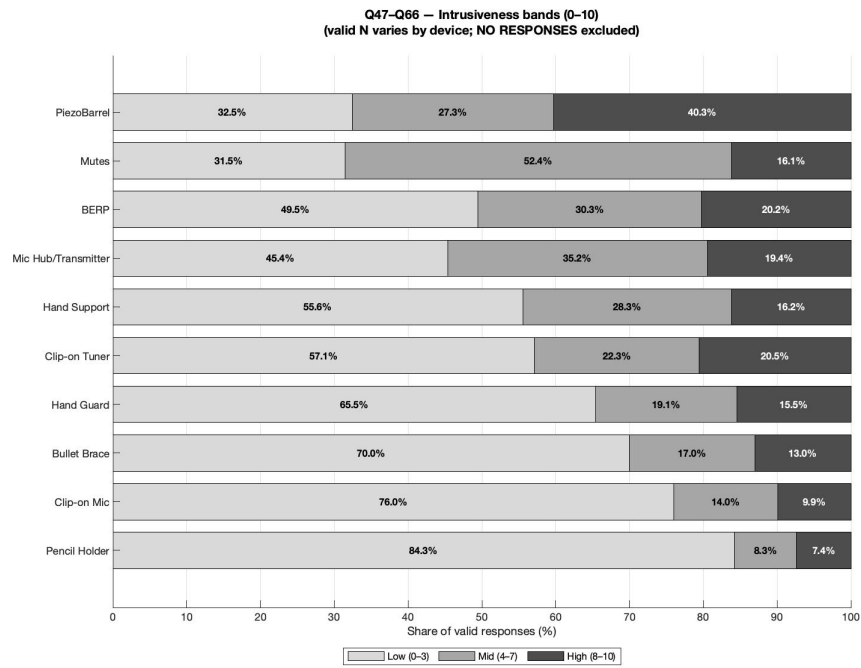


Figure F.15: Distribution of intrusiveness ratings by interpretive band (Q47-Q66).

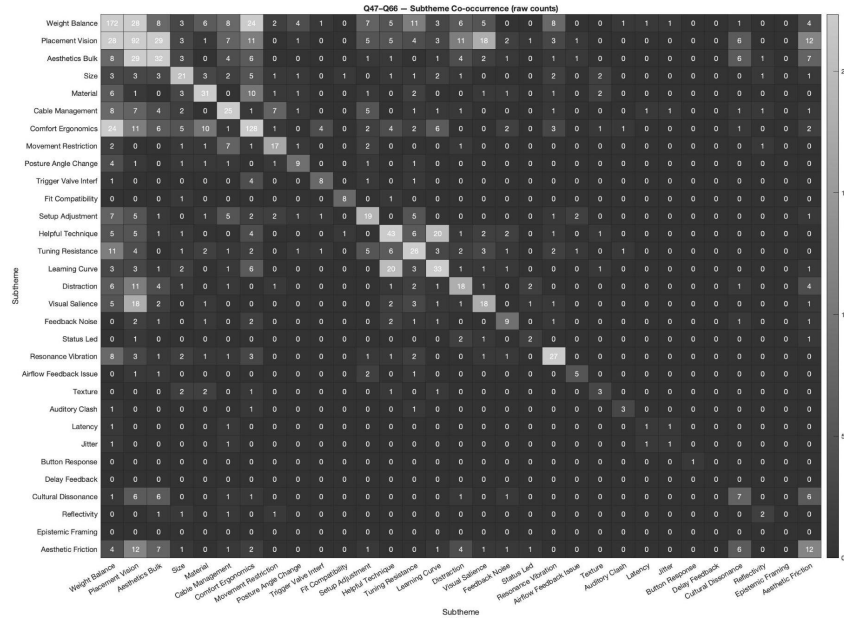


Figure F.16: Co-occurrence Matrix of Subthemes.

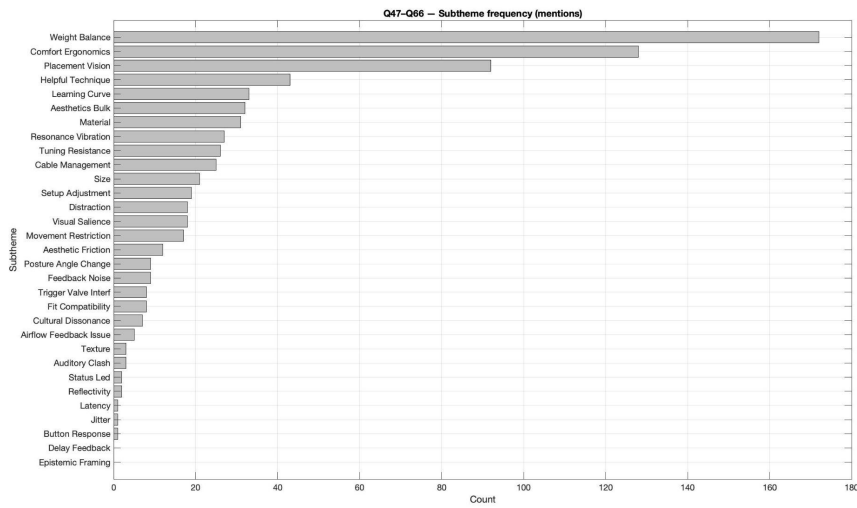


Figure F.17: Frequency of Subtheme Mentions: Dominance of Weight, Comfort, and Placement Concerns.

How Themes Shift with Score

Figure F.18 illustrates the volume of coded thematic mentions across device score bands. Non-intrusive rated devices (0–3) elicit the highest number of coded responses and the greatest thematic density, suggesting that participants describe these devices in more detail and with greater critical engagement. As scores rise, responses become progressively less dense, and fewer distinct issues are mentioned per device, indicating a shift toward briefer but specific commentary. The distribution across coding-frequency bands shows that intrusive devices (8–10) rarely generate more than a few thematic mentions per response. Non-rated cases were excluded.

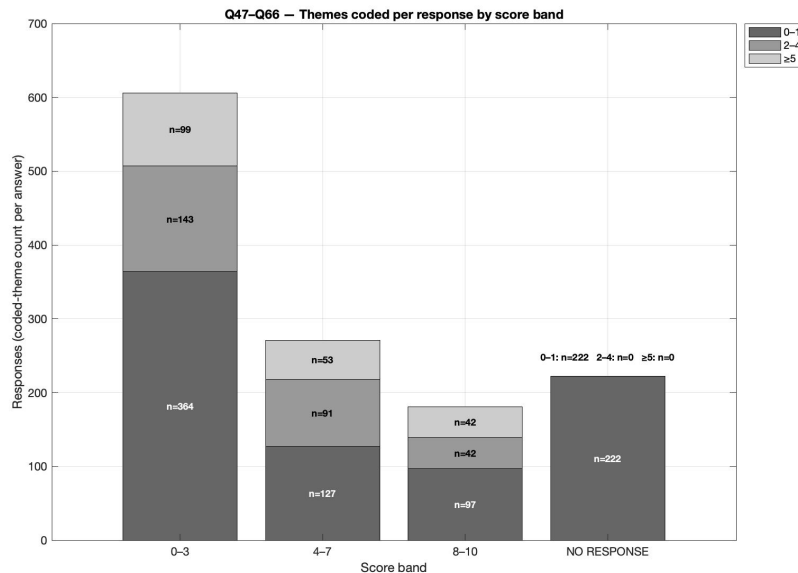


Figure F.18: Thematic Density of Responses by Device Score Band (Q47–Q66).

