

Investigating the Potential of 3D Printed Violins in Instrumental Teaching and Learning Contexts: Perspectives from Luthiers, Musicians and Instrumental Teachers.

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Declaration

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Summary

This research seeks to fuse two domains of practice: violin making and 3D printing. Although music performance has been one of three core strands of the post-primary music curriculum since the 19th century, musical instrument provision presents challenges for teachers (Conaghan, 2022). Recurring concerns include instrument access (Hallam & Rogers, 2016), instrument quality (Campbell, 2013), and sonic and material variations between brands that impede engagement and progression (Sturman, 2019). Distinctly, 3D scanning and printing tools for digital mapping and fabrication offer a model for democratising instrument access, redesigning structural quality, and standardising instrument sonics.

With the assistance of five luthiers, 10 professional musicians, and five instrumental music teachers, and under three headings of conservation and making, perceptions and value, and performance and musicking, this exploratory study aimed to accomplish the following goals:

- i. To map the technical specifications and material properties required to achieve comparable sound quality and durability between traditional and 3D printed violins.
- ii. To evaluate the perceptions and values of musicians and luthiers who use 3D printed instruments.
- iii. To synthesise how 3D printed violins affect opportunities for teachers in music performance.

Small (2012) coined the term “musicking” to encapsulate all actions that contribute to the music-making process. In relation to this research, the term encompasses all actions taken to scan, model, print, prepare, test, and perform 3D printed violins.

The study involved a total of 20 participants, and the fieldwork occurred over three years. Year one involved meetings with five music teachers to assess potential users' instrumental needs. Based on their feedback, musical instruments were identified, 3D scanned, modelled, and printed, and initial feedback from using 3D printed violins was received from the teachers. Year two included five professional luthiers and 10 musicians. Its focus was on printing and trialling instruments and collecting data through questionnaires and sound recordings. The interviews in year three took place with instrumental music teachers in a Dublin city centre post-primary school. These instrumental teachers had trialled the 3D printed violins alongside a small cohort of their students for an academic year. Although student data was initially collected for this research, it was omitted from the final thesis. This decision was driven by a shift in the research focus, which evolved into a more technical investigation of the material and sonic properties of 3D filaments. As the research developed, the core narrative became more reflective of professional musicians, luthiers, and instrumental teachers' critical feedback on prototyping and developing a sonically compatible instrument. For the reader's clarity, it is important to distinguish that although some of the instrumental teacher interviews discuss examples of students using 3D printed violins, these examples are a synthesis of student experience as viewed through the instrumental teacher rather than distinct data collected from the students themselves.

Data was generated from multiple sources using a mixed-methods research design and based on socio-cultural learning theories. Semi-structured interviews with instrumental teachers aimed at assessing user needs, as well as instrument scanning, modelling and 3D printing were conducted in Year one. Moreover, luthiers were asked to complete questionnaires in Year two, while professional musicians were asked to complete sound recordings and questionnaires. Finally, interviews with instrumental music teachers were

completed in Year three. Recordings of participants performing using the 3D printed violins completed the dataset. Subsequently, the analyses comprised reading, coding, thematic classification, and triangulation.

Three key findings emerged from the study. The first, which relates to the 3D printed instruments' material composition and acoustic properties, is that, although polymer-based materials cannot replicate the unique variations of traditional woods, filaments with strategic layering and infill patterns can be used to engineer the density and flexibility approximation needed to achieve comparable acoustic performance. This finding extends existing literature from Doddamani et al. (2023). The second, which relates to acceptance and adaptation in the music community, is that 3D printed instruments garnered mixed responses from musicians and luthiers. While some musicians appreciated their affordability, customisability, and preservation potential, others remain concerned about their sonic authenticity and durability. Meanwhile, luthiers expressed concerns about losing their traditional craftsmanship but acknowledged the instruments' innovative potential for custom designs. This finding aligns with research conducted by Duerinck et al. (2020), which found that participants viewed 3D printed musical instruments as educational or experimental rather than professional performance tools. The third key finding, which relates to the educational viability of 3D printed instruments, found that their potential integration into an educational context offers pedagogical advantages, such as cost-effectiveness and ease of repair. Teachers reported the potential of 3D printed violins to aid access to instruments, increase provision, and foster tangible links to STEAM (science, technology, engineering, arts and mathematics and their interconnectivity), which aids in aligning this research with curriculum outcomes (Ulbrich et al., 2024).

Three perspectives emerged from the data. First, 3D printed violins provided a short-term provision for musicians beginning their musical journey. However, instrument deterioration rates should be evaluated in longitudinal studies to establish long-term value. Second, developing post-digital practices through real-world engagements with luthiers, musicians, and music teachers promoted a collaborative culture of instrument development. However, this mode of instrument production needs sustained infrastructural support to develop it from a novelty to an integrated post-digital practice. Third, luthiers, musicians, and instrumental music teachers play a pivotal role in selecting instruments for digitisation. However, iterative feedback from participants regarding design adjustments ensures that prototypes have the potential to extend beyond their immediate audience and have value beyond this research.

The results from this study have implications for musical instrument conservation, redesign, and fabrication and for how instrumental teachers might diversify technologies in music education. 3D printing based on school needs offers a decentralised, individualised, and localised model of instrument acquisition. This study explores the conservation, adaptation, performance potential, and limitations of 3D printing in a music context. In the process, it provides an alternative 3D printed violin model that builds on prior digital modelling research.

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List of Acronyms and Abbreviations

ABS	Acrylonitrile Butadiene Styrene
CAD	Computer-Aided Design
CPD	Continued Professional Development
DEAP	Digital Education Action Plan
DES	Department of Education and Skills
DMI	Digital Musical Instruments
GAL	Guild of American Luthiers
IME	Instrumental Music Education
IP	Intellectual Property
IPR	Intellectual Property Rights
ISME	International Society for Music Education
PBL	Project-Based Learning
PLA	Polylactic Acid
PIL	Participant Information Leaflets
PGR	Post-Graduate Research Conference, Trinity College Dublin
RQ	Research Question
SDP	Social Diversity Programme
SLS	Selective Laser Sintering
SMEI	Society for Music Education in Ireland
STEAM	Science, Technology, Engineering, Arts, and Mathematics
STL	Standard Triangle Language

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Chapter 1 Introduction

1.1 Overview of the Research

This chapter will introduce this research problem, the research aims and objectives, as well as the key terms used within this research. Music performance resides within all curriculum levels in Ireland (Sugrue, 2004), and musical instrument access is connected to music making. Nonetheless, financial, geographic, and cultural factors continue to influence access to musical instruments (Conaghan, 2022). In recent years, feasibility studies for the provision of musical instruments have been suggested. However, according to a feasibility study released in 2003 by Music Network, Ireland's music development organisation, Ireland lacks "the kind of systematic provision appropriate to a twenty-first-century European country so distinguished by its cultural achievement and identity" (Music Network, 2003, p. vii). Music Generation, a national partnership programme, was established in 2010 (Cawley, 2024). It addressed the need for local access to specialised instrumental music teachers. In 2014, a feasibility study by Moloney and McCrea (2014) indicated that a national musical instrument fund was necessary, particularly in socioeconomically underprivileged communities. Moloney and McCrea (2014) presented a range of government-led, public and private partnership collaborations, as well as non-profit models. It also identified funding opportunities and government grants, which emphasised shared responsibility for a model development.

Since the publication of Moloney and McCrea's (2014) feasibility study, Music Network has established the National Musical Instrument Hub to enable applicants to identify grants or rent musical instruments and thus increase access to musical instruments nationally. However, despite instrumental music provision initiatives (Conaghan, 2022), gaps in provision remain. Hopkin (1996) outlines that traditional methods of instrument

fabrication are both expensive and time consuming to produce, but acknowledges that some mass-produced musical instruments may have inbuilt sonic and physical limitations, limiting music students' development. Regarding instrument banks, Moscardini et al. (2012) discuss the popularity of musical instruments such as violins, flutes and saxophones, but acknowledge that this popularity affects availability and choice for students reliant on instrument banks. While Conaghan (2022) recognises that the financial burden of purchasing a musical instrument can deter student access and engagement. This research has sought to explore the potential for increased musical instrument access and provision through developing a 3D printed violin in consultation with luthiers, musicians, and instrumental teachers. The research provides an alternative 3D printed instrumental provision model that has the potential to be activated in environments with access to 3D printing. 3D printing has emerged as a possible solution; Lipson and Kurman (2013) highlighted its potential to provide a cost-effective and customisable approach to instrument construction. While the literature has presented conflicting views of the effectiveness of 3D printed instruments (Mendonça et al., 2004; Rindfleisch et al., 2017), they offer an alternative for addressing deficiencies in current instrument provision and construction. This alternative model of musical instrument production could provide a cost-effective and open-access solution to musical instrument provision that is separate from the current model.

The purpose and background of this study are presented in the current chapter. First, the potential of using 3D printed violins in an educational setting is positioned within the framework of STEAM integration and multidisciplinary collaboration for ongoing professional development (CPD), which supports educators in incorporating technology into the classroom. The research questions are subsequently presented to try to better understand how 3D printed violins might democratise access to music education and

address current provisional challenges. The researcher then discusses their positionality as a researcher and post-primary art and music teacher. The chapter concludes by outlining this thesis's structure.

