Longitudinal Evaluation of User Experience with Digital Musical Instruments: Development and Demonstration of a New Method

P. J. Charles Reimer

Department of Music Technology
Input Devices and Music Interaction Laboratory
Centre for Interdisciplinary Research in Music Media and Technology
McGill University
Montréal, Canada

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Abstract

This thesis introduces and demonstrates a method for studying the evolution of user experience (UX) with digital musical instruments (DMIs) over time. This work begins by discussing DMI performance practice, stakeholders in DMI development, elements of music interaction and the user-instrument relationship, and DMI evaluation. Based on limitations of current evaluation strategies, including idiosyncrasy, informality, lack of focus on experiential components, and limited research describing how experience changes over time, a new longitudinal method for studying UX as users learn to play a DMI was developed. Following description of the procedure and data collection strategies, this work presents initial execution of the method. Over twenty days, three participants of diverse musical backgrounds learned to play a DMI, the T-Stick, through a series of musical tasks, and developed an original musical excerpt. At multiple points, experiential data was collected using surveys and interviews. Results illustrated how each individual approached and experienced their interaction with the T-Stick based on their specific background, and highlighted aspects of the instrument and methodology that could be revised prior to conducting a longer, more thorough, replication with more participants. Three contributions are noted. Methodologically, this work describes a demonstration of a new method for studying changes in UX with DMIs over time. Practical contributions include feedback related to the hardware, mapping, and sound synthesis used. Finally, this research contributes theoretically to the understanding of differing DMI stakeholder perspectives, suggesting existing categorical models may not sufficiently characterize the multidisciplinary DMI user.

Resumé

Cette thèse présente une méthode d'évaluation longitudinale de l'expérience utilisateur dans l'utilisation d'instruments musicaux numériques (IMNs). Ce travail commence par discuter le jeu musical avec des instruments numériques, les principaux agents impliqués dans l'usage des IMNs, des notions d'interaction musicale assistée par ordinateur, et la relation entre l'utilisateur et l'instrument, puis l'évaluation des IMNs. Plusieurs limites affectent les méthodes d'évaluation actuelles, incluant l'utilisation de méthodes idiosyncrasiques ou informelles, le manque de rigueur vis-à-vis des composants expérientiel, et le manque d'études sur l'évolution de l'expérience de l'utilisateur dans le temps. Pour pallier ces limitations, une nouvelle méthode est proposée et testée pour évaluer l'expérience utilisateur de l'apprentissage des IMNs dans la durée. Pendant vingt jours, trois participants venant d'univers musicaux variés ont appris à jouer d'un instrument numérique, le T-Stick, à travers une série d'exercices et par la création d'un extrait musical original. Les données de l'expérience furent récoltées au moyen de questionnaires et d'entretiens avec les utilisateurs. Les résultats illustrent comment chaque participant s'est approprié le T-Stick et comment l'expérience d'interaction a évolué au cours de l'apprentissage. Trois contributions sont à noter. Au niveau méthodologique, ce travail présente une nouvelle méthode d'évaluation longitudinale de l'expérience utilisateur d'IMNs. Au niveau pratique, des améliorations sont proposées à propos du matériel, du mapping, et du synthétiseur de son utilisés. Au niveau théorétique, cette étude a permis de comprendre les différentes perspectives des agents impliqués dans l'usage des IMNs, suggérant que les modèles catégoriels existants ne représentent pas la pluridisciplinarité des utilisateurs de ces instruments dans leur complexité.

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List of Abbreviations

CHI Conference on Human Factors in Computing Systems

CIRMMT Centre for Interdisciplinary Research in Music Media and Technology

DMI Digital musical instrument

EFP Experienced freedom and possibilities (MPX-Q subscale)

EMI Electronic musical instrument

EN Endurability (UES subscale)

ENI Entrance interview

ESQ Evaluation session questionnaire

EXI Exit interview

FA Focused attention (UES subscale)

FI Felt involvement (UES subscale)

FIQ First impressions questionnaire

HCI Human-computer interaction

ICMC International Computer Music Conference

IDMIL Input Devices and Music Interaction Laboratory

IMU Inertial measurement unit

MIDI Musical Instrument Digital Interface

MPX-Q Musicians' Perception of the Experiential Quality of Musical Instruments Questionnaire

NIME New Interface(s) for Musical Expression

NO Novelty (UES subscale)

PCC Perceived control and comfort (MPX-Q subscale)

PSQ Pre-screening questionnaire

PSSQA Perceived stability, sound quality, and aesthetics (MPX-Q subscale)

PU	Perceived usability (UES subscale)
S1 to S5	Evaluation sessions 1 to 5
SMC	Sound and Music Computing Conference
SPU	Sound processing unit
UES	User Engagement Scale(s)
UX	User experience
UIR	User-instrument relationship
YPR	Yaw/Pitch/Roll

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Chapter 1: Introduction

Interaction with electronic interfaces has been an active area of music composition, performance, recording, and consumption for several decades, especially following the advent of electronic musical systems, such as analog and digital synthesizers [1; 2]. More recently, music interaction with general-purpose computers has been a notable area of research, development, and experimentation in the musical community, as evidenced by papers published in venues such as the International Computer Music Conference (ICMC; established 1974), Computer Music Journal (established 1977), and, more recently, the International Conference on New Interfaces for Musical Expression (NIME; established 2002). Although music interaction with computers is now widespread, the field lacks formal, structured, and replicable methods for longitudinal evaluation of user experience (UX) with digital musical instruments (DMIs) [3; 4; 5; 6; 7].

Digital technology has profoundly influenced composition, performance, and consumption of music [8]. This influence is particularly observable in the domain of DMI design and practice. A DMI can be defined as *"[a]n instrument that uses computer-generated sound … and consists of a control surface or gestural controller, which drives the musical parameters of a sound synthesizer in real time"* through a series of gesture-parameter correspondences collectively referred to as 'mapping' [9, p. 1]. Although terminology is varied, this work uses the abbreviation DMI to include reference to New Interfaces for Musical Expression (NIMEs), Electronic Musical Instruments (EMIs), etc.

This thesis reports on development and demonstration of a method to understand the dynamic nature of UX as individuals learn to play and perform with a DMI.

1.1 Digital Musical Instrument Interaction: An Overview

This introduction presents basic background relevant to DMI design, interaction, and evaluation, including principles of human-computer interaction (HCI), characteristics of DMI musicianship, and facets of the user-instrument relationship (UIR).

1.1.1 Interdisciplinarity in Digital Musical Instrument Research

The study of DMI design and use is a highly interdisciplinary field, involving aspects of music, computer science, electrical engineering, human psychology, and many other domains. Jordà [10] summarizes the multidisciplinary nature of DMI design as follows: *"digital instrument* *design is quite a broad subject, which includes highly technological areas …, human-related disciplines …, plus all the possible connections between them …, and the most essential of all, music in all its possible shapes" [p. 321].*

The study of music interaction borrows many concepts from early research in computer music conducted in the 1950s and '60s [1; 2], as well as from HCI [11; 12], a field that emerged in the early '80s as computers proliferated and became a part of everyday life. HCI research and practice centres on relationships between human 'users' and computer-based interfaces or environments. The goal of HCI is to create and enhance digital technologies, and to understand factors that contribute to usable devices. More recent approaches to HCI, such as emotional design, suggest that, in addition to usability, technologies should endeavour to facilitate positive, meaningful, or useful experiences [13; 14]. In this context, UX has emerged as a fundamental concept in the design and evaluation of interactive technology.

Conceptualizations of UX are informed by research from philosophy, design, cognitive psychology, anthropology, and other fields [15]. The International Organization for Standardization [16] defines UX as a *"person's perceptions and responses resulting from the use and/or anticipated use of a product system or service."* This includes the individual's *"emotions, beliefs, preferences, perceptions, physical and psychological responses, behaviours and accomplishments that occur before, during and after use"* and occurs as a result of *"brand image, presentation, functionality, system performance, interactive behaviour and assistive capabilities of the interactive system, the user's internal and physical state resulting from prior experiences, attitudes, skills and personality, and the context of use"* [16].

UX is also an essential component of music interaction [5; 12; 17], which refers to the intersection of music and HCI, and emphasizes aspects of interaction with DMIs that differ from more generic technology. Focal points include the role of motivation in developing high-level musical skill over time, the embodied nature of musical activity, the complex motor and cognitive skill required, and the temporal precision of musical movement [8; 11]. Given that, to this author's knowledge, there is no widely-accepted term for this combination of factors, the abbreviation UIR (user-instrument relationship) is introduced in this work as a terminological shorthand encompassing the many dimensions that characterize the relationship between performer and instrument.

1.1.2 A Brief Overview of Digital Musical Instruments Usage

While several new DMIs are created every year and presented through venues such as

NIME, many are not taken up by active performers and do not establish longevity or sustained use beyond their initial design and presentation [18; 19; 20; 21; 22; 23]. Barriers to adoption and longevity include idiosyncratic design, technical obsolescence, and lack of developed technique, notation, existing repertoire, or standard training methods [19; 20; 24].

The continued development and presentation of new instruments is an important facet of the DMI community, and may be ascribed to a pursuit of novelty [24], an active and growing design community [25], or a lack of incentive for researchers to replicate or build upon each other's work [26]. While this is an important fact to acknowledge in discussions of DMI adoption, availability, longevity, and widespread use, it is not the focal point of this work to determine whether this prevalence of novel designs is indicative of productivity or of dysfunction within the DMI community.

Despite barriers to adoption and ongoing use, DMIs offer distinct novel musical and interactive possibilities that cannot be replicated with acoustic instruments or more widespread keyboard or pad-based controllers. DMI musicians adapt themselves to the idiosyncratic nature of their instruments, capitalizing on these devices' unique features to develop novel interaction strategies and musical works [27]. As a result, several DMIs have developed longevity, remaining in use in research, performance, and compositional contexts for 10 years or more [28; 29].

While the formation of relationships between users and technology is common in the modern age, the UIR is special in music interaction contexts, demonstrating complex interplay between skill development, embodiment, emotion, and control. Furthermore, *"[t]he relationship between player and instrument is not stationary"* [30, p. 683]; facets of experience interact and evolve over the trajectory of the relationship, from initial adoption, through the learning process, to ongoing use and eventual mastery. While traditional HCI has many useful frameworks and strategies to illustrate and evaluate usability, these concepts and methods in their standard form may not be sufficiently flexible to unravel the rich interplay of experiential factors that characterize the UIR. For several reasons, these traditional frameworks may prove too restrictive to facilitate an understanding of creative technology use. While traditional HCI focuses on ease of use and efficiency with respect to tasks that have an identifiable state of completion, musical learning and interaction is categorically different, as it generally occurs over extended periods of time [31], may necessitate some level of frustration [32], and is often characterized by open-ended, continuous interaction, rather than discrete tasks [17].

1.1.3 Iterative Design and Evaluation

Iterative design is a central tenet of user-centred design in musical and non-musical contexts. In the iterative process, technological prototypes are systematically created, evaluated, and refined based on test results in a cyclical manner until the artefact is deemed appropriate for its intended purpose. In the DMI development cycle, evaluation is crucial. Processes of design and evaluation often occur in parallel, and each provide information complementary to the other [30]. There are several important incentives for designers to evaluate their DMIs, including to examine how their instruments function in real-world settings, to observe how users interact with the technology, to understand how users think and feel during interaction, and to assess whether the produced artefact has met its design goals [6]. While evaluation can provide useful insight into these phenomena, it is also important to acknowledge that it is entirely appropriate for DMIs not to be subjected to this sort of assessment, and that many DMIs are not evaluated at all [4].

Task-based evaluation approaches drawn from classical HCI, which focus on ergonomics and efficiency, may be insufficient for providing a comprehensive understanding of musical or other creative technologies. While tools and methods borrowed from classical HCI can be useful in studying aspects of user interaction [11], a singular focus on task performance is unlikely to provide a comprehensive sense of a musician's experience using an instrument. While it is an important contributor to UX, usability alone does not guarantee the experiential success of a technology, particularly in a domain as multifaceted and complex as music interaction [5].

Many aspects of musical practice (e.g. enjoyment, creativity, and aesthetic response) are less easy to quantify or assess than efficiency, and lack established or standardized tools to do so [17]. Additionally, the highly subjective nature of music interaction renders many traditional HCI methods relatively uninformative with respect to performer experience [33]. Mackay [34] notes that lab-based classical HCI evaluation methods are only effective *"if the goal is to increase performance, not to provide creative tools for creative professionals. You end up pretending to do something that is not real"* [p. 118]. Instead of focusing on device performance, Mackay suggests that creative interfaces should be assessed based on other attributes, such as their discoverability, potential for appropriation and expression, and the extent to which they allow varied and subtle control [34].

1.1.4 The Need for Structured Longitudinal Evaluation

Reviews of DMI evaluation [3; 4; 5; 6; 7] note several limitations of existing strategies, include idiosyncratic approaches to evaluation, lack of formal structure, insufficient inclusion of detail necessary for replication, use of untested ad-hoc data collection methods, and absence of studies conducted over substantial periods of time (i.e. more than a single session). In response to these limitations, a previous work by this author [6] advocates thorough evaluation planning, noting that *"evaluation strategies will have unique implications in any scenario, and it is essential to consider the consequences of any particular strategy for a given technology and evaluation target"* [p. 19]. This requires careful consideration of the device, experiential factors of interest, and strategies that would yield meaningful results in relation to these phenomena.

Several researchers [6; 12; 31; 35; 36; 37] have also identified the need for an increased prevalence of longitudinal evaluation research, as the prolonged use of DMIs necessitates strategies capable of capturing information related to dynamic aspects of UX, including development of expertise and musical technique [6; 36], hedonic and cognitive facets of experience [6], and evolution of the UIR over the learning period [31]. Given the extended lifespan and sustained use of DMIs, research conducted over periods of time ranging from weeks, to months, and potentially to multiple years is required to understand learning processes and experiential aspects of interaction with these instruments.

Formal and replicable longitudinal evaluation can be achieved through careful planning and execution of evaluation strategies, as well as by leveraging existing structured tools from DMI research and other domains [6]. Use of existing tools and procedures could allow researchers to provide more informative and meaningful data to the community, and could encourage them to formalize their strategies, share them, and replicate each others' work [6].

In response to these concerns, the original research presented herein describes the development and initial demonstration of a procedure suited to such longitudinal research. Three participants of diverse musical backgrounds learned to play an existing DMI, the T-Stick [38], through a series of musical tasks and creation of an original musical excerpt. They reported on their experience at multiple points throughout the study through surveys and interviews. Third-party evaluators also provided ratings and commentary on participants' performances.

1.2 Motivation and Research Questions

In combination with a lifelong love of music and musical instruments, as well as an academic and professional background in both psychology and music production, I was drawn to the idea of undertaking an academic programme focused on the intersection of music, computer technology, design, and human psychology. Early on in my programme, I was eager to understand the nature of musicians' experience using novel musical interfaces for which there was no established tradition or pedagogy. I learned early on that this line of inquiry was fundamentally a question of evaluation, and that generalized methods for evaluating the experiential trajectory of music interaction were limited. Evaluations carried out were often informal and idiosyncratic, and investigations into the relationship between performers and their DMIs seldom provided insight with the respect to the extended nature of these entanglements.

The research presented in this thesis was carried out in response to the field's lack of formal, empirical, and replicable long-term evaluations examining UX when interacting with DMIs. This work proposes and executes a previously-unused methodology for studying changes in UX with a DMI over a limited learning period. By using a small sample size and limited time period, this work assesses the effectiveness of this protocol in examining dynamic aspects of the UIR. The study objectives are twofold:

1. To test a methodology for studying UX as an individual learns to play a DMI;
2. To better understand DMI qualities that promote adoption, ongoing musical practice, and long-term engagement.

The study methodology was developed to address two research questions:

1. To what extent is an evaluation method able to capture dynamic aspects of UX and development of the UIR over the process of learning to play an unfamiliar DMI?
2. What do these measures of UX reveal regarding factors that contribute to adoption, sustained use, and longevity of DMIs?

To provide insight into these research questions, three participants learned to play a DMI through a series of musical tasks of increasing complexity, created and performed an original musical excerpt, and participated in surveys and interviews investigating their experience over a short period of time.

1.3 Structure of the Thesis

Chapter 2 reviews literature from DMI and HCI research. Differences between practice with DMIs and their acoustic counterparts are introduced and a brief description of theoretical frameworks and different stakeholder perspectives with vested interest in DMI design and evaluation is provided. Following this, the nature of DMI adoption and longevity is linked to considerations for DMI practice and design. Music interaction is defined, noting the influence of HCI and UX research. The UIR is characterized in the context of this discussion, and dynamic aspects of the UIR, such as appropriation, affordances and constraints, hedonic and cognitive factors, learning, embodiment, absorption, and expression, are introduced. Two frameworks for understanding the UIR, the User Engagement Scales (UES; [39]) and the Musicians' Perception of the Experiential Quality of Musical Instruments Questionnaire (MPX-Q; [40]) are outlined. To conclude, an overview of DMI evaluation strategies is provided, and several reviews of evaluation are summarized. Limitations of these existing strategies are highlighted as motivation for the current longitudinal study into the changing nature of the UIR.

Development and execution of the procedure and data collection methods used in this work is detailed in Chapter 3, which presents the musical hardware (the T-Stick), mapping, and sound synthesis, as well as the musical tasks used. A detailed overview of the study is provided, including details of participant recruitment and research environment. Questionnaires and interview guides used for data collection are reproduced in full in Appendices A and B.

Chapter 4 reports the analysis of collected data and subsequent findings. Scale ratings, interview data, and third-party evaluator commentary is presented, along with description of the analysis methods used to code interview data. The complete interview coding scheme is provided in Appendix C.

Chapter 5 provides interpretation of these results in the context of the literature reviewed in Chapter 2. This discussion is divided into four areas:

1. A summary of participants' perspectives, experiences, and approaches to their interaction with the T-Stick during the study;
2. Comparison of participants' experiences, with a focus on similarities and differences between participants in the context of their differing musical backgrounds and preferences;
3. Additional noteworthy aspects of participants' experiences during the study;
4. Changes in UX over time and development of the UIR.

Following description of these themes, limitations of the study are acknowledged, and ideas for future modifications to the research protocol and musical apparatus to address these limitations are discussed, incorporating participants' reflections on the study and suggestions for improvement.

Finally, Chapter 6 notes three distinct contributions of this work to DMI research:

1. Practical: How the DMI used in this research (the T-Stick) can be improved based on results of the evaluation;
2. Methodological: How the method used in the current study shows strong potential for future structured longitudinal evaluation of UX with DMIs over a learning period;
3. Theoretical: What the observed results indicate for research into understanding UX in the context of music interaction with DMIs.

In addition to this thesis, this research has also resulted in one published conference paper [6], as well as one journal article currently in revision [41].

Chapter 2: Background

2.1 Digital Musical Instruments: Design and Performance

> *"We need useful, playable, thought-provoking and enjoyable instruments, capable of interesting, surprising, enjoyable music"* [10, p. 326]

As indicated previously, interest in DMI design and evaluation has grown over recent decades [4; 8; 25; 33; 42; 43], and matured into a discipline with an active design, research, and performance community. A notable development was the inception of the NIME conference, initially a workshop in the 2001 Conference on Human Factors in Computing Systems (CHI), a leading HCI research forum (cf. [44]). It has since become a yearly conference that brings together designers, performers, composers, researchers, and professionals, to interact, attend workshops, and present new DMIs, sound installations, compositions, and peer-reviewed research.

2.1.1 Comparing Digital and Acoustic Musical Instruments

A number of key differences exist between DMIs and their acoustic counterparts. In a traditional acoustic musical instrument, gestural input is directly linked to sonic output by mechanical means. DMIs instead make use of a mapping layer between an individual's gestures and the sound produced, which serves to decouple gestural input from sonic output. In DMIs, these input-output linkages are created through digital means [9].

Decoupling of input and output in DMIs allows designers almost unlimited freedom when designing mappings, as any input can be linked with any output. As a result, mapping is critical in determining how musicians can use an instrument, and is a key aspect of the identity of new musical interfaces [45; 46]. Thus, mapping is of paramount importance in determining users' musical, emotional, and cognitive experience with a given DMI [45]. While mapping flexibility allows for tailored control and UX specific to user requirements [45; 47], lack of pre-determined mapping means that designers and evaluators must consider the mapping layer directly, as it is not governed by predictable mechanical and physical principles [45].

Mappings can range from elementary, one-to-one correspondences to more complex input-output relationships. For instance, Rovan and colleagues [48] define divergent mapping as consisting of a single gestural input controlling multiple sonic parameters, while convergent mapping consists of many gestural inputs which are combined to affect a single sonic parameter. Hunt and Kirk [49] suggest acoustic instruments demonstrate *"complex relationships between physical control variables and the resulting sound"* [p. 433]. Such nuanced relationships play an important role in contributing to the 'feel' of an instrument [10], meaning that careful attention should be paid when designing DMI mappings. While the ability to tailor a technology to users' specific performance needs or the task at hand may come with a cost if mappings are overly simplistic, mapping flexibility can also contribute to DMI adoption and longevity, as a uniquely-mapped DMI cannot be readily replaced by something more popular or commercially available [21; 50].

Ultimately, it is not the presence of the mapping layer that differentiates acoustic and digital instruments, but that DMI mapping is flexible, and is explicitly and intentionally designed. Mappings can be designed effectively or ineffectively, and it has been argued that mapping design is at least as important as the design of the hardware controller [51]. In a study which required participants to create their own DMI mappings, West and colleagues [51] noted three themes in how users created their mappings. The first was the need for the mapping to provide the user with a sense of control and musical agency, by ensuring actions had repeatable consequences (although participants with prior DMI experience were more open to surprising or unpredictable aspects of instrument behaviour). The second theme was the importance of legibility: mappings should be understandable for both player and audience. Finally, the authors noted that sounds produced by the instrument should be effective in the context of a performer's musical goals.

A second, related difference between DMIs and their acoustic counterparts is the nature of the materials used in construction [46; 52]. While the physical properties of wood or vibrating strings govern the nature of the sound produced with acoustic instruments, the sound of a DMI is not subject to these inherent laws [46]. Wessel and Wright [53] describe this difference as one of sonic character, stating that while acoustic instruments are *"constrained by the sound production mechanism"* [p. 11], DMIs allow for *"immense timbral freedom"* [p. 11]. Additionally, the presence of the mapping layer means that the player is not placed in a direct mechanical relationship with the sound production mechanism, as is the case with acoustic instruments [53].

Finally, in contrast to acoustic musical instruments, DMIs offer possibilities to interact with sound at several different levels of performance, and in different contexts [31; 54]. While skill-based interaction is the standard in acoustic musicianship, DMIs might allow for rule-based interaction behaviours, such as sequencing, or model-based strategies, such as live coding [31; 54]. These different strategies vary in their level of abstractness, embodiment, and the extent to which they require conscious thought [31].

As a direct result of the features introduced above, the nature of musical practice with acoustic instruments and DMIs is notably divergent: *"[s]kill acquisition, the path to mastery, and the nature of virtuosity are all features that are transformed with the digital musical instrument"* [52, p. 174]. For example, it has been suggested that few DMI performers have obtained a level of mastery that can be considered 'virtuosic' [10]. While this observation might seem straightforward, it is crucial to remember that DMIs lack an established tradition, and thus, the cultural context and history necessary to identify and define virtuosity may not yet exist [31]. While mastery of acoustic instrumental practice might take ten or more years [11], it is not yet understood how long it might take to achieve a comparable skill level with a DMI, how such skill can be evaluated, or whether comparison of skill between digital and acoustic instruments is scientifically valid.

To summarize, while traditional conceptions of musicianship can serve as a useful point of inspiration, the application of these concepts or practices to DMI contexts must be done with extreme caution and appropriate adaptation, as the nature of sound production, flexibility of operation, and available options for interaction are fundamentally different.

2.1.2 DMIs in Design: Frameworks and Stakeholders

To more thoroughly understand the multidisciplinary design space of DMIs, several authors have suggested frameworks that can be applied to DMI design and evaluation. These frameworks can facilitate systematic thinking and reflection for designers, illuminate new design directions or existing limitations, and serve as a reference for understanding UX by providing conceptual scaffolding for understanding interaction [55; 56]. Given that DMI design and evaluation are often informed by HCI concepts and practices, some authors [11; 12; 57] suggest application of existing HCI models to DMIs, while others have developed DMI-specific frameworks. Some of these frameworks are device-centric, with the design space focused on descriptive aspects of the designed technology [55]. Other frameworks focus on the DMI user, design, and activities for which the interface was intended [55]. An additional human-centred type of framework of interest with respect to this work focuses on the different categories of individuals with stake in DMI development and evaluation. DMI design and use necessitates consideration of perspectives with priorities and areas of concern that may overlap or differ [4; 56]. Frameworks can also be focused on these different types of individuals, and researchers and evaluators may target different user groups including designers, performers, audiences, non-musicians, amateurs, experts, or individuals with specific disabilities [6; 56; 58].

In the literature, these roles have typically been conceptualized as distinct stakeholder perspectives that often overlap. O'Modhrain's stakeholder-based framework [56] defines three perspectives with vested interest in DMI evaluation: the performer, the designer, and the audience. Brown, Nash, and Mitchell [5] also advocate for inclusion of a fourth stakeholder, the composer. Often, it is the performer perspective that is considered primary in design and evaluation contexts [4; 56], as the performer is the only one capable of speaking to the quality of an instrument's operation in live music-making contexts [9; 56]. With DMIs, however, this may be an oversimplification, as designer and performer might be the same person, able to oscillate between performance, design, and compositional concerns [47; 52]. When considering DMI usage and stakeholders, one should be aware of additional possible interaction scenarios, including instruments that are played by both individual users and small or large groups, as well as improvisational, compositional, and performance contexts [10]. Each of these scenarios is likely to entail differences in interaction, and these differences should be acknowledged and considered when contemplating stakeholders in DMI design, use, and evaluation.

Young and Murphy [12] take a more holistic approach, suggesting that each perspective is necessary at different points in the design process; categorical stakeholder models may not address the overlapping nature of these perspectives or might overlook musical practitioners who engage more recreationally with DMIs, such as hobbyist users, or those who engage with DMIs primarily through research. Each of these groups will likely have different needs and priorities, which might also overlap with the concerns of stakeholders already identified in the literature. As such, an understanding of factors that contribute to DMI adoption, longevity, and engagement requires openness towards diverse musical practices, styles, and skill levels [59], which may not be represented by categorical stakeholder models.

What is most crucial, when considering the varied perspectives with vested interest in DMI design and evaluation, is that there are several sets of goals and objectives at play which can change over time, overlap, or compete. As such, it is worthwhile to consider as many relevant perspectives as possible during design and evaluation. While a designer is likely to be concerned with technical factors and quantitative performance measurements of a device, a performer might focus on how immediately the instrument responds to their movements, and a composer might be interested in the extent to which the instrument inspires them creatively. Similarly, a hobbyist might focus on whether they find casual, short-term interaction to be fun and pass the time, while an audience member may be interested in the legibility of the relationship between gesture and sonic result, or the extent to which an instrument can facilitate an engaging and entertaining performance. Consideration of each of these perspectives is a vital part of DMI design and evaluation, as each viewpoint is valid and provides complementary information which, when synthesized, can provide a more complete understanding of DMI interaction.

2.1.3 DMIs in Practice: Adoption and Longevity

As identified in Subsection 2.1.1, fundamental differences between DMIs and their acoustic counterparts mean that knowledge and practice from one domain cannot necessarily be applied to the other without adaptation. Compared with acoustic instruments, there is relatively little in the way of established DMI technique, musical notation, pedagogical resources, or existing repertoire [19; 20; 24; 31; 60]. Given that social factors play an important role in initial uptake and ongoing use of DMIs [53], the relative absence of such history, repertoire, and resources poses important consequences for adoption and longevity [24]. McPherson and Kim [21] refer to the fundamental issue of adoption as *"The Problem of the Second Performer"* [p. 10], which describes the difficulty of attracting musicians beyond the original user to a DMI. This is caused, in part, by the fact that DMIs are often developed in service of a specific composition or performance without thorough consideration of the instrument's future role in the musical community.

Despite these concerns, the unique musical possibilities offered by DMIs have encouraged development of a global design, research, and performance community, and new DMIs are introduced every year in both research and commercial domains [24, 25]. Furthermore, several motivations exist for the adoption of new instruments. A survey of electronic musical instrument users conducted by Sullivan, Guastavino, and Wanderley [59] found that the most important contributing factors to adoption and ongoing use thereafter were novel interactions, creative and expressive possibilities, and the ability to support intimate and embodied UIRs. Other reasons included the extent to which instruments showed complexity, provided challenge to users, and allowed for the creation of nuanced, original music. Finally, the authors noted the importance of instruments being functional with minimal barriers to operation. Users adapt themselves to the idiosyncratic nature of DMIs, developing interaction strategies that capitalize on DMIs' unique features [27]. There are several examples of DMIs that have remained in use for over ten years [28; 29], due precisely to the unique musical and interactive possibilities they offer.

This being said, continued efforts to increase uptake and ongoing use of DMIs are beneficial in allowing the community to expand, evolve, and flourish. For such efforts to be informed and effective, an understanding of the barriers to DMI adoption and longevity is essential. In addition to the social factors described above, several other contributing factors have been examined, including, but not limited to:

1. The required technical expertise necessary to operate some DMIs [24; 50];
2. Instruments that become unstable or unusable due to lack of upkeep, deprecated electrical components, or compatibility issues between software, hardware, operating systems, and/or communication protocols [18; 29; 47; 59];
3. An absence of individuals with the skills, knowledge, and availability necessary to repair or maintain these instruments [29; 61];
4. A related lack of documentation necessary to replicate existing DMIs, which decreases the availability of these instruments [18; 28; 61; 62; 63];
5. A prevalence of DMIs that remain as unfinished prototypes [23; 24; 64]; and
6. An inability to attract the attention of new musicians [19; 20; 21; 24], due in part to a lack of exposure resulting from factors listed previously.