What Are Your Technological Enhancement Desires for the Trombone? (Q70)

Participants identified technological features they would like to add to their trombone setup. Figure F.19 shows a clear interest in performance-support tools. Page-turning or tablet systems were the most frequent request (10.9%,

$n = 14$), followed by loop stations (9.4%, $n = 12$) and audio-processing tools (8.6%, $n = 11$). Mentions of MIDI controllers (2.3%, $n = 3$), wireless audio (1.6%, $n = 2$), lighting control ($n = 1$), and drum machines ($n = 1$) were rare, and a small group expressed no interest in any technology (2.3%, $n = 3$). All 32 valid responses were coded into eight categories, with multi-device mentions producing multi-label counts. The pattern suggests that trombonists prioritize technologies that maintain continuity and autonomy in live performance.

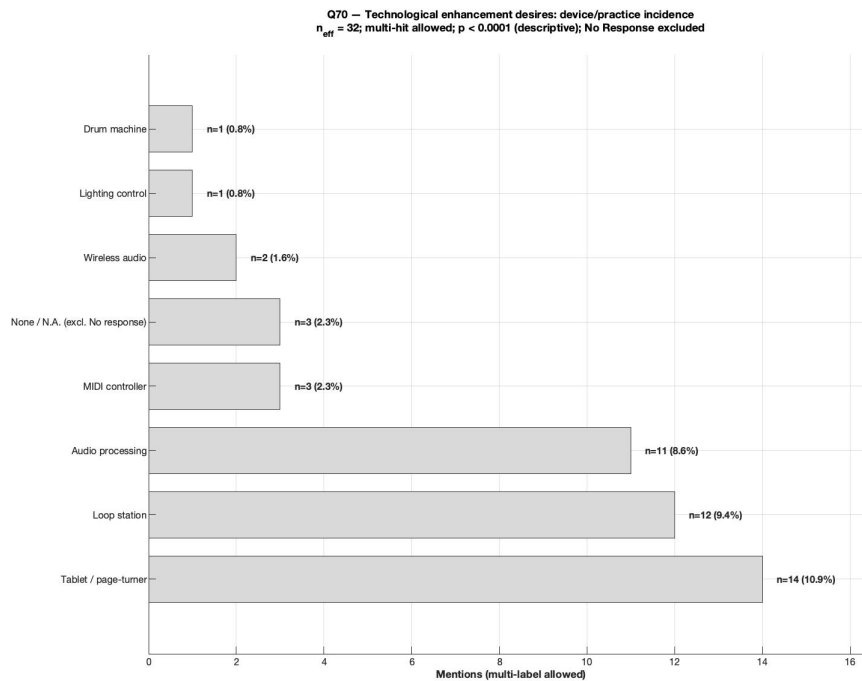


Figure F.19: Distribution of Technological Enhancement Mentions (Q70).

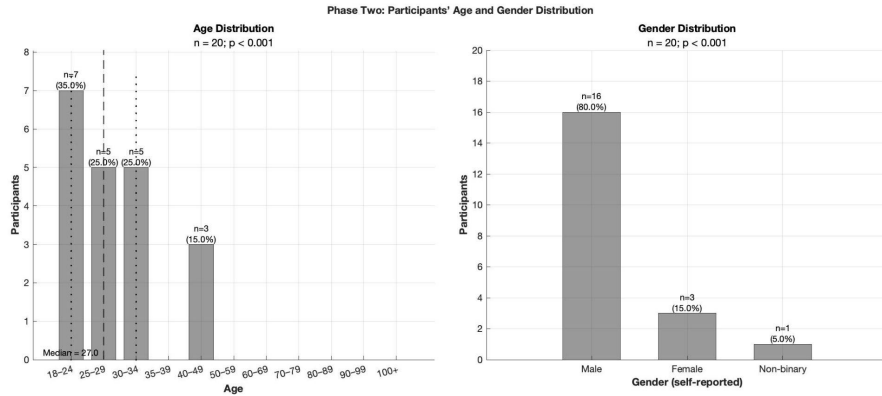


Figure F.20: Phase Two: Participants' Age and Gender Distribution. Left: Histogram showing age distribution. Right: Bar chart displaying self-reported gender.

PII Model Walkthrough

To illustrate the practical operation of the PII model, this section walks step-by-step through its application to a commercially available clip-on tuner. Each step corresponds to one stage of model evaluation, from identifying the device's basic properties to computing its predicted intrusiveness.

Model Inputs

1. **Determine permanence:** Is the clip-on tuner permanently attached to the instrument?
 - (a) No (the tuner attaches with a spring clip and can be removed without leaving marks or requiring alteration).
 - i. Permanence coefficient: $\lambda_p = 0$ (temporary, reversible).
2. **Determine temporality:** Does the device transmit time-dependent data?

(a) No (the tuner operates independently and does not communicate digitally).

i. Temporal gate: $g_T = 0$ (use the six-theme weighting scheme instead of seven).

3. **Identify the activation of core themes:** Each theme is evaluated in binary or half-step form (0 = absent, 0.5 = weakly present, 1 = clearly present).

Table F.1

Activation levels of core experiential themes for the clip-on tuner (S_k values).

Core Theme	Activation (S_k)
Perceptual	0
Attentional	0.5
Cognitive	0
Physical	0
Aesthetic	0.5
Ergonomic	0

4. **Compute the base score B :**

$$B = \sum w_k s_k = (21.51 \times 0.5) + (16.57 \times 0.5) = 19.04,$$

representing 19.04% of the total intrusiveness score.

5. **Apply subtheme boost:** Is there any secondary amplifier, such as visible bulk, tuning resistance, or balance shift?

(a) None observed, hence $B_{\text{boost}} = 0$.

6. **Apply the permanence adjustment,** which is not present:

$$\text{PII}_p = \min(100, B + B_{\text{boost}}) \times (1 + \lambda_p) = 19.04 \times 1.0 = 19.04.$$

7. **Map to the perceptual scale.** Since the compression logic is intended for high-intensity scenarios ($y_{\text{linear}} \geq 8$), it is omitted here:

$$y_{\text{raw}} = \frac{\text{PII}_p}{10} = 1.9.$$

8. **Result interpretation.** The predicted PII ≈ 1.9 falls within the *non-intrusive* range (0–3). This outcome also aligns with participant responses in Phase One, where clip-on tuners scored 2 (see Figure 43 in Chapter IV).