1.2 Aim and Motivation

The aim of this research was to explore a model of 3D printed violin provision as a possible alternative to current construction and provision models (Conaghan, 2022; Moloney & McCrea, 2014). This was enacted by exploring and evaluating the perceptions of 20 participants, comprising luthiers, violinists, and teachers, on their experiences of using 3D printed violins. It seeks to determine whether 3D printing can improve access to music-making alternatives. The research, which was carried out over three years, focused on the technical requirements, user perceptions, and musical implications of playing 3D printed instruments.

Based on feedback from industry professionals and instrumental teachers, after every data collection phase, the 3D printed violins were adjusted to reflect its userbase preferences. This research was driven by three dominant factors: infrastructure, instrumental music education, and musical instrument provision. The first factor connected with the researcher's intention to explore the broader literature on sonic and material discrepancies between established and new musical instrument brands (Blackshields et al., 2014; Buxton, 1997). For example, Buxton (1997) suggested that traditionally fabricated luthier instruments can prove too expensive, while Blackshields et al. (2014) indicated that lesser-quality mass-produced musical instruments can restrict musical progression. These cost and fabrication barriers to musical instruments demonstrate access and musical development issues of musicians.

The second motivation was the need for instrumental providers to develop an alternative infrastructural instrument provision model. Although the National Musical

Instrument Hub and InstrumentHub.ie have successfully established centralised platforms for locating musical instruments in Ireland, the literature suggests that this instrument access can be developed further (Conaghan, 2022). Internationally, Kantaros and Diegel (2018) have researched the technical viability of 3D printed musical instruments, viewing 3D printing as a possible cost-effective alternative to traditional fabrication techniques in the future. Equally, Ratto and Ree (2012) have suggested that, with collaboration from industry professionals, 3D printed musical instruments have the potential to democratise instrument files and designs. Through focusing on developing the sonic and material properties of 3D printed violins in comparison to traditionally made instruments, and encompassing industry professionals' perspectives, the researcher has sought to address Kantaros and Diegel (2018) and Ratto and Ree's (2012) recommendations.

The third motivation was to develop a model for educational collaboration and arts education. The researcher's existing professional practice is as a post-primary art and music teacher who works in both collaborative and interdisciplinary settings and leads ukulele and guitar-making classes that use traditional construction methods. This professional practice raised broader questions about how teacher-artist collaborations can provide a model for Continued Professional Development (CPD) and notions of object authenticity when replication through 3D printing and rapid prototyping has never been more accurate and available. Like Theseus' paradox, which questions the point at which an original artefact becomes a replica (Roberts, 2017), this research explores the metaphysics of identity in the age of digital reproducibility. With regard to technology, it explores how 3D scanning can help to preserve fabrication data on world-renowned instruments beyond the scope of their sonic existence. This line of enquiry led to the formulation of research questions related to three areas: conservation and making, perceptions and value, and performance and musicking. The collaborative nature of this research enabled educators,

musicians, luthiers, and researchers to be part of the conversation and contribute their perspectives on 3D printed violin designs, sound and tactility.

Located within a sociocultural theoretical framework, this study aims to assess the technical specifications needed for 3D printed violins to achieve comparable instrument quality to traditionally constructed instruments, how luthiers and musicians' perspectives of 3D printed violins can indicate long-term viability, and the musicking implications of instrumental teachers using 3D printed violins. Once prototyped, a 3D printed model of violin provision may build trust (Murphy, 2014) between schools and existing provisions. In line with existing literature on 3D printed musical instruments, a 3D printed model of provision may provide a complementary model of democratised and cost-effective instrument provision alongside the existing mode of provision. Based on existing literature (Cano, 2015; Kantaros & Diegel, 2018; Ulbrich et al., 2024), 3D printed musical instruments might begin to provide an alternative model of dissemination, access, and provision for luthiers and instrumental teachers. This study introduces 3D printed violins as a provision to support access (Cano, 2015); explores luthiers, musicians and teachers experiences of using these instruments to ascertain their viability (Kantaros & Diegel, 2018); and ascertains possible opportunities for STEAM development through 3D printing (Ulbrich et al., 2024).

1.3 The Changing Context of Instrument Making

Framing the changing context of musical instrument making is important to the development of this research argument because it highlights how incremental design developments can affect access to instruments. This, in turn, can inform instrument viability as education tools. Bovermann et al. (2016) contend that as new technologies for constructing musical instruments advance, so too must traditional luthier construction methods. In this instance, Bovermann et al. (2016) view new technologies as having a

complementary rather than substitutive role within instrument design and production. Furthermore, Feldman and Contzius (2020) view access to high-quality musical instruments as the foundational building blocks to music education. Although Feldman and Contzius (2020) focus on instrumental music education within the United States, which places a greater emphasis on musical ensembles than the Irish context, the provision of high-quality musical instruments is still applicable to an Irish context. Although Blackshields et al. (2014) note that while traditionally constructed luthier instruments are regarded for their high craftsmanship, they acknowledge that they can often be too costly for student musicians. Equally, Buxton (1997) contends that more cost-effective, mass-produced musical instruments can sometimes lack the sonic and material resonance needed for students' musical development. Both Blackshields et al. (2014) and Buxton's (1997) perspectives prioritise musical instrument quality, but acknowledge fluctuations in instrument quality based on price.

Moore (2014; 2021; 2023) has written extensively on the cultural and economic capital necessary to access instrumental music provision in Ireland. Specifically, in Chapter 1, *The Music Education National Debate, 1994–6: Contested legacies, pivotal conversations and future aspirations* (Moore, in O'Flynn & Flynn, 2023), Moore discussed concepts that shaped music education since the Music Education National Debate (MEND). Although this chapter primarily focused on educational policy and discourse, themes such as broadening the definition of music education, curricular integration and support, have applicability for musical instrument acquisition, and provision. Furthermore, Moore's (2014) *Mind the gap: privileging epistemic access to knowledge in the transition from Leaving certificate to higher music education* used a mixed-methods methodology to survey (n = 441) and interview (n = 30) students and lecturers on the disparities in musical skills and "powerful" knowledge (Moore, 2014, p. 252) between private and state-provided education. The findings indicated

that enabling equal access to music in higher education was predicated on establishing equal provisions and opportunities within earlier stages of the curriculum. Moore's (2014) finding is developed further in Chapter 12, *'Fish out of water?' Musical Backgrounds, Cultural Capital and Social Class in Higher Music Education*, (Moore, in Wright et al., 2021), where the author used Bourdieu's habitus, capital, and field to contextualise how students' early musical formation "affirm[ed]" (p. 191) or "alienate[ed]" (p. 193) their transition to higher education. Although these examples (Moore, 2014; 2021) focused on student experience in higher education, their findings have implications for musical instrument acquisition, provision, and making. Particularly, the author's observation that some interviewees' access to music has been "an invisible norm" (Dibben, 2004, p. 8) showed the degree to which both domains are influenced by cultural, social, and economic capital. Furthermore, in Chapter 6, *David Elliott on Music Education Legacies and Aspirations: A conversation with John O'Flynn (with an introduction by Patricia Flynn)* (in O'Flynn & Flynn, 2023), O'Flynn and Elliott discussed the changing context of Irish and American music education. This chapter focused on the principles underpinning Elliott's praxial philosophy (p. 99), the gap between theory and practice within an American context (p. 106) as well as the development of musical identity or "personhood" (p. 108). However, in relation to the changing context of instrument making, his interview provided a broader context for conceiving of musical performance as a social practice, and it positioned the individual as central to the act of music making, or "enactive cognition" (p. 108).

Literature from Murphy (2014) has highlighted the sonic and material durability limitations of existing 3D printed musical instruments that have led to market scepticism of this mode of instrument production. However, recent studies by Brezas et al. (2024) assessing the sonic properties of 3D printing materials and filaments suggest that 3D printed musical instrument research is prioritising sonic and resonance. Although O'Flynn

and Flynn (2023) and Murphy's (2014) perspectives complexify issues of funding, curriculum integration, and market acceptance, these challenges also provide opportunities to reflect on the possibility of producing cost-effective instrumental music solutions (Lipson & Kurman, 2013) that are also sonically and physically compatible with student musician expectations.

1.4 From Increased Access to Musicking

Diversifying platforms for musical instrument access is crucial because it broadens potential music-making audiences. This research addresses “access” rather than “inclusion.” While inclusion relates to integrating students with additional educational needs into mainstream educational contexts (Sobol, 2017), access addresses socioeconomic, geographic, and availability issues that affect participation in music-making (Kidner et al., 2002). This distinction is important because it delineates the intended audience for this research.