Given the varied contributing factors, several distinct but complementary strategies have been employed to address concerns related to DMI uptake and sustained use. Examples include:

1. Encouraging the development of repertoire [19], technique [21], and pedagogical strategies [24] for DMIs;
2. Creation of high-level gestural descriptors to reduce technical overhead [50];
3. Enhancing replicability of DMIs through development of instrument-building frameworks [63], increased availability of necessary documentation [26], or adoption of an apprenticeship model for designers [61];
4. Creation of dedicated musical communities or social structures centred around DMI development and performance [19; 21; 60; 65];

5. Leveraging performers' existing technical skill with acoustic instruments [21].

In addition to the strategies described above, evaluation of UX with DMIs can provide important information about factors that contribute to uptake and ongoing engagement with DMIs. An understanding of hedonic and cognitive factors in interaction, the challenges and breakthroughs experienced when practicing or performing with a DMI, and the relationship that evolves between instrument and user, can illuminate barriers to adoption and longevity, as well as the ways in which individuals overcome these barriers. This approach, drawing from work on HCI, UX, and cognitive psychology, is that which inspires the research herein.

2.2 Human-Computer Interaction, User Experience, and Music Interaction

> *"There is an impetus for technology developers to exceed usability and provide an experience … [T]he question is no longer only whether an application is efficient, effective, or satisfying, but how well it is able to engage users and provide them with an experience."* [66, p. 2].

As computer technology has progressed and permeated many aspects of human life, the focus of many HCI researchers has expanded beyond just usability to include additional topics and lines of inquiry. More specifically, there has been a shift from measuring device usability using quantitative, task-based performance measures to, focus on users' experiences when interacting with technology [7; 67]. In this respect, it has been recommended that designers strive to create devices that, in addition to being usable, promote engaging, satisfying, and rewarding experiences [13; 66].

2.2.1 The Evolution of HCI

It has been suggested that research in HCI has developed through a series of three 'waves,' describing a shift in the discipline from a focus exclusively on usability, to a broader understanding of the relationships between humans and technological products, as well as the sociocultural contexts in which interactions take place. This has been summarized by Bødker [68] as follows:

> *"The first wave was cognitive science and human factors. It was model-driven and focused*

> *on the human being as a subject to be studied through rigid guidelines, formal methods, and systematic testing … In the second wave, the focus was on groups working with a collection of applications. Theory focused on work settings and interaction within well-established communities of practice … Proactive methods, such as a variety of participatory design workshops, prototyping, and contextual inquiries were added to the toolbox. In the third wave, the use contexts and application types broadened, and intermixed, relative to the second wave's focus on work ... Research in the third wave challenged the values related to technology in the second wave (e.g., efficiency) and embraced experience and meaning-making …"* [pp. 24-25]

While the metaphor of 'waves' is helpful in illustrating that the HCI discipline has undergone notable evolution, it is important to indicate that development of new models and understandings is not categorical; newer understandings do not eclipse older methods of inquiry. Rather, these paradigms co-exist, in that theoretical and practical knowledge from each stage of the discipline's development can be combined to provide a more holistic picture of the complex and multi-faceted relationships between humans and technology. This notion of complementary approaches which highlight and address different facets of a single topic is similar to the strategies for approaching DMI adoption and longevity, cited as examples in the previous section; use of co-existing strategies based on differing conceptual foundations, across a variety of disciplines or approaches, serves to provide a more holistic illustration of the subject of inquiry.

The nuanced relationship between computing technology, cultural values, and everyday human behaviour necessitates such a multifaceted approach. In HCI, this requires consideration of not only control and ergonomics, but individual and social behaviour, cognition, and emotion [8]. Recent approaches draw on a wealth of interdisciplinary perspectives, with special attention paid to the sociocultural context of technology use and the ultimate experience of the end-user, from initial basic patterns of interaction to the larger-scale unfolding and coalescing of experience in real-world contexts [8; 15; 17]. In the design and evaluation of musical interfaces, in-depth consideration of the user and context is particularly important, as specific aspects of music interaction that diverge from general HCI paradigms merit special attention [17].

Prior to a more in-depth discussion of music interaction, user experience (UX), a key concept from human-centred HCI research, requires definition. While no definitive theory of UX exists, the many overlapping definitions of the term used share the central tenet of adopting a user-centred perspective towards the study of technology, which encompasses physical, sensory, cognitive, hedonic, and aesthetic experiences [15]. Given the highly intimate nature of the UIR in musical practice, a designer's failure to understand or consider the experience of the user can lead to frustration or confusion for a musician when interacting with a DMI.

2.2.2 Music Interaction

Music interaction offers a foundation for understanding how digital technology has affected the manner in which music is created, learned, recorded, performed, and distributed [21]. While many HCI principles and methods are applicable, *"music raises many distinctive challenges for interaction design"* [8, p. 5]. In this respect, several researchers [10; 21; 23; 53; 59; 69] have developed specific heuristics or recommendations for DMI design. Given that the focus of the research presented herein is not design practice, but evaluation of experience, a comprehensive review is beyond the scope of this work. Bearing this in mind, an overview of several of these guidelines serves to illustrate the complexities of music interaction with DMIs, as well as the ways in which music technology artefacts differ from more general computing interfaces. Furthermore, several of these recommendations were referenced in the development of the research materials used in this study (Chapter 3), while others were reflected in data collected from participants (Chapter 4):

1. Balance between initial approachability and the potential for ongoing learning and discovery of musical possibilities (*"Low 'Entry Fee' with No Ceiling on Virtuosity"* [53, p. 121]) is a challenge [30; 53; 69]. While ease-of-use is beneficial in initial interaction, opportunities for long-term skill development and eventual mastery may facilitate sustained interest and use;
2. Instrument responsiveness is an asset; high latency or variation thereof can negatively impact user confidence and perceptions of control, disrupting the flow of expression between user and instrument, and potentially leading to frustration or disengagement [10; 53];
3. Relatedly, while predictability is generally desirable [10; 53], DMI players may also appreciate some degree of random or nonlinear behaviour [35; 70]. In most cases, the degree of stochastic behaviour should not negatively affect perceptions of playability [35];
4. Feedback provided through visual or other perceptual channels can enhance confidence in interaction and provide essential performance-related information, thereby easing the load on musicians' memory, and freeing up cognitive resources for more abstract elements of performance or practice [53]. Feedback can be particularly useful during initial

exploratory learning, as it can provide real-time information about the effects of users' actions on the instrument [49];

5. A *"silencer mechanism"* [53, p. 14], which allows users to control the amplitude of a sound and *"gracefully shut down a musical process"* [p. 14] is particularly important; and
6. User perceptions of various DMI attributes have an impact on UX, as well as adoption and longevity [59]. These include complexity, aesthetics, reliability, stability, engagement, and appropriateness of the instrument for a given user and context of use [59].

The motivation for music interaction, instrumental learning, and ongoing skill development, often intrinsic, merits remark, as musical activities are typically taxing and involve the overlap of many disparate human capabilities, two observations that may not be true of general computing [8]. Despite lack of external motivation or incentive, *"many amateur musicians take pains to develop virtuosic music skills far beyond those required for universally accessible musical activities and dedicate lifetimes to refining highly specialised musical expertise for its own sake"* [8, p. 2]. Crucially, this implies that the interaction may not initially be rewarding, with Jordà [10] noting that *"[m]any traditional instruments are quite frustrating for the beginner"* [p. 331]. The process of musical learning is highly emotional, including components of boredom and frustration, failure and success, and mistakes and recovery from errors, which can enhance or impede the learning process [71]. The ongoing process of learning and skill development in DMI musicianship is a cornerstone of the user-instrument relationship (UIR), the focal point of the research reported in this thesis.

2.2.3 The User-Instrument Relationship

The UIR serves as a convenient umbrella term which encompasses the many experiential aspects of music interaction, including learning and skill development. A preliminary element of the formation of this relationship is appropriation, which describes users' adoption and adaptation of technology based on their personal needs or practices [72], as well as how users transcend basic adoption to personalize their interaction within the context of their unique knowledge and practices, thereby making the technology their own [73]. Appropriation allows technology to be shaped based on user needs through processes such as modification, personalization, or creative leveraging of a technology's possibilities [73]. As such, affordances and constraints, which indicate the perceptible interactive possibilities and limitations of a system, respectively [46; 47], play an important role in DMI appropriation [74], learning [46], and ongoing creative use [46; 52].

Throughout the processes of adoption, appropriation, and sustained use, facets of the UIR shift and evolve as users encounter DMIs' possibilities and limitations, develop their skill and expertise, and experience various challenges and breakthroughs [6; 10; 31; 36]. Hedonic and cognitive factors, identified in a recent work by this author [6], and introduced in Chapter 1, are two such areas of UX and the UIR. To reiterate, hedonic factors are aspects of UX that relate to human affect, emotion, and sensory appeal, and are reflective of the importance of emotion to the perception, communication, and expression of human experience [6; 30; 75]. Cognitive factors relate to psychological constructs, including memory, expertise, motivation, confusion, creativity, conceptualizations, perceived possibilities and limitations, mental effort, and cognitive load [6; 10; 76]. These factors are distinct from pragmatic characteristics, which relate more closely to usability, acceptance, predictability, and trust [17; 75].

Hedonic and cognitive factors are highly intertwined, exert considerable influence on one another, and evolve through the course of interaction [6; 14; 76]. Furthermore, both areas are closely related to users' previous interactions with technology, which set up systems of expectations with respect to users' conceptual models of, and emotional responses to, technological interactions [15]. An understanding of these aspects of the UIR is beneficial not just theoretically, but practically, as modern technology shows promise in utilizing real-time detection of affect and cognitive load to create musical interfaces that adapt fluidly to users' state to facilitate musical learning and creative interaction [71].

With time and development of skill, the UIR can also demonstrate embodiment, absorption, and flow, overlapping phenomena that are important hallmarks of music interaction [8; 30; 77]. Embodied interactions describe a special relationship in which an individual and artefact become integrated such that the object feels like a direct extension of the user's body and mind, allowing musical intent and expression to flow without friction or resistance [30; 78]. Flow states [79] represent one manifestation of embodiment, describing experiences in which a user is fully absorbed in an interaction, operating in a *"holistic state of consciousness where actions happen continuously, accompanied by sharpened senses acting in a unified manner … [and] associated with feelings of success and being uplifted"* [45, p. 435]. Such fluent automatic states can typify skilled musical behaviour when the balance between a user's skill and the complexity of the interaction is ideal [79], and can be a useful indicator of pleasurable and enjoyable user experiences [17].

Finally, the notion of expressivity is important in the DMI community, though definitions of the concept may be inconsistent or vague [80]. While thorough dissection of the term is beyond the scope of this work, a number of conceptual themes from discussions of expressivity are noteworthy. One interpretation considers musical expression a method of communication, by which emotional content encoded in a piece of music is transmitted between a performer and an audience [80]. Even within this interpretation, however, there is no consensus as to what exactly the expressive content of music should be, though it might include components of emotion, style, and aesthetic content, among others [80]. Expressivity might also describe the potential of any instrument for a diverse set of musical possibilities which allows performers choice between available interaction strategies [40]. While this work will not venture into the question of how expression is conceived, it is important to note that definition of the term is contentious, but likely includes aspects of the interpretations provided above, to a greater or lesser extent.

2.2.4 Frameworks for Understanding User Experience in Music Interaction

The study described herein is contextualized in the context of two multi-factor frameworks which offer some description of UX: the User Engagement Scales (UES) [66; 76], from HCI, and the Musicians' Perception of the Experiential Quality of Musical Instruments Questionnaire (MPX-Q) [40], from music technology.

Within music interaction and user-focused HCI, engagement is a key concept [59], particularly given trends towards experience-focused and human-centric design research. Engagement is related to the *"depth of participation the user is able to achieve with respect to each experiential attribute"* [39, p. 4], and can be defined as a quality of UX that characterizes interactions with successful technology, and includes multiple components related to interaction context, users' attitudes, previous experience, cognition, affect, and behaviour [39; 66; 67; 76]:

> *"Engagement is a category of user experience characterized by attributes of challenge, positive affect, endurability, aesthetic and sensory appeal, attention, feedback, variety/novelty, interactivity, and perceived user control."* [67, p. 241]

The original six interrelated factors of engagement [66; 76] are as follows:

1. Focused attention (FA): Absorption in the interaction, losing track of time, and the extent to which users are aware of aspects of the world external to the interaction. FA is

closely associated with flow states and cognitive absorption;

2. Perceived usability (PU): Negative emotions experienced by users over the course of an interaction, based on the degree of control and effort expended;
3. Aesthetics (AE): Specific visual and design features (such as conformance with design principles) that contribute to users' overall sense of attractiveness and sensory appeal;
4. Endurability (EN): Willingness to engage with a technology in future and recommend it to others. EN is the *"summation of the experience"* [67, p. 22] and provides a general indication of an interface's success;
5. Novelty (NO): Interest in or curiosity about an interactive task resulting from surprising, unexpected, or original aspects of the interaction;
6. Felt involvement (FI): Fun, involvement, and being drawn-in to an interactive task.

Given the shift to more experientially-focused design and evaluation of technology, O'Brien and Toms [66] state that there is an impetus for designers to focus on providing positive experiences for users: *"[f]acilitating engaging user experiences is essential in the design of interactive systems"* [p. 1]. Engagement provides an explanatory model for why users are attracted to a technology and how this attraction is cultivated [39]. Thus, the importance of engagement underscores the need to provide users with worthwhile cognitive and affective interactions. Engagement is also dynamic, evolving over time through the distinct stages of a point of engagement, sustained engagement, disengagement, and re-engagement [39; 67].

The MPX-Q [40] is a psychometric tool consisting of 43 items focused on musical experience, divided across three subscales. It inquires about the experience and perceptions of musicians when playing instruments. The MPX-Q was designed to provide music researchers with a standardized and rigorous method for musical instrument evaluation. The questionnaire consists of items that load on three inter-related subscales [40]:

1. Experienced freedom and possibilities (EFP): How exploration of novel musical ideas and techniques are facilitated by instruments and, more generally, how the diversity of the musical possibility space contributes to perceived freedom of choice;
2. Perceived control and comfort (PCC): Related to feature and timing controllability (discussed in Subsection 2.3.1), as well as ergonomic elements of musical interaction. These factors can be grouped under the notion of 'playability,' with high factor loading indicative of a tight coupling between performer expectation and sonic result; and

3. Perceived stability, sound quality, and aesthetics (PSSQA): General notions of quality in terms of instrument materials, sound, or visual appeal. The scale shows notable overlap between sound quality, stability, and sensory attractiveness. Schmid also points out a 'halo-effect,' in which positive perceptions of interface aesthetics can positively influence perceived usability. Conversely, poor usability can negatively impact perceptions of aesthetic appeal.

In addition to the questionnaire itself, Schmid [40] contributes a three-factor framework for understanding musical experience. Similar to the user engagement framework, this factor structure shows promise in helping to develop understandings of the UIR.

2.3 Digital Musical Instrument Evaluation

> *"[W]ouldn't it be a good idea to evaluate all new instruments that come to NIME periodically and systematically? Do they still exist? Are they still used as they were designed? And most importantly: what musical experience is there?"* [81, p. 349].

Within the NIME community, evaluation has been a topic of discussion since the first NIME workshop, prior to official establishment of the conference [82]. Evaluation allows designers to gain insight into how their technologies are used in real-world contexts, how users think and feel about their interactions with these interfaces, and the extent to which a design accomplishes its goals. In DMI development, evaluation is crucial, as it is often the case that several generations of an instrument are required to fully refine a design before the desired functionality is achieved [9]. Ongoing evaluation, conducted at multiple points in time, is also important, as it can indicate whether modifications made to an instrument have the intended results and how user interactions change over time.

Fundamentally, task-based evaluation based on classical approaches to HCI allows for performance, generally meaning speed or efficiency, to be measured quantitatively, thereby allowing direct comparison of input devices [11; 83]. Task-based quantitative research conducted in laboratory settings can be useful in understanding aspects of technology such as ergonomics, efficiency, and usability, but may not provide much insight into users' experience when interacting with creative interfaces in real-world musical practice contexts [7; 17; 34; 57; 83].

Unique challenges arise for task-based approaches when evaluating creative technologies.

In musical and other artistic contexts, evaluation might entail not only assessment of technology, but *"a broader study into performers and their creative practice"* [83, p. 280]. Mackay [34] notes that lab-based classical HCI evaluation methods are only effective *"if the goal is to increase performance, not to provide creative tools for creative professionals"* [p. 118]. Instead of focusing on device performance, Mackay suggests that creative interfaces should be assessed in terms of their discoverability (closely related to explorability; [11]), potential for appropriation and expression, and the extent to which they allow for varied and subtle control [34].

As identified previously, evaluation strategies in NIME, and HCI more generally, have become more diverse, incorporating methods that are less focused on task performance and device usability, but increasingly experientially-oriented [5; 56; 67]. This has contributed to a larger scale perspective shift towards more user-centric approaches to the study of technology [84], though more traditional approaches remain complementary, especially as device usability undoubtedly has an impact on UX. Task-based usability evaluation, drawing from classical HCI traditions, can be used to examine whether a technology's feature set is reasonable for users, consistency, efficiency, and effectiveness of its performance, and robustness of design [12].

In experientially-focused evaluation, it is important to consider an interface's target user. In musical contexts, skill level is an important aspect of this consideration [6]. Individuals will have differing levels of skill and expertise, and the way in which they interact with technology is likely to be different from the outset, but is also liable to change over time spent interacting and practicing with a DMI, as a result of the accumulation of skills from ongoing practice. Such experience-focused evaluations lend themselves to in-depth study of affective and cognitive factors in technology use, and can be used in conjunction with more traditional methods to illuminate different aspects of design and interaction [6; 37].

2.3.1 The Nature of Evaluation: Traditional HCI versus Music Interaction

Several unique requirements emerge when comparing traditional HCI evaluation strategies to those employed to study music interaction. First, the nature of time plays a different role in musical contexts than in more typical HCI scenarios [31]. In general, temporal precision is a major element of skilled musical performance, and thus, measurements like task completion time are unlikely to be sufficient to indicate whether an instrument is 'well-designed' [11]. Second, as already mentioned, it is expected that the UIR will change in numerous ways over time as a result of practice, skill development, and acquisition of expertise [4]. Finally, the nature of music interaction means that it is prone to disruption by some classical HCI protocols, due to both the requirement of precise timing, and the close coupling between gesture and sonic result [56]. In addition to disrupting the task at hand, in-the-moment measures may interrupt the overall musical intent [56]. These concerns prompt serious consideration of how to evaluate DMIs in an informative and systematic manner.

In what is likely the earliest paper on DMI evaluation, Wanderley and Orio [11] describe four aspects of DMI interaction design that contribute to usability in musical contexts. The first, learnability, refers to the amount of time required for a user to be able to perform with the DMI. Explorability describes the extent to which the instrument allows users to perceive its capabilities, gestural possibilities, and nuances. Feature controllability is defined as the extent to which the devices makes connections between gestures and sonic parameters perceptible, encompassing control factors of accuracy, resolution, and range. Finally, timing controllability refers to the temporal precision offered by the instrument in relation to the musical performance or tasks.

Young and Murphy [12] suggest that these four criteria can be expanded to include other factors, such as how taxing device usage is for a user with respect to cognitive load, physical energy, and temporal demands, as well as aspects of UX, such as the frustration levels or the amount of work necessary for task completion. They note additional hedonic and cognitive factors such as insecurity, stress, frustration, motivation, and annoyance. Commenting on feature and timing controllability, these researchers note that evaluators might consider the ergonomic impact of the interface's feature controllability, and that temporal demands of tasks should be appropriate to the instrument and context, and should be flexible based on user needs.

Initial open exploration and discovery are also of particular importance in DMI contexts, given that *"[t]he first few minutes of contact between a player and a new instrument are a particularly insightful moment"* [36, p. 79]. These initial interactions, involving components of play and experimentation, serve to reveal relationships between input gestures and output parameters (i.e. mappings), musical possibilities, and opportunities for nuanced control [49].

Finally, the various stakeholders in DMI interaction, as well as the potential overlap of perspectives (such as the case of performers who design their own instruments [46]), requires those planning evaluations to choose which perspective(s) to prioritize. Jordà and Mealla [33] suggest that *"enjoyment, playability, robustness, or achievement of design specifications … should be …*

confronted from the diverse perspective of each stakeholder" [p. 234], which complicates evaluation, as evaluators must then consider all relevant facets of interaction multiplied by the number of stakeholders of interest.

Evaluation-related complexities such as those listed above have led several researchers to make recommendations specific to the evaluation of DMIs [6; 11; 12; 17; 56]. While such recommendations are useful, some level of idiosyncrasy in evaluation may be unavoidable given the inherent uniqueness of the technologies being evaluated [85]. Consequently, to a lesser or greater degree, evaluations may need to be tailored to specific instruments, users, or performance contexts [6]. This does not mean, however, that evaluation should be conducted strictly on an ad-hoc, informal basis. Instead, this implies that evaluations should be thoroughly planned, as *"evaluation strategies will have unique implications in any scenario, and it is essential to consider the consequences of any particular strategy for a given technology and evaluation target"* [6, p. 19].

As emphasized previously in this work, the need to evaluate overlapping areas of concern in music interaction necessitates the use of complementary strategies with differing benefits and drawbacks. While experientially-focused strategies provide insight into the subjective nature of the UIR, they are likely unable to capture technical aspects of device performance. Conversely, classical HCI approaches focused on evaluating usability through measurement of task performance may not adequately replicate the complex nature of musical behaviour: *"reduction of musical interactions to maximally simple tasks risks compromising the authenticity of the interaction, creating situations in which the affective and creative aspects of music-making are abstracted away"* [7, p. 962]. Similarly, there are benefits and drawbacks to different evaluation environments. While lab-based research offers control over confounding variables, it is also the case that *"studying how musicians use instruments in their own personal environments ('in the wild') allows us to better examine their creative process, as it is difficult to capture this in laboratory environments"* [5, p. 374]. These examples illustrate the many necessary considerations in development of evaluation strategies. The remainder of this chapter addresses such decisions, focusing on evaluation of UX and the UIR.

2.3.2 Borrowing Tools from HCI

A major concern with respect to evaluation of UX with DMIs is that key hedonic and cognitive constructs, such as engagement, effectiveness, and expressivity, may not be appropriately defined, operationalized, or measured using agreed-upon methods [4]. Emotional (and cognitive) components of experience can play a pivotal role in encouraging the adoption and continued use of DMIs [37]. This necessitates evaluations capable of *"gauging the affective response of the user, explaining that response, pinpointing relevant design features and contextualising this within the purpose of and nature of the system"* [37, p. 197]. Moreover, affective components of experience cannot be adequately assessed with a single measure taken at one point in time [37]; UX evaluation with DMIs should consider the impact of time.

In the context of music interaction, user-centric evaluation strategies may be superior to task-based usability evaluation in assessment of experiential factors such as affect, fun, flow, and creativity [85]. Use of qualitative methods shows particular strength in studying the emotional and creative aspects of music interaction [7], allowing researchers to examine the ways in which individuals adapt to, use, and form relationships with technology. This is especially true given the highly subjective nature of musical and creative interactions with technology [7]. Qualitative methods can also be used to develop hypotheses which can later be tested quantitatively, or to provide meaning and context to quantitative data [85].

Despite limitations, there is also much value in the use of task-based approaches. Young, Murphy, and Weeter [57] suggest that task-based evaluation, while limited in isolation, may be a *"necessary precursor"* [p. 119] to the study of experiential factors. Wanderley and Orio [11] make several specific recommendations to make task-based evaluation informative and useful. They suggest that musical tasks should *"strive for maximal simplicity"* [p. 70] and *"allow measuring of the temporal precision at which the musician can control the performance and its relationship to tempo"* [p. 71] to ensure that the centrality of time in music is respected. Furthermore, one should not develop tasks to assess every single function of a musical instrument, thereby compromising the holistic nature of musical experience. Rather, a set of simple tasks should be used to provide a *"general description of a controller"* [p. 71]. Crucially, the authors note that *"[e]ven though it may seem entirely non-musical, the use of a few simple tasks may help in a first step in evaluating controllers"* [p. 71]. Tasks may also provide a way to determine the set of musical gestures that are possible with a given DMI [11].

Several strategies may allow evaluators to increase the musical realism of task-based approaches. For example, when developing a set of tasks, one can begin with very simple tasks which instruct users how to control the elementary functions of an instrument. Tasks might then gradually increase in complexity, become more challenging, require more nuanced control, or employ combinations of previous tasks [11]. A natural extension of this idea is the development of short musical études, analogous to those written for acoustic instruments, that individuals can learn to replicate [24]. While études would likely be more difficult to develop than elementary musical tasks, they could provide a useful avenue for informing learners how to combine tasks or learn specific techniques, potentially increasing interest and realism, while also contributing to the ongoing evolution of DMI pedagogy. Stowell and colleagues [7] also recommend a period of open exploration to provide authentic scenarios for assessment of musical experience.

While this is by no means a comprehensive review of all the available options for DMI evaluation strategies, these considerations were influential in development of the research method presented herein (Chapter 3).

2.3.3 Reviews of DMI Evaluation

The various considerations in the development of evaluation strategies can be understood not just theoretically, but through an understanding of current DMI evaluation practices. Several reviews have examined published literature from NIME and other venues to assess how evaluation is currently conducted. This subsection briefly describes five notable reviews.

The first review was conducted by Stowell and colleagues [7] on published proceedings from three years of the NIME conference (2006 to 2008). The authors noted that evaluation methods reviewed often lacked a formal or structured approach, utilizing ad-hoc, researcher-developed data collection methods. As a result, the evaluations described did not facilitate replication or generalization of results [7].

The second review, conducted by Barbosa and colleagues [3] on published proceedings from NIME 2009 to 2011, also indicated that evaluation methods were frequently informal. In response, the authors recommended the development of more structured methodologies to evaluate DMIs, suggesting that an increased methodological structure *"[could] increase the efficiency of user feedback and provide better tools for its analysis"* [p. 1].

Another review conducted by Barbosa and colleagues [4] took a different approach, attempting to determine the meaning of the term *"evaluation"* in the community by studying proceedings and posters from NIME 2012 to 2014. These researchers found that the term was not used in a consistent manner throughout the community. Additionally, it was common for researchers to omit important aspects of their methodology, including evaluation goal(s), criteria used to determine whether goal(s) had been met, and detailed description of the method used that would facilitate replication. Finally, they noted that existing approaches did not usually consider how time might affect aspects of the evaluation process, such as development of expertise. In response to these findings, they made the following observation:

> *"… if one wants to 'evaluate' something, it is essential to provide basic information such as the goal of the evaluation, how it was performed … and what results were achieved. Otherwise, the information provided is not meaningful to the community."* [4, p. 160]

Brown, Nash, and Mitchell's [5] meta-analysis examined music interaction evaluations from 2014 to 2016 in three venues: the NIME conference, the ICMC, and the Sound and Music Computing (SMC) conference. In contrast to the reviews already discussed, Brown, Nash, and Mitchell focused on evaluation of UX. Like previous reviews, they noted the ongoing prevalence of informal methods. They also reported that, while certain components of UX, such as aesthetic response, were evaluated fairly frequently, other experiential factors, such as enchantment, motivation, and frustration were less examined, meaning that current strategies may not provide insight into the process by which users develop an emotional attachment to DMIs.

The final review, performed by the author of this thesis [6] conducted a systematic literature review of the published proceedings from four recent years of the NIME conference (2017 to 2020), with the goal of understanding how UX-focused evaluations were planned and executed, as well as their intended goal(s). To be comparable to previous research, this review used many of the same descriptor categories and category members as prior reviews (such as time span, stakeholder implicated, data collection methods used, etc.). This final review illustrated that UX evaluation strategies employed within NIME were often short-term, focused on novices' initial interactions with an instrument, and conducted without the use of available formal and structured evaluation tools. Thus, evaluations conducted were unlikely to provide insight with respect to expert use, or how dynamic experiential factors and the UIR might evolve over time. Additionally, lack of methodological information rendered these evaluations difficult or impossible for other researchers to replicate [6].

In general, these reviews suggest that evaluation methods are often informal, idiosyncratic, lacking structure, and conducted over short time periods with novice users [6; 12]. Given these limitations, a number of possible strategies exist to improve and expand DMI evaluation research. Several of these strategies are introduced in the following subsection.

2.3.4 Expanding Evaluation Strategies

Several authors [6; 12; 31; 35; 36; 37] have identified a need for increased longitudinal study of DMI usage, as research conducted over time is necessary for understanding expertise development [6], evolution of musical technique [36], and formation of the UIR [31].

The short timeframe of many DMI evaluation strategies, by its very nature, produces temporally-limited data. This means that performers are not given adequate time to accumulate skill or develop relationships during the evaluation period. Moreover, such evaluation strategies do not lend themselves to studying how aspects of experience (such as hedonic and cognitive factors) change over time, meaning that much of the information reported about UX with DMIs is temporally-limited [6]. Use of existing structured frameworks and assessment tools could increase the extent to which such evaluations are formal and systematic, facilitating replicability and comparison of different DMIs or iterations thereof. One very recent demonstration of longitudinal DMI evaluation was conducted by Mice and McPherson [78], who studied the effect of reducing instrument size on embodiment over a three-week period.

The second major limitation of current strategies is their idiosyncratic nature [12]. While some particularities of NIME research provide impetus for such approaches, it is still possible to make use of existing structured frameworks and assessment tools, though these are often ignored by the community [12]. While established techniques from HCI may not be fully compatible with the study of DMI use [12], adaptation of pre-established methods for use with DMIs could allow researchers to increase the rigour and formality of their evaluations and facilitate replicability and comparison. Reimer and Wanderley [6] suggest that well thought-out evaluations, with specific goals, outcome measurements, and formal structure, could produce more communicable and replicable results when compared with ad-hoc and idiosyncratic approaches.