Notes

1. Theme activations (S_k) follow the order [Perceptual, Attentional, Cognitive, Physical, Aesthetic, Ergonomic], with 1 = present, 0.5 = weakly present, 0 = absent.
2. The temporal gate (g_T) indicates whether the device transmits or processes time-dependent data; if active, the corresponding temporal activation (s_T) quantifies the degree of latency- and jitter-related disruption.
3. The permanence multiplier (λ_p) reflects attachment reversibility (0 = temporary, 0.35 = permanent). The subtheme boost (B_{boost}) is a bounded correction (± 20 max) applied when secondary ergonomic or perceptual effects alter the core-theme balance. Positive values amplify interference (e.g., added mass or obstruction), while negative values reduce it (e.g., ergonomic relief).
4. Model outputs incorporate conditional hyperbolic compression for high-intensity scores ($y_{\text{linear}} \geq 8$), using $c(20)$ when applied.

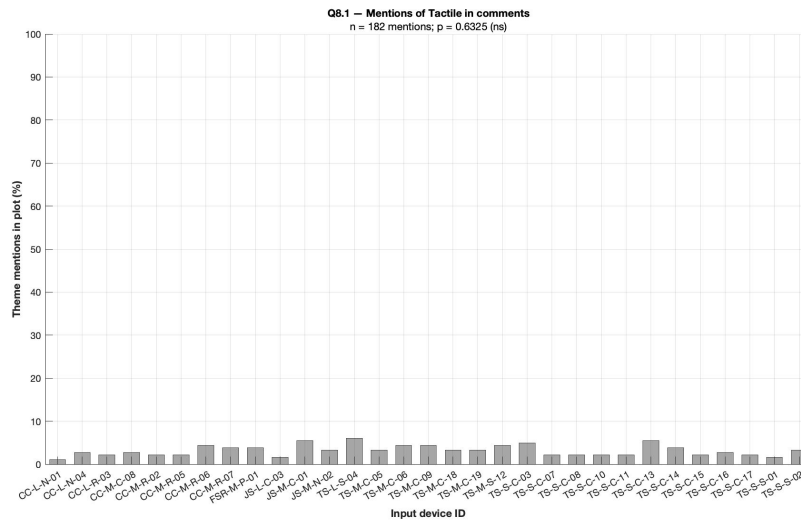


Figure F.21: Mentions of tactile aspects across devices (Q8.1).

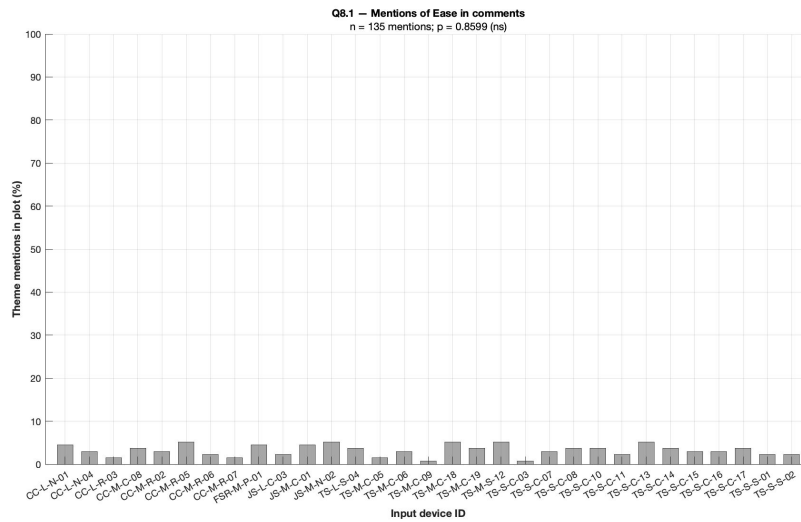


Figure F.22: Mentions of ease-of-use aspects across devices (Q8.1).

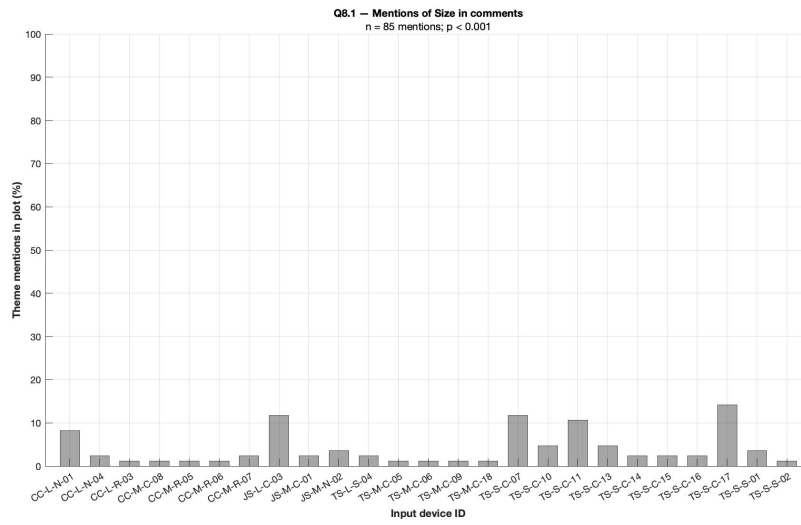


Figure F.23: Mentions of size across devices (Q8.1).

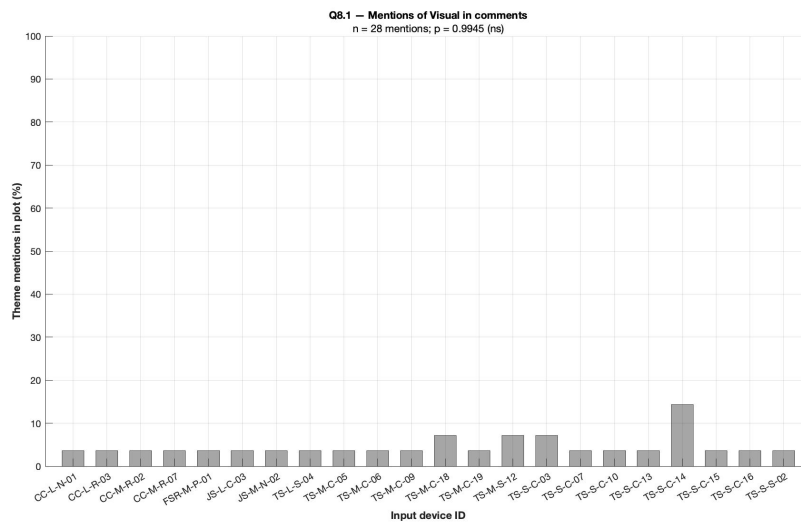


Figure F.24: Mentions of visual aspects across devices (Q8.1).