Although music performance has been described as one of Ireland's main exports (O'Flynn, 2009), support for nurturing musical talents has been described as a “geographical lottery” (Flynn & Johnston, 2016, p. 7), and socioeconomically contingent (Moore, 2014). A 2018 Oireachtas committee meeting titled “Music in Ireland today” called for a national music policy to address concerns in music education and emphasised the need for policy changes. It was argued that “no matter what socioeconomic group we come from, an education in music is the one aspect of education – allied to literacy – that can add value to the whole of our lives” (McDonagh, 2018, p. 2). This statement underscores the societal benefits, value, and importance of music education and the crucial role played by educators, policymakers, and researchers in developing society through music education. Echoing over half a century of music education literature (Cox & Stevens, 2016), this statement indicates a gap in music policy provision and a direct

connection between music and social mobility. It also concedes that, although music has social, emotional, and intellectual benefits (Váradi, 2022), they are yet to be equitably addressed through policy. This perspective highlights how access to music can enrich educational experiences.

Beyond increasing opportunities to access music, the production of 3D printed musical instruments aligns with Small's (2012) concept of musicking, which has its basis in social constructivist epistemology (McPhail et al., 2024). The constructivist epistemology of this research in relation to the existing literature (Atkinson, 2017; Greene, 1994; Howell, 2013) is discussed in Section 3.4. Small (2012) used the term “musicking” as a verb and viewed music "not [as] a thing ... but an activity, something that people do" (2012, p. 2). Moreover, he framed musicking with everyday shared social practices (DeNora, 2017) enabled through performance. Small's (2012) concept of musicking is divided into four sub-categories based on dimensions of musical engagement. First, musicking-in-any-which-way relates to informal music-making processes. Second, musicking-in-the-small involves community-based music making in informal venues. Third, musicking-in-the-large relates to formal groups in formal venues. Finally, musicking-in-the-world refers to musical practices that reflect the social, cultural, and communal characteristics of music making. Regarding 3D printed musical instruments, musicking-in-any-which-way is the most pertinent sub-category because it involves a broad range of informal and experimental musical activities and emphasises personal exploration within an educational context. Small's (2012) concept of musicking connects with social constructivism by indicating that social interactions aid in the construction of meaning. In this research, musicking was used to contextualise the components of sociocultural music education, and the term itself is used to indicate shared social practices that can occur both virtually and physically (Reily & Brucher, 2018), be both recorded and

in real-time (Cascone, 2000), and have both social and individual potential for change (Sanford, 2017). Musicking has influenced broader research on music and identity (Fitzgerald & O'Flynn, 2016), community engagement (Reily & Brucher, 2018), music pedagogy (Campbell & Lum, 2019), and performance practices (Reily & Brucher, 2018). By adopting Small's (2012) musicking lens, it becomes clear that acts and actions related to musical performance have the potential to promote access to music.

Since its inception, the concept of musicking has undergone three main iterations: as a site-specific, shared experience (Reily & Brucher, 2018); as an individualised privatisation of public space (Bull, 2015); and as an integrated return to a form of collective cultural practice (Purcell & Randall, 2016), albeit through digital platforms. Various authors have considered musicking to be grounded in process rather than a formalised entity (Reily & Brucher, 2018), a form of social action rather than experiential documentation (Purcell & Randall, 2016), and informed by site rather than unaffected by the conditions of its performance (Bull, 2015). Subsequently, the meaning and consequences of musicking have changed since its original intention (Nathaus & Rempe, 2020). Holdhus et al. (2021) argued that a greater focus on the material engagements that shape musical experiences is needed to advance musicking. Although Holdhus et al. (2021) emphasise how music devices shape musical practices and user choices, it does not extend their focus to collective social practices such as musicking. Although musicking is inherently social (DeNora, 2017), the mechanisms for accessing music have shifted and challenged how sociality has been enacted throughout history (Bull, 2015). These literature perspectives contribute to an understanding of music engagement as deeply entwined with technologies.

1.5 From Interdisciplinary STEAM Integration to Postdigital Practices

A number of education documents have outlined the possible benefits of STEAM in Irish education (Department of Education and Skills, 2015; Department of Education and Skills, 2017; Department of Education, 2023; Department of Culture, Heritage and the Gaeltacht, n.d.). Specifically, the STEM Education Policy Statement (Department of Education and Skills, 2017) emphasises how incorporating the arts into STEM subjects could enhance students' learning outcomes. This policy, combined with the Digital Strategy for Schools (Department of Education and Skills, 2015), highlighted the sustained need for teacher CPD in STEAM education to ensure that new technologies are integrated within teacher pedagogies and teaching practice reflects learning outcomes. Both the Action Plan for Education (Department of Education, 2023) and the Creative Ireland Programme (Department of Culture, Heritage and the Gaeltacht, n.d.) discuss the significant role that industry professionals could play in collaborating with educationalists to develop CPD and projects that aligns with industry professional goals. It progresses the Action Plan for Education (Department of Education, 2023) by suggesting that a STEAM curriculum could be developed and shaped by industry professionals. As part of the proposed iterative process, industry professionals could help bridge knowledge gaps and identify areas for further curriculum development. In summary, the STEM Education Policy Statement (Department of Education and Skills, 2017), the Digital Strategy for Schools (Department of Education and Skills, 2015), the Action Plan for Education (Department of Education, 2023), and the Creative Ireland Programme (Department of Culture, Heritage and the Gaeltacht, n.d.) all emphasise the need to develop the curriculum, teacher CPD, as well as industry and teacher collaboration, in order to systematically integrate STEAM education within Irish education. However, despite policy

guidelines promoting STEAM education, Harris and DeBruin (2017) contend that there is a gap between policy and practice.

Furthermore, there is a gap in the music education literature regarding integrating technology and engineering principles across STEAM subjects, CPD for music educators, and access to interdisciplinary curriculum resources (Longo & Gates, 2021). Longo and Gates (2021) cited funding, interdisciplinary collaboration, and curriculum revisions as barriers to enacting change in the current educational framework. These constraints highlight the need to explore new ways of viewing technologies in relation to music. Roza (2014) contends that 3D printed musical instruments function as an engaging model for developing music performance within technology and engineering. While Santos et al. (2018) consider the pedagogical potential of such a provision model, and Longo and Gates (2021) indicate that such a model could aid in merging STEM and music practices.

Postdigitalism provides a lens to unpack STEAM principles and frame human engagement with technologies. Postdigitalism is a concept that emphasises the point when digital technologies became seamless and pervasive in society (Cascone, 2000). It aligns with the STEAM framework because it combines analytical and digital creative skills. However, while STEAM education centres on new and emergent technologies, postdigitalism sharply diverges in focus because it is concerned with digital tools, gestures, and languages that are fully immersed and pervasive in a culture. Viewing digital tools as pervasive rather than separate from real-world interactions enables them to become intertwined materials rather than differentiated tools. Post-digital aesthetics strongly emphasise people's relationships with digital technologies (Jandrić et al., 2023). This characteristic allows for a discussion of digital materiality as an integrated component of the physical environment.

On a related note, “the postdigital turn” is a term that signifies the shift from a focus on digital technologies to the more integrated and pervasive use of these technologies. Although it is in its relative infancy, it permeates the theoretical and creative disciplines of philosophy (Jandrić et al., 2023), music (Cascone, 2000), art (Alexenberg, 2011), technology (Savin-Baden, 2021), and education (Weich & Macgilchrist, 2023). Although Alexenberg (2011) argued that it may be too soon to consider the digital in the past tense, a post-digital framework provides a context to critique the 3D printing domain beyond that of novelty. The term “postdigitalism” is used in this research to explore how technologies can make people more human. Combined, “postdigital musicking” gestures towards the technologies that enable us to engage in acts of music-making (Savin-Baden, 2021) rather than merely the semiotic concept of the medium (Jandrić et al., 2023). It becomes an active and participatory model for democratising music making and its related tools.

1.6 Research Questions

The subsequent research questions were devised based on reflexive engagement with the literature.

Table 1.1

Research Questions

RQ1:	What technical specifications and material properties are required
Conservation and making	for comparable sound quality and durability between traditional and 3D printed violins?
RQ2: Perceptions and value	What are the perceptions and values of musicians and luthiers who use 3D printed instruments, and how do these affect instrument viability?

RQ3: What are the implications of integrating 3D printed instruments into **Performance and musicking** music performances for teachers?

1.7 The Blended Role of Researcher and Modeller

The researcher was aware of their dual identity as both an insider and outsider (Kvale & Brinkmann, 2009) and how maintaining a balance was necessary for the research's reliability (Creswell & Poth, 2023). Kvale and Brinkmann (2009) suggest that this dual identity can be mitigated by considering the research positionality, reflexivity, pre-existing relationships, and how this affects the data collection, analysis, and interpretation. Throughout the course of this research, the researcher was engaged in scanning, modelling, and 3D printing violins and sought participant feedback on the 3D printed violin designs. Some of the practical and technical challenges included developing the sonic and material limitations produced through 3D printing by reflective iterative prototyping. While some of the research challenges included a resistance to oversimplifying the possible access benefits for musicians seeking to play the violin, without recognising the current quality and functionality limitations (Kerr, 2022).

1.8 Potential Impact of the Study

The current research is relevant to considering how alternative instrument fabrications might contribute to musical instrument programmes in the future. In addition, it has curatorial implications for how to preserve musical instruments beyond their physical life. This aligns with the existing literature, which suggests that music performance can provide opportunities for personal enrichment (Kaufman & Scripp, 2019) and social mobility (Mjos, 2013). This research draws from recent music, science and technology studies that focus on the social rituals that accompany technologies (Savvides,

2021), the philosophical language that supports their visibility (Michelfelder et al., 2016), and the aesthetic choices that shape user engagement (Khan, 2021).