While short-term exploratory research with novice users can provide rich data sets that can be used to inform design modifications and future evaluation targets, this sort of research often lacks the scientific rigour or structure to facilitate formal hypothesis testing, or to produce comparable measurements at multiple points over a longer period of time. Evaluations that examine generic UX can be useful in understanding some aspects of emergent behaviour in users during their first experience with a new technology, but are also liable to miss important aspects of interaction due to their lack of predetermined aspects of UX to target [6]. Additionally, qualitative methods may be more useful than quantitative ones for understanding the creative and expressive affordances of a musical interface [7].

In light of the limitations of current UX evaluation strategies discussed in [6], the authors identified a number of evaluation tools that are not commonly used in NIME research, but that show potential for studying dynamic aspects of UX in a formal and systematic manner. Reimer and Wanderley [6] list four areas of less common evaluative tools that demonstrate promise for rigorous and structured evaluation, and that could be administered at multiple points during longitudinal research:

1. Systematic strategies from within music technology research, including the MPX-Q [40] and crowd-sourced tagging [86];
2. Standardized questionnaires from HCI and product design, such as System Usability Scales, the NASA Task Load Index, Semantic Scales, and the Positive Affect Negative Affect Schedule [12; 75; 85], which show potential for delving into user perceptions of usability, learnability, explorability, and controllability, as well as affective and cognitive states;
3. Non-intrusive continuous physiological measures, including facial expression and biosignals, which can be taken with minimal interruption to musical tasks [7; 56; 71], and offer insight into cognitive and affective state [85; 87];
4. Questionnaires from affective computing, interactive arts, and ludology (the study of gaming), which assess experiential phenomena such as aesthetic response, skill, joy of use, concentration, creativity, pleasure, flow, and immersion [17; 56; 85].

Through use of structured tools, in addition to careful planning and execution of evaluations, it is hoped that evaluation research could be improved to provide insight into experiential aspects of DMI musicianship [6]. Increased use of established tools, longitudinal formats, systematic approaches, and replicable methods facilitates further understanding of dynamic experiential aspects of music interaction with DMIs, encourages community members to formalize, share, and replicate each others work, and, ultimately, provides informative and meaningful data to the DMI research and performance community [6]. Development and demonstration of just such an approach is the primary contribution of this thesis.

Chapter 3: Materials and Methods

To investigate the development of the relationship between a musician and a DMI over a period of time, a research procedure for structured longitudinal evaluation was developed with the goals of understanding the dynamic nature of hedonic and cognitive aspects of experience, characterizing the changing UIR over a learning period, and measuring changes in UX and engagement over time, using interview and survey methods. A study designed to demonstrate this method and inform further research in this area was conducted at the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT), located on the McGill University campus. Over a twenty-day period in the spring of 2022, three participants learned to play the T-Stick through a series of musical tasks of increasing complexity, created and performed an original musical excerpt, and participated in surveys and interviews investigating their experience. This research was approved by the Research Ethics Board at McGill University.

The methodology was created to address the research questions introduced in <u>Chapter 1</u>:

1. To what extent is an evaluation method able to capture dynamic aspects of UX and development of the UIR over the process of learning to play an unfamiliar DMI?
2. What do these measures of UX reveal with respect to factors that contribute to adoption, sustained use, and longevity of DMIs?

3.1 Participants and Research Environment

Four participants were recruited by requesting volunteers from research labs affiliated with music technology and HCI, although one was unable to participate beyond the introductory session for personal reasons. The remaining participants completed the entire study. Given that this project was primarily intended as a demonstration of a new longitudinal evaluation method, recruited participants were only required to meet two general inclusion criteria:

1. They responded *"Yes"* to an item on a pre-screening questionnaire (PSQ) item indicating they were interested in DMIs;
2. They had some familiarity with music technology setups.

These criteria were deemed sufficient, as individuals with existing knowledge of music technology (including limited knowledge of the T-Stick) would have the vocabulary and knowledge to provide insight related to the design of the instrument hardware, mappings, and sound synthesis, as well as to provide critical commentary on the overall methodology.

Three participants completed the full study, consisting of seven sessions over 20 days, and were compensated with $80.00 CAD. The study was conducted in the Perceptual Testing Lab at CIRMMT. Participants were provided with a T-Stick, connected wirelessly to a GuitarAMI Sound Processing Unit (SPU), a standalone Wi-Fi-compatible device capable of audio processing and hosting synthesis patches [88]. Mono audio from the SPU was routed through an Allen & Heath ZED-FX10 mixer to two Genelec 8020A monitors, mounted at approximately shoulder height (when standing). Audiovisual recordings were taken using the internal webcam and microphone on a MacBook Pro. A desktop computer was used to record participant responses to survey questions. Additionally, a large TV screen was mounted on the wall of the room.

3.2 Materials and Tools

The instrument apparatus for the current project consisted of hardware (Sopranino T-Stick; Figure 3-1), a sound synthesis patch, created in Pure Data and hosted on the SPU (Figure 3-2; [88]), and a mapping layer which created correspondences between the T-Stick's embedded gestures [50; 89] and synthesizer parameters. Further information on construction and operation of the T-Stick is publicly available at https://github.com/IDMIL/T-Stick.

Figure 3-1: Fully-Assembled Sopranino T-Stick Hardware

3.2.1 Hardware

The T-Stick is a DMI created by embedding sensors (accelerometers, force-sensitive resistors, and capacitive sensors) within ABS plumbing pipe [19; 38]. Pipe length can be varied, such that a family of instruments (alto, soprano, sopranino, etc.), based on *"spectral and temporal features"* [38, p. 66] is possible [29; 38]. The T-Stick was chosen for several reasons [29; 38]:

1. The T-Stick's design has had a relatively stable design over its 15-year history, and the instrument has been used by multiple individuals in research, composition, workshop, and public performance contexts;
2. More than 30 copies were built, at least 10 of which were sopranino T-Sticks, allowing for a comfortable choice of devices for longitudinal studies involving multiple performers;
3. In tandem with the SPU, the T-Stick could be used wirelessly without direct connection to a computer, providing a practice scenario more akin to that of acoustic instruments;
4. The development of embedded gestures for the T-Stick [50; 89] meant that it was already possible to extract meaningful gestural data from the hardware's raw sensor data;
5. Ongoing research conducted at the Input Devices and Music Interaction Laboratory (IDMIL) meant that T-Stick performers and researchers were readily available to assist with development of synthesis, mappings, and tasks, representative of real-world T-Stick practice;
6. The T-Stick was developed at the IDMIL, meaning technical support and redundant hardware was readily available in the event of small glitches or hardware failure.

Figure 3-2: GuitarAMI Sound Processing Unit (SPU)

Table 3-1 displays the list of embedded gestures available for the T-Stick [50; 89] and to which sensors they correspond.

Gesture	Sensor	Task Instructions
Touch	Capacitive Sensors	Uses capacitive sensors along the length of the T-Stick to sense the amount of surface area being touched. Calculated for three zones (Top/Middle/Bottom), which can be combined into one (All), which includes the entire length. Positive values only.
Brush/MultiBrush	Capacitive Sensors	Senses movement along capacitive sensors on the surface of the T-Stick, in two directions parallel to the length. Higher velocity movement will output a higher value. Can be sensed using one point of contact (Brush), or multiple (up to four; MultiBrush). Positive or negative values depending on Brush direction.
Rub/MultiRub	Capacitive Sensors	Senses continuous, bidirectional movement applied to the capacitive sensors. Higher velocity movement and increased distance of movement (length) will output a higher value. Values accumulate over time before smoothly decreasing when rubbing is stopped. Can be sensed using one point of contact (Rub), or multiple (up to four; MultiRub). Positive values only.
Shake	Gyroscope	Uses the gyroscope to sense the energy of rapid continuous movement in three dimensions (XYZ). More vigorous movement will output a higher value. Values accumulate over time. Positive or negative values depending on Shake direction.
Jab	Gyroscope	Uses the gyroscope to sense the energy of short, impulsive, forward-back movements in three dimensions (XYZ). Higher speed will output a higher value. Positive or negative values depending on Jab direction.
YPR (Yaw/Pitch/Roll)	Inertial Measurement Unit (IMU)	Uses the IMU to sense the orientation, rotation, and tilt of the T-Stick in three dimensional (XYZ) space. Positive or negative values.

Table 3-1: T-Stick Embedded Gestures

3.2.2 Sound Synthesis

The sound synthesis portion of the instrument apparatus consisted of the SPU and a sound synthesis patch hosted on the device. The patch was a dual-voice synthesizer with sawtooth and square wave voices, as well as a low-pass filter and reverb generator. The synthesizer was developed by T. West in Pure Data and was inspired by a patch previously developed by West for research that investigated how participants created T-Stick mappings from scratch [51]. The patch was further developed by K. Pocius, an active T-Stick performer, who added functionality and refined operation for the specific hardware, mapping, and task requirements of this research.

The Pure Data patch made six sonic parameters available for mapping. These parameters were then mapped to respond to incoming data from the T-Stick's sensors and embedded gestures. These parameters are detailed in Table 3-2.

Parameter	Description
Energy	Controls both amplitude and brightness, sounding harsh at higher parameter values.
Frequency	Controls the fundamental frequency of the two oscillators in the patch, limited to a baritenor range.
Timbre	Controls a crossfade between the two voices of the synthesizer.
Cutoff	Controls the cutoff frequency of the synthesizer's low-pass filter. Cutoff can be used to dampen excessive brightness resulting from high Energy values.
Resonance	Controls the Q value of the low-pass filter. High values result in self-oscillation.
Reverb	Controls both the crossfade and time of the synthesizer's reverberation. High values result in infinite reverb.

Table 3-2: Synthesis Patch Parameters

3.2.3 Mappings

Development of mapping and tasks involved consultation and brainstorming sessions with active T-Stick performers and researchers at the IDMIL, including T. Fukuda, J. Malloch, E. A. L. Meneses, K. Pocius, D. A. Stewart, M. M. Wanderley, and T. West. Performance materials, including videos, mappings, and synthesis patches, were collected from performers and reviewed to develop an initial list of potential mapping correspondences and tasks based upon these mappings. Following exploration of these resources, the lists of potential mappings and tasks were revised based on the parameters available in the synthesizer patch (Table 3-2). Rather than using an existing T-Stick mapping, a new mapping was developed drawing inspiration from the mappings of existing performers that were reviewed. This strategy was chosen for two reasons: first, many of the mappings reviewed existed in an archived form, and it was unclear whether they would be compatible with current software setups or current iterations of the T-Stick hardware. Furthermore, many of these existing mappings were created in Max/MSP, and, as such, were not compatible with the SPU. Second, in developing an original mapping for the T-Stick, it was possible to draw inspiration from the mappings of multiple T-Stick musicians, rather than relying on the setup of a single performer. It was hoped that this would produce an interaction scenario that resembled an averaging of several setups rather than using a mapping developed by a single performer for a single piece.

The next phase of development involved meetings of the research group to identify which of the possible mapping choices would allow for development of a set of achievable tasks of increasing complexity that would also be representative of real-world T-Stick performance practice. Once the mappings were decided upon, Pocius aided in further development of West's synthesis patch to support these mappings and optimize performance of the patch for the specific hardware, mapping, and task requirements of this study. One major alteration was the addition of a Rain Stick Mode which allowed users to access a second synthesis mode that was more percussive than the primary Drone Mode. The list of mappings used is displayed in Table 3-3.

Input Data	**Mapping**
Touch - Position	Touch position detected using capacitive sensors along the length of the T-Stick is used to activate five frequency zones at different locations along the length of the instrument. Rain Stick Mode is activated when touch is detected at both ends of the T-Stick.
Touch - Pressure	Force-sensitive resistors sense the amount of pressure applied to the T-Stick's surface. Pressure is mapped to amplitude, such that more applied force increases the energy parameter of the synthesizer.
Jab	The Jab gesture sets the low-pass filter cutoff frequency. A higher energy jab will set a higher frequency cutoff, allowing more high frequency content through the filter.
Shake	The Shake gesture changes the value of the synthesizer's reverb parameter. More energetic movements increase the amount of reverberation applied to the signal, to an infinite amount.
YPR - Pitch	Controls the resonance parameter of the low-pass filter.
YPR - Roll	Controls the timbre parameter of the synthesizer.

Table 3-3: Mappings between T-Stick Data and Synthesis Parameters

3.2.4 Task Cycles

Ten gestural tasks, divided into four task cycles, were developed concurrently with mapping such that ideation related to mapping was used to develop the tasks and vice-versa. Tasks were designed to be learnable within a short period of time, to be representative of real-world T-Stick performance, and to allow for the combination of tasks in a manner that produced useful musical results. While HCI evaluation tasks are commonly designed to assess functionality, the nature of music interaction over an extended timespan required that it also be possible for participants to use these tasks in a musically expressive manner, and to be able to incorporate them into a musical performance. As such, the order of tasks was intended to increase in complexity, beginning with control over fundamental sonic parameters (such as amplitude and frequency), and gradually exposing additional parameters for manipulation. The specific tasks and mapping for which they were developed have not been used previously in DMI research.

Tasks were provided to participants in the form of audiovisual tutorials. Each video consisted of a task title, a depiction of Pocius executing the task, and embedded text instructions describing how the task is performed. The set of tasks is presented in Table 3-4. Each task name is linked to the audiovisual demonstration.

Task ID	Task Name	Task Cycle	Presentation Session	Evaluation Session	Task Instructions
T01	Framing	C1	ENI	S1	To hold the T-Stick without producing any sound, the instrument can be grasped by the top cap, the bottom cap, or both. Sound is produced when the surface of the T-Stick between the two caps is contacted.
T02	Filter Cutoff	C1	ENI	S1	The cutoff of the low-pass filter sets the frequency below which sound will be passed through. If the cutoff is set too low, no audible sound will be produced. The value is set using the T-Stick's Jab gesture. More physical effort will result in a higher acceleration value, and thus, a higher filter cutoff.
T03	Amplitude	C1	ENI	S1	The volume of the output can be set by applying varying levels of pressure along the surface of the instrument between the two caps.

Task ID	Task Name	Task Cycle	Presentation Session	Evaluation Session	Task Instructions
T04	Frequency	C2	S1	S2	Five frequency zones are distributed along the length of the T-Stick. Touching each zone will produce a different frequency, the amplitude of which can be controlled by the amount of pressure applied.
T05	Timbre	C2	S1	S2	Timbre controls the mix between two voices of the synthesizer. It is mapped to the roll parameter of the accelerometer, and can be controlled by moving the T-Stick through space in the roll dimension.
T06	Resonance	C2	S1	S2	The resonance of the low-pass filter is mapped to the pitch parameter of the accelerometer, and can be controlled by moving the T-Stick through space in the pitch dimension.
T07	Infinite Reverb	C3	S2	S3	Reverb is controlled by shaking the T-Stick. A more energetic Shake gesture will produce more reverberation. When the maximum amount of reverb is attained through continuous shaking, an infinite reverb can be produced by maintaining this energy.
T08	Low Level Reverb	C3	S2	S3	Reverb is controlled by shaking the T-Stick. A low to moderate level of reverb can be maintained by shaking the T-Stick with a small to medium amount of energy. Reverb can be sustained by continuously applying this same amount of energy to the shaking gesture.
T09	Rain Stick Mode	C4	S3	S4	The Rain Stick Mode changes the sound of the T-Stick from the Drone Mode synthesizer to a more percussive granular sound. This mode can be activated by grasping the T-Stick at each end of the touch-sensitive surface (beyond the caps).
T10	Mode Switching	C4	S3	S4	This tasks consists of shifting fluidly between the Drone Mode and the Rain Stick Mode.

Table 3-4: Task List and Instructions

3.3 Study Overview

This study consisted of six stages, containing a variety of components and data collection strategies. These stages are summarized in Table 3-5, and detailed in the sections following.

Stage Number	Stage Name	Stage Components
1	Pre-Screening Questionnaire	Eligibility screening
		Participants' background and experience
2	Introductory Session	Informed consent
		Entrance interview
		Open exploration
		First impressions questionnaire
3	Task Cycle (x5)	Task demonstration (x4). Participants were provided with demonstrated tasks for the first four practice sessions. The fifth session was to prepare their original excerpt.
		Practice session (x5)
4	Evaluation Session (x5)	Task performance (x4)
		Evaluation session questionnaire (x5)
		Evaluation session interview (x5)
5	Final Evaluation Session	Final performance of original musical excerpt
		Exit questionnaire
		Exit interview
6	Third-Party Evaluation	Third-party ratings of participants' final performances

Table 3-5: Study Overview

3.3.1 Pre-Screening Questionnaire

A call for participants was distributed through mailing lists for music technology and HCI labs affiliated with the research group. Four participants expressed interest. Prior to being admitted to the study, these individuals were emailed the PSQ to assess their eligibility and to collect information about their interest in, and previous experience with, music technology setups. Inclusion criteria for the study are outlined in Section 3.1. The full PSQ is presented in Section A.1 in Appendix A. All four individuals were deemed eligible to participate, although one was unable to participate beyond the introductory session for personal reason. This participant's introductory session data was discarded. The remaining three participants completed all stages of the study.

3.3.2 Introductory Session, Entrance Interview, and Open Exploration

After it was determined that participants met the inclusion criteria for the study, they were each invited to an individual introductory session consisting of informed consent, entrance interview (ENI), open exploration of the musical apparatus, and the first impressions questionnaire (FIQ). At the end of the session, the first task cycle (T01 to T03) was presented. Participants were first asked to review and sign a consent form to indicate their willingness to participate. They were informed of the risks (no perceived risks), as well as details of their compensation.

ENI questions related to participants' performance experience and general attitudes about DMIs. Questions were developed by the researchers or sourced from the Electronic Musical Instrument Survey [59], which investigates factors that influence uptake of, and long-term engagement with, DMIs. ENI questions are reproduced in Section B.1 in Appendix B.

Following ENI, participants were given five minutes of unguided exploration using the T-Stick without researchers present. After five minutes had elapsed, participants were asked to complete the FIQ, hosted on Microsoft Forms. Participants were asked to rate the extent to which they agreed or disagreed with five survey items, related to their first impressions of the T-Stick. While all participants were aware of the T-Stick prior to beginning the study, this questionnaire was intended to assess their first, direct interactions with the instrument, as users in a music-making context. Items were scored using a 5-point Likert Scale, ranging from *"Strongly Disagree"* to *"Strongly Agree."* Items were sourced from the UES Short Form [76], and the MPX-Q [40]. An additional item, added by the researchers, asked participants to rate the extent to which they found the mapping intuitive. The questionnaire is provided in Section A.2 in Appendix A.

After completion of the FIQ, participants were shown demonstration videos for the first task cycle, and asked to schedule practice times for the remainder of the study. They were given the option to practice either immediately before, or immediately after, each evaluation session. All participants opted to schedule their practice time before each evaluation session.

3.3.3 Task Cycles and Evaluation Sessions

The majority of data collection occurred during the four task cycles (C1 to C4), conducted three to four days apart, each of which had a corresponding evaluation session (S1 to S4) in which participants responded to a series of interview and survey questions related to their experience that cycle. Following the four task cycles, participants were given one additional hour of practice time to review all previous tasks and work on their original musical excerpt. After this practice, the final evaluation session (S5) was conducted. Evaluation sessions ranged in length from 15 to 45 minutes.

Task cycles consisted of demonstrations, followed by a period during which participants were asked to practice the tasks for that cycle. Tasks were demonstrated for participants using videos uploaded to a private YouTube channel. Researchers were present during the demonstration to answer task-related questions for participants. After the initial demonstration with researchers present, participants were emailed links to each video and informed that they could watch the videos as many times as desired.

For each set of demonstrated tasks, participants were given up to 60 minutes of independent practice time. They were asked to practice with the T-Stick until they felt able to comfortably replicate each task. Participants were left alone in the lab with the door closed for the practice period, though a researcher was available on the premises to answer questions or provide technical support. Participants were instructed to retrieve the researcher to conduct the evaluation session when they finished practicing. If a participant used the full amount of allotted time, they were interrupted by a researcher to initiate the evaluation session after one hour.

Evaluation sessions consisted of three components. First, participants were asked to perform each task from the cycle in front of the researchers. For S5, there were no tasks to be evaluated, but participants performed their original musical excerpt. Audio and video of each task and performance was recorded.

Second, participants completed the evaluation session questionnaire (ESQ) on Microsoft Forms. The survey asked participants to rate their ability to perform each task on a 3-point scale (*"No," "Sometimes," "Yes"*), and to rate the extent to which they agreed with 14 statements on a 5-point Likert Scale (from *"Strongly Disagree"* to *"Strongly Agree"*). Items were sourced from the UES Short Form [76] and MPX-Q [40]. The ESQ is reproduced Section A.3 in Appendix A.

Finally, an evaluation session interview was conducted with each participant consisting of three open-ended interview questions related to individuals' practice experience during the task cycle. Audio and video of each interview was recorded. Interview questions and prompts are reproduced in Section B.2 in Appendix B. Following the session interview, the next cycle was initiated and participants were shown demonstration videos for that set of tasks.

3.3.4 Final Performance

During the introductory session, participants were informed that, in addition to the completion of each cycle, they would be required to prepare and perform a short musical excerpt of their own creation prior to the final evaluation session (S5). They were also informed that AV recordings of their performances would be reviewed by members of the research team. These team members contributed to development of the musical apparatus, but were not directly involved in creation of the methodology or in data collection. Participants were instructed to incorporate as many of the learned gestural tasks as possible. Following the final practice period, participants were asked to perform their original excerpt for the researchers. Audio and video recordings were taken of each performance. After their performance, the final evaluation session was conducted.

3.3.5 Exit Questionnaire and Exit Interview

Following their final performances and S5, participants completed an exit questionnaire (on Microsoft Forms) and interview, related to their cumulative experience over the entire study, specific positive and negative experiences, and suggestions for improvements to the musical apparatus. Questions were primarily developed during meetings of the research team, though three items were sourced from the MPX-Q [40]. Audio and video recordings were taken of the interviews. The exit questionnaire is reproduced in Section A.4 in Appendix A. Exit interview questions and prompts are available in Section B.3 in Appendix B.

3.3.6 Third-Party Evaluator Ratings

The final component of data collection consisted of a short survey distributed to two third-party evaluators using Google Forms. Evaluators were both members of the IDMIL who have been involved with the T-Stick research project for multiple years as researchers and performers. Both evaluators aided in development of the synthesis and mapping of the instrument used in this research, but did not contribute to the study design or data collection. Given their affiliation with the IDMIL, as well as their research and performance experience with the T-Stick, these evaluators were considered to have a level of expertise appropriate for providing assessment of participant performances. Evaluators were provided with the videos of each participants' final performance and asked to rate and comment upon the range of gestures used, the smoothness of the performer's motion, the apparent responsiveness of the instrument to the performer's gestures, and the overall quality of the performance. The full third-party evaluator questionnaire is available in Section A.5 in Appendix A.

This component was included to provide a third-party assessment of the extent to which the tasks could be learned and used, as well as how successful a novice could be in learning to perform with the instrument over a period of time. Results could then be used to refine the instrument hardware, mappings, sound synthesis, and the study methodology.

3.3.7 Measurements and Data Collection

Both qualitative data and scale ratings about participant experience were collected throughout the study. Questions used for the survey and interview components were either researcher-developed or sourced from one of three existing surveys: the EMI Survey [59], the UES Short-Form [76], or the MPX-Q [40]. Table 3-6 provides a complete record of question sources. Questionnaires and interview guides are reproduced in full in Appendices A and B.

Data Collection	Construct of Interest	Researcher -Developed	EMI	MPX-Q	UES
Pre-Screening Questionnaire (PSQ)	Potential participants' interest in and experience with DMIs	Q1, Q4, Q6	Q2, Q3, Q5	N/A	N/A
Entrance Interview (ENI)	DMI use, performance, and general attitudes, as well as previous experience with the T-Stick and other music technology	Q1, Q3, Q5, Q9 to Q11	Q2, Q4, Q6 to Q8	N/A	N/A
First Impressions Questionnaire (FIQ)	First impressions of the musical apparatus	Q5	N/A	Q4	Q1 to Q3
Evaluation Session Task Performance (x4)	Participants' ability to perform tasks from each block	N/A	N/A	N/A	N/A
Evaluation Session Questionnaire (x5; ESQ; S1 to S5)	Participants' perceptions of the instrument while learning to perform the tasks from each block	N/A	N/A	Q5 to Q14	Q1 to Q4
Evaluation Session Interviews (x5; S1 to S5)	Participants' experience learning to perform the tasks from each block	Q1 to Q3	N/A	N/A	N/A

Data Collection	Construct of Interest	Researcher -Developed	EMI	MPX-Q	UES
Final Performance	Participants' ability to recall, perform, and combine tasks from each block, in the context of a larger musical structure	N/A	N/A	N/A	N/A
Exit Questionnaire	Participants' overall perceptions of the instrument after learning all tasks, and their interest in ongoing use of the instrument	Q4 to Q5	N/A	Q1 to Q3	N/A
Exit Interview (EXI)	Participants' experience over the entire study, and their relationship with the instrument	Q1 to Q10	N/A	N/A	N/A
Third-Party Evaluator Questionnaire	Third-party evaluators' perceptions of the range of gestures, smoothness of motion, and overall quality of participants' final performance	Q1 to Q4	N/A	N/A	N/A

Table 3-6: Target Constructs and Question Sources for Data Collection

3.4 Related Works: Procedural and Methodological Similarities

With regard to the procedural structure and data collection strategies used in the current study, several similarities to recent music interaction evaluations are of note. A brief description of these similarities is presented for two reasons: 1) to partially illustrate the shift of DMI evaluation research towards more experientially-focused strategies; and 2) to credit these researchers for helping to inspire aspects of the methodology described in this chapter.

Young, Murphy, and Weeter [57] investigated the influence of haptic feedback on DMI interaction. The authors used specific pitch selection tasks, free exploration, and user training. Data collection included pre-existing, validated HCI surveys, and semi-structured interviews, which captured aspects of participant perceptions related to instrument functionality, usability, and UX.

Moro and McPherson [36] evaluated an augmented keyboard to investigate how musicians already skilled at piano performance leveraged existing techniques in the development of their relationship with this DMI. Similar to [57], the researchers incorporated open evaluation and training of musical tasks. Additionally, the authors required participants to create original musical content for the evaluation, the performance of which was assessed by third-party evaluators. Finally, the authors made use of semi-structured interview techniques focused on UX.

Research presented by Leigh and Lee [90] at NIME 2021 investigated the learning of skilled techniques with a robotic guitar. Similar to [57], the researchers employed both survey questions and semi-structured interviews to collect data about participants' experience.

Finally, in a study carried out at the same time as the research described in this work, Mice and McPherson [78] studied the effect of instrument size on the embodiment relationship between performer and instrument. Notably, this evaluation was longitudinal, spanning a three-week period. The researchers asked individuals to develop and perform original musical works, which were captured using audio and video recording. Finally, the authors made use of semi-structured interview techniques and thematic analysis methods.

Commonalities between recent publications and the research reported in this work are summarized as follows:

1. Use of open exploration, training of specific musical tasks or techniques, and creation of original musical content presented to researchers or third-parties;
2. Adaptation of existing survey questions for data collection; and
3. Development of focused, semi-structured interviews to investigate aspects of UX.

Chapter 4: Analysis and Results

This chapter describes analyses performed on the data, introduces observed patterns in scale ratings data, and describes themes that emerged from analysis of qualitative data. All collected data is also available at https://gitlab.com/creimer/longitudinal-evaluation-of-dmis. Analysis is divided into three sections, based on the different strategies used for data collection.

Section 4.1 addresses ratings data, including participants' ratings of their ability to perform each task, and their responses to survey questions. Results from these sources indicate the effectiveness of the research strategy used, demonstrating that the task set used is learnable and that the method is sufficient in capturing the experiential constructs of interest. Furthermore, scale ratings taken at multiple points in time provide insight into how UX changes during learning. Evidence of both general trends and trajectories unique to each participant is provided.

Section 4.2 describes the qualitative data collected through participant interviews. This data further characterizes the parallels and divergences of participants' experiences when learning to play the T-Stick, and provides detailed insight into hedonic and cognitive factors, the developing UIR, the learning process, and ideation for future use of the instrument.

Section 4.3 concerns ratings and related commentary provided by third-party evaluators. This data serves as further indication of the effectiveness of the methodological approach employed in this work, illustrating that, even over a limited time period, participants were able to become competent T-Stick performers, whose skill level was apparent to third-party observers. Additionally, third-party evaluator data provides further evidence that the research structure and musical tasks used were an effective method for participants to learn to play the T-Stick and develop a competent level of skill, despite having little to no prior experience with it.

Key analytical findings, discussed in detail in Chapter 5, are summarized as follows:

1. While learning and UIR development showed high-level similarities, each participant's experience demonstrated distinct character, trajectory, and interaction strategies, largely reflective of their individual musical backgrounds, performance practices, and priorities;
2. Even over a limited time, there was evidence for appropriation and the development of an intimate UIR. Furthermore, hedonic and cognitive aspects of UX showed changes over the course of learning and the corresponding development of this relationship;
3. Finally, and of most importance with respect to the goals of this research, the

methodology and data collection strategies used were shown to sufficiently capture the constructs of interest, as well as their dynamic nature. Consequently, this method shows strong potential for structured longitudinal evaluation of UX with DMIs.

To provide necessary context for the analyses presented, it should be noted that participants represented three differing musical perspectives, self-identified in responses to PSQ and ENI questions. P1 reported being a composer, P2 was a performer who played for audiences regularly, in-person and online, and P3 was a hobbyist. Responses to the PSQ are presented in Table 4-1.