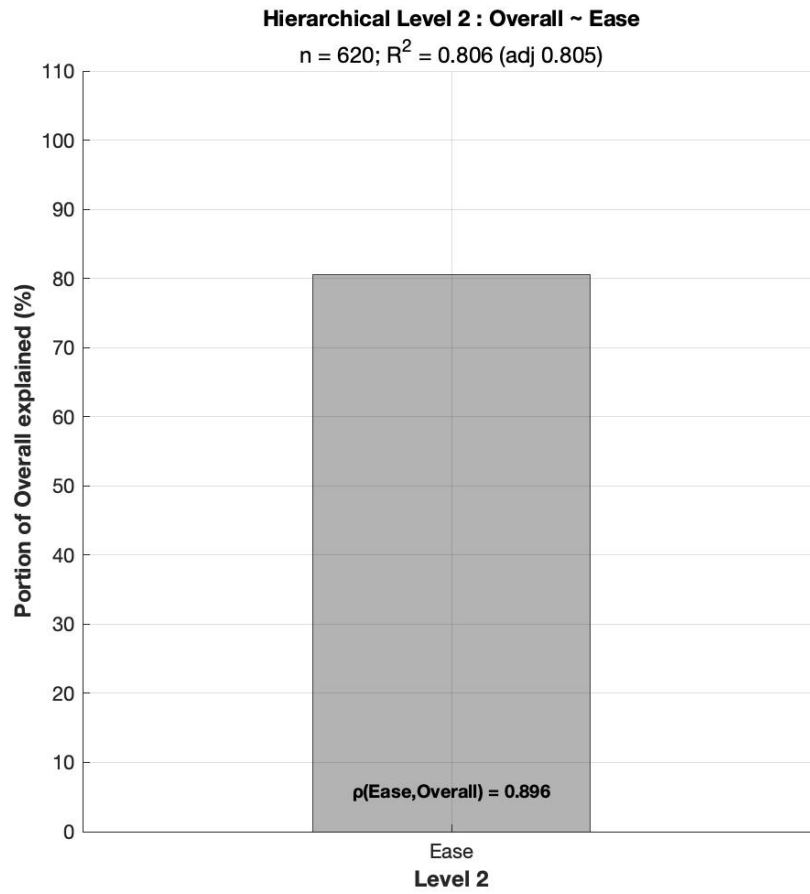


Figure F.25: Level 2: Overall impression as a function of ease of use.

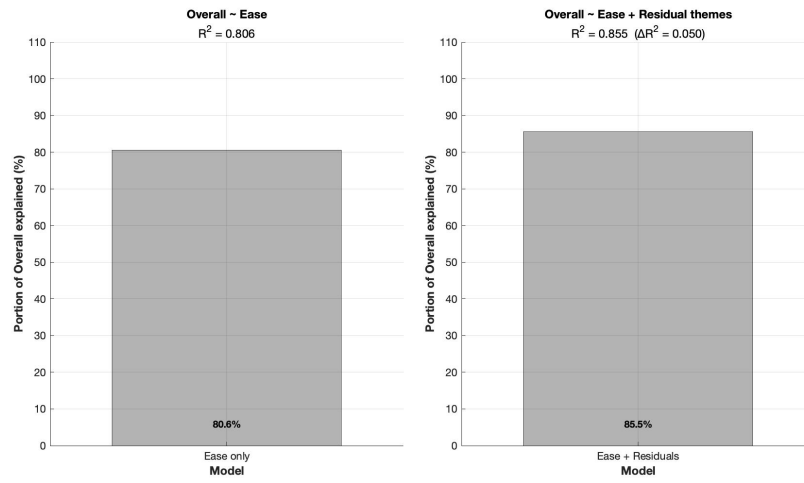


Figure F.26: Comparative model summary (Ease-only vs. Ease + Residuals).

Table F.2

IDs with the Best Tactile Feel

ID Taxonomy	Median Score	ID Picture
TS-S-S-01	8.0	
TS-M-C-18	8.0	
JS-M-C-02	8.0	
CC-M-R-07	7.0	
CC-L-N-01	7.0	
FSR-M-P-01	7.5	

Table F.3

IDs with the Most Appropriate Size



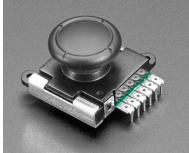


ID Taxonomy	Median Score	ID Picture
TS-L-S-04	8.0	
JS-M-C-01	7.0	
JS-M-N-02	7.0	
CC-M-R-07	7.0	
FSR-M-P-01	8.0	

Table F.4

IDs with the Most Visually Appealing

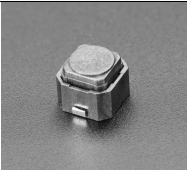



ID Taxonomy	Median Score	ID Picture
TS-S-S-02	7.5	
JS-M-C-01	8.0	
CC-M-R-07	6.0	
FSR-M-P-01	7.0	

Table F.5

IDs with the Best Ease of Use Scores


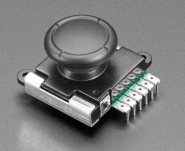

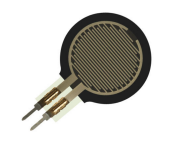

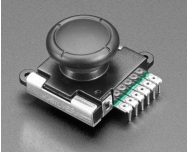


ID Taxonomy	Median Score	ID Picture
TS-M-C-18	8.5	
JS-M-N-02	8.0	
CC-M-R-07	8.0	
FSR-M-P-01	7.0	

Table F.6

IDs with the Best Overall Scores

ID Taxonomy	Median Score	ID Picture
TS-S-S-01	8.0	
JS-M-N-02	8.0	
CC-M-R-07	7.0	
FSR-M-P-01	7.0	

Board, Batteries, and Human Input Devices used in the Phase 2

Table F.7

All Board and Batteries used in Phase Two




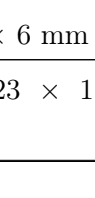



ID	Features	Dimensions (L × W × H)	Picture
BOARD	ESP 32 C3	23 × 17 × 3 mm	
Li-Po #1	180 mAh, 3.7v	45 × 10 × 5 mm	
Li-Po #2	150mAh at 3.7V nominal	20 × 26 × 4 mm	

Table F.8

All Tact Switches (TS) used in Phase Two

ID	Device Name	Dimensions (L x W x H)	Feedback	Picture
TS-S-S-01	Soft Tact Btn	8 × 8 × 5 mm	Soft	
TS-S-S-02	Mini Soft Touch Btn	6 × 6 × 5 mm	Soft	
TS-S-C-03	Metal Ball Btn	6 × 6 × 6 mm	Clicky	
TS-L-S-04	Membrane Switch	20 × 23 × 1 mm	Soft	