Pei et al. (2023) views the twenty-first-century classroom as one of multiple learning sites, indicating that students consume information in diversified formats and environments. Peppler et al. (2016) promote integrating technology into arts education, suggesting that it supports novel thinking. Muijs et al. (2011) promote collaboration between industry professionals and teachers, indicating that real-world problem solving can inform in class learning. The logistical process involved in 3D printing connects with experiential learning theories, that, in turn, could promote music engagement (Lovett, 2022). This is exemplified in Chapter 2, which mentions the JCT4 and Taiscéalaí initiatives, aimed at developing 3D printing skills for post-primary teachers. This study explores the collaborative actioning of 3D printing in a post-primary music context. Therefore, the anticipated impact is on music performance. Faber (2012) suggests that conservation issues such as temperature, humidity and continued playing affect the lifespan of all instruments. However, merely replicating an instrument served a curatorial purpose but undermined the immense potential of this technology. Instead, this methodology focused on using instruments of historical prominence as starting points to redesign new construction methods, sound, haptics, and user ergonomics, extending the technology functionality beyond the realm of replication towards creating instruments not possible before. This impacts the domain of musical instrument design.

1.9 The Effects of the COVID-19 Pandemic on This Research

This research was conducted from September 2018 to August 2023 and adversely affected by the COVID-19 pandemic. During this time, music and sonic engagement were used to unite people through sound in an unprecedented isolation (Fraser et al., 2021). More formally, the rise of the virtual ensemble exemplified how technology provided the

illusion of real-time sonic and physical engagement (Savin-Baden, 2021). Although these technologies existed before the COVID-19 pandemic, the latter prompted a general audience to engage in acts of music-making and become digital (Giordani & Rullani, 2020) and prioritised technologies that united rather than isolated people (Salam, 2019). Although the lens of time is needed to justify these responses as anything more than an isolated occurrence borne out of necessity, it provides an instance where the human desire to be involved in acts of musicking can be typified, even through isolation. It is suggested that the term musicking still applies within this guise, but now it bears a stronger relationship to postdigital aesthetics.

Although most field research was initially expected to occur early in the study, the COVID-19 pandemic restrictions made this impossible. As an alternative, the researcher concentrated on developing 3D scans of virtual musical instruments that could be developed at a future date. Also during this time, the researcher undertook a remote ukulele luthier project with transition year students to assess student interest in musical instrument making. This practical process aided in extending the space for music making beyond performance, towards exploring the processes that enable musicking (Small, 2012). When students returned to the physical classroom, the researcher undertook a guitar making module using traditional construction techniques. Both the ukulele and guitar making modules incorporated key transferrable skills that could be applied to the process of 3D printing and fabrication. Regardless of the aforementioned challenges, trialling aspects of musical instrument making with students ultimately enriched this final research design.

1.10 Thesis Outline

This thesis presents the researcher's process for constructing a 3D-printed violin and the participants' perceptions of instrument viability from a small sample of Irish luthiers, musicians, and instrumental music teachers.

Chapter 2 presents the literature review. The factors that influence and impede the use of digital musical instruments (DMIs) and new instrument fabrication are articulated by exploring their potential and limitations. Moreover, the possibility of accessing 3D printed musical instruments is explored, and whether this model of instrument access promotes sustained engagement or represents a short-term solution to broader curriculum issues is assessed by reflecting on the success and limitations of previous initiatives. Next, Chapter 3 presents the methodology for this research. It explains the scanning, modelling, and comparative instrument testing of a 3D printed violin. In addition, it details the quantitative data on its sonority and physicality that were collected from instrument makers, modellers, and professional violinists. Chapter 3 also describes the mixed-methods data collected from instrumental teachers regarding their musical and pedagogical experiences of using the 3D printed violin. Finally, it outlines the steps involved in cleaning, coding, and analysing the data.

Chapters 4 to 7 present the findings from the data collected from luthiers, musicians, and instrumental music teachers. Derived from content and thematic analysis, they revealed emerging themes across the data. The results are presented in tables, figures, and sound samples, presented within this text as tables and figures in compliance with APA7 guidelines. Moreover, Chapters 4 to 7 have reflections on the connection between the results and the research questions. Then, Chapter 8 examines the findings in context to the research questions. Common and contrasting findings are discussed. Chapter 9 concludes the thesis by synthesising salient findings, assessing the study's contributions to

the field and practice, and providing suggestions for future research. The limitations of this investigation are considered. Then, it returns to the research questions and considers how the objectives were achieved. The study's research contributions and possible significance for music education and 3D printing are indicated.

Chapter 2 Literature Review

2.1 Introduction

This chapter is split into three areas of study and articulates the musical, technical, and educational aspects of the literature on 3D printed musical instruments. These sections refine the research questions presented in Chapter 1, situate the anticipated research within the existing literature, and provides context for the discussion of the findings. Section 2.2, “The Established Role of Sound and Material Properties in Stradivarius Violins: A Review of Two Contrasting Case Studies,” begins by discussing the qualities and challenges of fine and mass-produced musical instruments. It presents two contrasting case studies that investigate the sound and material qualities of Stradivarius violins. Presenting these case studies enables the reader to reflect on the sonic and material characteristics of high-quality violins, and some of the research on this to date. These case studies also provide a reference point from which 3D printed musical instruments can be assessed relationally. Section 2.3, “The Emerging Role of 3D Printing in Musical Instrument Making,” addresses the more technical aspects of 3D printing to date, indicating a relatively modest body of research on this topic. Section 2.4, “The Potential Role of 3D Printed Musical Instruments in Education,” concludes the chapter by discussing and critically evaluating the literature on 3D printed instruments in educational contexts and emphasising the practical applications and pedagogical innovations that can be derived from research in this area. Together, these three sections provide a structured overview connecting 3D printing, sonic and material logistics of musical instrument making, and its potential role within an education context.

Literature from Lammert (2016), Murphy (2014) and Calignano et al. (2017) provide a research context to the rise of 3D printed musical instruments, and exemplify the challenges that stem from altering a historical mode of production. Lammert (2016), an

advocate of 3D printing, has discussed the potential for 3D printing to be a democratising force for musical instrument acquisition. In Lammert's (2016) instance, instrument cost and customisation play a crucial role in shifting public perception of 3D printed musical instruments as a viable alternative to traditionally constructed models. In contrast, Murphy (2014) and Calignano et al. (2017) are critical of the sonic and durability inconsistencies between 3D printed and conventionally constructed musical instruments. Additionally, the authors contend that current 3D printing technologies cannot reproduce comparable musical instruments, therefore reducing rather than enhancing musicians' musical experience. This literature review seeks to outline the critical arguments and provide a scholarly assessment of the potential and limitations of 3D printed musical instruments for instrument makers, musicians, and teachers.

2.2 The Established Role of Sound and Material Properties in Stradivarius Violins: A Review of Two Contrasting Case Studies

This section begins by establishing the qualities and production challenges of fine and mass-produced musical instruments. It provides a foundation for exploring two contrasting case studies that challenge and promote the sound and material properties of Stradivarius violins as a cultural marker of quality. It is necessary for the researcher to evaluate these case studies in order for the reader to recognise how sonic and material properties affect public perception of Stradivarius musical instruments. The first case study, the Paris Experiment (Fritz et al., 2012), questioned the myth surrounding Stradivarius musical instruments through blind listening tests incorporating modern instruments. By demonstrating that the sound produced through modern instrument construction techniques was more preferable for listeners than Stradivarius instruments, this case study highlighted a disparity between modern performance preferences and modern listening preferences.

By contrast, the Stradivarius Sound Bank (Kiefer, 2021), a recording project dedicated to acoustically preserving the acoustic fidelity of a selection of Stradivarius instruments, emphasised the importance of preserving historical sound qualities, which are integral to the cultural and historical value of Stradivarius instruments. This recording project highlighted the cultural value of Stradivarius musical instruments by ensuring that future digital musicians could compose using these sonorities. Combined, the Paris Experiment (Fritz et al., 2012) and the Stradivarius Sound Bank (Kiefer, 2021) case studies offer contrasting perspectives on sound quality, sound preservation, and sound perception. Both case studies highlight the interplay between violin tradition and innovation.

2.2.1 Characteristics of Luthier Legacy Instruments

By outlining the key characteristics of luthier legacy instruments, we can begin to articulate the musical characteristics that make violins musically desirable. The term “legacy instrument” denotes instruments that distinguish themselves by their craftsmanship, materials, and sound quality. They are highly responsive vocally (Hart, 2019); light and easy to play ergonomically (Beament & Beament, 2000), and provide strong resonance, projection, dynamics, and repertoire versatility sonically (Thompson & Olsen, 2021). The material components of these instruments mature rather than deteriorate with age (Faber, 2012), which makes them a multigenerational investment. Fine musical instruments are usually associated with reputable luthiers, workshops, and regions (Moro, 2018).