Item	P1	P2	P3
Do you have an interest in digital/ electronic musical instruments?	Yes	Yes	Yes
Which types of DMIs/EMIs have you used before?	MIDI controllers, Computer software	Keyboard synthesizers, Modular synthesizers, Samplers, Drum machines, FX processors, FX pedals, MIDI controllers, Computer software	MIDI controllers, Computer software
Which DMIs/EMIs do you use regularly?	Karlax	Drum machines, Keyboard synthesizers, Samplers, Computer software, FX pedals	MIDI keyboard connected to a DAW or SuperCollider
In which of the following contexts do you use DMIs	Personal practice	Live performance	Personal practice
How many times in a typical year do you perform in public?	0 to 10	21 to 50	0 to 10

Table 4-1: Pre-Screening Questionnaire Responses

The PSQ showed that all participants had some previous experience with DMIs. While P1 and P3 identified their primary context of DMI usage was *"Personal practice"* (they performed for public audiences between 0 and 10 times per year), P2's primary context of use was *"Live performance"* (they performed 21 to 50 times per year). P2 also indicated they had used (and currently use) a variety of DMIs, including modular synthesizers, keyboards, samplers, drum machines, effects processors and pedals, computer software, and MIDI controllers. In contrast, P1 and P3 both indicated previous experience with MIDI controllers and computer software only. P3 indicated that their current DMI usage was *"a MIDI keyboard connected to a DAW or SuperCollider"* [PSQ]. P1 reported regularly using the Karlax, a DMI that has been manufactured for several years, and has been made commercially available in limited quantities.

4.1 Participant Ratings Data

Ratings data consisted of four components: participants' self-rated ability to perform each task, as well as responses to items from the FIQ, ESQ (x5), and exit questionnaire. Ratings data serves the purposes of demonstrating the tasks used, data collection strategy, and overall methodology, as well as providing general insight into changes in participants' learning experience over time, characterized in more detail through qualitative data described in the following section.

4.1.1 First Impressions Questionnaire

Table 4-2 displays responses to the FIQ, as well as the mean value for each question.

Item Number	Item	P1	P2	P3	Mean
1	I found this instrument confusing to use.	4	3	4	3.7
2	This instrument was aesthetically appealing.	3	2	3	2.7
3	This instrument appealed to my senses.	4	2	4	3.3
4	This instrument produces high quality sound.	3	3	3	3
5	The mapping used is intuitive.	4	3	2	3

Table 4-2: First Impressions Questionnaire Responses
Participants responded with a rating between 1 (*"Strongly Disagree"*) and 5 (*"Strongly Agree"*). A response of 3 was neutral (*"Neither Agree Nor Disagree"*).

Excluding responses to item 5, related to mapping intuitiveness, P1 and P3's ratings were identical. P1 and P3 suggested that the T-Stick was confusing, but appealing to the senses, though they were neutral on the sound quality and aesthetic appeal. P2 was generally more negative, indicating neutrality towards the instrument's sound quality and the extent to which it was confusing, and rating the instrument as not appealing. The most variability occurred in response to the final question; P1 found the mapping intuitive, P2 was neutral on this point, and P3 disagreed. Overall, mean ratings suggested that, while the T-Stick was perceived as somewhat confusing, participants were neutral towards its appeal, sound quality, and mapping intuitiveness, which might be expected given their general lack of previous experience with the instrument.

4.1.2 Task Performance Ability

During the first four evaluation sessions (S1 through S4), participants rated their ability to perform each task from the corresponding cycle (C1 to C4). Responses are displayed in Table 4-3.

Task	Task Cycle	Evaluation Session	P1	P2	P3
Framing	C1	S1	Yes	Yes	Yes
Filter Cutoff	C1	S1	Yes	Sometimes	Sometimes
Amplitude	C1	S1	Yes	Yes	Yes
Frequency	C2	S2	Yes	Sometimes	Sometimes
Timbre	C2	S2	Yes	Yes	Sometimes
Resonance	C2	S2	Yes	Yes	Sometimes
Infinite Reverb	C3	S3	Yes	Yes	Sometimes
Low-Level Reverb	C3	S3	Yes	Yes	Sometimes
Rainstick Mode	C4	S4	Yes	Yes	Yes
Mode Switching	C4	S4	Yes	Yes	Yes

Table 4-3: Participants' Self-Rated Ability to Perform Tasks
Participants were asked to respond with *"Yes," "Sometimes,"* or *"No."*

Three observations from Table 4-3 merit remark. First, responses from P2 and P3 suggest that the filter cutoff (C1) and frequency (C2) tasks posed some difficulty. Second, P3 appeared to struggle more overall with the tasks than other participants, reporting that they were able to perform the majority of tasks (six of ten) only sometimes. Finally, there were no instances in which any participant indicated being entirely unable to perform a task, indicating that all tasks were achievable, but posed differing degrees of difficulty. More detailed discussion of participants' experiences with specific tasks is provided in Section 4.2 on qualitative data.

4.1.3 Evaluation Session Questionnaires

Figure 4-1 displays the mean rating of all three participants for each of the 14 items in the ESQ, and how each of these ratings changed over time. Graphs illustrate that each participant's experiential trajectory over the learning process was unique, although average ratings provide indication of general patterns in experience.

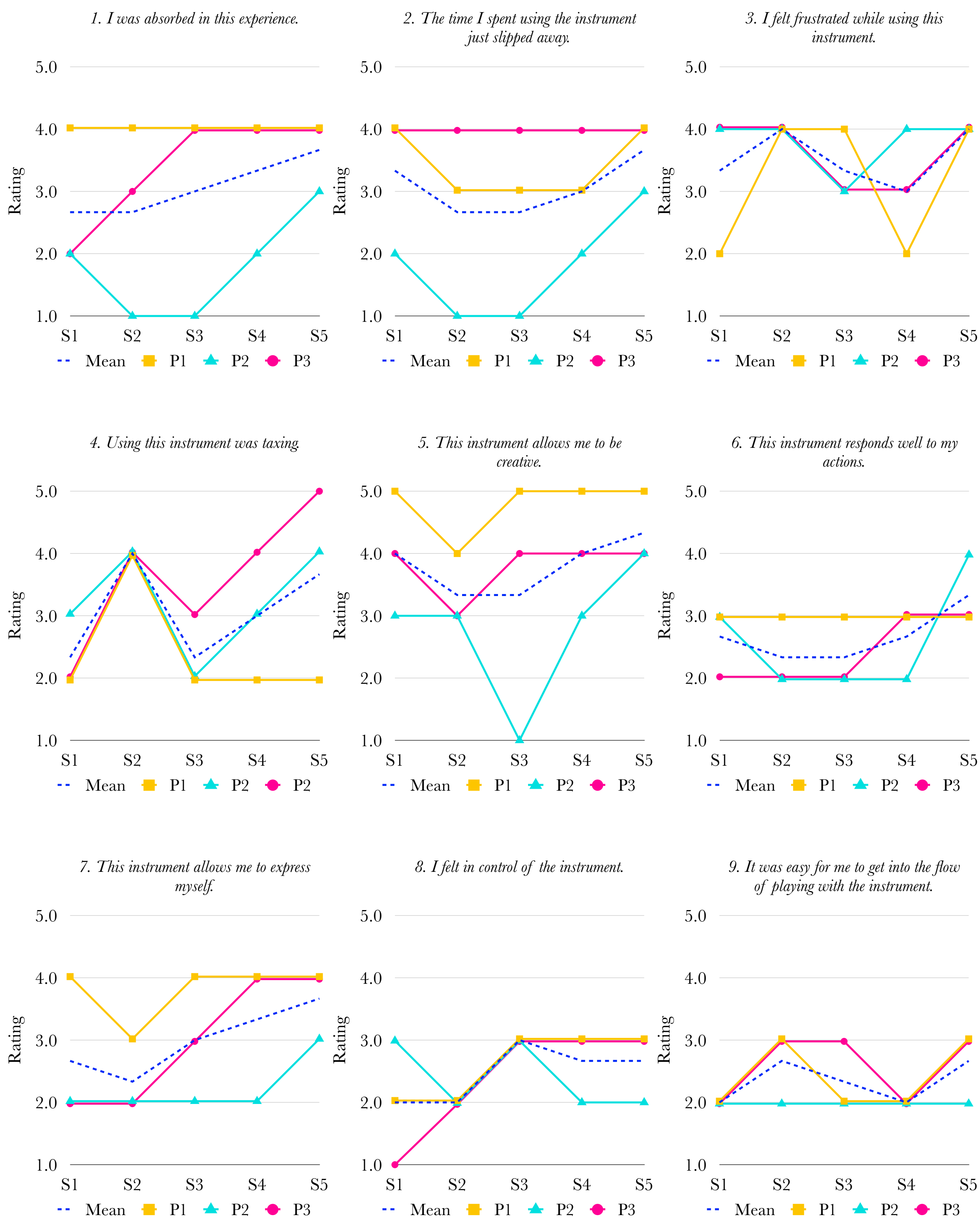

Figure 4-1: Evaluation Session Questionnaire Responses

Ratings (y-axis) for each participant, plotted over time (x-axis), for the five sessions. Participants responded with a rating between 1 (*"Strongly Disagree"*) and 5 (*"Strongly Agree"*). A response of 3 was neutral (*"Neither agree nor disagree"*).

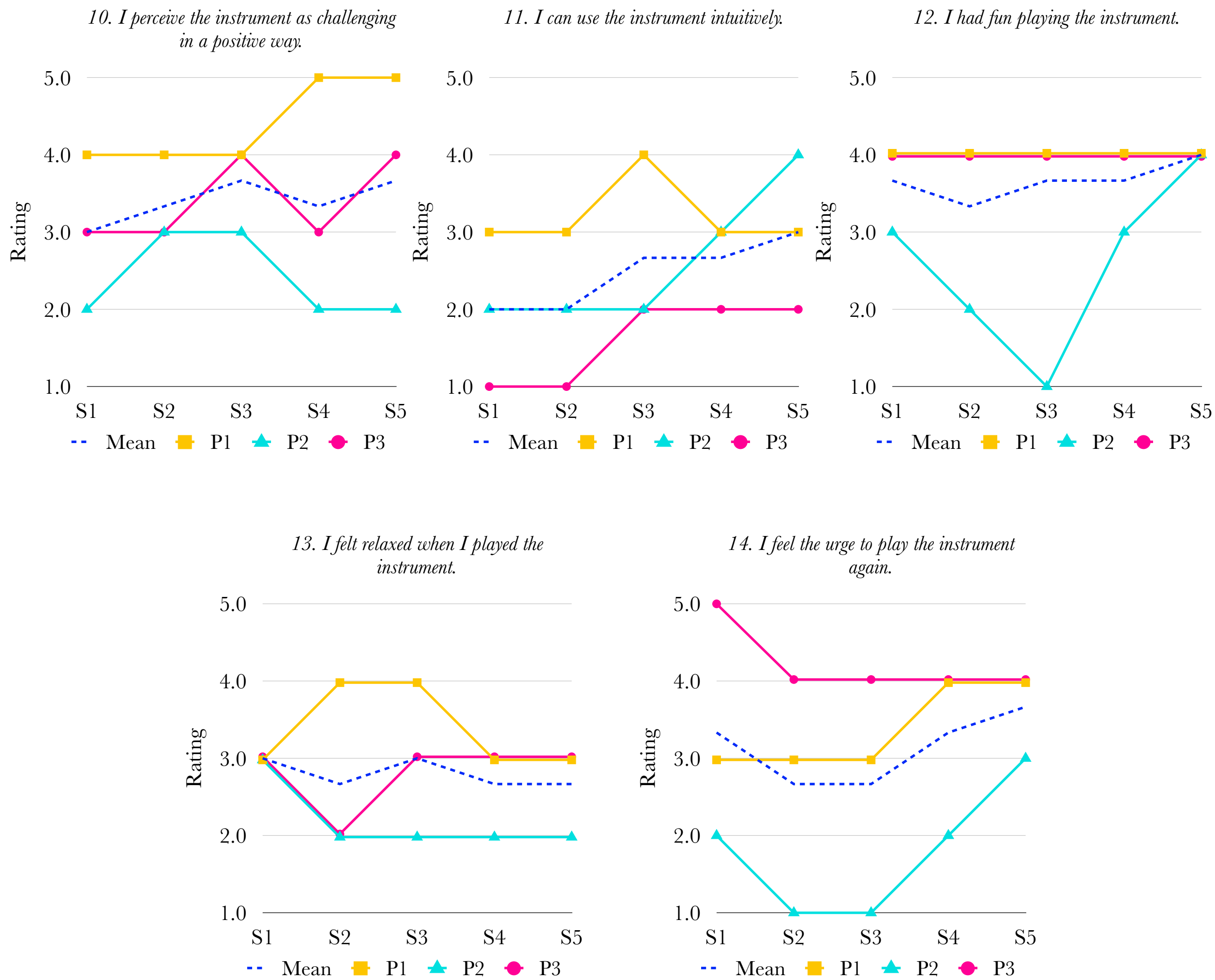

Figure 4-1: Evaluation Session Questionnaire Responses

Ratings (y-axis) for each participant, plotted over time (x-axis), for the five sessions. Participants responded with a rating between 1 (*"Strongly Disagree"*) and 5 (*"Strongly Agree"*). A response of 3 was neutral (*"Neither agree nor disagree"*).

Visual inspection indicates a common checkmark or 'u' shape in several graphs (items 2, 4, 5, 7, 12, and 14), in which participants' average agreement with the statement decreases between S1 and S2, and then increases from S3 through S5. These items related to feelings of time slipping away, instrument responsiveness, feelings of creativity and fun, expressiveness, and a desire to play the instrument again. This could suggest a sort of novelty 'shadow,' in which participants were absorbed in exploring the instrument for the first time, encountered more issues and barriers to absorption during their second practice session, and were then able to rebuild a sense of engagement and enjoyability through continued practice. Alternatively, this dip can be interpreted in the context of the second task cycle (C2), which included frequency, timbre, and resonance, and was evaluated in S2. As indicated in Table 4-3, participants found the frequency task (as well as filter cutoff, from the previous cycle) particularly challenging. Section 4.2 discusses challenges associated with specific tasks in more detail, based on qualitative data.

Other graphs (items 1 and 11), related to absorption and intuitiveness, show a clearer upward trajectory, with the average rating increasing over the learning period, from negative ratings or neutrality, to positive ratings. These findings indicate development of the UIR, in that users became more immersed in playing the instrument as control became more intuitive. It is also likely that continued practice resulted in tasks becoming more natural, intuitive, and unconscious, lowering participants' cognitive load and, thus, facilitating further absorption in the interaction. Given the overlap of experiential factors, such correlations are to be expected.

Visualizations for frustration and the extent to which using the T-Stick was taxing (items 3 and 6) show more variation, fluctuating in different directions over the sessions, and illustrating that changes during the course of learning were not unidirectional. Notably, P1 was the only participant who disagreed with feeling frustrated (S1 and S4), while P2 and P3 were frustrated or neutral throughout. This correlates with the observation that P1 was the only participant who responded exclusively with *"Yes"* when reporting their ability to complete each task (Table 4-3), providing further evidence for an association between specific tasks and experiential factors. Likewise, the S2 spike in ratings of how taxing it was to play the instrument could result from difficulties experienced with the filter cutoff (S1/C1) and frequency (S2/C2) tasks. Finally, P3's ratings for this item increased from S3 to S5, likely as a result of pain experienced when playing the T-Stick, which they reported in later session interviews (Subsection 4.2.4).

Finally, items 8 and 9, related to perceptions of control and ability to reach a flow state, were consistently rated neutral or below for all participants. Two explanations are worthy of consideration. First, this may suggest that control difficulties and responsiveness of the interface presented a barrier to achieving flow. Alternatively, it could indicate that the study was not long enough to allow adequate time for these perceptions of control or flow states to manifest.

It is also noteworthy that for some items, participants provided the same rating across all sessions. In every session, P1 indicated feeling absorbed and having fun, but was neutral towards the instrument's responsiveness. Likewise, P3 reported in every session that they felt as though time was slipping away, and that they were having fun. In contrast, P2 consistently indicated that it was not easy for them to get into the flow of playing. Notably, there were no items for which all three participants provided static ratings across all sessions, suggesting these repeated ratings are reflective of divergent individual experience, rather than a global trend.

With respect to the methodological contributions of this research, ratings data provides evidence that questionnaire items were able to capture changes in the constructs of interest over the learning period. With regard to theoretical contributions, it is worthwhile to note that the factors of interest *do* change, even over periods as short as two to three days.

4.1.4 Exit Questionnaire

Table 4-4 displays participant responses to the exit questionnaire questions.

Item Number	Item	P1	P2	P3	Mean
1	I think the instrument is reliable	2	1	3	2.0
2	I perceive the instrument as solid	4	1	2	2.3
3	In the context of this instrument, I think the sound quality is appropriate	4	3	4	3.7
4	I feel this instrument could be useful in my everyday musical practice	4	3	4	3.7
5	The instrument allows me to do things I cannot do with acoustic instruments/other DMIs I have used in the past	5	4	5	4.7

Table 4-4: Exit Questionnaire Responses
Participants responded with a rating between 1 (*"Strongly Disagree"*) and 5 (*"Strongly Agree"*). A response of 3 was neutral (*"Neither Agree Nor Disagree"*).

Three notable points emerge from the exit questionnaire. First, the T-Stick is generally not perceived as solid or reliable. Second, participants do indicate that the instrument could be useful in their musical practice. Participants also found the sound quality generally appropriate. Finally, the strongest agreement (the highest rating of all the items for all participants) was related to the T-Stick allowing for different possibilities than previously-used acoustic instrument or DMIs.

4.2 Participant Interview Data

This section reports patterns in qualitative data from participant interviews (ENI, S1 through S5, and EXI). Prior to presentation of the data, description of the coding scheme used for analysis is provided. The full interview coding scheme is detailed in Appendix C.

4.2.1 Interview Transcription and Coding Procedures

To prepare data for analysis, audio recordings of all interviews were transcribed. Transcriptions were reviewed for clarity by removing filler words (e.g. *"like," "um," "you know,"* etc.) and repeated words or phrases. Transcriptions were then divided into individual incidents of one or more sentences, focused on a single concept or idea. This resulted in a full set of 277 incidents for all participants over all interviews. Interview data was coded using an approach similar to thematic analysis [91], a method of qualitative analysis in which data is interpreted by assigning codes based on 1) specific themes of the research inquiry (deductive approach), and 2) patterns that emerge from the data (inductive approach). Interview coding took place over three passes. The first pass used a deductive approach with pre-defined codes selected by the research team, based on constructs of interest with respect to the project's research questions, conceptual frameworks from the literature, and the survey and interview questions that participants responded to. The initial set consisted of 25 codes divided into six areas: UES framework, MPX-Q framework, hedonic and cognitive factors of interest, challenges and breakthroughs, affect, and methodological considerations.

Incidents were reviewed one at a time and assigned each relevant code. During the first pass, new codes were added inductively as they emerged from the data. Three areas were added, two existing areas were combined, and a third area was divided in two. Modifications were made during the first pass, and were fully considered during the second.

The final set of interview codes contained 51 codes in total, spanning nine areas:

1. UES framework (7 codes): Six codes comprising O'Brien and Toms' [66] original engagement framework. A seventh was added to include reasons for disengagement.
2. MPX-Q framework (3 codes): Codes corresponding to MPX-Q [40] subscales.
3. Hedonic and cognitive factors (5 codes): Emotional and cognitive factors of interest.
4. Personal factors (Added; 7 codes): Individuals' backgrounds, previous experience, opinions, and preferences.
5. Affect (Revised; 4 codes): Specific emotional responses encountered during users' interactions with the instrument.
6. Technical factors (Added; 7 codes): Construction of hardware, implementation of mapping, sound synthesis, and overall musical apparatus.
7. Methodological factors (Added; 4 codes): Aspects of the tasks, research environment,

and method that impacted participant experience.

8. Interaction factors (Added; 9 codes): Specific aspects of HCI and music interaction.
9. Temporal factors (Added; 5 codes): How the UIR changes over time.

The second pass was carried out in the same way as the first, but used the final coding scheme. Any incidents already coded in the first pass were reviewed to ensure that all newly-added codes had been considered. During the second pass, cases where the coder was unsure about assigning a particular code to an incident were flagged. During the third pass, these flagged incidents were reviewed with the project collaborators to assign the appropriate codes. Each incident was assigned at least one code, although many were assigned multiple.

4.2.2 Interview Data by Category

Coded data is presented in Figures 4-2 and 4-3. These graphs serve to summarize the overall nature of the qualitative data collected, reviewed in detail in the following subsections. Figure 4-2 shows the number of coded incidents across the 9 areas, outlined in Subsection 4.2.1, over time, from ENI (red), through S1 to S5 (blue), to EXI (red), illustrating differences between the content of evaluation session interviews and ENI/EXI. Two types of pattern are illustrated.

The first pattern type, demonstrated by the MPX-Q framework and personal factors, shows spikes for ENI and EXI, with lower counts for those categories in intermediate interviews. For the personal factors category, this is easily explained by the nature of the questions asked. Since ENI focused on previous musical experience and performance preferences, a spike in this category is to be expected. Similarly, questions in EXI asked participants to reflect on how they might use the T-Stick in their future musical practice. Spikes for MPX-Q codes, while less pronounced, are similarly explained. In ENI, participants were asked to reflect on experiential factors that affected their adoption and continued use of DMIs in the context of their background and preferences. EXI asked participants to reflect on their experience across the entire study, as well as how aspects of their experience with the T-Stick might have affected their willingness to continue using the instrument. Given the MPX-Q's focus on experiential facets of music interaction, it is logical that these spikes would appear, based on the content of interview questions.

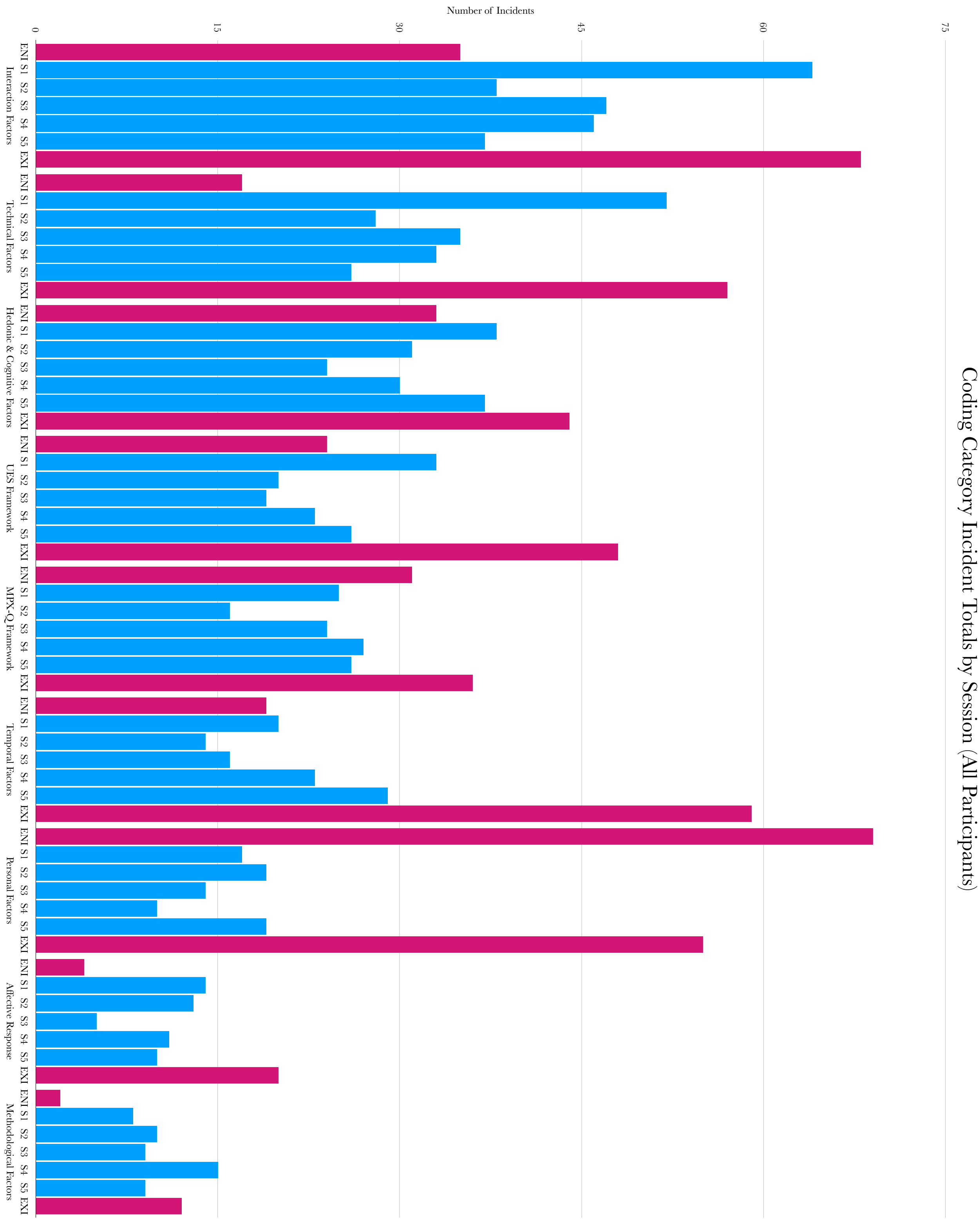

Figure 4-2: Coded Interview Responses for All Sessions

The total number of incidents (y-axis) in nine categories, summed for all participants over time. Entrance interview (ENI) and exit interview (EXI) are coloured red, while evaluation session interviews (S1 through S5) are blue.

The second type of pattern was a notable spike for some categories in EXI, without a spike in ENI. This pattern tends to show a small spike for S1, with a larger spike for EXI. This describes the categories of UES framework, technical factors, factors of interest, temporal factors, and interaction factors. The S1 spike can be explained by novelty effects; since this interview took place after participants' first practice session, it is likely that they had more items to report, based on this being their first extended exposure to the T-Stick. It is logical that users would report items related to technical factors (e.g. glitches, errors), and interaction factors (e.g. explorability, discoverability), as they were experienced for the first time, and not reported these same items in subsequent sessions. Similarly, aspects of the UES framework (such as novelty), and hedonic and cognitive factors, are likely to have been mentioned as they were encountered for the first time. With respect to temporal factors, it is logical that these show an increase over time.

The final category, methodological factors, does not demonstrate either of these patterns. Instead, the frequency of methodology-related comments is relatively consistent, excluding ENI. This can be attributed to the study design. While it is unlikely that users had spent enough time in the study to be able to comment on the methodology during ENI, they were able to make such observations in each subsequent interview. Codes for both methodological factors and affective response were generally assigned less than those for the other seven categories.

Figure 4-3 displays the same areas, divided by participant, for S1 to S5, providing a more in-depth look at how the number of incidents for each category changed over the evaluation sessions. ENI and EXI are excluded as they utilized different questions and therefore illustrate different data patterns that may not be directly comparable to evaluation session interviews.

A number of categories (UES framework, factors of interest, and temporal factors) show a spike during S5, generally preceded by an increase, starting at S1 or S2. This is likely due to the study structure. During the initial session, participants were likely to encounter more obvious aspects of interaction they found remarkable, and reported this during S1 or S2, but not during sessions immediately following (S2 or S3). As participants spent time with the T-Stick, increased their amount of playing experience, and explored more tasks, they began to notice more nuanced aspects of interaction or comment on newer tasks, accounting for the increase from S2 to S4.

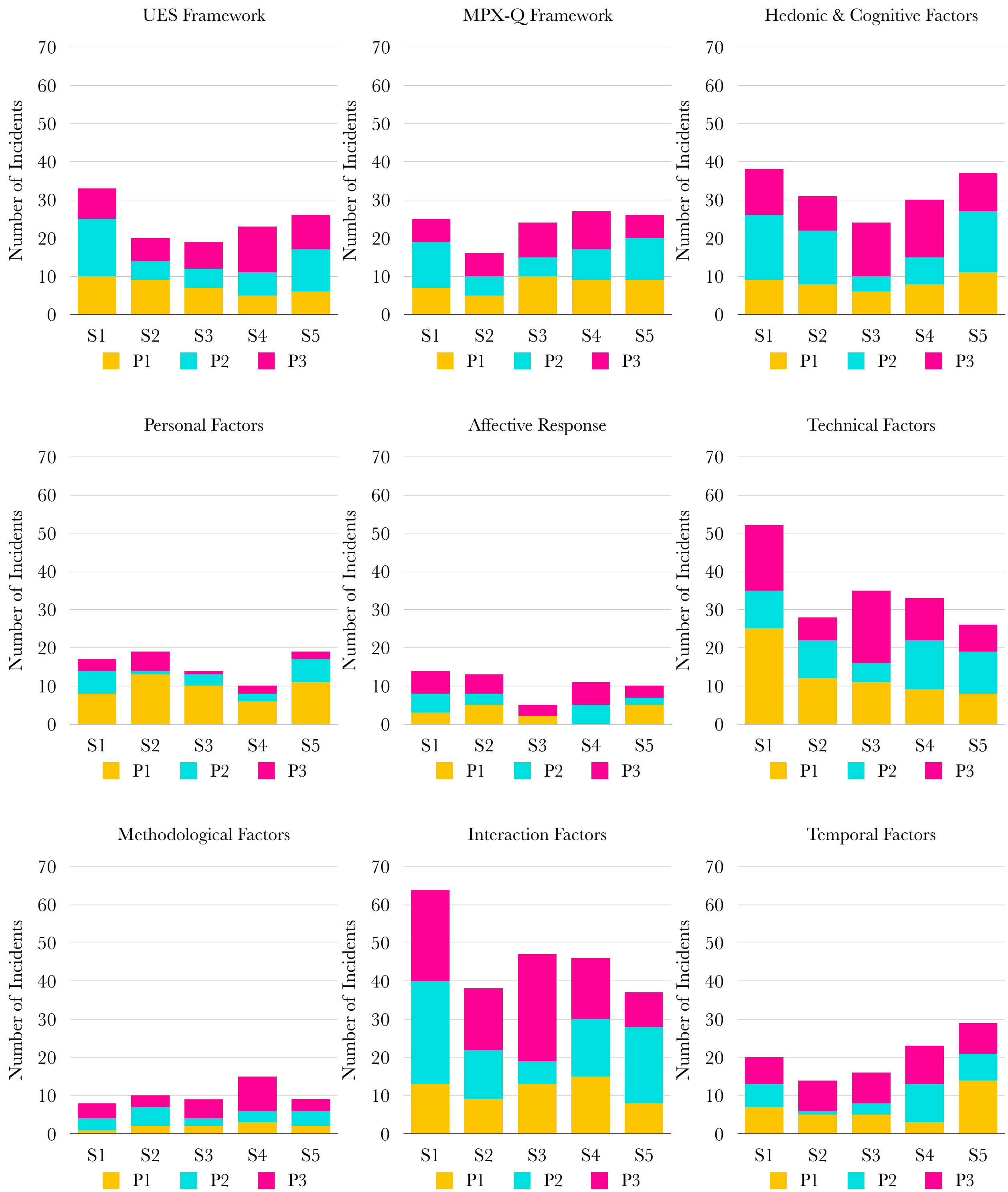

Figure 4-3: Coded Interview Responses by Participant, for Evaluation Sessions Only

The total number of incidents (y-axis) in nine categories, grouped by participant, for each evaluation session interview (S1 through S5). Entrance interview (ENI) and exit interview (EXI) are not included.