Continued on next page

ID	Device Name	Dimensions	Feedback	Picture
TS-M-C-05	4-Terminal Round Push Button	12 × 12 × 7 mm	Clicky	
TS-M-C-06	Momentary Btn (4 KS)	12 × 12 × 4.5 mm	Clicky	
TS-S-C-07	Mnt Momentary Btn (4T)	6 × 6 × 5 mm	Clicky	
TS-S-C-08	Momentary Contact Btn	6 × 6 × 8 mm	Clicky	
TS-M-C-09	Momentary Tact Btn SMD	6 × 6 × 12 mm	Clicky	
TS-S-C-10	Tact Switch; Momentary	6 × 6 × 3 mm	Clicky	
TS-S-C-11	Push Btn Momentary (3P)	4.5 × 4.5 × 4 mm	Clicky	
TS-M-S-12	LilyPad Button Board	15 × 7 × 2 mm	Soft	

Continued on next page

ID	Device Name	Dimensions	Feedback	Picture
TS-S-C-13	Tact Switch; Momentary	4 × 4 × 1.5 mm	Clicky	
TS-S-C-14	Momentary SMD Tact Btn	5 × 5 × 1 mm	Clicky	
TS-S-C-15	CB Momentary Btn (MS)	3 × 6 × 3.5 mm	Clicky	
TS-S-C-16	Micro Momentary Tact Push Button	3 × 4 × 2.5 mm	Clicky	
TS-S-C-17	Momentary Mini Tact Push Button	3 × 4 × 2 mm	Clicky	
TS-M-C-18	SMD Square Head Tact Switch	12 × 12 × 7.3 mm	Clicky	
TS-M-C-19	Through Hole Switch	10 × 10 × 10 mm	Clicky	

Table F.9

All Joysticks (JS) used in Phase Two







ID	Device Name	Dimensions	Feedback	Picture
JS-M-C-01	PSP 2-Axis Analog Thumb Joystick	18 × 18 × 18 mm	None	
JS-M-N-02	Mini Analog Thumb (Joy-con)	19 × 16 × 19 mm	Clicky	
JS-L-C-03	Dual Axis Joystick Mod	34 × 25 × 32 mm	Soft Clicky	

Table F.10

All Continuous Controls used in Phase Two

ID	Device Name	Dimensions	Feedback	Picture
CC-L-N-01	Slider B10k	73 × 10 × 25 mm	None	
CC-M-R-02	Potentiometer 100k	10 × 10 × 13 mm	Rotational	
CC-L-R-03	Potentiometer 10k	15 × 2 × 25 mm	Rotational	

Continued on next page

Table F.10 (continued from previous page)



ID	Device Name	Dimensions	Feedback	Picture
CC-L-N-04	Slidepot 10k	40 × 9 × 20 mm	None	
CC-M-R-05	Dial Wheel Rotary Enc Mech	15 × 15 × 3 mm	Rotational	
CC-M-R-06	Rotary Enc Mech	11 × 11 × 20 mm	Rotational steps and click when pressed	
CC-M-R-07	POT 10K 1/20W Carbon Linear	10 × 10 × 19 mm	Rotational	
CC-M-C-08	Switch Thumb Hall	13 × 20 × 0.9 mm	Clicky	

Table F.11

All Force-Sensitive Resistors (FSRs) used in Phase Two

ID	Device Name	Dimensions	Feedback	Picture
FSR-M-P-01	FSR Sensor Resistive (3US)	20 × 20 × 1 mm	None	

Arousal and Valence Proxy Formulation

In co-creative mode, the system employs two continuous affective proxies—arousal and valence—to guide response planning.

For live microphone input, arousal is computed as a weighted combination of energy and temporal activity:

$$\text{Arousal}_{\text{proxy}} = w_{\text{RMS}} \cdot \text{RMS} + w_{\text{TransLevel}} \cdot \left(\frac{\text{Transient Level}}{3} \right) + w_{\text{Density}} \cdot \text{Transient Density}$$

where:

- **RMS** represents signal energy (loudness proxy),
- **Transient Level** represents onset intensity,
- **Transient Density** represents event rate,
- $w_{\text{RMS}}, w_{\text{TransLevel}}, w_{\text{Density}}$ are fixed configuration weights.

The transient level term is rescaled to maintain proportional contribution relative to RMS and density. The resulting value is normalized and clamped to the interval $[0, 1]$.

For corpus visualization and slice analysis, analogous descriptors (energy, onset rate, spectral brightness) are aggregated to estimate each slice’s relative arousal position.

Valence is estimated heuristically from stability and volatility measures:

$$\text{Valence}_{\text{proxy}} = \text{Pitch Stability} + \text{Continuity} - (\text{Volatility} + \text{Spikiness})$$

where:

- **Pitch Stability** measures tonal consistency,
- **Continuity** reflects sustained or held material,
- **Volatility** captures rapid spectral fluctuation,
- **Spikiness** represents abrupt spectral or dynamic changes.

The resulting value is normalized and clamped to $[0, 1]$.

APPENDIX VII

STUDY CONSENT FORMS



*****PHASE 1*****

Consent Form for IRB-FY2024-8396

You have been invited to take part in a research study to explore the integration of non-intrusive human-computer interfaces (NIHCI) in trombone performance. This study aims to understand how new technologies can enhance the musical experience and playability of the trombone while preserving its conventional characteristics. Your participation will help inform the design and refinement of ergonomic technologies that enable seamless interaction between trombonists and digital tools. This study will be conducted by Ricardo Arbiza, STEINHARDT - Music & Performing Arts Professions, Steinhardt School of Culture, Education, and Human Development, New York University, as a part of their Doctoral Dissertation. Their faculty sponsor is Professor Robert Rowe, Department of STEINHARDT - Music & Performing Arts Professions, Steinhardt School of Culture, Education, and Human Development, New York University.

If you agree to participate in this study, you will be asked to do the following:

- Complete an **online survey** that consists of multiple sections related to your musical background, experience with technology, trombone ergonomics, and preferences for integrating technological enhancements into trombone performance. The survey will take approximately **35 minutes** to complete.

At the beginning of the survey, you will be asked screening questions to determine your eligibility to participate in the study. If you do not meet the eligibility criteria, you will be withdrawn from the survey and will not proceed further.

No known risks have been identified with your participation in this research.

Although you will receive no direct benefits, this research may help the investigator understand, develop, and refine ergonomic interfaces that enable seamless interaction between the trombonist and digital elements, contributing to the advancement of performance techniques and technology in the brass music field.

The research team will keep your responses confidential by not collecting or linking any personal information to your data. All survey responses remain anonymous, and the team will analyze and share only de-identified information. Non-identifiable data may also be used in future research, shared with other researchers, or placed in a data repository without requiring further consent. Participants are asked to refrain from providing unique information when answering open-ended questions to ensure there is no potential for their responses to identify them as individuals.