As a prime example of luthier legacy instruments, Stradivarius musical instruments hold a significant position in the field of musical instrument making. They are renowned for their superior sound and craftsmanship (Faber, 2012) and their distinguished historical lineage of renowned musicians (Whitney, 2016). The “brand” of Stradivarius exists as a platonic ideal for string players (Pollens, 2015, p. 13), serves as an exemplary blueprint for

luthiers (Montagu, 2007), and is a coveted acquisition for collectors (Rice, 2015). However, there is a dearth of literature on the physical (Faber, 2012), sonic (Beament & Beament, 2000), and ethereal qualities (Moro, 2018) that resonate with musicians and contribute to the myth of the Stradivarius brand. Specifically, Faber (2012) attributed their sound to the flatter shape and distinctive form of the instrument plates, while Moro (2018) and Schubert (2018) suggested that it is the violins' close phonic similarity to the human voice that captivates listeners. Bucur (2016) discussed Idrobo-Ávila and Vargas-Caña's studies on the effects of wood materials on sound projection, which revealed that climate, age, variety, and finish all affect the instrument's sound. Although not exclusive to Stradivarius instruments, it has been documented significantly (Hutchins, 1981). In addition, Hutchins (1981) emphasised the effect of wood varnish on the superior tonal and material characteristics of Stradivarius violins. This view was reinforced by Petherick (2022), who suggested that legacy luthier instruments have a distinct “ageing quality” (Petherick, 2022, p. 41). This particular ageing quality may affect user perception of newer musical instruments. Additionally, Thompson and Olsen (2021) assessed historical string construction techniques that are still in operation in luthier workshops today. This assessment acknowledges that musicians have a sustained appreciation for historical luthier techniques.

By contrast, several collaborative studies have challenged the long-held belief in the superior sound quality, unique construction techniques, and high cultural value of Stradivarius instruments. For instance, Fletcher and Rossing (2012) argued that modern luthiers with technological tools can replicate or even surpass the tonal richness of legacy luthier instruments, which challenges the perceived superiority of historical models. Invernizzi et al. (2015) have assessed the material properties of Stradivarius instruments, and found that, although innovative, the luthier techniques would not account for such a

unique sound. Furthermore, Fritz et al. (2014) blind listening tests established that both listeners and professional musicians could not consistently distinguish Stradivarius violins from modern counterparts. Reinforcing Fritz et al. (2014), Nagyvary et al. (2006) found that modern instruments outperformed Stradivarius instruments in blind listening tests, indicating that the perceived superiority of the Stradivarius is not based on listening alone.

This contrasting body of literature indicates that the cultural value of Stradivarius musical instruments might outweigh their contemporary musical indicators as a functional musical instrument. Although these authors' perspectives may be reliant on subjective listener assessments (Fritz et al., 2012), researcher-generated listener evaluation methods (Nagyvary et al., 2006), and a narrow focus on sound perception through a Western classical lens (Invernizzi et al., 2015), these perspectives contribute to a balanced understanding of the characteristics of luthier legacy instruments.

2.2.2 Mass Production

In the previous section, the researcher discussed the intricate craftsmanship of luthier-made instruments. By contrast, the following section will explore the accessibility of their mass-produced counterparts. Table 2.1 shows the differences between luthier and mass-produced instruments. It evidences that luthier and mass-produced instruments can vary in cost, craftsmanship, customisation, sound, material, and tactility.

Table 2.1

Differences Between Luthier and Mass-Produced Instruments, adapted from Nagyvary et al. (2006)

Distinctions	Luthier	Mass-Produced
Craftsmanship	Handmade by specialists	Automated processes and techniques
Customisation	Tailored individual option	Limited customisation options

Materials	High-quality tone-woods	Cost-effective materials
Sound	Designed for optimum sound quality	Balancing sound production with cost factors
Cost	More expensive	More affordable

Although cost and construction efficiency have made mass production the norm in contemporary industrialisation, studies have addressed the comparative quality of mass-produced and traditionally handcrafted musical instruments, often emphasising the superior tonal characteristics and craftsmanship of the latter. For example, literature from Chaigne and Kergomard (2016) and Tai et al. (2018) have emphasised that mass production techniques cannot replicate luthier production techniques. Chaigne and Kergomard (2016) contended that traditional luthier construction methods enabled luthiers to work more intuitively and bring experience and skill sets to each instrument. While Tai et al. (2018) argued that the possibility of adjusting an instrument based on user preferences elevated the traditional luthier model of production.

In contrast, Moro (2018) contends that mass production places a greater emphasis on productivity and cost-effectiveness. Although this is necessary for the instrument supply chain, it can affect the material and sonic qualities of the instrument. As an extension of this, Schmid (2017) suggested that learning to play a musical instrument with inherent physical, structural, and sonic limitations can affect musicians' engagement and their potential for progression. Schmid's (2017) perspective highlights that, although mass production may facilitate wider instrument access, this access can be aesthetic rather than functional if the musical instrument does not perform to musicians' expectations.

2.2.3 Bridging the Gap Between Luthier Models and Mass Production

In attempting to bridge the gap between traditional luthier models and mass production, this section will outline literature exploring the intersection between traditional

luthier techniques and mass-production instrument techniques. Specifically, as these construction methods are not mutually exclusive, there is an emphasis on the cyclical rather than sequential evolution of these methods. For example, literature from Roohnia (2015) argued that traditional wood crafting and wood treatments can affect the tonal resonance of a musical instrument. This challenges the mass production model but forces a reflection on the existing mass production steps. However, Tahiroğlu (2021) assessed recent advancements in the use of composite materials for use with computer-aided design (CAD), asserting that it was possible to engrain handcrafted techniques into digitally operated systems. Bucur (2016) discussed Šali and Kopač's research looking at how machine-based construction techniques affected sound. The results indicated that instruments constructed using less construction joins produced a more robust sound. As Bucur (2016) recognises that traditional luthier instruments are constructed using over 70 pieces of wood, this finding provides an instance where traditional luthiers may learn from contemporary machining techniques.

2.2.4 Case Study 1: The Paris Experiment

This section outlines the Paris Experiment (Fritz et al., 2012, 2014), two double-blind listening tests undertaken to compare the sound of historic and modern violins. This case study is important because it differentiates listener perceptions from listener preferences. In their first study, Fritz et al. (2012) asked 21 professional violinists to aurally assess six modern and six old Italian violins under double-blind listening conditions. Since visual and brand-related clues can influence participants' perceptions of sound quality, the study aimed to measure instrument quality based on aural perception alone. The findings revealed that expert violinists could not consistently differentiate between the sound of Stradivarius violins and high-quality modern instruments, with an identification accuracy of 50% (Fritz et al., 2012). Furthermore, based on the criteria of

playability, projection, and sound quality, 60% of participants rated modern violins higher than the old violins. These findings challenged the belief in the superior tonal qualities of historical instruments, which had been culturally accepted without scientific testing (Bissinger, 2008; Rossing, 2010). However, Bucur (2016) criticised Fritz et al. (2012) for their acoustically compromised sound testing conditions, limited selection of instruments, and recruitment of semi-professional musicians for the study.

Fritz et al. (2014) second study involved 55 professional and amateur violinists, a more extensive range of instruments, and a concert hall setting. It confirmed the initial results from 2012 and indicated that listener biases and the “halo effect” surrounding famous instruments impacted perceptions of the instrument sounds (Fletcher & Rossing, 2012, p. 23). In addition, there appeared to be significant variation in instrument preferences, which implies that individual subjectivity plays a significant and complex role in the perceived quality of sound. Lehmann et al. (2007) argued that this complexity is further compounded by cultural expectations and experience of specific sound profiles, which makes a clear interpretation of the results challenging. However, the consistency in results across different performance contexts, participant groups, and instrument brands highlighted the strength of Fritz et al.'s findings (2012, 2014). It indicated that cultural biases play a strong role in instrument preferences. However, research that criticised Fritz et al. (2012, 2014) studies (Bucur, 2016; McLennan, 2020) emphasised a broader challenge in musical acoustics research: reconciling subjective auditory experiences with objective scientific measurements, which remains a critical area of study.

McLennan (2020) viewed The Paris Experiment within the broader body of research on the sound and acoustics of musical instruments (Bucur, 2016; Gren et al., 2006). While Bucur (2016) provided models to rationalise the sound radiation patterns of violins, Gren et al. (2006) focused on the mechanics of violin string vibrations and

provided a foundational understanding for much of the acoustical analysis in the Stradivarius project. In contrast to McLennan (2020) and Bucur's (2016) research, the Stradivarius project emphasised empirical testing through double-blind trials. These approaches have contributed to the formation of more critical discourse surrounding sound perception (Duerinck et al., 2020; Fritz et al., 2017; Vaiedelich & Fritz, 2017). Through demonstrating that modern violin constructions could surpass the sonic expectations of the Stradivarius instruments, Fritz et al. (2012, 2014) aided in shifting violin research from historical replication towards modes of experimentation. Moreover, the Paris Experiment challenged traditional assumptions and fostered a more nuanced understanding of superior sound quality, which underscored the role of subjective perception alongside objective measurement in comparative sound studies, and was a testament to the depth and complexity of the research.