Several graphs (factors of interest, MPX-Q framework, temporal factors, interaction factors) show a dip following S1, similar to that observed in the ratings graphs (Figure 4-1). This can be attributed to aspects of novelty; participants would likely mention these factors when first encountered, without necessarily returning to them during each evaluation session.

Other categories (affective response, methodological factors, and personal factors) show somewhat less variation over time, and are generally mentioned less. While these categories show small dips and spikes, patterns are less pronounced than those previously discussed.

Finally, some differences between participants are noteworthy. First, P1 referred to personal factors somewhat more than the other two participants. This is likely related to the fact that P1 often discussed philosophical aspects of musicianship and composition, while the other two participants were less likely to do so. P3 was generally more likely to discuss methodological factors, including the nature and structure of the practice time.

4.2.3 Entrance Interview

Responses to questions from ENI highlight differences between participants' backgrounds and preferences. These differences notably affected the ways in which each participant approached and conceptualized the T-Stick. For example, P1 mentioned being a composer:

> *"[I]t's a kind of philosophical problem with the identity of an instrument that interests me … as a composer … to expand the possibilities of an acoustic instrument."* [P1, ENI].

P1 indicated that their experience with DMIs was somewhat recent, but mentioned aspects of their experience using the Karlax, relating this experience to the T-Stick: *"I know a bit [about] the [T-Stick] … I can make [a] connection with Karlax"* [P1, ENI].

P2 described their performance schedule and setup:

> *"I play a weekly show at a cafe … I do a performance involving drum machine and acoustic piano … I also used to play a similar format of show where I'd play different synths … I've used a lot of different digital musical instruments, mostly in live performance"* [P2, ENI].

When describing their background, P2's performance history, experience with, and thoughtfulness about, DMIs was evident. When asked about factors that might prevent them from adopting or continuing to use DMIs, they noted both interface robustness and performance concerns, including cognitive load, and the importance of feedback in live settings:

> *"Portability is also a concern 'cause I'm taking this stuff to a gig and I don't have a car, so I have to throw it all in a backpack and just go. So it has to be small enough"* [P2, ENI].

> *"Complexity really, and inability to perceive the state of the system. So if I'm using a very complex synthesizer … and … the visual state doesn't reflect what's actually happening … that just kills it for me"* [P2, ENI].

P2 also described previous experience developing an original mapping for the T-Stick:

> *"I found it very challenging. The T-Stick has such a wide parameter space that coming up with something that satisfies all these constraints: sounds compelling, looks compelling to an audience, feels compelling to play for the performer … I feel like I might have hit some of those, but [it was] definitely … not as good as it could have been … It's as much as you want to give to it … It'll soak up as much time as you put into it"* [P2, ENI].

Finally, P3 described themselves as *"very much a hobbyist"* [ENI], and indicated that they don't perform, but do practice with a MIDI keyboard and SuperCollider when they have time. In their personal practice, they reference notions of play and experimentation:

> *"I see [my DMI setup] as a way to play around with some different audio synthesis techniques, or … implement them myself rather than use something out of the box. … not for any particular purpose, but mainly just for the … in the moment aesthetic"* [P3, ENI].

They mentioned barriers to DMI use, including skill, reliability, and setup. They also compared their use of SuperCollider to their classical guitar practice, noting the sonic limitations of the acoustic instrument, and the spatial limitations imposed by their DMI setup:

> *"In favour of SuperCollider and keyboard setup … there's a wider range of possibility and sometimes I like that … [S]ometimes I want to try and do something where I don't want it to just sound like a classical guitar"* [P3, ENI].

> *"The guitar only needs my lap and maybe … a bit of space around me so I'm not banging into anything … With [my DMI setup], I need somewhere to lay everything down and that just requires a bit more table space that's not always available"* [P3, ENI].

As described in this chapter's introduction, differences in participants' perspectives, practices, and priorities, provided important context for how they experienced interaction with the T-Stick over the course of the their learning. These differences are discussed further in Chapter 5.

4.2.4 Evaluation Session Interviews

Results from evaluation session interviews are organized by patterns observed in the data, highlighting similarities in participants' interactions, as well as divergences in experience based on their individual musical backgrounds. These patterns are presented in the following order:

1. Exploration and discovery, during initial interaction and throughout;
2. Participants' attitudes, expectations, and perceptions of the instrument;
3. Aspects of the learning process, including frustration, specific task-related challenges, and development of the UIR.

Exploration and discovery played an important role in initial and ongoing learning. During S1, all participants engaged in exploration of the T-Stick to assess its possibilities and limitations, though each of them made use of a unique strategy based on their prior experience. P1 used the metaphor of tennis to explore the instrument: *"the gestures … the shape of the T-Stick … makes me feel to create a piece about tennis"* [P1, S1]. P2 explored the limits of the gestures: *"[I] tried to exaggerate the gestures that were done, see what I could do"* [P2, S1]. P3 described more general exploration: *"I was mainly just trying to explore what I could do with the T-Stick"* [P3, S1].

While explicit descriptions of exploration were more limited in other sessions, participants continued to discover new functionality, sometimes by accident. In several cases, participants encountered states they were unable to get out of. All participants discovered the reverb functionality in the first practice session, well before the reverb task videos were shown. P2 also discovered a glitch, in which the reverb persisted after shaking was discontinued, though they later discovered that they found other tasks easier to perform when the reverb was stuck, even though this was not an aspect of the mapping design, but a technical error: *"I think I glitched it so that the reverb was just stuck on which actually made it easier to do the tasks"* [P2, S4].

P1 and P2 both discovered 'sweet spots' that allowed them the most control and predictability with respect to sonic parameters:

> *"I was trying to have a position to have something that is quite easy to perform and [is] stable … I have [a] simple thing. Stable and the maximum of possibilities … [W]hen you do bigger gestures, it's getting really expressive"* [P1, S5].

> *"I found that there was a sweet spot in the middle where I felt like I had the most control over the amplitude. If I positioned my hands too close to either end, it felt like it would either be insanely loud or totally quiet"* [P2, S1].

Participants' previous experiences and preferences influenced their attitudes towards and expectations of, the instrument. This was especially pronounced for P1, the composer, and P2, the performer. P1 felt that they were unable to control basic musical parameters such as pitch in the manner they were familiar with when playing acoustic instruments:

> *"I'm not sure if it can be so musical because I have not so much control about the elementary … You need rhythm, pitch … the timbre aspect is quite limited"* [P1, S3].

P2 suggested that the instrument did not match their sonic aesthetic, and that this limited their motivation to interact with it. They did, however, acknowledge that the sound could potentially be useful in some musical contexts:

> *"It's not really my aesthetic, but, you know, it's noisy, it's loud, it's rambunctious … like it's a big dronelike soundscape, almost. So pleasing not so much, but useful maybe"* [P2, S5].

Relatedly, P2 had the most previous experience with the T-Stick before the study began, and generally had the most negative attitude towards the instrument throughout. P2 made several comments, over the course of the study, about the perceived fragility of the T-Stick as a major limitation, attributing it to the instrument's lab-based construction:

> *"[T]hings that are built by students in a lab aren't going to be as sturdy as an industrially-engineered instrument that's mass-produced … I experience that all the time"* [P2, S1].

Attitudes and expectations did not, however, remain static over the entire learning process. P2's attitude began to shift near the final evaluation session, as they acknowledge in their commentary. Excerpts from S1 and S5 illustrate this development:

> *"I wouldn't choose to use [the T-Stick] in performance or anything like that"* [P2, S1].

> *"[M]y positioning going into it was like 'Man, the T-Stick … I'm never going to be able to get sound out of it I like.' And that's not necessarily the case. But it kind of prevented me from wanting to experiment with it a fair amount. Today I just tried to let that go and mess around with it. I was walking around the room more and involving more of my body in the movements … [T]hat made it feel more expressive."* [P2, S5].

P3 also described a change in their attitude towards their interactions with the T-Stick, providing some insight into their own personal learning process and goals:

> *"Whether or not I would be happy recording what I did and showing it to people, I don't think it's quite there yet … but I definitely feel like there's more movement in that direction and it's going not just from having the sounds that are separately something I can see as being pleasing, but I'm starting to put them together in a way where, in combination, they're also somewhat pleasing"* [P3, S4].

Challenges related to the T-Stick's responsiveness were common elements of the learning process, impacting perceptions of control over the instrument. All participants perceived inconsistencies in how the T-Stick responded to their gestures, leading to unanticipated states:

> *"I feel like there's a lot of inconsistencies … I don't really have any insight into that process. Other than the audio, I'm not getting any kind of feedback. I don't really know what the system state is. I don't know what the sensor values are, so I really can't adjust my behaviour appropriately to get the effect I want, or to create the same effect in a reliable way"* [P3, S1].

Latency was also flagged as an issue, by both P1 and P2, with respect to the onset of notes and their ability to keep time and establish musical rhythm. These comments reflect expectations based on previous experience with acoustic instruments in compositional and performance settings:

> *"[The] pressure makes the attack of it a bit low … I felt that … restriction in terms of rhythm … you have only the pressure aspect that gives you rhythm, and it's not so precise or … it's too difficult to control … the attacks are always a bit the same"* [P1, S3].

> *"There's just a slight delay. If I was playing this in a context where I had other loops going that were very metric, like on beat, I would find it really difficult"* [P2, S1].

As a consequence of these perceived inconsistencies, participants suggested they did not feel entirely in control of the instrument:

> *"I'd say there are some aspects of it that feel very intuitive, like it's following the contour of my gesture. But then there are times where it just completely falls off a cliff and stops responding well or at all"* [P2, S5].

A more serious challenge, reported by both P1 and P3, was that the grip required to maintain pressure on the surface of the T-Stick, in order to control the amplitude, led to pain in their hands. P3 noted that they experienced the pain outside of the study environment as well:

> *"[T]he grip I've been using to play the T-Stick with my right hand has increasingly led to some pain and cramping … it's also sort of impacted myself outside of this. A few days ago, I was eating and found just holding a fork was very painful in this hand"* [P3, S5].

In response to several challenges encountered over the course of their learning, including the level of perceived control over the sonic parameters participants' were asked to modify, the sound of the synthesizer, and perceptions of inconsistent response, frustration was common:

> *"I was frustrated with pitch because the instrument is all around B and B minor … even if I jab it stays within the same tonality … I'm a musician so pitch is important"* [P1, S2].

> *"I was just kind of frustrated today. I'm just not feeling it. I was not enjoying the sound … I was eventually able to perform the tasks, but it was kind of like rote replication"* [P2, S2].

> *"In terms of frustrations … the lack of perceived consistency … I can't tell exactly what I am doing wrong, or if I am doing something wrong"* [P3, S1].

This frustration was not necessarily perceived as negative, however, and, upon reflection, P1 suggested that frustration was an expected part of the learning and creative processes *"When you are creative and you want to, it's interesting to be frustrated"* [P1, S5].

Participants also commented on the learning process itself, noting that the mapping, while not necessarily intuitive, was learnable and understandable, especially with the aid of demonstration videos: *"[T]he mapping is clear. It's fairly straightforward to learn with instruction"* [P3, S3].

Demonstration videos could, however, also be a hindrance, leading to confusion when the instrument did not respond for the participants in the same manner as was demonstrated:

> *"I'm doing what is being shown in the video and I'm not getting the same results … it wasn't clear to me what I was doing wrong"* [P2, S4].

Three tasks caused notable difficulty. The first two of these, filter cutoff and frequency, were also perceived as challenging based on participants' task performance ratings (Table 4-3). Filter cutoff, mapped to the jab gesture, presented persistent problems for P2 and P3:

> *"The jab gesture wasn't working, so there were some basically areas or things that I was avoiding in order to try to keep the performance more consistent"* [P2, S5].

> *"[T]he cutoff frequency is a sticking point for me. I don't know if that's just for me personally or if it's a common feature, but that's been difficult"* [P3, S5].

Participants noted difficulty with the frequency control, mapped to five positional zones along the length of the T-Stick:

> *"[I]t looked like the person doing the demo for the frequency … was able to get a consistent response across the full length of the T-Stick. I wasn't able to do that … I had to contort my hands … really kind of push hard against the instrument"* [P2, S2].

Finally, participants cited the reverb tasks as difficult, as an energetic shake could cause the battery to temporarily dislodge itself, leading the instrument to power cycle. Participants also encountered cases where the reverb would become stuck and would not dissipate:

> *"I was working on reverb—low level reverb and infinite reverb. Trying to get it to work without … disconnecting the battery, which is a challenge. Once I figured out … sort of like a rotational gesture, that seemed to work OK"* [P2, S3].

For P2, however, the reverb glitch became beneficial in performing the other tasks, and they were able to take advantage of this unintended behaviour:

> *"All of a sudden I didn't need to shake it at all. I could just position my hands and that would change the sound … it was the shake gesture that felt so fragile, so by bypassing that, I was able to play around with it"* [P2, S4].

In the course of participants' learning, development of the UIR was evident. Participants reported cases of appropriation and embodiment, developing an intimate understanding of the

T-Stick, and situating it within their personal knowledge, abilities, and musical practice:

> *"I was concentrating on having quite stable position … not exploring the big gesture but just have a good control, and the position was stable … this kind of a rest position to explore around … to have the maximum possibilities [with] maximum expression"* [P1, S5].

> *"I think … you have to see [the T-Stick] as a platform, more so than an instrument in its own right, 'cause it can evolve based on the sound layer and the mapping layer, which is critically important. So this is just one iteration of the instrument as it's evolving … I'd say that I have opened up to it more"* [P2, S5].

> *"I can kind of just focus on the stuff I've been able to do well, and minimize the stuff that is particularly difficult for me"* [P3, S5].

Participant comments over the course of the evaluation session interviews provide insight into their distinct experiences, but also demonstrate aspects of the learning process common to all participants, such as the influence of their previous experience and expectations on emotion and perception, as well as development of the UIR. Furthermore, this participant commentary provides further context and insight with respect to the ratings data collected over the course of these sessions, described previously (Section 4.1).

4.2.5 Exit Interview

EXI provided an opportunity for participants to reflect on their experience over the entire learning period, and to provide suggestions for improvements to the musical apparatus, the set of tasks, and aspects of the study procedure they felt were notable. A number of themes emerged.

First, all participants agreed that the T-Stick offered musical possibilities that were different than those offered by acoustic instruments or other DMIs:

> *"It's one of the few gestural movement and pressure-based instruments I've used … It also lets me walk around the room while I'm shaking it … that's fun … It does afford things that other [instruments] don't"* [P2, EXI].

Relatedly, all participants spoke about how they might make specific use of the T-Stick in the future, based on their perceptions of the instrument's possibilities and limitations:

> *"I am a composer, so I think it's interesting because it's quite new … so I want to write for it … to explore it further"* [P1, EXI].

> *"I do live looping … maybe having some meta-parameters of the loops … or the interactions between the sounds that I'm looping, that I'm controlling with the T-Stick"* [P2, EXI].

> *"[T]here would definitely be a period where I would delve into the guts of it a bit … I feel like there's a lot of interesting new things that I haven't been able to do with it … I could see it being something challenging and engaging for quite a while"* [P3, EXI].

When reflecting on challenges they experienced, P2 and P3 mentioned their ability to control the instrument, both in terms of the T-Stick's responsiveness and its technical limitations:

> *"I was cursing at it the whole time. I said 'you piece of shit fucking thing.' When it would reset, when it would stop making sound … I was expecting it to have a certain contour of reliability. It didn't and that frustrated me"* [P2, EXI].

> *"[I]t's been very frustrating to feel like I am getting something and then suddenly have that flow broken … [I]n the time it takes to either let it reboot or turn it on and off again myself, it feels like I'm starting up again rather than … something I could recover from"* [P3, EXI].

Conversely, all participants also identified specific breakthroughs (P1's was reported in S5 rather than EXI) that occurred in the course of their learning, both spontaneously and gradually:

> *"I have [a] simple thing. Stable and the maximum of possibilities and, when you do bigger gestures, it's getting really expressive"* [P1, S5].

> *"I got into it and I was able to just play with it. It felt like it was sonifying the motions of my body without me having to think too much about it, and that was really exciting. … I was doing more of a continuous motion; it was capturing that gesture pretty effectively*" [P2, EXI].

> *"The learning process I've had over this has been a particularly positive one … [O]ver the course of the sessions, having the module tasks come together and explain, 'Oh, that's what was happening there. It wasn't some mysterious, unexplainable thing. It's that I was doing this, and now … I know that that's a thing that matters'"* [P3, EXI].

In addition to learning to play the instrument, participants pointed to affective and cognitive aspects of their experience that changed over the course of the study, demonstrating that, even over a limited time period, the UIR was evolving:

> *"[A] lot of the more basic aspects are a bit more natural, and it feels more like the gap between my intention and the sound being produced has shrunk … it's not an exact thing, but I can definitely feel it getting easier"* [P3, EXI].

Participants also provided suggestions for alterations to the interface and methodology, including modifications to the mapping, improvements to stability and responsiveness, changes to the sound synthesis, and addition of visual feedback. P1 and P3 identified areas in which the instrument's responsiveness could be improved, or in which the mapping could be altered:

> *"[Y]ou need to press to have the amplitude … [F]or me … I don't like it … because with the pressure, even if you press very fast, the attack is more slow … I don't know how we can do that, but maybe combining gesture … combining any kind of jab, or … maybe you can activate some sound with jab"* [P1, EXI].

> *"I might want to change the gesture for cutoff frequency to something different … I found myself accidentally triggering it so much that, even if there's just a safety sort of thing … If there was some similar sort of keying you could do to set up that … I think that is something I would do for myself"* [P3, EXI].

P2 also identified issues with the inability to repeat gestures:

> *"Reliability and repeatability have been major issues … I feel like I have to gingerly treat the instrument, worrying about breaking it, trying not to get it to hard reset … That really kills the experience of trying to be creative … I know, when I get into the music, I'm gonna want to play it harder … If the instrument can't handle that and it resets in the middle of performance, that's going to prevent me from using that instrument"* [P2, EXI].

Additionally, P3 expressed a desire for tactile or visual feedback to guide new users in learning the tasks, particularly for the distribution of frequency zones along the length:

> *"[H]aving some sort of visual or tactile indicator of those [frequency zone] limits … would be very useful, especially near the start of the learning experience"* [P3, EXI].

Finally, both P1 and P2 suggested that they might make changes to the synthesis patch:

> *"I would have liked the ability to choose how harsh I want it to be … to set limits as to how extreme it can get. Sort of like tuning the instrument"* [P2, EXI].

Results from EXI provide further evidence of the developing UIR, as well as the personal nature of this relationship. Participants' unique plans for use, and specific suggestions for improvement, illustrated how previous experience played a role in appropriation of the T-Stick. The dynamic nature of experience was also demonstrated through changing affective and cognitive factors, as well as breakthroughs experienced in the course of participants' learning, such as P2's vivid description of embodied performance:

> *"I felt like my movements were being captured by the instrument and converted into sound in a way that I enjoy … and made me want to move differently. The feedback loop between the instrument and my gesture was established … [I]t felt very direct"* [P2, EXI].

Findings from participant interview data related to UX and the UIR are synthesized and discussed more thoroughly in Chapter 5, and are situated in relation to results from ratings provided by participants (Section 4.1), as well as ratings and commentary from third-party evaluators, presented in the following section.

4.3 Third-Party Evaluator Ratings and Commentary

Figure 4-4 displays ratings of various aspects of participants' final performances provided by two third-party evaluators, both familiar with T-Stick research and performance. Third-party evaluator ratings were incorporated in the research design to demonstrate that participants were able to learn to play the T-Stick using the tasks and demonstrations provided.

Overall, ratings between the evaluators were remarkably consistent. In every case except for two (ratings for P1 on question 1a, related to variety of tasks used, and ratings for P2 on question 2a, related to quality of motion), evaluators gave ratings that were equal, or differing by one point on the scale. Even in these exceptions, the difference was small (only two points). Additionally, all ratings were neutral or above, suggesting that participants had learned the tasks, and were able to create a musical excerpt of moderately high quality. Evaluator ratings also corresponded with participants' self-rated ability to learn and perform the tasks, displayed in

Table 4-3. In this case, a test of inter-rater reliability (Cohen's Kappa) could not be used, as an unweighted Kappa is unsuitable for ordinal scales [92], while a weighted Kappa assumes that all questions use the same ratings categories (while Q1 to Q3 have five levels, Q4 has ten) [93].

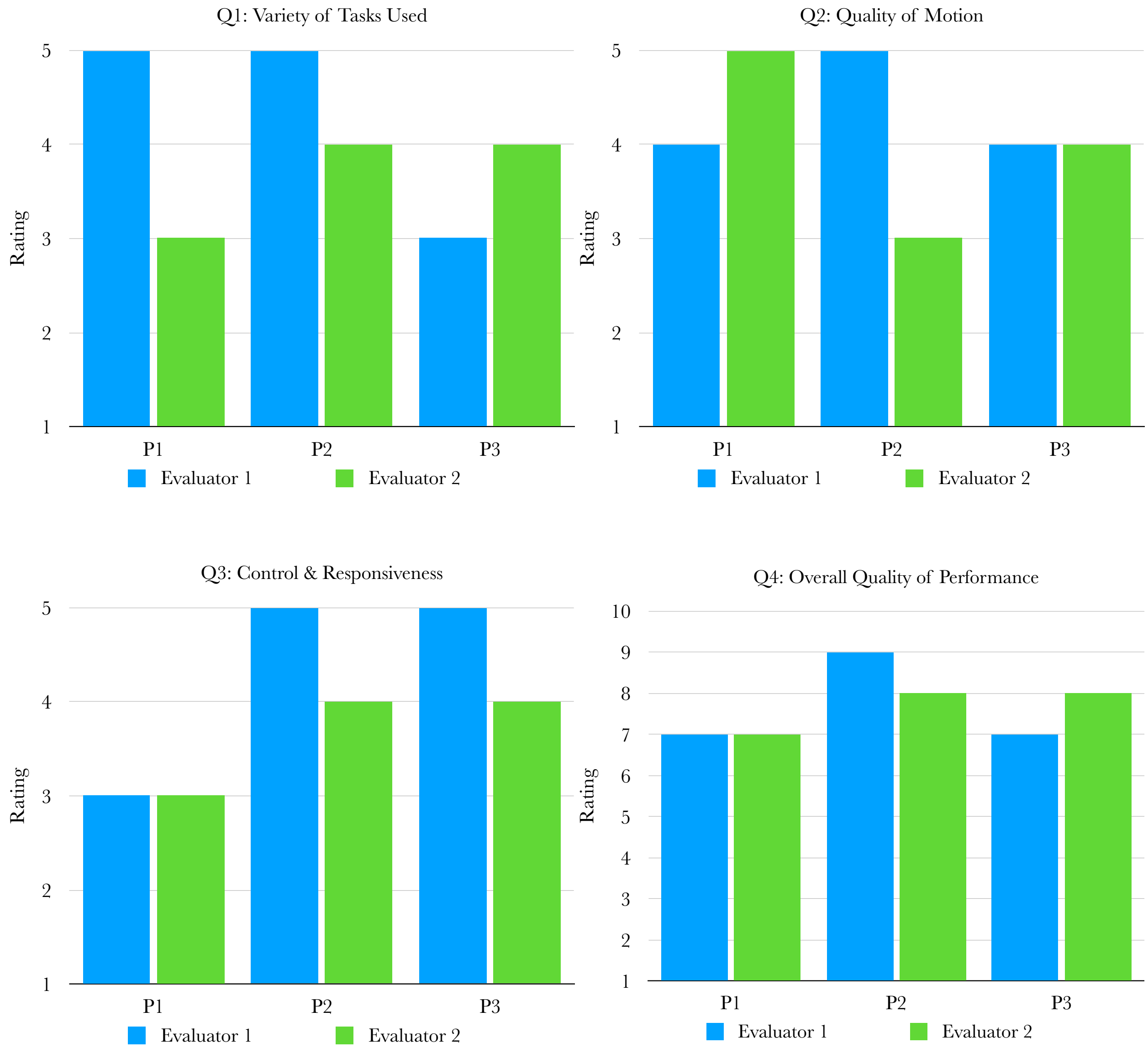

Figure 4-4: Third-Party Evaluator Ratings of Participant Performances

For Q1 to Q3, evaluators responded with a rating between 1 (*"Strongly Disagree"*) and 5 (*"Strongly Agree"*). A response of 3 was neutral (*"Neither Agree Nor Disagree"*). Q4 asked evaluators to rate overall quality on a scale from 1 (*"Low Quality"*) to 10 (*"High Quality"*).

Two other points merit remarks. First, both evaluators were neutral on the extent to which they felt that P1 was in control of the T-Stick, and that it responded to their gestures. Second, the performance of P2, the only active performer of the three, had a slight edge over the other two.

For each of the ratings provided, evaluators were asked to briefly elaborate. In reference to P1's performance, the evaluators differed by two points in their ratings (one of two relatively large differences). This divergence is reflected in their comments:

> *"The performance demonstrates clear integration of the demonstrated gestures, as well as some not demonstrated (e.g. pressing the button?). The gestures tend to fuse together; it's not as though you can identify each distinct gestural ingredient"* [E1].

> *"The performer explores the possibilities of timbre, amplitude, mode switching, filter cutoff, and resonance mostly well. They explore some of the base of the reverb mappings, and briefly touch some of the more physically demanding mappings, but don't stay there long. They obviously struggle with the T-Stick at times, with some mode switching during gestures and unexpected dropouts that seem to guide the user away from more adventurous outcomes"* [E2].

The evaluators generally agreed that P1's motion was smooth and fluid, with E1 noting that *"[p]arts of the performance were rather hectic … but overall the movements seen are more or less smooth"* and E2 suggesting that technical issues were to blame for less smooth aspects of the performance.

With respect to P1's control over the T-Stick, and the instrument's responsiveness to that control, both evaluators provided neutral ratings, noting technical issues:

> *"At several moments throughout the performance, the performer appears to have lost touch with the instrument somehow … It does not inspire a sense that the performer is in complete control of the instrument"* [E1].

Both evaluators gave positive ratings of P1's performance, with some caveats:

> *"The breakdown in my trust that the player's gestures are deliberate … impedes my enjoyment of the performance. The sonic and gestural vocabulary is somewhat limited, lacking variety. But … I still enjoyed it"* [E1].

> *"This performance is largely good, with well defined gestures which explore many of the mappings … The overall quality is mostly hindered by the user struggling with the device, which seems to guide the performance as much as their own compositional flow"* [E2].

When referencing P2's use of gestures, both evaluators gave high ratings. E1 remarked again on the fusion of gestures: *"[D]emonstrated gestures are completely integrated together. There's no clear line between them."* E2 identified limited use of the frequency and Rain Stick Mode tasks:

> *"The user explores the timbre, reverb, amplitude, FM depth, filter cutoff, and resonance quite well. They find a novel use of the mode switching as a sort of audio gate, and explore it quite well. The frequency feature space and other synth engine are largely unexplored"* [E2].

Both evaluators felt that P2's motion was fluid, and that the performer seemed in control of the instrument. E1 noted the intentionality of P2's movements and how this related to control:

> *"Overall, the performer's movements are clearly deliberate and planned out, and their movement is controlled and fluid as a consequence. Where the movements are more explosive (e.g. jab), the sense of deliberateness counteracts the non-smoothness"* [E1].

Both evaluators rated P2's overall performance highly. E1 based this on the performer's *"clear attention to detail, deliberate movement, and intentional structure."* Interestingly, E2 disagreed with E1's assessment of structure: *"The musical structure of the performance is a bit lacking,"* but still rated the performance highly: *"The user … is still successful in creating varied sonic results and finding new modes of interacting with the existing mappings"* [E2].

Finally, the evaluators characterized P3's use of gestures as slightly more limited than other participants, but described their movements as *"clear and smooth"* [E1] and *"largely smooth"* [E2]:

> *"The performer appears to get to each of the demonstrated gestures at one point or another, but there is not much integration or combination of these gestures"* [E1].

In reference to perceived control over, and responsiveness of, the instrument, both evaluators noted isolated issues, but provided high ratings:

> *"The user is able to maintain musical phrasing while switching between modes and provide variations on the gestures … When the user does encounter the errors … they are audibly unhappy with the results, [but] keep going and are largely unfazed by this issue"* [E2].

Both evaluators rated the quality of the performance positively, which was also reflected in their commentary, though E1 noted being affected by the performer's demeanour:

> *"The otherwise reasonable composition of the piece is detracted from by the performer's*

> *apparent discomfort and sense that they could or should be doing better. It seems like it just needs some more practice"* [E1].

Overall, ratings and commentary from the third-party evaluators were remarkably similar, suggesting there are observable aspects of a T-Stick performance that contribute to performance quality, and that these can be agreed upon by third-party assessors. More importantly, the commentary provided by the evaluators suggests that, even over a limited time period, individuals with little to no experience are able to learn musical gestures, execute them appropriately, and develop original musical ideas with the T-Stick. Furthermore, as noted by E1, confidence and skill would likely increase through further extended practice with the T-Stick. Finally, and of most relevance with respect to the aims of this project, reports from third-party evaluators indicated that the musical task set used was appropriate. Results indicated that the tasks used were generally reproducible for participants, offered varying degrees of complexity and challenge apparent to an observer, and were sufficient in enabling participants to learn to play the T-Stick.