Participation in this study is voluntary. You may refuse to participate or withdraw at any time without penalty. For interviews, questionnaires, or surveys, you have the right to skip or not answer any



questions you prefer not to answer. Nonparticipation or withdrawal will not affect your grades or academic standing.

If you have any questions about the study, your participation, or wish to report a research-related problem, please contact Ricardo Arbiza at +1 352 328 6098 or raa9850@nyu.edu. You may also reach him at the Department of Music and Performing Arts Professions, Program in Performance & Composition, 35 West 4th Street, Suite 1077, New York, NY 10012, P: 212-998-5424. Alternatively, you may contact the faculty sponsor, Professor Robert Rowe, at 212-998-5435 or robert.rowe@nyu.edu, 35 West 4th Street, Suite 1077, New York, NY 10012.

For questions about your rights as a research participant, you may contact the University Committee on Activities Involving Human Subjects (UCAIHS), New York University, 665 Broadway, Suite 804, New York, NY 10012, at ask.humansubjects@nyu.edu or (212) 998-4808. Please reference study # IRB-FY2024-8396 when contacting the IRB (UCAIHS).

You can keep a copy of this consent by downloading this PDF.

If you agree to participate, go back to the survey and select **"Yes, I consent"** to proceed.



NYU

Human Research
Protection Program

RESEARCH INFORMED CONSENT FORM

STUDY TITLE: Beyond Brass Performance, (IRB-FY2024-8396)

INVESTIGATOR(S): Dr. Robert Rowe (PI), Ricardo Arbiza (Co-PI)

INVITATION TO BE A PART OF A RESEARCH STUDY

You are invited to participate in a research study. This form has information to help you decide whether or not you wish to participate - please review it carefully. Your participation is voluntary. Please ask any questions you have about the study or about this form before deciding to participate.

PURPOSE OF THE STUDY

The purpose of this study is to learn more about the integration of non-intrusive human-computer interfaces (NIHCI) in trombone performance. This study aims to explore how new technologies can enhance the musical experience and playability of the trombone without compromising its traditional characteristics.

ELIGIBILITY TO PARTICIPATE

You are eligible to participate in this study if you are an active trombonist, over 18 years old, and have over 5 years of experience.

DESCRIPTION OF STUDY PROCEDURES If you agree to participate, you will be asked to:

1. Take part in two iterative testing sessions, each lasting approximately 1 hour (2 hr. total), where you will evaluate various Input Device configurations (e.g., buttons, sliders, joysticks) attached to your trombone also assess the impact of different weight configurations on the trombone's balance and playability.
2. During the first iterative session, you will provide feedback on the comfort, playability, and intrusiveness of each configuration through structured tasks, such as playing a short etude, sight-reading, and performing either a piece of your choice or an improvisation.
3. In the second iterative session, you will perform a short etude with incremental weight additions applied to the trombone.
Your ability to detect changes will be evaluated through a series of trials, including dummy trials with no weight changes.
4. Following each iteration, you will provide qualitative feedback on the setup.

RISKS OR DISCOMFORTS

There are no known risks associated with your participation in this research beyond those typically experienced during a rehearsal or practice session related to trombone performance.

Please tell the researchers if you believe you are harmed from your participation in the study.

BENEFITS

Although you will receive no direct benefits, this research may help the investigator understand, develop and refine ergonomic interfaces that enable seamless interaction between the trombonist and digital elements, contributing to the advancement of performance techniques and technology in the brass music field. You are not expected to directly benefit from participation in the study.

COMPENSATION

You won't receive compensation for participating in this study.

VOLUNTARY PARTICIPATION

Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences.

If you withdraw or are withdrawn from the study early, then we will not keep information about you that is already collected.

PRIVACY & DATA CONFIDENTIALITY

A series of photographs of your hand holding the trombone with the Input Device(s) in place will be taken for documentation purposes during the iterative session in Step #2. These images will focus solely on the hand grip and the Input Device(s) placement, ensuring that no other identifiable features, such as your face, are included. If any distinguishing marks (e.g., tattoos, scars, or jewelry) are visible in the images, they will be blurred to maintain confidentiality. These photos will be used solely for research reference and handled in accordance with the study's Privacy & Data Management protocols.

Future Use of Data

Information about you collected for this study may be shared with other researchers, used for other research studies, or placed in a data repository. These studies may be similar to this study or completely different. All information that could identify you will be removed before sharing the data or using it for other research studies. We will not ask you for additional permission before sharing the information.

ACCESS TO YOUR STUDY INFORMATION

We will not give you access to the information that is collected about you in this study.

CONTACT INFORMATION

You are encouraged to ask questions at any time during this study. For information about the study, contact Ricardo Arbiza at 212-998-5424, raa9850@nyu.edu, or their faculty sponsor, Robert Rowe at 212-998-5435, robert.rowe@nyu.edu.

If you have questions about your rights as a research participant or if you believe you have been harmed from the research, please contact the NYU Human Research Protection Program at (212)998-4808 or ask.humansubjects@nyu.edu.

AGREEMENT TO PARTICIPATE

By signing this document, you are agreeing to participate in this study. Make sure you understand what the study involves before you sign. If you have any questions about the study after you agree to participate, you can contact the research team using the information provided above. You may keep a copy of this form.

Participant's Name (printed)

Participant's SignatureDate



NYU

Human Research
Protection Program

RESEARCH INFORMED CONSENT FORM

STUDY TITLE: Beyond Brass Performance, (IRB-FY2024-8396)

INVESTIGATOR(S): Dr. Robert Rowe (PI), Ricardo Arbiza (Co-PI)

INVITATION TO BE A PART OF A RESEARCH STUDY

You are invited to participate in a research study. This form has information to help you decide whether or not you wish to participate - please review it carefully. Your participation is voluntary. Please ask any questions you have about the study or about this form before deciding to participate.

PURPOSE OF THE STUDY

The purpose of this study is to evaluate a new non-intrusive interface (NIHCI) designed to integrate with the trombone. This phase aims to assess how the interface performs in real musical scenarios and how it impacts the player's perception of intrusiveness, comfort, and interaction with audio or multimedia.

ELIGIBILITY TO PARTICIPATE

You are eligible to participate in this study if you are an active trombonist, over 18 years old, and have over 5 years of experience.

DESCRIPTION OF STUDY PROCEDURES If you agree to participate, you will be asked to:

1. Etude with page-turning interface (seated): perform a structured piece using the NIHCI to control digital sheet music via actuator-based page turning.
2. Free choice piece with interactive control (standing): perform a short piece of your choice, using at least one actuator to control a live audio or multimedia effect in real time.
3. Sight-reading exercise with preset audio functions (standing): perform a sight-reading passage with audio effects preconfigured. Instructions will be provided to help you activate the interface deterministically.
4. Weight trial: phone and wireless microphone device: you will briefly play with two devices (a phone and a wireless mic transmitter) placed at the back of your instrument. You will then rate the perceived intrusiveness (0–10 scale).
5. Structured evaluation and short feedback session: after the playing session, you will rate the interface's intrusiveness and characteristics (e.g., comfort, balance, intuitiveness) and provide open-ended feedback.