2.2.5 Case Study 2: The Stradivarius Sound Bank

This section rehearses the Stradivarius Sound Bank (Kiefer, 2021), a sound recording study led by the sound technician Étienne Thoret, the Institut Jean le Rond d'Alembert, and the Laboratoire de Mécanique et d'Acoustique (Kiefer, 2021) that aimed to digitally preserve the sound of the Stradivarius for future listeners. This case study is important because it represents a systematic effort to capture the sonic properties of Stradivarius for use in industry. The collaborators were aware of the physical limitations of ageing instruments and aimed to create a comprehensive digital archive of the acoustic characteristics of Stradivarius instruments. Since their recording in 2019, the sound files have been disseminated as a virtual collection of digital instruments called Native Instruments Komplete (2020). The latter are compatible with industry-standard digital audio workstations (DAWs), making the sound of Stradivarius instruments available through sound software programmes such as Ableton Live, Logic Pro, and FL Studio.

Thus, it is possible to compose, arrange, and produce music using digital Stradivarius instruments.

Although the Stradivarius Sound Bank (Kiefer, 2021) contains high-fidelity sound recordings from professional violinists, its production format does not contain performance limitations. Fink et al. (2012; 2018) contend that although this may be more apparent to professional violinists, for the general listener, it creates an idealised version of the Stradivarius sound. Fink et al. (2012; 2018) show a key challenge in digital sound preservation: mapping a human technique into a digital format. Regardless of these limitations, the Stradivarius Sound Bank (Kiefer, 2021) archives the sounds of the Stradivarius for future listeners. This approach to sound conservation contrasts with Fritz et al. findings (2012, 2014) on the limitations of Stradivarius instruments. Instead, it follows the historical lineage of the Stradivarius brand to rationalise sonic preservation. Equally, encountering these instrument sounds on Native Instruments Komplete (2020), trains future listeners to connect the sound of the Stradivarius with superior sound quality, a sound preference that Fritz et al. (2012, 2014) debunked. The Stradivarius Sound Project build on previous studies from Leman (2007) and Rovetta et al. (2017). The Stradivarius Sound Bank contributes to comparative instrumental sound studies by providing a detailed digital repository. For future researchers, it provides a benchmark for evaluating the sound qualities of Stradivarius violins against modern and other historical violins.

2.2.6 Gaps and Future Research Opportunities in Comparative Sound Studies

Drawing on the previous literature, this section identifies gaps and future research opportunities in comparative sound studies. This can be useful for refining potential research questions. Fritz et al.'s (2012, 2014) findings suggest that newer instrument sounds align with contemporary aural preferences. Therefore, future research could encompass sound studies that involve synthetic composites, which would provide the

prospect of sound quality development and advanced durability (Bucur, 2016; Rossing, 2010). Similarly, this section evidenced that methodologies for evaluation can be subjective (Gough, 2000). Therefore, it would appear that future research could address this subjectivity by using a more quantifiable process, such as digital signal processing (Bissinger, 2008), to provide a counterpoint to user perceptions.

2.3 The Emerging Role of 3D Printing in Musical Instrument Making

In this section, the researcher will present an overview of and discuss advancements in 3D printing to provide a logical transition from manual to digital forms of construction, as it is crucial to contextualise current research and highlight technological innovations in 3D printed violins and musical instruments. Then, the researcher will outline how 3D printing has been applied to musical instruments. In addition, the researcher will use case studies to exemplify the advantages and disadvantages of producing musical instruments using 3D printing. Recognising how different materials affect the instrument's sonic properties is important because this informs further research in this field. Additionally, the current role of 3D printing in the music industry is reflected upon, in order to situate potential market demographics.

3D printing uses additive material processes to produce physical forms at a relatively efficient rate (Martinelli et al., 2020). The application of 3D printing to explore new sounds that were previously unattainable using conventional luthier methods has been influenced by a combination of patents, intellectual property (IP), and technological developments. Horvath (2014) contended that these contributing factors have affected wider accessibility, cost, and material reliability. However, in 2009, the expiration of the foundational patent behind 3D printing (Martinelli et al., 2020) and the subsequent expiration of 16 material patents in 2014 (Bourell, 2016) catalysed advancements by increasing the availability and reducing the cost of essential technologies. Moreover, the

expiration of 225 patents in 2022 (Mueller et al., 2020) accelerated innovation and diversification in non-commercial 3D printing sectors. This influx of expired patents into the public domain democratised the technology and made it more accessible; this resulted in smaller and more affordable printers (Prince, 2014), which enabled the on-demand production of models, parts, and tools.

The decentralisation and domestication of production spaces (Jain & Jain, 2021) have not only physically and economically transformed access to 3D printers, but also raised ethical considerations regarding the nature of printable objects (Wilson, 2016). Despite the existence of approximately 12,000 pending patents related to designs, materials, and software (Mueller et al., 2020), 3D printing's shift into non-commercial markets (Jain & Jain, 2021) and diverse disciplines (Birtchnell & Urry, 2016) signifies its broader acceptance and integration in various fields. Schaeffer (2017) contends that the intersection of 3D printing and instrument making has generated collaborations between designers, musicians, and engineers. This collaboration has been assisted through the reduction in initial barriers such as cost, infrastructural accessibility, and expired patents. Schaeffer (2017) affirms that the collaboration of diverse areas of expertise is critical for resolving modelling, structural, and sonic limitations of 3D printed musical instruments.

The researcher will now briefly make connections between technological innovation theory (Bijker, 1995) and 3D printing. Bijker's (1995) theory of social construction of technology contends that digital artefacts are shaped by both social and cultural factors. This can be exemplified by Yin et al. (2017), who used it to describe customisation trends in 3D printing and emphasise user-driven design and the democratisation of production. By contrast, the diffusion of innovations theory used by Mendonça et al. (2004) proposes that the adoption of 3D printing in music has been accessed at all skill levels and enabled through collaborative maker spaces. The notion of

collaboration through maker spaces has been echoed by Lipson and Kurman (2013), who acknowledge 3D printing's proliferation within luthier literature. However, it would appear that both Bijker's (1995) and Mendonça et al.'s (2004) theories posit a gap between the physical, constructed object and the social and sonic implications of using diminished production processes.

2.3.1 Applications of 3D Printing in Musical Instrument Manufacturing

The researcher will now explore additive, subtractive and hybrid manufacturing processes in relation to 3D printed musical instruments. It is important to assess the advantages and disadvantages of each 3D printing process in order to recognise gaps in existing processes. First, additive manufacturing is described by Bourell (2016) as the creation of a form through consecutive filament layers. Although initially used in product design prototyping (Beaman et al., 2013), the process enables the production of intricate designs (Horvath, 2014), is associated with print efficiency and cost (Bourell, 2016) and has been used as a medium for musical instrument production (Horvath, 2014). The Hovalin 3D printed violin and Openfab PDX modular fiddle (Pearse, 2020) are noted examples of musical instruments made using additive manufacturing methods. However, although both of these instruments are cost-effective, lightweight, and use novel designs, Pearce (2020) contends that they contain sound and durability constraints that limit the instruments' longevity. Hovalin's design, which prints the violin neck and body in two sections, makes the neck susceptible to warping when tensioned. Equally, the Openfab PDX modular fiddle uses a generative design printing process that is not possible to use on many desktop printers. Although these cost-effective and lightweight designs provide a model of instrument access, the structural integrity and printing processes limit their scope.

Second, subtractive manufacturing cuts sections from solid material to generate the final form. This process can be used to refine the hole placement of wind instruments,

which is crucial for tuning (Baines, 1993), and the resonance of string instrument bodies, which is essential for projection (Fletcher & Rossing, 2012). Literature from Sharma and Pandey (2022) promotes the precision and consistency of subtractive manufacturing, which are crucial factors when seeking to produce a specific sound characteristic. However, Li et al. (2018) have criticised subtractive manufacturing due to both the high volume of material waste as well as the higher infrastructural and production costs. Sharma and Pandey (2022) emphasised the importance of maintaining tonal quality and structural integrity when working with new construction methods, while Li et al. (2018) focused on the economic and environmental impact of production with excessive waste. While subtractive manufacturing enables accurate placement and the use of traditional materials, its material waste presents sustainability challenges.

Lastly, hybrid manufacturing blends both additive and subtractive printing processes to produce a final form. Although Du et al. (2016) acknowledge that this process is more expensive and infrastructurally reliant than the previous processes, hybrid manufacturing provides design options beyond the scope of additive and subtractive manufacturing alone. Recent hybrid manufacturing examples include ODD guitars' designs for futuristic guitar necks (Kantaros & Diegel, 2018) as well as Kalo and Essl's design development of sheet metal for cymbals (DeBoer et al., 2021). Although both of these examples provide novel designs and approaches to instrument acquisition, the price point reflects the quality of the infrastructure. Research from Steenhuis (2023) and Domanski (2020) states the importance of collaborative practice between musicians and designers, so that materials and sonorities can be critically explored. Outlining how additive, subtractive and hybrid manufacturing processes function in relation to 3D printed musical instruments has been useful for highlighting the challenges of balancing cost, speed, sonic and material variations.