4.4 Summary of Results

Given the amount of data presented, a brief reiteration of patterns in the results is provided prior to beginning the general discussion. Three general findings are noteworthy.

First, the influence of participants' backgrounds on the manner in which they approached learning and interaction with the T-Stick played a major role in their perceptual, cognitive, and affective experience with the instrument. While participants' experiential trajectories were highly unique in this respect, there were also several high-level commonalities, such as the use of exploratory strategies in initial interactions and throughout the learning process. It is also noteworthy that one key component of participants' backgrounds, in this scenario, was previous exposure to the T-Stick in classroom and research contexts. Thus, it was expected that their awareness of the instrument could lead to some level of pre-existing bias, such as P2's initial negative attitude towards the instrument. Such baseline attitudes, however, were not of interest with respect to the main goal of this research, which was to provide an initial demonstration of a general method for evaluating changes in UX and the UIR over a learning period. Whatever their initial attitude towards the T-Stick, all participants reported changes in their interaction and UIR over the study.

Second, this research illustrated that development of the UIR begins at an early stage, and is apparent even over a limited learning period, demonstrated through aspects of appropriation, embodiment, and thoughtfulness about the instrument and the nature of interaction.

Third, and most crucial, was the demonstration of the study procedure, data collection strategies, and set of musical tasks used in this research, evident from ratings-based and qualitative data, collected from both participants and third-party evaluators. This final point is the central contribution of this work. While the adoption of this procedure for a different instrument would likely require a different set of tasks based on the available options for gestural input, synthesis parameters, and mappings, the effectiveness of the given task set in this research indicates some general principles for task sets with different DMIs, such as providing control over fundamental sonic parameters such as frequency and amplitude, as well as utilizing task sets that demonstrate increasing complexity.

In addition to these major findings, several anecdotal insights from interview data are noteworthy, and will be referenced in the general discussion. These specific insights help to underscore the value of qualitative approaches to the study of experience, especially when used in tandem with complementary methods.

Both P1 and P3, during EXI, commented on the nature of the practice time, suggesting that it was not just the amount of practice that was important, but the time between practice sessions: *"Having the practice put into pre-defined, set-length sessions is a bit difficult. A lot of the time, that's exactly what I need, but other times … I would really just like to think about what I'm doing and reflect on it, and then have another 30 minutes tomorrow"* [P3, S5]. This provides useful insight into aspects of the study structure that could be reconsidered in future research.

The second insight relates to how participants adjusted their interaction strategies, as they spent more time with the instrument, and encountered its affordances and constraints. Several examples are of note, including P3's focus on the tasks they were able to comfortably perform, in order to alleviate the difficulty they felt in replicating other tasks, P2's use of the reverb glitch to obscure abrupt sonic transitions, and the discovery of 'sweet spots' by both P1 and P2. These changes in behaviour often marked participants' breakthroughs in the learning process. This evolution in interaction strategies can be attributed to both the learning of pre-defined tasks as well as the opportunities for open exploration given to participants through their practice. As participants learned each task, they were provided with new possibilities for sonic manipulation and gestural control, and were encouraged to combine these new interaction strategies with those learned previously when developing their original excerpt. Furthermore, participants were only provided with a rudimentary description of each task, and only through practice were they able to explore the limitations of each gesture and the range of each sonic parameter. More importantly, it was up to participants to determine how each task would fit into the musical context of the original excerpt they were asked to create.

Third, these behavioural adjustments also had cognitive corollaries. The principal ideological shift, which occurred for all participants, was the realization, after several practice sessions, that conceptual models based on acoustic instruments were not fully applicable to the T-Stick (i.e. that the T-Stick *was a DMI*). While the instrument presented limitations, especially when traditional understandings of musicianship and musical instruments were applied, it also allowed individuals to explore novel creative possibilities that are not replicable with acoustic instruments. This breakthrough is perhaps the most crucial, and raises important questions regarding how interaction and experience might have evolved further following this discovery, had the project been carried out with an extended timeframe.

Finally, in direct relation to the previous point, several concerns related to mapping and sound synthesis arose, including the pain experienced by P1 and P3 as a result of pressure-to-amplitude mapping, P1's suggestion that they might use the jab gesture to control a different parameter of the synthesizer, and P2's feeling that the sound was too harsh and did not match their aesthetic sensibility. These concerns, while useful and actionable from a design perspective, are reflective of a particular iteration of the T-Stick, characterizing but one of an infinite number of synthesis and mapping combinations. As such, they should not be considered representative of the hardware controller more generally. This was astutely observed by P2, who stated:

> *"[Y]ou have to see [the T-Stick] as a platform moreso than an instrument in its own right, 'cause it can evolve based on the sound layer and the mapping layer"* [P2, S5].

These patterns and results are addressed further in the following chapter.

Chapter 5: Discussion

"[I]t's so simple. It's a tube" [P1, S5].

As the above quotation illustrates, the T-Stick is a DMI that, superficially, might appear somewhat elementary. Results of this research demonstrate, however, that remarkable complexity exists below the surface, and that T-Stick interaction can be rich and nuanced, even for novices.

Based on the results provided previously, general discussion focuses on four notable themes:

1. Differences between participants' background and performance preferences, and how these affected interaction with the T-Stick (Section 5.1);
2. Similarities and differences in participants' experience, based on these diverse musical backgrounds (Section 5.2);
3. Other noteworthy aspects of interaction (Section 5.3);
4. Changes in UX and development of the UIR observed over the study (Section 5.4).

Following this discussion of the findings, Sections 5.5 and 5.6, respectively, address limitations of this study, and potential future modifications to the research protocol.

5.1 Three Perspectives

In the PSQ and ENI, participants spoke at length about their musical backgrounds and expectations of musical instruments. When examining responses to these questions and the trajectory of each participant's interaction with the T-Stick, it became clear that background and preferences greatly informed how they approached the T-Stick and interpreted their experience, thereby affecting the nature and extent of their engagement with the instrument.

5.1.1 The Composer

P1 came from a musical composition background, and was often concerned with complex, philosophical ideas related to instruments' inherent nature. P1 was the only participant who brought up philosophical questions (and did so in each evaluation session interview). They also discussed theoretical notions of musical creativity and inspiration more than other participants. At an early point in the study, P1 began thinking about the original musical excerpt they would be asked to present at the end, utilizing an aspect of their background (tennis) as an inspiration:

> *"I played tennis … when I was child … The gestures … and the shape of the T-Stick makes me feel to create a piece about tennis that could be interesting in terms of gestures and also in terms of sounds"* [P1, S1].

P1's focus on composition was ongoing, and at various points throughout the study they described how the T-Stick might afford particular musical possibilities or limit musical alternatives in a compositional context. At the conclusion of the study, they expressed a desire to compose a piece specifically for the T-Stick in combination with acoustic instruments.

In some ways, P1's experience bore similarities to that of P2, the 'performer,' in that they discussed notions of musicianship based on models of acoustic instrumental practice, including the need for an instrument to offer a level of control sufficient to afford *"secure tricks"* [P1, S4] and limitations of the T-Stick with respect to creating pitch-based music.

5.1.2 The Performer

P2 was an active performer with DMIs, and had the most prior experience with the T-Stick, having previously developed a mapping for the instrument. P2's comments were often related to pragmatic topics, such as reliability, ease of control, and how the instrument could be used in the context of their current performance practice:

> *"For my purposes, I'm looking at these instruments as part of a system that I'm working with. It's not just one instrument in a vacuum. I'm trying to make them fit into a broader context … For my specific needs, it's better if each instrument does something more specific and just sticks to that"* [P2, ENI].

P2 cited many practical concerns about the ability of instruments to withstand the physical stress of being jostled in a backpack, or being moved energetically when a musician was absorbed in the act of performing. These concerns, standard considerations for an individual who performs on a regular basis, were not considered at length by the other participants.

Notably, P2 also acknowledged a negative bias towards the T-Stick at the study's inception, based on their previous experience developing a mapping for the instrument. This bias manifested itself at multiple points throughout the study, but moderated towards the study's end, as P2 overcame frustrations they reported earlier in the learning process. While pre-existing bias should always be treated with caution in the context of research, this bias was deemed appropriate, given that the primary aim of this research was assessment of a research method, rather than of the instrument and its design. It is conceivable that, in this context, a negative bias towards the T-Stick may have allowed P2 to maintain a more critical eye towards the T-Stick's limitations and technical issues, providing useful information about aspects of operation that could be considered before conducting a longer, more rigorous version of this study.

5.1.3 The Hobbyist

Finally, P3 was a self-identified hobbyist with both classical guitar and a simple DMI setup, consisting of a MIDI keyboard controller and their own synthesis patches coded in Supercollider. They often cited topics related to the flexibility afforded by DMIs and the role of exploration and experimentation in their practice: *"I enjoy the ability to play around with the guts of something … really see all the parameters that are there, and … change them, even if that does break something"* [P3, ENI].

When compared with other participants, P3's openness was evident. In contrast to P1, who often thought in the context of composition, and P2, who was concerned with practical aspects of performance, P3 was most receptive to the musical apparatus as it was presented, and they did not frequently mention a desire to make major changes to the mapping or sound synthesis portions of the instrument. P3 was highly focused with respect to the tasks (although they found the task set most difficult overall), and did not report having an overarching concern that guided their interaction, such as development of a composition. Relatedly, P3 was very conscious of their learning process and of how their skills developed. They reported multiple instances of feeling as though they were improving with respect to performing the tasks, but also indicated that they didn't necessarily feel they would be able to use the learned gestures *"in a musical context"* [P3, S1].

While P2 was frequently critical of the instrument, P3 was often critical of themselves and their abilities, unsure whether it was them or the T-Stick that was the root cause of frustration:

> *"I can't tell exactly what I am doing wrong or if I am doing something wrong … I don't know if the gesture didn't register right. I don't know if maybe it registered but then the value is different. It's not something I really am able to get much insight into"* [P3, S1].

This uncertainty was also reflected in P3's desire to delve into the technical side of the instrument and examine what was going on inside the 'black box.' On multiple occasions, they expressed curiosity about how the sensors were interpreting their gestures, and expressed desire for feedback from the instrument through visual or other perceptual channels. At the conclusion of the study, they stated an interest in *"delv[ing] into the guts of [the T-Stick]"* [P3, EXI] in future.

5.2 Merging Perspectives: Similarities and Differences

Results of this research suggest that the handful of stakeholder categories identified in the literature may not be inclusive of all individuals who interact with DMIs, specifically amateurs and hobbyists. Additionally, lines between different categories of perspective are blurred. As such, the perspectives described herein are not intended to be representative of distinct categories, but of overlapping ideologies and approaches to interaction, each with differing priorities and processes of engagement. In many ways, the most informative data was related to areas where perspectives overlapped. Given this role-related complexity, the term 'perspective' is employed merely as a shorthand to contextualize participant responses with respect to their musical background and practice preferences. Methodologically, it is of note that both the procedure and data collection strategies used were able to accommodate these diverse perspectives.

Participants often fluidly shifted their thought patterns between describing performative aspects of their interaction, providing technical and design-related suggestions, reflecting on the nature of learning, interaction, and musicianship, and simply describing aspects of musical interfaces they liked or disliked. In conjunction with the blurred boundaries between DMI stakeholders, this implies that there is not simply overlap between patterns of thought, but that the DMI 'user' may constitute a more fluid, holistic perspective not well characterized by a categorical framework. Despite differences in background and perspective, participant experiences showed notable similarity, providing evidence for the overlapping and fluid nature of these roles. Areas in which perspectives diverged typically entailed preconceptions or specific requirements based on individuals' goals and prior experience. To further explore this notion, similarities and differences in participants' patterns of interaction are described in this section.

5.2.1 Experiential Similarities

A major area of consistency among participants was their sense that the T-Stick afforded different interaction styles and musical possibilities than other DMIs or acoustic instruments they had used in the past. This was closely related to the EFP subscale of the MPX-Q. Conversely, participants also identified musical limitations of the interface, though results suggest that a marked shift occurred for all participants when they discovered that models and ideals applicable to acoustic musicianship did not entirely capture the essence of DMI interaction. Through this breakthrough, participants were able to shift their focus from limitations of the T-Stick in the context of traditional musicianship, to the musical possibilities afforded by its unique features.

This breakthrough was facilitated through exploratory interaction with the instrument in order to identify its possibilities and limitations. While comments related to exploration were most common in early sessions as participants engaged with the T-Stick for the first time, exploration and discovery were ongoing, and participants encountered novel interaction possibilities throughout the learning period. All participants chose to engage in open exploration during their first practice session (corresponding to S1), with P1 indicating that they felt the device possessed hidden complexity, despite appearing relatively simple. P2 chose to explore the instrument through exaggerated performance gestures, testing the limits of its parameter space. As they encountered the instrument's affordances and constraints, participants cohered knowledge of these possibilities and limitations into specific ideas for future use of the T-Stick. Even by the end of the study, participants did not feel they had explored all of the available interactive or musical possibilities.

Frustration is often an aspect of learning to play a musical instrument. While frustration with technical and control-related aspects of the T-Stick was common in this study, all users found ways to overcome these limitations and mitigate frustration, especially in later sessions. P3 avoided frustration related to the filter cutoff by focusing on tasks they felt more comfortable performing. Similarly, P2 discovered that, by moving around the research space and using larger gestures, they were able to diminish frustration related to instrument response and latency. Incidents of overcoming frustration were often coded as breakthroughs. This process of altering conceptual and behavioural strategies to mitigate negative affect indicates appropriation and suggests that the process of adaptation to the interface's limitations and idiosyncrasies, such as that described in [27], may be important in DMI learning for any skill level.

Changes in affect were often accompanied by changes in how participants conceptualized or approached the T-Stick. For instance, at the outset of the study, P2's pre-existing negative bias towards the T-Stick was evident: *"I wouldn't choose to use [the T-Stick] in performance or anything"* [P2, S1]. By S5, P2 had opened up towards the T-Stick by changing their conception of it:

> *"[Y]ou have to see [the T-Stick] as a platform more than an instrument in its own right, 'cause it can evolve based on the sound and the mapping layer, which is critically important. So this is just one iteration of the instrument as it's evolving"* [P2, S5].

Likewise, P1 noted a change in their attitude towards the T-Stick by reconceptualizing the frustration they experienced during the learning process, noting that frustration was common to many creative endeavours, and that, in these contexts, some level of frustration could be motivating or interesting. P3's cognitive shift was of a different character, as they reported that their increased understanding of the instrument, through accumulated knowledge and expertise, helped to make the instrument more approachable and less surprising. They noted feeling as though the T-Stick was less *"mysterious"* [P3, EXI], and that they required less conscious effort to interact with it, indicative of phenomena such as absorption and flow.

5.2.2 Experiential Differences

While participants' reports shared common features, other aspects of experience were notably divergent in accordance with their unique goals and requirements. Each participant's plan for future use was thoughtful, specific, and reflective of their personal practice. Additionally, each individual's plan for future use leveraged the unique musical possibilities and idiosyncratic nature of the T-Stick. P1, the composer, expressed a desire to compose mixed pieces that make use of both T-Stick and acoustic instruments. P2 suggested the T-Stick could be useful in as a controller for parameters of other DMIs in their loop-based performances. P3, the hobbyist, wanted to explore the technical side, delving in to how the hardware and mapping worked:

> *"I feel like there's a lot of interesting new things that I haven't been able to do with it and that will take me, personally, quite a while … So I could see it being something challenging and engaging for quite a while"* [P3, EXI].

These specific plans suggest three different, real-world, practical uses for the instrument, further supporting the evidence for the instrument's musical and interactive possibilities, and suggesting creative uses for the instrument in the future. The notion that the T-Stick provides unique affordances, that are not available through other musical instruments, also provides a basis for its longevity; if 1) there is no substitute for the nature of the interaction provided by the T-Stick, and 2) the musical possibilities afforded by it are useful, then there is good reason for individuals to adopt it, engage in sustained practice, and utilize it in performance and composition. The thoughtful nature of these future plans also provides evidence for the development of an intimate relationship with the T-Stick, and a conceptualization of the instrument in the contexts of participants' distinct artistic practices, important aspects of appropriation and embodiment.

In several cases, participants referred to musical limitations of the T-Stick. This area, noticeably more than others discussed, was informed by previous musical experience. As such, it was P1, the composer, who discussed such limitations most frequently. They noted frustration related to the instrument's limited range of frequency, amplitude, and timbre. More specifically, they noted that all frequency zones seemed to exist in the same tonality and set of pitches. Given the prominence of pitch in traditional acoustic instruments, and this participant's composition background and training, this perceived limitation is logical. P1 also noted limitations with amplitude, again feeling as though the range available placed limits on their compositional ideas. They suggested timbre was constraining as well, as they found the sound noisy.

P2, a pianist and active DMI performer, echoed these sentiments, though they did not necessarily see these as restricting the expressive potential of the T-Stick. For P2, musical limitations often overlapped with responsiveness-related concerns, including control and latency, as they felt the musical expressiveness afforded by the instrument was limited by these factors. They suggested that simple melodic tasks, that would be typically relatively easy to accomplish using a traditional acoustic instrument, were more difficult on the T-Stick: *"If I tried to play Jingle Bells on it … I actually did try to play Jingle Bells … I couldn't … I mean I could, but it was off"* [P6, EXI].

P3, who was most interested in the exploration of music technology, was least concerned with the ability to replicate acoustic instrumental practice, though, as described previously, they also experienced a breakthrough when they were able to relax their adherence to traditional musical models.

While DMIs need not strive to afford the same performance possibilities as acoustic instruments, it is clear that individuals' previous experience with acoustic instruments may bias them in certain ways when approaching non-traditional musical interfaces. Although it is important to acknowledge the value of leveraging existing knowledge and technical skill with acoustic instruments in DMI learning, a key aspect of DMI practice and performance is the novel musical and expressive possibilities made available through this divergence from traditional musical practice [27], and participants' ability to adapt to and embrace these novel possibilities attests to this.

5.3 Notable Aspects of Interaction

This section addresses additional aspects of participant experience, including the anecdotal insights identified in Section 4.4, and serves to further develop discussion from the previous section, prior to synthesis of these findings in the context of UIR development, presented in Section 5.4. Topics in this section reference three themes, addressed in the following order:

1. Findings related to the T-Stick hardware, mapping, and synthesis used;
2. Instrument responsiveness, legibility, and perception of control;
3. Musical possibilities, expression, and future use.

5.3.1 Commentary on the Musical Apparatus

As stated in Chapter 3, the musical apparatus consisted of three components: T-Stick hardware, mappings, and a sound synthesis patch. As previously noted, the combination of these components represents one iteration of the T-Stick, and comments in this section should not be considered reflective of the hardware more generally. In addition to specific suggestions for adjustments and improvements to the T-Stick, provided during EXI, participants also noted certain aspects of interaction that related to specific aspects of instrument design. While it is not the goal of this work to set guidelines for design, or to indicate specific directions for revision of the T-Stick hardware, certain topics are worthy of comment, particularly technical errors that impacted on participant experience and perceptions of the instrument's responsiveness.

Throughout the study, participants reported that several demonstrated tasks did not seem to work in the manner that they were shown in the demonstration video. First, the filter cutoff control, mapped to the jab gesture, proved an ongoing problem for some participants. P3 noted issues with this control from when it was initially presented (S1), through to the end of the study (EXI), and stated that they felt little control over that parameter. P2 and P3 also reported that the response of the filter cutoff control seemed inconsistent, with P3 noting that, without insight into the internal state of the system, they felt unable to modulate their behaviour in order to improve their performance on the task. Finally, P3 discovered during S1 that an overly energetic jab gesture could cause the T-Stick's battery to dislodge, causing the instrument to power cycle, which interrupted the sound and the flow of their practice session.

The same battery issue was observed with the reverb tasks, which required participants to shake the instrument. P2 commented on this issue the most, though was able to overcome it by using a *"sort of rotational gesture"* [S3] when shaking. P3 found that battery issues would sometimes occur in association with specific gestures, but at other times seemed unpredictable.

Both P2 and P3 noted an additional glitch with the reverb tasks, in which reverberation would continue, even when they had stopped shaking the instrument. P2 embraced this, suggesting that the wash of reverb made the other tasks easier to perform.

While technical errors should be revisited to ensure that the instrument operates as intended and that demonstrated tasks are replicable for participants, it is worthwhile to note that users were even able to adapt their interaction to behaviours of the instrument that were not intentionally designed. In some cases, these behaviours even worked to participants' advantage. In this way, technical errors and glitches became less important to participants over time.

P2 also cited concerns about the instrument's physical robustness. Issues related to the battery disconnection and unexpected power cycling led to perceptions of the instrument as fragile, or not robust enough to withstand the rigours of real-world performance. For example, P2 cited this as a notable reason for disengagement, as the requirements of active performance necessitated that an instrument be *"gig-ready"* [P2, EXI]:

> *"I throw my instruments in my backpack and take them to a gig. They have to survive being jostled against each other"* [P2, EXI].

While it is valuable to consider modification to the hardware such that the battery connection is more stable, it is certainly not the case that fragility is solely a characteristic of DMIs developed in research labs. Indeed, many acoustic instruments are delicate, and most musical instruments, digital or otherwise, will have a threshold for the amount of force that can be applied before the instrument ceases to behave as expected, or is broken.

Finally, some participants experienced discomfort as a result of the effort expended, or the nature of the gestures they were asked to perform. In order to produce sound, it was necessary for participants to apply pressure to the force-sensitive resistors along the surface of the T-Stick. Pressure was mapped to the synthesizer's amplitude parameter, such that no sound was produced without continuously exerting pressure on the instrument. Both P1 and P3 noted that this forced them to maintain an awkward grip, which led to irritation and pain in their hands, a major ergonomic issue. The issue of physical discomfort was flagged by both of these participants in S2, and persisted through S5, with P3 noting that it was affecting use of their hand outside of the research context. This reflects a poor choice of mapping, rather than a fundamental hardware issue. Furthermore, given the flexibility of DMI mapping, this issue can be easily remedied by making the amplitude parameter correspond to a different input.

5.3.2 Responsiveness, Legibility, and Control

Participants experienced a number of difficulties in their interaction with the T-Stick, which negatively impacted perceptions of responsiveness and feelings of control. These challenges tended to yield interview incidents that were coded under the PU subscale of the UES, the PCC subscale of the MPX-Q, and the reasons for disengagement category. While participants cited these concerns as *potential* reasons for disengagement, it is worthwhile to note that none of the participants did, in fact, disengage from the study, and, in many cases, they overcame challenges that might have motivated them to abandon the instrument. While this observation is reason for optimism in considering the future longevity of the T-Stick, it is still important to note difficulties participants faced in achieving a consistent and predictable response with the DMI, as these challenges and how they were overcome were a key facet of participant experience.

All participants reported the T-Stick behaving in unexpected ways at various points during the study. P3 noted feeling as though they were unable to replicate sonic results even when they felt they were making the same gesture. P2 reported that *"there are times where [the T-Stick] just falls off a cliff and stops responding well or at all"* [P2, S4]. P1 felt that the instrument sometimes behaved at random, questioning whether this was an intentional aspect of the design (it was not). As described in [70], randomness can be desirable or useful in DMI interaction, and can offer interesting musical advantages. In this research, however, unpredictable behaviour caused challenges for participants, and negatively affected perceptions of the instrument's responsiveness and feelings of control. Issues related to responsiveness were also observable to third-party evaluators, as illustrated by this comment from E2 on P1's performance:

> *"For the most part the T-Stick seems to respond as intended. However there are obvious hiccups where the T-Stick has turned off at the beginning and end of the performance"* [E2].

Despite ongoing control issues, ratings of instrument responsiveness increased from strong disagreement to neutrality, from S3 to S5. Average ratings of feelings of control, however, did not indicate a trajectory, though they too ranged from strong disagreement to neutrality.

Some control issues related to the tasks and demonstrations provided to participants. Filter cutoff, frequency, and amplitude proved challenging for participants in terms of achieving consistent response. When initially practicing the filter cutoff, P2 expressed not feeling in control:

> *"[I]t feels like I have to … coax the instrument into making it … it doesn't feel like I'm playing the instrument so much as I'm trying to fight against the instrument"* [P2, S1].

With respect to legibility, P3 noted, in their suggestions for improvement, that it would be desirable for the instrument to have *"less hidden states"* [S5], as they felt that *"hidden modes"* [S5] were responsible for inhibiting their ability to produce predictable results from gesture to gesture. P3 made the most comments about a desire for instrument feedback throughout the study, and suggested that visual or tactile feedback would be beneficial in a number of ways. They suggested that being able to see the synthesis patch while working would allow them to understand the state of the system and how their gestures were being interpreted, and speculated that feedback could allow them to feel as though they were more reliably in control of instrument parameters.

For P1 and P2, latency also affected the extent to which they perceived the instrument as responsive. While P1 mentioned this in relation to the attack envelope of the sound (mapping of amplitude to pressure tended to cause a slow swell of sound rather than a discernible attack), P2 cited it as a more global concern. For P2, latency was a repeated source of frustration, as it negatively impacted their perceptions of control over the T-Stick. As in other instances, this was overcome in the later stages of the study as P2 adapted their behaviour by moving in a more fluid way, reporting that this enabled them to feel as though they were truly *playing* the instrument.

While participants cited challenges related to responsiveness and control, they were often able to overcome come them, and no potential reasons for disengagement led to actual attrition from the study. This finding holds promise for the T-Stick's musical future and longevity, suggesting that, despite limitations, the T-Stick is sufficiently responsive to allow for ongoing practice and performance. Furthermore, these limitations can be overcome in a relatively short period of time, suggesting that perceptions of control evolve with time and continued practice.

5.3.3 Musical Expression: Possibilities and Future Use

Further promising supporting evidence for the T-Stick's longevity is illustrated by participants' conceptualizations and perceptions of the instrument's musical value, particularly once participants were able to disregard preconceptions of music interaction based on mental models of acoustic instruments. Both P1 and P2 commented on the expressive potential of the T-Stick in S5, with P1 reporting that *"it's getting really expressive"* [P1, S5]. P2 indicated that they found certain methods of interaction to afford more expressivity than others, but that they were able to focus on particular parameters based on their musical intent: *"Mainly I was focusing on controlling amplitude, timbre, and reverb, which I found to be the most expressive for what I was trying to do"* [P2, S5].

Moreover, all participants strongly agreed that the T-Stick provided different musical possibilities than other DMIs or acoustic instruments they had used previously. Relatedly, ratings of the T-Stick allowing for creativity were generally positive (excluding S2), and increased from S2 to S5, suggesting that, over the learning period, participants were able to draw increasing inspiration from the T-Stick's musical possibilities. Average ratings of the T-Stick as allowing participants to express themselves showed a similar pattern, decreasing from S1 to S2 and increasing thereafter.

Average ratings of desire to use the instrument again dropped between S1 and S2, but increased for the remainder of the study. In EXI, all three participants expressed interest in using the T-Stick in the future, and each ideated on how they might leverage the unique affordances of the T-Stick for use in their specific musical practice. This is promising for instrument longevity, suggesting that even a limited learning period can help to make the T-Stick approachable for novice users, and can suggest affordances that might apply to their individual practice.

While each participant's plan for using the T-Stick in the future was distinct, based on the personal practice they outlined in the PSQ and ENI, each participant's ideation for future use was thoughtful and specific, demonstrating appropriation and initial development of the UIR.

5.4 Changes Over Time and Development of the User-Instrument Relationship

Ratings and interview data collected illustrate the many aspects of participant experience that evolved over the course of the study. With respect to the methodological goals of this research, data collection was a success: changes in the UIR were evident as participants learned to play the T-Stick and developed a relationship with it. Moreover, survey and interview data collection methods were able to capture these changes in detail. This section briefly reviews specific aspects of experience that changed for participants over the course of the study, including learning, affective changes, challenges and breakthroughs, and development of the UIR.

5.4.1 Learning

Ratings from both the participants and third-party evaluators provided evidence that the musical tasks used were learnable and that, by the end of this study, participants appeared to be somewhat competent T-Stick performers with these tasks, even though all participants had minimal T-Stick experience at the outset, and had no experience with the mapping used. Additionally, participants reported that, from S2 to S5, they increasingly felt as though the instrument responded well to their actions and allowed them to express themselves.

Although the sample size was small, participants' self-reported ability to perform the tasks suggests that the set of tasks used shows some degree of increasing complexity, though this bears further examination, especially given technical problems associated with specific tasks. While learning of these tasks should be re-examined after these issues have been resolved, it is posited that, with minor modifications (Section 5.6), the task set is adequate for use in an expanded study.

5.4.2 Affective and Cognitive Changes

While affective changes were readily apparent in the transcriptions of participants' interviews, they were less apparent in questionnaire responses, suggesting that data between survey and interview questions was not entirely aligned. This being acknowledged, the average rating in response to the question that asked participants whether their experience with the instrument was fun increased from S2 to S5. Users' average sense that the T-Stick facilitated creativity also increased from S2 to S5. The increase in ratings for fun and creativity can be attributed to training. As participants learned more about the operation of the instrument, they were able to adjust their methods of interaction to increase their amusement through acquisition of information about new interaction strategies that expanded the possibilities for creative engagement.

Of more importance with respect to the fundamental dynamic nature of DMI interaction, participants' general cognitive shift away from models of acoustic musicianship, and towards the musical and expressive possibilities that were specific to the T-Stick, is an important observation, illustrative of participants' ability to *"embrace the weirdness"* [27, p. 1] of novel musical devices. This, perhaps, was the most pivotal moment in the evolution of the UIR.

5.4.3 Development of the User-Instrument Relationship

Initial interactions with the T-Stick were often informed by participants' musical backgrounds, personal preferences, and expectations related to the instrument. These had notable impact on how participants developed their relationships with the instrument by appropriating it in the context of their personal practice and preferences, though participants' also shifted their expectations of the instrument through sustained interaction and appropriation.