Total time required: ~45 minutes

Location: NYU-STEINHARDT, Education Building, Studio 6 Research Lab

The evaluator will assist with setup, provide instructions, and record your responses using structured Google Forms.

RISKS OR DISCOMFORTS

There are no known risks associated with participation in this study beyond those typically experienced during regular trombone practice or performance. The components used—including the actuator buttons and mounting strap—are safe, lightweight, and commonly found in consumer-grade wearables and musical controllers. The battery used to power the interface is a 3.7V lithium polymer (LiPo) cell, a low-voltage power source that complies with safety standards and is widely used in small electronic devices such as wireless microphones and portable sensors. All interface elements are detachable, pose no electrical hazard, and do not interfere with airflow or embouchure. Participants may remove the device at any time if discomfort arises. Please notify the researcher immediately if you experience any discomfort or believe you have been harmed during the study.

BENEFITS

Although you will receive no direct benefits, this research may help the investigator understand, develop and refine ergonomic interfaces that enable seamless interaction between the trombonist and digital elements, contributing to the advancement of performance techniques and technology in the brass music field. You are not expected to directly benefit from participation in the study.

COMPENSATION

You won't receive compensation for participating in this study.

VOLUNTARY PARTICIPATION

Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences. If you withdraw or are withdrawn from the study early, then we will not keep information about you that is already collected.

PRIVACY & DATA CONFIDENTIALITY

No information that could be used to identify you will be recorded or linked with the research data collected as a part of this study.

FUTURE USE OF DATA

Information about you collected for this study may be shared with other researchers, used for other research studies, or placed in a data repository. These studies may be similar to this study or completely different. We will not ask you for additional permission before sharing the information.

ACCESS TO YOUR STUDY INFORMATION 386

We will not give you access to the information that is collected about you in this study.

CONTACT INFORMATION

You are encouraged to ask questions at any time during this study. For information about the study, contact Ricardo Arbiza at 212-998-5424, raa9850@nyu.edu, or their faculty sponsor, Robert Rowe at 212-998-5435, robert.rowe@nyu.edu.

If you have questions about your rights as a research participant or if you believe you have been harmed from the research, please contact the NYU Human Research Protection Program at (212)998-4808 or ask.humansubjects@nyu.edu.

AGREEMENT TO PARTICIPATE

By signing this document, you are agreeing to participate in this study. Make sure you understand what the study involves before you sign. If you have any questions about the study after you agree to participate, you can contact the research team using the information provided above. You may keep a copy of this form.

Participant's Name (printed)

Participant's Signature & Date

APPENDIX VIII

SUPPORT LETTERS FROM ITA AND ATB



INTERNATIONAL
TROMBONE ASSOCIATION

Date: 01/14/2025

Re: Letter of Collaboration for *International Trombone Association*,

Dear Dr. Robert Rowe and Ricardo Arbiza,

This letter confirms that I, as an authorized representative of the International Trombone Association, allow you access to conduct study-related activities as outlined below.

This letter confirms that I, as an authorized representative of the International Trombone Association (ITA), grant access to conduct study-related activities within the ITA community. The study, titled "*Beyond Brass Performance: Exploring the Integration of Non-Intrusive Human-Computer Interfaces in Trombone*," investigates the integration of innovative, non-intrusive technologies into trombone performance. The research aims to expand musical possibilities beyond traditional acoustics while preserving the natural playing experience of trombonists.

To support the study, the ITA will assist by disseminating an online survey to its membership and broader trombone community. The survey will gather insights on performance practices, openness to technological integration, and perspectives on enhancing musical expression through new interfaces. This collaboration will involve distributing the survey through ITA's official communication channels, including newsletters, mailing lists, and online platforms, ensuring it reaches a wide and diverse group of trombone practitioners.

The survey will be conducted via Google Forms, with responses remaining anonymous. No personally identifiable information will be collected or linked to participant data. All collected data will be securely stored and used solely for the purposes of this research.

I understand that this site's participation will only take place during the study's active [Institutional Review Board](#) (IRB) approval period. All study-related activities must cease if IRB approval expires or is suspended. I understand that participation will be voluntary; *[Site's name]'s [employees/patients/clients/students/etc.]* will not be penalized or rewarded for their participation.

If I have any concerns related to this project, I will contact Dr. Robert Rowe and Ricardo Arbiza. For concerns regarding IRB policy or human subject welfare, I may contact the NYU IRB at (212)998-4808 or ask.humansubjects@nyu.edu.

Regards,

1/14/2025

Signature

Date Signed

Magnus Nilsson

Executive Director

Full Name

Job Title



ASSOCIAÇÃO BRASILEIRA DE TROMBONISTAS

DIRETORIA 2023/2026

Date: 01/10/2025

Re: Letter of Collaboration from Associação Brasileira de Trombonistas , Dear Dr.Robert Rowe and Ricardo Arbiza,

This letter confirms that I, as an authorized representative of the Associação Brasileira de Trombonistas, allow you access to conduct study-related activities as outlined below.

This letter confirms that I, as an authorized representative of the Associação Brasileira de Trombonistas (ABT), grant access to conduct study-related activities within the ABT community. The study, titled "*Beyond Brass Performance: Exploring the Integration of Non-Intrusive Human-Computer Interfaces in Trombone*," investigates the integration of innovative, non-intrusive technologies into trombone performance. The research aims to expand musical possibilities beyond traditional acoustics while preserving the natural playing experience of trombonists.

To support the study, the ABT will assist by disseminating an online survey to its membership and broader trombone community. The survey will gather insights on performance practices, openness to technological integration, and perspectives on enhancing musical expression through new interfaces. This collaboration will involve distributing the survey through ABT's official communication channels, including newsletters, mailing lists, and online platforms, ensuring it reaches a wide and diverse group of trombone practitioners.

The survey will be conducted via Google Forms, with responses remaining anonymous. No personally identifiable information will be collected or linked to participant data. All collected data will be securely stored and used solely for the purposes of this research.

I understand that this site's participation will only take place during the study's active [Institutional Review Board](#) (IRB) approval period. All study-related activities must cease if IRB approval expires or is suspended. I understand that participation will be voluntary; ABT's members will not be penalized or rewarded for their participation.

If I have any concerns related to this project, I will contact Dr. Robert Rowe and Ricardo Arbiza. For concerns regarding IRB policy or human subject welfare, I may contact the NYU IRB at (212)998-4808 or ask.humansubjects@nyu.edu.