2.3.2 Distinctions Between Digital Musical Instruments and 3D Printed Instruments

After showing applications of 3D printing, the researcher will now concentrate on distinctions between digital musical instruments (DMIs) and 3D printed instruments. Although beyond the scope of this research, a brief reference to DMIs is necessary when tracing the transition from traditional modes of musical instrument construction and mass production to 3D printed instruments, because DMIs signalled a shift towards digital integration. DMIs and 3D printed instruments represent significant advancements in musical instrument technology, as they diverge from traditional luthier methods and mass production techniques in design and construction. According to Miranda and Wanderley (2006), DMIs focus on how digital interfaces can manipulate sound. By contrast, 3D printed instruments focus on innovating traditional aspects of musical instruments using digital layering techniques (Buehler et al., 2016).

DMIs and 3D printed musical instruments differ in their approach. While DMIs are software driven, 3D printed instruments rely on structural advancements (Miranda & Wanderley, 2006). While traditional luthier construction methods prioritise sonic and material fidelity, and mass-produced instruments may prioritise cost efficiency (Hipkins, 2015), by contrast, DMIs offer sound interfaces that are not reliant on material acoustics (Miranda & Wanderley, 2006). Notable DMI manufacturers that employ additive manufacturing include MONAD Studio (Goldemberg, 2016), which produces sculptural, avant-garde instruments, and Olaf Diegel's ODD Guitars (Loy et al., 2023), which is known for its highly customised instruments. However, although these DMIs circumvent the sonic limitations imposed by their form by adding digital interfaces, they may lack the tactile feedback and organic resonance of traditionally constructed instruments (Freedman, 2017). Although the sustainability and customisation potential of 3D printed instruments have been highlighted (Yin et al., 2017), they have also been critiqued for their material

limitations and acoustic fidelity (Zoran, 2011). Table 2.2, which was adapted from the work of Cano (2015) and Freedman (2017), shows contrasting perspectives on how DMIs and 3D printed instruments vary in conceptual logic, prior skill applicability, sound production, customisation, replicability, and dissemination.

Table 2.2

Differences Between Digital Musical Instruments and 3D Printed Instruments, adapted from Cano (2015) and Freedman (2017)

Distinctions	DMIs	3D printed musical instruments
Conceptual logic	Use of sensors and interfaces to produce sound	Uses traditional sound production logic to produce sound
Prior skill applicability	Physical, sonic, and skill-based learning curve	On balance with traditional instruments
Sound production	Produced electronically	Follows acoustic principles but can vary in quality based on the print material
Customisation	Customisable sounds, range, texture and haptic mapping	Customisable dimensions, materials and colours
Replicability and dissemination	Some DMIs are mass-produced	Physical dissemination is based on access to 3D printing infrastructures

Cano (2015) highlighted the interaction between digital design and physical fabrication and implied that this union promotes innovation in musical expression. By contrast, Freedman (2017) was more cautious and suggested that while 3D printing offers the potential for physical replication, its sonic replication may be more challenging. Specifically, Freedman (2017) distinguishes between instruments constructed for

technological novelty and instruments made for preserving established musical traditions. These contrasting assessments of technological innovation and tradition connect to musicians' potential acceptance or rejection of 3D printed musical instruments. Cano's (2015) techno-positivistic stance fails to capture the subtle nuances of how technologies impact the historical lineage of musical instrument making. While Freedman's (2017) cautious approach may affect the potential of 3D printing technologies.

2.3.3 Criteria for Designing New Instruments

After outlining the differences between traditional luthier instruments, mass-produced instruments, DMIs and 3D printed musical instruments, the researcher will now examine existing criteria for designing new instruments. This section includes theoretical frameworks and methodologies previously employed by luthiers and researchers. Firstly, Cooper et al. (2014) use a five-step criterion for interface design. This consists of a sequential process of (i) research, (ii) modelling, (iii) defining the requirements, (iv) defining the framework, and (v) design refinement. This sequence indicates iterative user feedback at all stages throughout the design process, which is also advocated for by Nielsen's (1994) heuristics for usability. Cooper et al. (2014) is valuable for instrumentalists and instrument makers because it promotes iterative feedback and a user-centred approach to instrument design, which connects with Norman's (2013) human-centred design approach. Secondly, Miranda and Wanderley (2006) also use a five-step approach when designing DMIs. This consists of (i) the concept development, (ii) awareness of specifications, (iii) producing a prototype, (iv) prototype evaluation, and (v) iterative refinement. This sequence is more relevant to instrument makers because it promotes iterative prototype refinement stages in its physical form. Having evaluation as a specific stage within the instrument design process reflects Schön's (1983) concept of the reflective practitioner, where designers develop ideas through iterative prototyping.

Miranda and Wanderley's (2006) criteria connect with Sullivan (2015), who contends that the musical development process is connected to the exchange between musicians and their instruments. Although Cooper et al. (2014) criteria for designing new instruments clearly focus on user-centred design and experience, Miranda and Wanderley's (2006) criteria complement Cooper et al. (2014) through providing iterative prototyping of the physical instrument. Reinforced by Norman's (2013) human-centred design approach and Schön's (1983) reflective practitioner, both Cooper et al. (2014) and Miranda and Wanderley's (2006) criteria for designing new instruments contribute to an understanding of user-centred musical instrument design based on iterative prototyping.

2.3.4 Material and Acoustic Limitations in 3D Printed Violins

In this section, the researcher will compare the material and acoustic properties of 3D printed and traditionally constructed violins, which is crucial to understanding gaps in the literature. Compared to traditionally constructed violins, the acoustic properties of 3D printed violins present significant variations, which are attributable to differences in materials and manufacturing processes.

Yao et al. (2016), Vasina et al. (2020), and Pei et al. (2023) investigated the sound projection capacity of 3D printing materials, otherwise known as filaments. First, Yao et al. (2016) experimented with the sonic properties of polylactic acid (PLA), a cost-effective all-purpose printing filament. Comparative acoustic tests revealed that PLA produced attack times equivalent to those of traditional instruments, but its decay rate was much faster. This finding suggests that, although 3D printed violins may capture musicians' real-time gestures, their diminished resonance affects listener perceptions. The finding also shows that, although such decay rates may be less audible in an ensemble context, 3D printed instruments may lack the textural expressiveness needed for solo performance, thus limiting the instrument's performance capabilities.

Second, Vasina et al. (2020) tested the acoustic properties of acrylonitrile butadiene styrene (ABS), which is known for its material strength, low distortion, and lightweight properties. The tests revealed that the layer height, printing speed, and temperature all contributed to the material's durability and resulting sonic properties. Vasina et al.'s (2020) research indicated that knowledge from both makers who were proficient in the technical knowledge of 3D printing and musicians who had the capacity to discuss the nuances of sound was necessary for actualising this research. In contrast, Blok et al. (2018) advised that ABS should not be used on musical instrument sections that are required to resonate or carry sound. In this instance, Blok et al. (2018) relegate ABS for use with DMIs, where sound is digitally manipulated. Combined, Vasina et al. (2020) and Blok et al. (2018) present a sonic profile of ABS, indicating that it does not have the resonance or projection qualities needed to replicate traditionally constructed musical instruments.

Finally, Pei et al. (2023) conducted a comparative analysis to assess the sonic abilities of four 3D printing filaments. Using PLA, ABS, nylon, and carbon fibre, the results indicated that print filaments and the print orientation of the design affected the strength and sound of the final test samples. Pei et al. (2023) made connections between denser materials and higher frequencies. The authors also made connections between horizontally printed designs and more resonant frequencies. This finding shows that print orientation on the x, y, and z axes influences the final sound. As the print orientation is influenced by the print bed size, this finding indicates the desirability of larger 3D printers to accommodate horizontal and more acoustically resonant material forms.

The research conducted by Pei et al. (2023), Vasina et al. (2020), and Yao et al. (2016) illuminated the potential and limitations of using 3D printed materials for musical instruments. While Yao et al.'s (2016) findings indicated that PLA could mimic certain aspects of traditional instrument sounds, its rapid decay rate limits its use for solo

performances, in which sustained notes and rich textures are essential. These results provide a snapshot of 3D printed resonance studies, and the findings provide source material for further research. Vasina et al.'s (2020) findings revealed the extent to which factors such as wall thickness and internal geometry can affect sound production and resonance of a material. These findings highlight the technical challenges of musical instrument replication. Pei et al. (2023) findings indicated that the infrastructural costs of larger printing beds to facilitate horizontal orientation and the periodic costs of using stiffer and denser materials could undermine the cost-effectiveness of 3D printing. As noted in Section 2.3.1, although 3D printing offers the prospect of a cost-effective and lightweight alternative to traditionally constructed musical instruments, their current physical and sonic profile does not align with traditionally made counterparts. The findings from Yao et al. (2016), Vasina et al. (2020), and Pei et al. (2023) demonstrate that filament, infill, and print orientation all affect sound production. Therefore, the notion of comparable instrument replication is complexified.