Additionally, participants reported instances of embodiment, indicative of an increasingly intimate and engaging relationship with the T-Stick. These reports often coincided with descriptions of absorption and flow: P1 described the process of finding a stable position that allowed them to maximize the expressive potential of the instrument, while P2 reported feeling able to express themselves by making using of the physical space, allowing them to establish a feedback loop between the sound of the T-Stick and their movement. P3 described the action of playing as becoming less conscious and more automatic over the learning period, and feeling as though their intentions and the resultant sound were becoming more aligned. These changes were also reflected in increases in average ratings, from S2 to S5, on items inquiring about feelings of absorption and time slipping away (related to the FA factor of the UES).

Accidental discoveries also facilitated changes in the UIR. For instance, P2's discovery of the shake gesture glitch, in which reverb did not dissipate as it was supposed to when the shaking gesture was stopped, made them feel that the other tasks were easier to accomplish, as the wash of the reverb obscured abrupt sonic changes. P1 discovered a *"rest position"* [P1, S5] which they could use as a stable base from which to explore other gestures, increasing their sense of the T-Stick's expressive possibilities. Evolution of the UIR over this study was succinctly expressed by P2:

> *"I started out bumbling around just like any new creative user and eventually I felt like I could just mess around on it a little bit. It's like learning to play tennis—getting to a point where you can hit it back over the net … [T]hat's a huge milestone because it means you can now play the game. You can play, you can participate. So I felt like I went from someone who could not participate to someone who could."* [P2, EXI].

5.5 Limitations

While results from this research demonstrate the effectiveness of the method in assessing changes in experiential aspects of DMI interaction while learning to play the instrument, the research described herein presents a number of limitations worthy of comment, based on feedback provided by participants, and the nature of the study as a demonstration of a previously-unused method. These limitations are divided into sections related to participants, scope, and the extent to which the research environment and scenario were representative of real-world musical practice. Strategies for addressing these limitations are discussed in the following section.

5.5.1 Participants and Exclusion Criteria

Three participant-related limitations are worthy of comment. First, the inclusion criteria for this study (Section 3.1) did not target a specific population. Consequently, findings cannot be generalized to a certain population of interest, or extrapolated to larger groups, especially given the second limitation, the small sample size (n=3). While these limitations are acknowledged, it is also important to highlight the idiosyncratic nature of the relationship between musical performers and their instruments. Music interaction and the development of the UIR is highly individual, personal, and intimate. As a consequence, aggregate measures of experience may not necessarily yield a valid description of a 'normal' or 'standard' performer experience. Furthermore, participant differences actually proved beneficial in the current research, as the three unique perspectives represented divergent, but equally valid, approaches to DMI learning, serving to illustrate both similar and contrasting facets of UX and the experiential trajectory. Furthermore, these commonalities and differences demonstrated the multifaceted nature of the DMI user, capable of shifting priorities between design, performance, and other areas of concern, a characterization not well described by categorical stakeholder models.

The third and final participant-related limitation is that all participants had previous knowledge of HCI concepts, DMI research, and the T-Stick itself. Consequently, this research did not fully control for pre-existing biases about the T-Stick, resulting in difficulty when attempting to disentangle aspects of participants' experience with the T-Stick during the study from their pre-existing thoughts and emotions about the instrument. Conversely, participants' prior DMI and HCI knowledge might also have been beneficial, given the research goal of demonstrating a specific method; participants were able to give informed feedback on aspects of instrument design, mapping, and methodology, providing useful and actionable information for revisions to the musical apparatus and research protocol. While these limitations are important, they also have corresponding advantages in the context of this specific project, and participant feedback will prove immensely useful in development of an expanded and more controlled study.

5.5.2 Scope: Timeframe, Tasks, and Instrument

In a number of ways, this research is limited in scope: specifically, the timeframe, musical apparatus, and tasks used. Given the goal of conducting longitudinal research over a learning period, the limitation of length is paramount. While this study was conducted over only 20 days, data collected still provided great insight into dynamic aspects of interaction as they evolved over time. Despite the limited duration, changes in participants' affect and attitude towards the T-Stick were observable, and results suggest that UIR development can occur over a short period.

In addition to conducting longitudinal evaluation, another important aim of this research was to begin to explore the possibility of a *generalized* method for evaluating UX with DMIs over time. As such, this study employed data collection strategies that were not specific to the T-Stick. The tasks and musical apparatus were, however, inherent to this specific iteration of the research project. As such, findings presented are confined to a single combination of hardware, synthesis patch, mapping, and set of tasks. As is the case with participant-related concerns, these limitations are not massively consequential for the present research goal of demonstrating a new method. Future research can gradually expand this research protocol to other hardware controllers, mappings, synthesizers, task sets, and longer spans of time, ideally spans of months or years, facilitating long-term study of the UIR with different DMIs in different contexts.

5.5.3 Ecological Validity

The third type of limitation relates to the extent to which this research was representative of how music interaction occurs in real-world settings. Ecological validity, or the extent to which a research setup mirrors the 'real world,' is a major concern in scientific inquiry, and affects the ability of researchers to generalize results obtained in a lab setting to other times, places, and people. It is conceivable that the practice setting (a research lab) and structure (scheduled sessions of pre-determined length) may not have been reflective of participants' ideal practice scenarios, and may have impacted their learning, experience, and attitudes, consciously or unconsciously.

While this is worthy of acknowledgement, there is unlikely to be a 'standard' real-world scenario for DMI practice, primarily due to the idiosyncratic nature of the discipline. This topic bears careful reflection, and it is worthwhile to consider that the nature of 'real-world' musical practice might always be compromised through the imposition of formal research controls. To elaborate, one might consider the ideal research scenario to be one in which a performer utilizes a DMI in the context of their existing musical setup and practice, without specific direction as to how the instrument is to be used. This, however, presents a challenge for researchers when attempting to implement control or structure, as a more 'organic' usage scenario would be more difficult to study with a high level of formality or scientific rigour when compared with a lab-based setup such as that used in the present study. Furthermore, having multiple participants integrate a new instrument into their personal creative practice and environment would lead to challenges when attempting to make comparisons between participants and draw general conclusions, as each individual's interaction would likely differ on several dimensions, such as musical goals or amount of time spent practicing. Inevitably, a compromise must be made between high ecological validity and scientific structure and control.

5.6 Future Changes

While an innumerable number of potential alterations to the research design are possible in light of the imitations previously described, several issues are pressing with respect to conducting an expanded version of this study over an extended timeframe. Potential changes will be framed with respect to the research objectives, and will be summarized into the areas of musical apparatus, task blocks, research environment and practice structure, and data collection methods.

5.6.1 Musical Apparatus

The musical apparatus, consisting of the T-Stick hardware, mapping, and synthesis patch, offers an infinite range of combinations and possibilities for modification. Rather than attempting a thorough exploration of this possibility space or a complete reinvention of the instrument, discussion of changes to the instrument will focus on aspects of the apparatus that impacted participant experience, as it is not the goal of this work to provide design guidelines.

First, and most important, the mapping of the amplitude to the pressure sensor of the T-Stick should be altered, as it caused pain and discomfort for two participants. Given that amplitude is a fundamental characteristic of sound and music, it is important for users to have the ability to control the presence, absence, and volume of sound with relative ease. More importantly, knowingly presenting participants with an interface known to cause pain and discomfort would be in violation of ethical research obligations.

Second, the T-Stick hardware should be modified to ensure that the battery does not come loose when individuals are performing energetic jab or shake gestures. Interruption of sound resulting from the power cycling process was a notable source of frustration for users, and was disruptive to the process of musical practice, taking users out of the flow of their interaction, and potentially presenting a confounding variable in the context of UX evaluation.

Finally, in addition to the modification to the amplitude mapping described above, it could be beneficial to revisit the mapping for the purposes of developing an increased number of musical tasks. This could be beneficial in extending the duration of the study and expanding the possible interaction strategies for future research.

5.6.2 Musical Tasks

In conjunction with adjustments to the mapping, a number of potential changes to the set of tasks used merit comment. These can be classified into two categories: 1) the tasks themselves and 2) the video demonstrations of tasks provided to participants. Motivation for altering the tasks is not fundamental alteration of the research protocol, but incremental improvement which could facilitate a longer study using an instrument with additional interaction strategies, and more complex and nuanced musical possibilities which could require spans of weeks or more to master.

While it is difficult to speculate on the exact nature of the tasks that should be created, a fundamental guiding principle should be the same as that used during initial task development, namely, task sets that demonstrate an increasing level of difficulty. This could include addition of more complex tasks, as well as revising the possibility of combining existing tasks, such as changing the frequency while also altering the timbre. Utilizing insights gleaned from this study, T-Stick performers consulted during the development stage of this study should be contacted again to provide ideas for additional tasks and any mapping alternations necessary to facilitate these tasks.

Relatedly, it could be beneficial to include these experienced performers in follow-up research in a more involved way, potentially as tutors or evaluators. For example, it could be beneficial to structure the learning process more similarly to music lessons, in which participants have short sessions with an experienced performer who has in-depth knowledge of the mapping. This would provide participants with direct access to an expert, who can provide real-time guidance and feedback, and who can suggest gestural modifications to aid participants in performing tasks. A similar form of tutelage was used in [36]. This could help to address problems related to the video demonstrations, which could be a source of frustration for participants when they felt unable to replicate the gestures and sonic results achieved by the performer in the videos.

In planning follow-up research, it is also worth exploring the creation of short musical excerpts or études for participants to replicate, ideally with some form of notation. This approach draws on work from Moro and McPherson [36], who made use of études in their evaluation of a continuous keyboard DMI. Score and pre-recorded audio may, however, be difficult to create in the same manner as [36], as their researched was designed to leverage existing knowledge of piano technique, notation, and repertoire.

5.6.3 Practice Structure and Research Environment

Several aspects of practice structure and research environment are worth revisiting when planning a follow-up study. First, the nature and structure of the practice time and learning process could be altered. Addition of one-on-one tutelage with an experienced performer, commented upon in the previous subsection, could provide participants with additional support and valuable mentorship, by employing a learning scenario akin to that of acoustic instruments.

The timing of practice sessions could be revisited as well. If key technical issues related to stability are overcome, and researchers are not required to be present for troubleshooting, it would be possible to allow participants to take the T-Stick home to practice, or to come into the lab at a time of their choosing. This could allow participants flexibility in structuring their musical practice as they please, allowing them to pick up the instrument when they feel inspired, or to put it down when they feel frustrated and return to it later. This is in accordance with suggestions made by P1 and P3 related to the nature of musical practice and the structure of the current study.

Both modifications described would, however, require methodological adjustments, such as asking participants to keep practice diaries, describing the amount of time spent practicing and what they were focused on during that time. Allowing participants to practice at home would also require that no advanced technical skill is required to set up the device or playback system.

Finally, with respect to the practice environment, one unexpected anecdote came from P1, who commented on the large television in the room where the study was conducted:

> *"I think what was nice was the screen … the television that is in front of us, because we have a reflection of what we are doing, a visual. I think it's … important … because you need to be a bit transparent with your gesture[s]"* [P1, S1].

The television was not considered when designing the study. It may be worthwhile, however, to consider inclusion of a mirror or other reflective surface in the practice environment, as this could provide participants with visual feedback related to their gestures, potentially benefitting the learning process. Considering the commentary provided by P2 in relation to large gestures, the inclusion of a reflective surface could be akin to the use of mirrors in a dance studio, where dancers use the mirror to maintain awareness of their bodies' position and movement:

> *"I was walking around the room more and involving more of my body in the movements. So instead of just doing the minimum amount, I was actually moving my whole body with what I was doing with the T-Stick, and that made it feel more expressive"* [P2, S5].

5.6.4 Measurements

Given the nature of this research as initial demonstration of a methodology, modifications to data collection measures will not be discussed at length. Participants provided little feedback on this aspect of the study, and results suggested that strategies used were sufficient in capturing experiential constructs of interest. Thus, measures-related recommendations are more practical.

The use of qualitative data collection strategies inherently engenders rich and detailed data, but in very large amounts. As such, it takes a significant amount of time to transcribe, code, and analyze this data, presenting a barrier to ongoing research. In order to reduce the impact of such problems, interview guides for all stages of the process could be revisited to ensure that questions directly target the constructs of interest. One strategy for making informed adjustments would be to conduct a more thorough analysis of coded data, to examine which questions yielded the most informative responses related to engagement, affect, and cognition.

The ratio of qualitative to scale-based data could also be altered to increase the amount of ratings data collected. For example, where prudent, interview questions could be adapted to a Likert Scale format. Given that both the UES and MPX-Q were developed with notable scientific rigour, it could be advantageous to use these measurement tools in their entirety, leveraging their empirical benefits.

5.7 Summary

Through description of the three distinct perspectives represented by the participants in this study, review of patterns and contrasts between their learning processes, and examination of experiential anecdotes, the discussion presented in this chapter offers insight into the nature of UX and the UIR, as individuals learned to play an unfamiliar DMI. The research presented highlights the impact of previous experience on DMI interaction, individuals' ability to adapt to their thoughts and behaviours based on an instrument's unique musical possibilities, the contribution of shifting hedonic and cognitive factors to overall UX, and the complex and multifaceted character of the DMI user.

In addition to building on existing understandings of the dynamic nature of music interaction during DMI learning, this work presents a notable achievement in the form of development and demonstration of a new methodology for the longitudinal study of UX with DMIs. While the method used has inherent limitations, to be addressed in future research, demonstration of the research protocol and data collection strategies used represents a major, original methodological contribution to DMI evaluation research.

Chapter 6: Conclusion

In the study of interaction with DMIs, the relationship between the musician and their instrument is of crucial importance. While this is acknowledged in the DMI community, existing strategies for evaluation present limitations, particularly in their ability to provide information related to the dynamic nature of UX and the role it plays in this relationship. The research presented herein described development of a new method to study UX and the UIR in an ongoing manner, as individuals learned to play a DMI, the T-Stick, with which they had little to no prior experience. Through learning a series of demonstrated tasks over a twenty day period, participants became competent T-Stick musicians, and reported on their learning experience through surveys and interviews, administered at multiple points in time. Through development and demonstration of a new method for longitudinal DMI evaluation, the research presented contributes to DMI research in practical, theoretical, and methodological ways. To conclude this work, these contributions are summarized, and plans for future research are briefly introduced.

6.1 Contributions

Using frameworks from HCI (UES) and music technology (MPX-Q), as well as a set of categories which contextualized the role of hedonic and cognitive UX factors in DMI learning, a longitudinal evaluation of the T-Stick was conducted using a novel mapping and set of musical tasks. This conclusion describes three notable contributions of this research in three different areas. The first of these is the benefit of this study in extending research into the T-Stick's use and development through a more detailed understanding of how it is experienced by novice users. Second, this research makes a notable addition to the body of literature addressing how individuals' experiences and relationships with DMIs might develop over time. The final and most important contribution is the introduction of a previously unused method for evaluation of UX with DMIs that has the potential to be expanded across multiple instruments and timescales.

6.1.1 Practical Contributions: Musical Apparatus

The clearest and most immediately applicable contribution of this research is one that is both practical and actionable. Throughout the course of this evaluation of the T-Stick, participants reported several technical issues that affected perceptions of the instrument's responsiveness and their sense of control. By incorporating participant feedback, it will be possible to make modifications to the T-Stick that can render the instrument more robust, and remove barriers to use stemming from technical issues causing frustration or incentive for disengagement. By increasing the stability and reliability of the interface, it may be possible to diminish barriers to adoption, potentially increasing use and longevity of the instrument.

Relatedly, this project required development of a set of musical tasks of increasing difficulty for the T-Stick, informed by experienced researchers and performers. When necessary changes to mappings have been implemented, and the task set modified accordingly, these resources could serve as a useful starting point for individuals interested in learning to play the T-Stick. Given the open-source nature of the T-Stick, it is hoped that providing basic mappings and sound synthesis patches for members of the public, in tandem with video resources that demonstrate how these can be used, might encourage more individuals to build, learn, and perform with the T-Stick.

6.1.2 Theoretical-Conceptual Contributions: Understanding Perspectives in Music Interaction

Two important theoretical contributions are noteworthy. First, results indicate that accepted categorical models of stakeholders with vested interest in DMI design and evaluation may be overly simplistic. While participants explicitly identified themselves as performer, composer, and hobbyist, interview responses often shifted between performance, design, compositional, and other concerns, not isolated to one specific role. Further investigation into how the DMI user is characterized should be carried out. Specifically, models of DMI users should be inclusive of a wide range of skill levels, musical styles, and patterns of engagement, and should promote a holistic understanding of the 'DMI musician' as not just a constellation of distinct yet overlapping perspectives, but individuals with knowledge spanning the many component disciplines of music interaction, who are capable of fluid ideation that seamlessly transitions between design, performance, composition, technical, and interaction priorities.

Second, findings provided several insights into novices' experiences during DMI learning:

1. Open exploration of musical possibilities is useful in the DMI learning process.
2. Frustration is an important aspect of performer experience when learning to play a new instrument. While some frustration is normal, frustration resulting from fundamental technical problems should be avoided. Even so, musicians may find creative ways to mitigate frustration by adapting their interaction strategies, potentially even taking advantage of

technical errors;

3. Conversely, breakthroughs are also important to performer experience, and can be indicative of increasing appropriation and embodiment in the UIR, processes that are likely gradual, but appear to begin at an early stage. An important cognitive breakthrough in DMI learning is the realization that traditional models of musicianship, based on acoustic instruments, do not fully apply. This conceptual shift allows for users to fully embrace the unique possibilities and 'weird' nature of DMIs;
4. Development of the UIR can show aspects of intimacy and engagement, even at early stages in the learning process. Furthermore, individuals' background and previous experience affect the manner in which this development proceeds;
5. Instruction through the use of isolated musical tasks is sufficient for individuals learning to play a DMI to create original musical ideas;
6. Even in the short term, interaction with a DMI can allow individuals to extrapolate ideas for the instrument's use in their own personal performance practice, potentially providing incentive for individuals to adopt a new DMI and use it in an ongoing manner;
7. Finally, it is clear that aspects of affect and cognition do change over time spent learning a DMI, and further research should examine the trajectory of these experiential aspects over longer timeframes, potentially from months to years of practice.

6.1.3 Methodological Contributions: Novelty and Generalizability

The final and most notable contribution of this work was execution and demonstration of a new generalized methodology for longitudinal DMI evaluation. Given that existing strategies tend to be short-term, exploratory, and lacking rigour, application of a systematic methodology for studying UX with DMIs over time is a significant achievement, with great potential for future research. The evaluation protocol developed effectively detected changes in participants' emotional and cognitive reactions to a DMI, and made it possible to observe the development of expertise and skill, as well as initial development of an engaging UIR, over a limited time period.

The most valuable aspect of this proof-of-concept for longitudinal evaluation research lies in its flexibility and replicability. While a longer replication with the T-Stick is intended after considering potential modifications discussed previously, this procedure can also be applied to other DMIs, sets of tasks, and participants. It could also be useful to adapt this design for more experienced performers, potentially allowing researchers to compare how the experience of expert and novice players differs, and to assess the impact of skill on UX in music interaction. As such, it is hoped that this methodology will be adopted by other research groups, such that results from different users with different instruments can be compared, providing further insight into how features of different instruments affect UX and the UIR. For these purposes, questionnaires and interview guides, collected and coded data, as well as the coding guide, are provided in the appendices and online at https://gitlab.com/creimer/longitudinal-evaluation-of-dmis.

6.2 Summary and Future Research Directions

This thesis reported on development and demonstration of a method to examine UX and the UIR with a DMI over a learning period. Using frameworks from HCI (UES) and music technology (MPX-Q), as well as categories contextualizing the role of affect and cognition in the UIR, an evaluation of the T-Stick was conducted using a novel mapping and set of tasks.

Results indicated that the procedure and data collection strategy were suitable for capturing and characterizing experiential music interaction phenomena. Participants were able to learn the instrument through a series of tasks and develop an original musical idea. Furthermore, data collected suggests that, even over limited time periods, the development of an intimate and embodied UIR was evident across a small sampling of individuals with differing musical backgrounds and experience. By the end of the study, participants were able to come up with unique plans for future use of the T-Stick based on their backgrounds and preferences. These specific plans suggest three different, real-world uses for the instrument, further evidence for the instrument's musical possibilities and future creative use. The thoughtfulness of these plans also demonstrates development of intimate relationships with the T-Stick, and conceptualizations of the instrument in the context of distinct artistic practices, important aspects of appropriation.

In future, it is intended that this research will be replicated and expanded upon, though initial data collected provides useful insight with respect to interaction between musicians and DMIs. Future studies using larger numbers of participants, longer spans of time, and different musical hardware, mappings, and sound synthesis are possible. Furthermore, it is hoped that, by providing all relevant details of this generalized research protocol, other researchers will adopt and improve the procedure, thereby providing one avenue for increasing formality and replicability of UX evaluation research in the larger DMI community.

References

[1] Chadabe, J. (1997). *Electric sound: The past and promise of electroacoustic music.* Prentice Hall. Upper Saddle River, NJ, USA.

[2] Théberge, Paul (1997). *Any sound you can imagine: Making music/Consuming technology.* Wesleyan University Press. Middletown, CT, USA.

[3] Barbosa, J., Calegario, F., Teichrieb, V., Ramalho, G., & McGlynn, P. (2012). Considering audience's view towards an evaluation methodology for digital musical instruments. In *Proceedings of the 2012 International Conference on New Interfaces for Musical Expression (NIME 2012).* Ann Arbor, MI, USA. https://doi.org/10.5281/zenodo.1178209

[4] Barbosa, J., Malloch, J., Wanderley, M. M., & Huot, S. (2015). What does "evaluation" mean for the NIME community? In *Proceedings of the 2015 International Conference on New Interfaces for Musical Expression (NIME 2015).* Baton Rouge, LA, USA. https://doi.org/10.5281/zenodo.1179010

[5] Brown, D., Nash, C., & Mitchell, T. (2017). A user experience review of music interaction evaluations. In *Proceedings of the 2017 International Conference on New Interfaces for Musical Expression (NIME 2017).* Copenhagen, Denmark. https://doi.org/10.5281/zenodo.1176286

[6] Reimer, P. J. C., & Wanderley, M. M. (2021). Embracing less common evaluation strategies for studying user experience in NIME. In *Proceedings of the 2021 International Conference on New Interfaces for Musical Expression (NIME 2021).* Shanghai, China. https://doi.org/10.21428/92fbeb44.807a000f

[7] Stowell, D., Robertson, A., Bryan-Kinns, N., & Plumbley, M. D. (2009). Evaluation of live human-computer music-making: Quantitative and qualitative approaches. *International Journal of Human-Computer Studies, 67*(11), 960-975. https://doi.org/10.1016/j.ijhcs.2009.05.007

[8] Holland, S., Mudd, T., Wilkie-McKenna, K., McPherson, A., & Wanderley, M. M. (2019). Understanding music interaction, and why it matters. In Holland, S., Mudd, T., Wilkie-McKenna, K., McPherson, A., & Wanderley, M. M. (Eds.). *New directions in music and human-computer interaction* (pp. 1-20). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-92069-6_1

[9] Miranda, E. R., & Wanderley, M. M. (2006). *New digital musical instruments: Control and interaction beyond the keyboard.* A-R Editions. Middleton, WI, USA.

[10] Jordà, S. (2004). Instruments and players: Some thoughts on digital lutherie. *Journal of New Music Research, 33*(3), 321-341. https://doi.org/10.1080/0929821042000317886

[11] Wanderley, M. M., & Orio, N. (2002). Evaluation of input devices for musical expression: Borrowing tools from HCI. *Computer Music Journal, 26*(3), 62-76. https://doi.org/10.1162/014892602320582981

[12] Young, G. W., & Murphy, D. (2015). HCI models for digital musical instruments: Methodologies for rigorous testing of digital musical instruments. In *Proceedings of the 2015 International Symposium on Computer Music Multidisciplinary Research.* Plymouth, UK. https://doi.org/10.13140/RG.2.1.3949.9364

[13] Norman, D. (2004). *Emotional design: Why we love (or hate) everyday things.* Basic Books. New York, NY, USA.

[14] Triberti, S., Chirico, A., La Rocca, G., & Riva, G. (2017). Developing emotional design : Emotions as cognitive processes and their role in the design of interactive technologies. *Frontiers in Psychology, 8*(1773). https://doi.org/10.3389/fpsyg.2017.01773

[15] Forlizzi, J., & Battarbee, K. (2004). Understanding experience in interactive systems. In *Proceedings of the 5th Conference on Designing Interactive Systems.* Cambridge, MA, USA. https://doi.org/10.1145/1013115.1013152

[16] International Organization for Standardization. (2010). *Ergonomics of human-system interaction —Part 210: Human-centred design for interactive systems (ISO 9241-210:2010).* https://www.iso.org/obp/ui/#iso:std:iso:9241:-210

[17] El-Shimy, D., & Cooperstock, J. R. (2016). User-driven techniques for the design and evaluation of new musical interfaces. *Computer Music Journal, 40*(2), 35-46. https://doi.org/10.1162/comj_a_00357

[18] Berdahl, E., & Ju, W. (2011). Satellite CCRMA : A musical interaction and sound synthesis platform. In Jensenius, A. R., & Lyons, M. J. (Eds.). *A NIME reader: Fifteen years of New Interfaces for Musical Expression* (pp. 373-389). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-47214-0_24

[19] Fukuda, T., Meneses, E., West, T., & Wanderley, M. M. (2021). The T-Stick music creation project: An approach to building creative community around a DMI. In *Proceedings of the 2021 International Conference on New Interfaces for Musical Expression (NIME 2021).* Shanghai, China. https://doi.org/10.21428/92fbeb44.26f33210

[20] Mamedes, C. R., Rodrigues, M. G., Wanderley, M. M., Manzolli, J., Garcia, D. H. L., & Ferreira-Lopes, P. (2014). Composing for DMIs – Entoa, music for Intonaspacio. In *Proceedings of the 2014 International Conference on New Interfaces for Musical Expression (NIME 2014).* London, UK. https://doi.org/10.5281/zenodo.1178861

[21] McPherson, A. P., & Kim, Y. E. (2012). The problem of the second performer: Building a community around an augmented piano. *Computer Music Journal, 36*(4), 10-27. https://doi.org/10.1162/comj_a_00149

[22] Morreale, F., & McPherson, A. P. (2017). Design for longevity: Ongoing use of instruments from NIME 2010-14. In *Proceedings of the 2017 International Conferences on New Interfaces for Musical Expression (NIME 2017).* Copenhagen, Denmark. https://doi.org/10.5281/zenodo.1176218

[23] Morreale, F., McPherson, A. P., & Wanderley, M. M. (2018). NIME identity from the performer's perspective. In *Proceedings of the 2018 International Conference on New Interfaces for Musical Expression (NIME 2018).* Blacksburg, VA, USA. https://doi.org/10.5281/zenodo.1302533

[24] Marquez-Borbon, A., & Martinez-Avila, J. P. (2018). The problem of DMI adoption and longevity: Envisioning a NIME performance pedagogy. In *Proceedings of the 2018 International Conference on New Interfaces for Musical Expression (NIME 2018).* Blacksburg, VA, USA. https://doi.org/10.5281/zenodo.1302541

[25] Fasciani, S., & Goode, J. (2021). 20 NIMEs: Twenty years of new interfaces for musical expression. In *Proceedings of the 2021 International Conference on New Interfaces for Musical Expression (NIME 2021).* Shanghai, China. http://doi.org/10.21428/92fbeb44.b368bcd5

[26] Calegario, F., Tragtenberg, J., Frisson, C., Meneses, E., Malloch, J., Cusson, V., & Wanderley, M. M. (2021). Documentation and replicability in the NIME community. In *Proceedings of the 2021 International Conference on New Interfaces for Musical Expression (NIME 2021).* Shanghai, China. http://doi.org/10.21428/92fbeb44.dc50e34d

[27] Lepri, G., & McPherson, A. (2022). Embrace the weirdness: Negotiating values inscribed into music technology. *Computer Music Journal,* 1-47. https://doi.org/10.1162/comj_a_00610

[28] Casciato, C., & Wanderley, M. M. (2007). Lessons from long-term gestural controller users. In *Proceedings of the 4th International Conference on Enactive Interfaces.* Grenoble, France. https://www-archive.idmil.org/_media/publications/2007/casciato_2007_enactive.pdf

[29] Nieva, A., Wang, J., Malloch, J., & Wanderley, M. M. (2018). The T-Stick: Maintaining a 12-year-old digital musical instrument. In *Proceedings of the 2018 International Conference on New Interfaces for Musical Expression (NIME 2018).* Blacksburg, VA, USA. https://doi.org/10.5281/zenodo.1302545

[30] Fels, S. (2004). Designing for intimacy: Creating new interfaces for musical expression. *Proceedings of the IEEE, 92*(4), 672-685. https://doi.org/10.1109/jproc.2004.825887

[31] Malloch, J., Garcia, J., Wanderley, M. M., Mackay, W. E., Beaudouin-Lafon, M., & Huot, H. (2019). A design workbench for interactive musical systems. In Holland, S., Mudd, T., Wilkie-McKenna, K., McPherson, A., & Wanderley, M. M. (Eds.). *New directions in music and human-computer interaction* (pp. 23-40). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-92069-6_2

[32] McDermott, J., Gifford, T., Bouwer, A., & Wagy, M. (2013). Should music interaction be easy? In Holland, S., Wilkie, K., Mulholland, P., & Seago, A. (Eds.). *Music and human-computer interaction* (pp. 29-48). Springer-Verlag. London, UK. https://doi.org/10.1007/978-1-4471-2990-5_2

[33] Jordà, S., & Mealla, S. (2014). A methodological framework for teaching, evaluating, and informing NIME design with a focus on mapping and expressiveness. In *Proceedings of the 2014 International Conference on New Interfaces for Musical Expression (NIME 2014).* London, UK. https://doi.org/10.5281/zenodo.1178824

[34] Wanderley, M. M., & Mackay, W. E. (2019). HCI, music, and art: An interview with Wendy Mackay. In Holland, S., Mudd, T., Wilkie-McKenna, K., McPherson, A., & Wanderley, M. M. (Eds.). *New directions in music and human-computer interaction* (pp. 115-120). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-92069-6_7

[35] Gelineck, S., & Serafin, S. (2012). Longitudinal evaluation of the integration of digital musical instruments into existing compositional work processes. *Journal of New Music Research, 41*(3), 259-276. https://doi.org/10.1080/09298215.2012.697174

[36] Moro, G., & McPherson, A. P. (2020). Performer experience on a continuous keyboard instrument. *Computer Music Journal, 44*(2-3), 69-91. https://doi.org/10.1162/comj_a_00565

[37] Springett, M. (2009). Evaluating cause and effect in user experience. *Digital Creativity, 20*(3), 197-204. https://doi.org/10.1080/14626260903083637

[38] Malloch, J., & Wanderley, M. M. (2007). The T-Stick: From musical interface to musical instrument. In *Proceedings of the 2007 International Conference on New Interfaces for Musical Expression (NIME 2007).* New York, NY, USA. https://doi.org/10.5281/zenodo.1177175

[39] O'Brien, H. L., & Toms, E. G. (2013). Examining the generalizability of the User Engagement Scale (UES) in exploratory search. *Information Processing and Management, 49*(5), 1092-1107. https://doi.org/10.1016/j.ipm.2012.08.005

[40] Schmid, G.-M. (2017). *Evaluating the experiential quality of musical instruments: A psychometric approach.* Springer. Wiesbaden, Germany. https://doi.org/10.1007/978-3-658-18420-9

[41] Reimer, P. J. C., Gupta, A., Guastavino, C., & Wanderley, M. M. (2023). *User experience with digital musical instruments: Development and demonstration of a longitudinal evaluation method* [Manuscript submitted for publication]. Department of Music Technology, McGill University.