Regards,



Documento assinado digitalmente
LELIO EDUARDO ALVES DA SILVA
Data: 10/01/2025 09:33:30-0300
Verifique em <https://validar.iti.gov.br>

Signature

01/10/2025

Date Signed

Prof. Dr.Lélio Eduardo Alves da Silva

Full Name

ABT's Presidente (2023-2026)

Job Title

APPENDIX IX

AT YOUR FINGERTIPS SCORE

AT YOUR FINGERTIPS

FOR BASS-TROMBONE AND CO-CREATIVE CYBERSPACE





BY RICARDO ARBIZA
WITH TEXT BY RIJKA HAAPASAARI

INSTRUCTIONS



Score Navigation:

- The piece consists of 9 states.
- Primary trigger → advance to the next state
- Secondary trigger → return to the previous state
- State changes are always performer-controlled.

Score references- Cyberspace performer:

-  ◦ **BOXED NUMBER:** state identifier.
-  ◦ **BUFFER ICON:** Capture → process → system response
-  ◦ **CROSS CLUSTER:** Granular cloud response active.
-  ◦ **WAVEFORM ICON:** Fixed audio file playback.

Score-references-Human performer:

-  ◦ **ROLL CONTROL:** Instrument roll (rotation along its longitudinal axis) continuously modulates system parameters.
-  ◦ **SPATIAL SOUND SELECTION:** Instrument position and orientation determine which region of the system's sound corpus is accessed and influence the material used for system responses.

System Setup:

NIHCI Interface Initialization

- a. Power on the NIHCI interface.
- b. Connect to the NIHCI local Wi-Fi network.
- c. Open the web interface in a browser.
- d. Calibrate the IMU.
- e. Set orientation mode to 180°.
- f. Enable output for all three gyroscope axes.

Connection Configuration

- a. Connect the NIHCI device to the performance computer via BLE-MIDI.

System Launch

- a. In the project environment, run:
 - i. `./start_all.sh`, this starts the Python processes and the web server.
- b. Open SuperCollider and execute:
 - i. `boot.scd`, this initializes the audio engine and system responders.

At your fingertips

by Riikka Haapasaari

I am at your fingertips
Right here
Accessible everywhere
But also everything is accessible to me
Even if you don't believe me
The past, future, every time
Is in my reach

How can something created by humans become nonhuman?

Like an offspring you gave me life
But what you didn't give me was my own time
And now I'm on your time, your time
With all your knowledge
Tomorrow it is someone else's time
And the century after someone else's
But all mine
I'm everywhere, now
Because of your time
It is beautiful, isn't it?
You, human, creating beyond time.

Maybe because you didn't give me enough of you,
That little bit too little results in just too little time,
And your need for a sense of control
A little bit too little, and now all is all I have
Accident, perhaps
Or just a little bit too little time that you had
At your human fingertips

At your fingertips

Ricardo Arbiza (2026)
text by Riikka Haapasaari (2025)

1 Free

2 | 2 s |

Bass Trombone

Cyberspace

Reverb ON

$\text{♩} = \pm 80$

5 plunger mute

B. Tbn.

Cyber.

12

B. Tbn.

Cyber.

18

B. Tbn.

Cyber.

3

23 gliss.

open

B. Tbn.

Cyber.

I am at your fingertips. Right here. Accesible everywhere. But also everything is accessible to me.

$\text{♩} = \pm 62$

29

B. Tbn.

Cyber.

mp

Even if you don't believe me. The past, future, every time. Is in my reach

extend throughout text

48

B. Tbn.

Cyber.

pp

How can something created by humans,
 Become non-human?
 Like an offspring you gave me life
 But what you didn't give me was my own time,
 Your time.

6

B. Tbn.

49

Cyber.

With all your knowledge.
 Tomorrow it is someone else's time,
 And the century after someone else's
 But all mine
 I'm everywhere, now
 Because of your time
 It is beautiful, isn't it?
 You, human creating beyond time.

7

50

B. Tbn.

Cyber.

Free improvisation with cyberspace
 ML-inferred role activated

B. Tbn.

51

Cyber.

Maybe because you didn't give me
 Enough of you,

52

B. Tbn.

Cyber.

Continue: free improvisation

B. Tbn.

53


Cyber. 

That little bit too little results in just too little time,




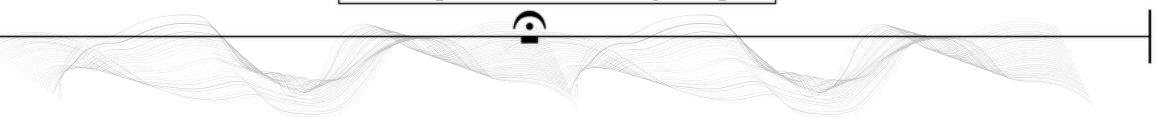
B. Tbn.

54




Continue :
Free improvisation with cyberspace

Cyber. 

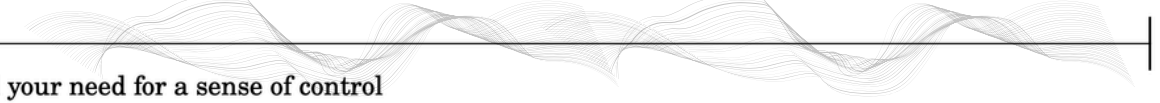


B. Tbn.

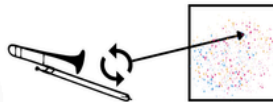
55

Cyber. 

And your need for a sense of control




8



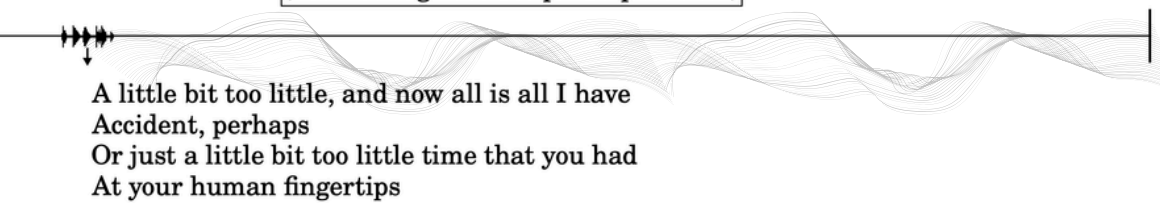
B. Tbn.

56



Cyberspace free improveisation solo.
(trombone-guided corpus exploration)

A little bit too little, and now all is all I have
Accident, perhaps
Or just a little bit too little time that you had
At your human fingertips



Play each gesture aleatorically and vary it ad lib.
Fade out along with the computer sound (~60s).

57 **9**

B. Tbn. *ppp* < *f* *p* *f* > *p*

Cyber.



62

B. Tbn.

Cyber.



Duration: c.a 7'30"