[42] Wanderley, M. M. (2017). Expert commentary: Perry Cook's principles still going strong. In Jensenius, A. R., & Lyons, M. J. (Eds.). *A NIME reader: Fifteen years of New Interfaces for Musical Expression* (pp. 11-12). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-47214-0_1

[43] Jensenius, A. R., & Lyons, M. J. (Eds.). (2017). *A NIME reader: Fifteen years of New Interfaces for Musical Expression*. Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-47214-0

[44] Poupyrev, I., Lyons, M. J., Fels, S., & Blaine, T. (2001). New interfaces for musical expression. In *Proceedings of the 2001 Conference on Human Factors in Computing Systems (CHI 2001).* Seattle, WA, USA. https://doi.org/10.1145/634067.634348

[45] Hunt, A., Wanderley, M. M., & Paradis, M. (2003). The importance of parameter mapping in electronic instrument design. *Journal of New Music Research, 32*(4), 429-440. https://doi.org/10.1076/jnmr.32.4.429.18853

[46] Magnusson, T. (2010). Designing constraints: Composing and performing with digital musical systems. *Computer Music Journal, 34*(4), 62-73. https://doi.org/10.1162/comj_a_00026

[47] Magnusson, T., & Hurtado, E. (2007). The acoustic, the digital and the body: A survey on musical instruments. In Jensenius, A. R., & Lyons, M. J. (Eds.). *A NIME reader: Fifteen years of New Interfaces for Musical Expression* (pp. 317-333). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-47214-0_21

[48] Rovan, J. R., Wanderley, M. M., Dubnov, S., & Depalle, P. (1997). Instrumental gestural mapping strategies as expressivity determinants in computer music performance. In *Proceedings of KANSEI: The Technology of Emotion: AIMI International Workshop.* Genova, Italy. https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.52.4788

[49] Hunt, A., & Kirk, R. (2000). Mapping strategies for musical performance. In Wanderley, M. M., & Battier, M. (Eds.). *Trends in gestural control of music.* IRCAM. Paris, France.

[50] Meneses, E. A. L., Fukuda, T., & Wanderley, M. M. (2020). Expanding and embedding a high-level gesture vocabulary for digital and augmented musical instruments. In *Proceedings of the 2020 International Conference on Human-Computer Interaction (NIME 2020).* Copenhagen, Denmark. https://doi.org/10.1007/978-3-030-50017-7_27

[51] West, T., Caramiaux, B., Huot, S., & Wanderley, M. M. (2021). Making mappings: Design criteria for live performance. In *Proceedings of the 2021 International Conference on New Interfaces for Musical Expression (NIME 2021).* Shanghai, China. https://doi.org/10.21428/92fbeb44.04f0fc35

[52] Magnusson, T. (2009). Of epistemic tools: Musical instruments as cognitive extensions. *Organised Sound, 14*(2), 168-176. https://doi.org/10.1017/s1355771809000272

[53] Wessel, D., & Wright. M. (2002). Problems and prospects for intimate musical control of computers. *Computer Music Journal, 26*(3), 11-22. https://doi.org/10.1162/014892602320582945

[54] Malloch, J., Birnbaum, D., Sinyor, E., & Wanderley, M. M. (2006). A new conceptual framework for digital musical instruments. In *Proceedings of the 2006 International Conference on Digital Audio Effects (DAFx 2006).* Montréal, QC, Canada. http://www-new.idmil.org/wp-content/uploads/2021/07/DAFx06_Malloch_etal.pdf

[55] Morreale, F., De Angeli, D., & O'Modhrain, S. (2014). Musical interface design: An experience-oriented framework. In *Proceedings of the 2014 International Conference on New Interfaces for Musical Expression (NIME 2014).* London, UK. https://doi.org/10.5281/zenodo.1178879

[56] O'Modhrain, S. (2011). A framework for the evaluation of digital musical instruments. *Computer Music Journal, 35*(1), 28-42. https://doi.org/10.1162/comj_a_00038

[57] Young, G. W., Murphy, D., & Weeter, J. (2018). A functional analysis of haptic feedback in digital musical instrument interaction. In Papetti, S. & Saitis, C. (Eds.). *Musical haptics* (pp. 95-122). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-58316-7_6

[58] McPherson, A., Morreale, F., & Harrison, J. (2019). Musical instruments for novices: Comparing NIME, HCI, and crowdfunding approaches. In Holland, S., Mudd, T., Wilkie-McKenna, K., McPherson, A., & Wanderley, M. M. (Eds.). *New directions in music and human-computer interaction* (pp. 179-212). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-92069-6_12

[59] Sullivan, J., Guastavino, C., & Wanderley, M. M. (2021). Surveying digital musical instrument use in active practice. *Journal of New Music Research, 50*(5), 469-486. https://doi.org/10.1080/09298215.2022.2029912

[60] Ferguson, S., & Wanderley, M. M. (2010). The McGill Digital Orchestra: An interdisciplinary project on digital musical instruments. *Journal of Interdisciplinary Music Studies, 4*(2), 17-35. https://doi.org/10.4407/jims.2010.11.002

[61] Zayas-Garin, L., Harrison, J., Jack, R., & McPherson, A. P. (2021). DMI apprenticeship: Sharing and replicating musical artefacts. In *Proceedings of the 2021 International Conference on New Interfaces for Musical Expression (NIME 2021).* Shanghai, China. https://doi.org/10.21428/92fbeb44.87f1d63e

[62] Calegario, F., Tragtenberg, J., Wang, J., Franco, I., Meneses, E., & Wanderley, M. M. (2020). Open source DMIs: Towards a replication certification for online shared projects of digital musical instruments. In *Proceedings of the 2020 HCI International Conference (HCII 2020).* Copenhagen, Denmark. https://doi.org/10.1007/978-3-030-60114-0_5

[63] Tom, A., Venkatesan, H., Franco, I., & Wanderley, M. M. (2019). Rebuilding and reinterpreting a digital musical instrument - The Sponge. In *Proceedings of the 2019 International Conference on New Interfaces for Musical Expression (NIME 2019).* Porto Alegre, Brazil. http://doi.org/10.5281/zenodo.3672858

[64] Jack, R. H., Harrison, J., & McPherson, A. P. (2020). Digital musical instruments as research products. In *Proceedings of the 2020 International Conference on New Interfaces for Musical Expression (NIME 2020).* Birmingham, UK. https://doi.org/10.5281/zenodo.4813465

[65] Pestova, X., Donald, E., Hindman, H., Malloch, J., Marshall, M. T., Rocha, F., Sinclair, S., Stewart, D. A., Wanderley, M. M., & Ferguson, S. (2009). The CIRMMT/McGill Digital Orchestra Project. In *Proceedings of the 2009 International Computer Music Conference (ICMC 2009).* Montréal, QC, Canada. http://hdl.handle.net/2027/spo.bbp2372.2009.066

[66] O'Brien, H. L., & Toms, E. G. (2010). The development and evaluation of a survey to measure user engagement. *Journal of the American Society for Information Science and Technology, 61*(1), 50-69. https://doi.org/10.1002/asi.21229

[67] O'Brien, H. L., & Toms, E. G. (2008). What is user engagement? A conceptual framework for defining user engagement with technology. *Journal of the American Society for Information Science and Technology, 59*(6), 938-955. https://doi.org/10.1002/asi.20801

[68] Bødker, S. (2015). Third-wave HCI, 10 years later: Participation and sharing. *Interactions, 22*(5), 24-31. https://doi.org/10.1145/2804405

[69] Cook, P. (2001). Principles for designing computer music controllers. In Jensenius, A. R., & Lyons, M. J. (Eds.). *A NIME reader: Fifteen years of New Interfaces for Musical Expression* (pp. 1-27). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-47214-0_1

[70] Mudd, T., Holland, S., & Mulholland, P. (2019). The role of nonlinear dynamics in musicians' interactions with digital and acoustic musical instruments. *Computer Music Journal, 43*(4), 25-40. https://doi.org/10.1162/COMJ_a_00535

[71] Yuksel, B. F., Oleson, K. B., Chang, R., & Jacob, R. J. K. (2019). Detecting and adapting to users' cognitive and affective states to develop intelligent musical interfaces. In Holland, S., Mudd, T., Wilkie-McKenna, K., McPherson, A., & Wanderley, M. M. (Eds.). *New directions in music and human-computer interaction* (pp. 163-177). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-92069-6_11

[72] Dourish, P. (2003). The appropriation of interactive technologies: Some lessons from placeless documents. *Computer Supported Cooperative Work, 12*(4), 465-490. https://doi.org/10.1023/A:1026149119426

[73] Bar, F., Weber, M. S., & Pisani, F. (2016). Mobile technology appropriation in a distant mirror: Baroquization, creolization, and cannibalism. *New Media & Society, 18*(4), 617-636. https://doi.org/10.1177/1461444816629474

[74] Zappi, V., & McPherson, A. P. (2014). Dimensionality and appropriation in digital musical instrument design. In *Proceedings of the 2014 International Conference on New Interfaces for Musical Expression (NIME 2014).* London, UK. https://doi.org/10.5281/zenodo.1178993

[75] Díaz-Oreiro, I., López, G., Quesada, L., & Guerrero, L. A. (2019). Standardized questionnaires for user experience evaluation: A systematic literature review. In *Proceedings of the 2019 International Conference on Ubiquitous Computing and Ambient Intelligence.* Toledo, Spain. https://doi.org/10.3390/proceedings2019031014

[76] O'Brien, H. L., Cairns, P., & Hall, M. (2018). A practical approach to measuring user engagement with the refined User Engagement Scale (UES) and new UES short form. *International Journal of Human-Computer Studies, 112*(2018), 28-39. https://doi.org/10.1016/j.ijhcs.2018.01.004

[77] Lesaffre, M., Maes., P.-J., & Leman, M. (Eds.). *The Routledge companion to embodied music interaction*. Routledge. New York, USA. https://doi.org/10.4324/9781315621364

[78] Mice, L., & McPherson, A. P. (2022). Super size me: Interface size, identity and embodiment in digital musical instrument design. In *Proceedings of the 2022 Conference on Human Factors in Computing Systems (CHI 2022).* New Orleans, LA, USA. https://doi.org/10.1145/3491102.3517626

[79] Csikszentmihalyi, M. (1990). *Flow: The psychology of optimal experience.* Harper-Collins. New York, NY, USA.

[80] Gurevich, M., & Treviño, J. (2007). Expression and its discontents: Towards an ecology of musical creation. In *Proceedings of the 2007 International Conference on New Interfaces for Musical Expression (NIME 2007).* New York, NY, USA. https://doi.org/10.5281/zenodo.1177107

[81] Leeuw, H. (2017). Expert commentary: Hyper-instruments and musicianship. In Jensenius, A. R., & Lyons, M. J. (Eds.). *A NIME reader: Fifteen years of New Interfaces for Musical Expression* (pp. 349-350). Springer. Cham, Switzerland. https://doi.org/10.1007/978-3-319-47214-0_22

[82] Orio, N., Schnell, N., & Wanderley, M. M. (2001). Input devices for musical expression: Borrowing tools from HCI. In *Proceedings of the CHI 2001 Workshop on New Interfaces for Musical Expression.* Seattle, WA, USA. http://doi.org/10.5281/zenodo.1176370

[83] Johnston, A. (2011). Beyond evaluation: Linking practice and theory in new musical interface design. In *Proceedings of the 2011 International Conference on New Interfaces for Musical Expression (NIME 2011).* Oslo, Norway. https://doi.org/10.5281/zenodo.1178053

[84] Rajeshkumar, S., & Omar, R. (2013). Taxonomies of user experience (UX) evaluation methods. In *Proceedings of the 2013 International Conference on Research and Innovation in Information Systems.* Kuala Lumpur, Malaysia. https://doi.org/10.1109/icriis.2013.6716765

[85] Khalid, H. M., & Helander, M. G. (2006). Customer emotional needs in product design. *Concurrent Engineering: Research and Applications, 14*(3), 197-206. https://doi.org/10.1177/1063293x06068387

[86] Everman, M., & Leider, C. (2013). Toward digital musical instrument evaluation using crowd-sourced tagging techniques. In *Proceedings of the 2013 International Conference on New Interfaces for Musical Expression (NIME 2013).* Daejeon, Korea. https://doi.org/10.5281/zenodo.1178510

[87] Zhou, F., & Jiao, R. (2013). Eliciting, measuring, and predicting affect via physiological measures for emotional design. In Fukuda, S. (Ed.). *Emotional engineering, volume 2* (pp. 41-62). Springer. London, UK. https://doi.org/10.1007/978-1-4471-4984-2_4

[88] Meneses, E. A. L., Wang, J., Freire, S., & Wanderley, M. M. (2019). A comparison of open-source Linux frameworks for an augmented musical instrument implementation. In *Proceedings of the 2019 International Conference on New Interfaces for Musical Expression (NIME 2019).* Porto Alegre, Brazil. https://doi.org/10.5281/zenodo.3672934

[89] Meneses, E. A. L. (2022). *Iterative design in DMIs and AMIs: Expanding and embedding a high-level gestural vocabulary for T-Stick and GuitarAMI* [Doctoral dissertation, McGill University]. https://escholarship.mcgill.ca/concern/theses/bg257k661

[90] Leigh, S.-W., & Lee, J. (2021). A study on learning advanced skills on co-playable robotic instruments. In *Proceedings of the 2021 International Conference on New Interfaces for Musical Expression (NIME 2021).* Shanghai, China. https://doi.org/10.21428/92fbeb44.002be215

[91] Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77-101. https://doi.org/10.1191/1478088706qp063oa

[92] Sim, J., & Wright, C. C. (2005). The Kappa statistic in reliability studies: Use, interpretation, and sample size requirements. *Physical Therapy, 85*(3), 257-268. https://doi.org/10.1093/ptj/85.3.257

[93] IBM. (2022). *Weighted Kappa.* https://www.ibm.com/docs/en/SSLVMB_sub/statistics_mainhelp_ddita/spss/base/idh_cwk.html

Appendix A

Appendix A contains the full list of items used for each questionnaire in the study.

A.1 Pre-Screening Questionnaire

Item Number	Item	Response Format	Source
1	Do you have an interest in digital/ electronic musical instruments? (A digital musical instrument can be defined as an instrument that uses computer-generated sound and consists of a control surface or gestural controller, which drives the musical parameters of a sound synthesizer in real time).	Open-ended	Researcher -developed
2	Which types of DMIs/EMIs have you used before?	Select all that apply: Keyboard synthesizers, Modular synthesizers, Samplers, Drum machines, FX processors, FX pedals, Computer software, MIDI controllers, Other	EMI
3	Which DMIs/EMIs do you use regularly?	Open-ended	EMI
4	In which of the following contexts do you use DMIs/EMIs?	Select all that apply: Live performance, Personal practice, Recording, Group settings (e.g. Band, Orchestra), Other (Please specify)	Researcher -developed
5	How many times in a typical year do you perform in public?	Select one: 1 to 10 times, 11 to 20 times, 21 to 50 times, 51 to 100 times, More than 100 times	EMI
6	Would you be willing to spend up to 2 hours per week practicing with a novel DMI for a span of two weeks?	Select one: Yes, No	Researcher -developed

Table A-1: Pre-Screening Questionnaire (PSQ)

A.2 First Impressions Questionnaire

Item Number	Item	Response Format	Source
1	I found this instrument confusing to use.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	UES Short-Form
2	This instrument was aesthetically appealing.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	UES Short-Form
3	This instrument appealed to my senses.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	UES Short-Form
4	This instrument produces high-quality sound.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
5	The mapping used is intuitive.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	Researcher-developed

Table A-2: First Impressions Questionnaire (FIQ)

A.3 Evaluation Session Questionnaire

Item Number	Item	Response Format	Source
1	I was absorbed in the experience.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	UES Short-Form
2	The time I spent using the instrument just slipped away.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	UES Short-Form
3	I felt frustrated while using this instrument.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	UES Short-Form
4	Using this instrument was taxing.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	UES Short-Form
5	This instrument allows me to be creative.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
6	This instrument responds well to my actions.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
7	This instrument allows me to express myself.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
8	I felt in control of the instrument.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
9	It was easy for me to get into the flow of playing with the instrument.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q

Item Number	Item	Response Format	Source
10	I perceive the instrument as challenging in a positive way.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
11	I can use the instrument intuitively.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
12	I had fun playing the instrument.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
13	I felt relaxed when I played the instrument.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
14	I feel the urge to play the instrument again.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q

Table A-3: Evaluation Session Questionnaire (ESQ)

Used from S1 to S5. Participant were asked to respond to each item based on the prompt: "*While practicing this cycle's tasks with the instrument …*"

A.4 Exit Questionnaire

Item Number	Item	Response Format	Source
1	I think the instrument is reliable.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
2	I perceive the instrument as solid.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
3	In the context of this instrument, I think the sound quality is appropriate.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	MPX-Q
4	I feel this instrument could be useful in my everyday musical practice.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	Researcher -developed
5	The instrument allows me to do things I cannot do with acoustic instruments/other DMIs.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	Researcher -developed

Table A-4: Exit Questionnaire

A.5 Third-Party Evaluator Questionnaire

Item Number	Item	Response Format	Source
1a	The performer used a variety of the demonstrated gestural tasks, combinations of the demonstrated tasks, or gestures not used in the videos.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	Researcher-developed
1b	Please provide a 3-5 sentence rationale for your rating.	Open-ended	Researcher-developed
2a	The performer's motion was smooth and fluid.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	Researcher-developed
2b	Please provide a 3-5 sentence rationale for your rating.	Open-ended	Researcher-developed
3a	The performer appeared in control of the instrument and the instrument was responsive to the performer's gestures.	5-point Likert Scale (*"Strongly Disagree"* to *"Strongly Agree"*)	Researcher-developed
3b	Please provide a 3-5 sentence rationale for your rating.	Open-ended	Researcher-developed
4a	Please provide a general rating of the overall quality of the performance.	10-Point Likert Scale (*"Low Quality"* to *"High Quality"*)	Researcher-developed
4b	Please provide a 3-5 sentence rationale for your rating.	Open-ended	Researcher-developed

Table A-5: Third-Party Evaluator Questionnaire

Appendix B: Interview Guides

Appendix B contains the full list of questions and prompts used for each interview in the study.

B.1 Entrance Interview

Questions, 1, 3, 5, and 9 were developed through discussions with the research group. Questions 2, 4, 6, 7, and 8 were adapted from the EMI survey [59]. Questions 10 and 11 were researcher-developed and asked participants about their previous experience with the T-Stick. Questions 1 to 8 and 10 to 11 allowed for open-ended responses. Question 9 asked participants to select an answer from three options. If participants indicated that they did not use DMIs in active performance, they were asked to respond to question 1.

1. Why don't you currently use DMIs/EMIs in active performance? What would it take for you to use them in performance?
    a. Could you elaborate on the other contexts in which you use DMIs/EMIs?
2. What is the name of the DMI/EMI that you use?
3. How long have you used it for?
4. During a typical performance, what percentage of time do you use it?
5. How many times a year do you use it in performance?
6. What do you like about this instrument?
7. What factors influence you to stop using certain DMIs/EMIs?
8. On average, how long do you typically use a DMI before retiring it?
9. How often does your musical performance setup change?
    a. Once a month
    b. Once a year
    c. Once every 5 years
10. Are you familiar with the T-Stick?
    a. Have you performed with it previously?
    b. Have you watched someone else perform with it?
    c. Do you know how to use it?
    d. Are you familiar with previous research conducted related to the T-Stick project?

11. If you have used it before, did you create your own mapping for the instrument?
    a. If so, please describe how you approached the process of creating a mapping.
    b. How challenging did you find the process of creating your mapping?
    c. How-time-consuming did you find the process of creating your mapping?
    d. How did the process of developing your own mapping affect your approach to playing the T-Stick?

B.2 Evaluation Session Interview

All three questions were developed through discussions with the research group. Question 2 asked participants to elaborate on their response to one question (item 8) from the ESQ. All three questions allowed for open-ended responses. The evaluation session interview was conducted a total of five times from S1 to S5.

1. Please provide a quick summary of what you did with the instrument during the practice for today's session.
    a. How much time did you spend practicing with the instrument?
2. Please elaborate on your response to the statement *"I felt in control of the instrument."*
    a. What parameters are you trying to control?
    b. What effects are you trying to achieve?
    c. Please elaborate about the mapping, interface, and sound.
        i. Do you feel that you are able to produce sounds that you find pleasing or useful in a musical context with this instrument?
        ii. Do you think the mapping is easy to learn?
        iii. Is the mapping intuitive?
        iv. Is the interface easy to control?
3. Please describe any other notable aspects (e.g. breakthroughs, frustrations, etc.) of your experience using the T-Stick over this time period.

B.3 Exit Interview

All ten questions were developed through discussions with the research group. Questions 1 and 2 asked participants to elaborate on their responses to two questions (items 4 and 5) from the EXI. Questions 5 and 6 asked participants to describe specific negative and positive experiences they had during the study. All questions allowed for open-ended responses.

1. Please elaborate on your response to the statement *"The instrument allows me to do things I cannot do with acoustic instruments/other DMIs I have used in the past."*
2. Please elaborate on your response to the statement: *"I feel this instrument could be useful in my everyday musical practice."*
    a. In what context will you be using the instrument?
    b. Along with which other instruments?
3. Do you plan on using this instrument in the future? In what context?
4. How long do you estimate you will be using the instrument?
5. Focus on one particularly negative experience you had during this process. Please describe your experience.
6. Focus on one particularly positive experience you had during this process. Please describe your experience.
7. How did your engagement with the instrument develop over time?
8. Did you feel as though your interactions with the instrument became more intuitive or automatic over the time spent with the T-Stick?
9. Do you think this process (and the time you spent with the T-Stick) was:
    a. Rewarding?
    b. Worthwhile?
    c. Frustrating?
10. Do you have any suggestions for improvement?
    a. If you could change the sound, what changes would you make?
    b. If you could change the mapping, what changes would you make?

Appendix C: Interview Coding Scheme

This appendix contains the scheme used to code data from ENI, evaluation session interviews (S1 through S5), and EXI.

1. Area 1: User Engagement Scale (UES) framework: Codes related to the six factors comprising O'Brien and Toms' [66] original framework of engagement. A seventh code was added to include reasons that a user might choose to disengage with the interface.
    a. Focused attention (FA): Comments related to feeling absorbed in the interaction and losing track of time.
    b. Perceived usability (PU): Comments describing negative affect experienced as a result of the degree of control and effort expended during the interactive task.
    c. Aesthetic appeal (AE): Comments related to the attractiveness, visual appeal, and sonic appeal of the musical instrument.
    d. Novelty (NO): Comments describing curiosity and interest resulting from the interactive task.
    e. Felt involvement (FI): Comments related to users' sense of being drawn-in to the interactive task and having fun.
    f. Endurability (EN): Comments describing the overall success of the interaction, users' willingness to recommend the interface to others, and users' interest in engaging with the instrument in the future.
    g. Reasons for disengagement: Comments describing reasons that users might choose to engage with the instrument less or not at all.
2. Area 2: Musicians' Perception of the Experiential Quality of Musical Instruments Questionnaire (MPX-Q) framework: Codes related to the three MPX-Q [40] subscales.
    a. Experienced freedom and possibilities (EFP): Comments related to exploring new ways of developing musicianship and musical expressivity facilitated through use of the musical instrument.
    b. Perceived control and comfort (PCC): Comments related to musical controllability and ergonomic factors that contributed to the perceived comfort of the instrument.
    c. Perceived stability, sound quality, and aesthetics (PSSQA): Comments describing classical notions of instrument quality based on materials, sound, or visual appearance.

3. Area 3: Hedonic and cognitive factors of interest: Codes related to specific emotional and psychological factors of interest.
    a. Quality: Sound, aesthetics, and mappings: Comments referring to sound quality, visual appearance, mapping effectiveness, and other visceral attributes of the interface.
    b. Absorption and flow: Comments describing feelings of immersion occurring as a result of a users' interactions with the instrument.
    c. Control and intuitiveness: Comments related to the level of control users feel over their interactions with the instrument, as well as the extent to which this control seems intuitive or natural.
    d. Challenges and difficulties: Comments describing challenges experienced by individuals during their interactions with the T-Stick.
    e. Motivation, fun, and reward: Comments describing enjoyable and rewarding aspects of users' interactions with the instrument, as well as their motivation to engage with it in the future.
4. Area 4: Personal factors: Codes related to individuals' background, past experience, opinions, and preferences.
    a. Background: Comments related to users' previous life experience and knowledge (both music-related and non-music-related).
    b. Performance practice and preferences: Comments describing preferences or typical behaviours that characterize a users' individual musical performance practice.
    c. Comparison with acoustic instruments: Comments that compare aspects of the digital interface with acoustic musical instruments.
    d. Motor factors: Comments related to movement, proprioception, or pain.
    e. Philosophical considerations: Comments referring to high-level abstract concepts linked with music and musical practice.
    f. Creativity and creative practice: Comments describing how the instrument inspires users creatively or how users imagine they would incorporate the instrument in their personal creative practice.
    g. Audience and external appearance: Comments describing how users imagine their interaction with the instrument might be perceived by an external audience.

5. Area 5: Affective response factors: Codes related to specific emotional responses encountered during users' interactions with the instrument.
    a. Frustration: Comments describing frustration felt by users as a result of challenges experienced when interacting with the instrument.
    b. Breakthroughs: Comments related to overcoming challenges in interaction, discovering a new way to use the interface, or learning to conceptualize the instrument in a manner that improves the interactive experience.
    c. Confusion: Comments describing confusion or uncertainty felt by users as a result of challenges experienced when interacting with the instrument.
    d. Excitement and reward: Comments describing positive affect and reinforcement resulting from users' interactions with the interface.
6. Area 6: Technical factors: Codes related to the construction of the hardware, the implementation of the mapping layer, and the overall musical apparatus, including hardware, sound synthesis, and gestural control.
    a. Hardware: Comments related to the physical hardware object and the sensors used in the interface.
    b. Mappings: Comments related to the design of the mapping layer between gestural input and sound synthesis.
    c. Gestures: Comments related to the physical actions used to control parameters of the sound synthesizer.
    d. Sound synthesis: Comments related to the quality of the instrument's sound or the synthesizer parameters made available for users to modify.
    e. Feedback: Comments related to the visual, tactile, and sonic feedback provided to users by the instrument.
    f. Perceived glitches and bugs: Comments describing technical issues experienced by users and attributed to errors in the implementation of the musical apparatus.
    g. Suggestions for improvement: Comments describing ways in which participants might choose to make improvements to the interface by modifying the hardware, mappings, gestures used, sound synthesis, or feedback.

7. Area 7: Methodological factors: Codes related to the research methodology.
    a. Tasks: Comments related to tasks participants were asked to learn.
    b. Instructions and demonstrations: Comments related to tasks' written instructions or video demonstrations provided to users.
    c. Practice time: Comments related to the amount of practice time provided and how it was distributed over each task block and the study overall.
    d. Practice environment: Comments related to the physical practice environment in which the research was conducted.
8. Area 8: Interaction factors: Codes related to specific HCI topics.
    a. Affordances and constraints: Comments describing the perceived affordances and constraints of the instrument.
    b. Perceived flexibility and possibilities: Comments describing the range of musical and performance possibilities offered by the instrument.
    c. Perceived limitations: Comments describing aspects of the instrument that users interpreted as limiting the available range of musical and performance possibilities.
    d. Transparency and understanding: Comments related to users' ease in understanding the relationship between gestural input and sonic output.
    e. Fragility and stability: Comments related to how fragile, stable, durable, or robust the instrument seems to users in the context of their musical practice.
    f. Responsiveness and consistency: Comments referring to the degree to which users found the instrument responsive to their gestures in a timely and consistent manner.
    g. Error recovery: Comments describing how easily users were able to overcome errors encountered while interacting with the instrument.
    h. Explorability: Comments describing the extent to which users found the instrument allowed them to explore and the exploration strategies they use.
    i. Discoverability: Comments related to features or affordances of the instrument that users were able to come upon of their own accord.

9. Area 9: Temporal factors: Codes related to the dynamic nature of the UIR and how this relationship changes over time.
    a. Appropriation: Comments related to how participants made the instrument their own and situated it within their personal knowledge, practice, and taste.
    b. Embodiment: Comments that indicated development of an intimate and engaging relationship between the participant and the musical interface.
    c. Learning: Comments describing the acquisition of knowledge and skill relevant to playing the instrument.
    d. Long-term adoption: Comments describing users' intentions to use the instrument in the future and their ideas of how they might do so.
    e. Changes over time: Comments that described any aspect of users' interaction with the instrument that developed over time.