2.3.5 Impact of 3D Printed Instruments on Luthiers, Modellers, Musicians, and the Music Industry

By exploring the current impact of 3D printed instruments on luthiers, modellers, musicians, and the music industry, the following section seeks to establish how user perceptions can shape choice, integration, and acceptance of new instruments. With regard to luthiers, Birtchnell and Urry (2016) and Lipson and Kurman (2013) contended that, although 3D printing offers the prospect of precision and customisation that cannot be manually achieved, current variations in the sound and material quality of 3D printed instruments challenges their meaningful market integration alongside traditional luthier instruments. In this case, these limitations have affected 3D printed musical instruments as a viable alternative for musicians. These limitations have also affected the adoption

practices of luthiers. Ultimately, although Birtchnell and Urry (2016) and Lipson and Kurman (2013) acknowledge the precision and customisation potential of 3D printing technologies, without comparable sound and materiality qualities, these technologies will remain peripheral to luthiers, musicians, and the music industry.

Similarly, Bills (2015) argued that luthiers' skills in selecting, shaping, and finishing wood cannot be digitally replicated. This perspective indicates a more significant resistance to an alternative mass production model and the potential marginalisation of luthiers. Unlike traditional luthiers, who may be hesitant to use 3D printing and focus on the craftsmanship of making instruments, modellers, who are experts at creating 3D models, specialise in 3D printing but have less expertise in the technical aspects of instrument design. Bills' (2015) argument connects with the need for more collaborative research between luthiers, modellers, and musicians, discussed in Section 2.3. This is reinforced by Hopkins (1996), who noted the luthiers and musicians' learning curve, and modellers' limited understanding of the role of sonic properties for musical instruments, as prime barriers to the development of fully formed designs. Equally, regarding collaborative skillsets, Patteson (2016) contended that new instrument designs that build on existing instrument fingering systems, haptic logic, and visual cues, are more likely to be adopted and integrated. Patteson's (2016) argument reinforces the notion that new instrument design should be informed by collaborative voices.

With regard to musicians and the music industry, Pranadani (2023) and Birtchnell and Urry (2016) discussed the marketing of 3D printed musical instruments as a cost-effective, customisable, and accessible substitute for traditionally constructed instruments. By contrast, Manapat et al. (2017) and Karana et al. (2015) discussed sonic discrepancies, and Shaer (2009) emphasised the tactile differences that continue to marginalise 3D printed musical instruments in the music industry. These authors' perspectives connect

with the sonic and material limitations outlined in Section 2.3.4. However, in this context, the sonic and material limitations noted by these authors affect market integration and acceptance of 3D printed instruments. Cottrell (2013) viewed brand recognition and loyalty, as well as a general resistance to change once a musical style has been established, as major factors that influence musicians' instrument choice. This affects market penetration for new instruments. Murphy (2014) noted that instrument reliability was a key influence in the instrument choice of musicians, with Schmid (2017) emphasising the emotional connection with instruments, it would appear that without resolving key sonic and material differences, 3D printed instruments will remain a peripheral choice. Both Murphy's (2014) and Schmid's (2017) points emphasise the social, emotional, and technical aspects involved in musical instrument selection. Isacoff (2012) discussed longstanding distribution channels, whether physical or digital, as challenging markets for new instruments to penetrate. The above literature indicates that further research that bridges the gap in the sound and material properties of 3D printed instruments is necessary for musicians and luthiers to consider 3D printed instruments as a viable alternative to traditionally produced instruments.

For makers and modellers, online file sharing of 3D printed instruments is viewed as a democratised form of access (Depoorter, 2014), which can problematise intellectual property rights (IPR). The Patents Act (Irish Statute Book, 1992) and the Industrial Designs Act (Clark, 2001) govern instrument making IPR in the Irish music industry. They have protected contemporary designs and technologies used in instrument making for over 20 years (Irish Statute Book, 1992), which can be vital for Irish instrument makers. However, current Irish legislation does not extend to the file sharing of 3D printed instruments. Provisional discussions on extending European Union IPR laws (Mendis et al., 2019) and state-led provisions for digital weapon distribution laws in the United States

(Walsh et al., 2021) provide a template for how this could be actioned in an Irish context. These governmental efforts emphasise the complexities of regulating digital files for 3D printing and balancing innovation with IPR. Therefore, for 3D printed musical instruments to advance from novel devices to industry competitors, the technology must resolve significant sonic and material challenges, and IPR must be regulated to support new designers. The above literature has discussed the impact of 3D printed instruments on luthiers, makers, musicians, and the music industry. The literature contrasts technopositivistic approaches with the practical limitations that affect the acceptance of new instruments by musicians. They also indicate that a collaborative approach that incorporates luthiers' practical skills, modellers' digital skills, musicians' performance skills, and the industry's marketing and IPR knowledge is necessary for developing the acceptance and material viability of 3D printed musical instruments.

2.3.6 Gaps and Future Research Opportunities in 3D Modelling, Printing, and Production

By exploring the gaps in current 3D printing literature, the following section seeks to establish future research opportunities. From a conservation perspective, Burgess (2018) has researched the preservation potential of 3D scanning and printing. Therefore, future research could use 3D scanning, mapping, and printing as quantifiable methods for capturing and reproducing instruments for conservation purposes. In addition, Malik et al. (2024) explored the time, assembly, and aftercare advantages of 3D printing multifaceted instrument parts as a single form. As factors such as temperature and age contribute to seam maintenance issues, further research could attempt to redesign the seams which contribute to instrument degradation. Equally, from a sound and physics point of view, Pei et al. (2023) tested the sonic resonance of 3D printing filaments and their potential application to musical instrument making. Although alternative materials have been used

in the construction of bows (Wegst et al., 2007) and instrument cases (Mueller et al., 2020), future research could explore their application for musical instrument forms (Singh et al., 2022). Finally, from a user-centred design perspective, Bourell (2016) asserted that some 3D printing studies overemphasise the technical innovation of new technologies, without considering viable audiences for such technologies. Therefore, the researcher suggests that future research could utilise a collaborative design and prototyping process to ensure market viability.

2.4 The Potential Role of 3D Printed Musical Instruments in Education

By exploring the educational possibilities of 3D printed musical instruments in education, the following section seeks to establish future research opportunities. Through viewing recent examples of 3D printed instrument research within education, as well as existing models of instrumental provision in Ireland, the researcher seeks to establish current gaps in the existing model and the advantages and disadvantages of an alternative mode of provision. This section will also assess educators' perceptions of 3D printed instruments to date, in order to assess the potential integration challenges. Finally, the researcher will briefly outline theoretical perspectives regarding technology and education in order to build a framework from which future research can be assessed.

Rogers's (2003) diffusion of innovation theory, previously referenced in this chapter (Section 2.3), stated that in order for new technologies to be adopted and integrated within any environment, infrastructural support and social communication channels must be present. This view rationalises how infrastructural support for 3D printing in an education context could provide the social communication channels for the growth and dissemination of 3D printed musical instruments. Building on this, Herring et al. (2016) technological pedagogical content knowledge framework emphasised the connection between teaching, technology, and content knowledge. The successful

integration of the Herring et al. (2016) framework is contingent on teachers' deep understanding of the new technology, as well as an understanding of how this technology supports existing pedagogical goals. The researcher acknowledges the crucial role that these three aspects have in the successful integration of new technologies within education. Both of the above frameworks emphasise the importance of an educationally focused structure that requires technical and pedagogical support.

Sahin (2006) asserted that Rogers's (2003) diffusion of innovation theory undervalued and simplified the effect that teachers and educational environments have on the integration of new technologies and processes. As already outlined in Section 2.2.1, Faber (2012) stated that instrument brands are imbued with historical and cultural values. With this in mind, it would appear to the researcher that teacher perceptions and historical preferences play a pivotal role in the integration of new technologies and practices, which indicates a gap within the existing 3D printed instrument literature. Furthermore, Kidd and Morris (2017) were critical of the Herring et al. (2016) framework on digital integration due to its general guidance on pedagogical approaches. This also challenges the possibility of pedagogical change.

2.4.1 Integration of 3D Printing Into Irish Education

By discussing the current integration of 3D printing into Irish education, the researcher seeks to acknowledge research to date, as well as existing infrastructural and pedagogical challenges that could impact further research. Relevant research has occurred in art (Togou et al., 2018) and mathematics (O'Reilly & Barry, 2021) primary school contexts. Togou et al. (2018) completed an online digital fabrication course with Irish primary school students during COVID-19 to explore how student engagement could be elevated and how STEAM principles could be applied to the classroom. Findings from an art project by Togou et al. (2018) showed increased levels of student engagement (34%),

with 15% of student participants indicating that STEM education should incorporate relevant technologies. Equally, O'Reilly and Barry (2021) explored how integrating Computer Aided Design (CAD) software into an Irish primary school maths class affected their spatial awareness, attitudes and aptitude for the subject. To date, 3D printing has yet to be applied to a music education context in Ireland. The findings from Togou et al. (2018) and O'Reilly and Barry (2021) suggest that while 3D printing is visible in Irish primary schools, its potential in post-primary schools, specifically in music education, has yet to be explored. However, Margot and Kettler (2019), McLean and Rowsell (2020), and Ralls et al. (2018) contended that integrating 3D printing within education posed challenges to CPD and curriculum integration. Specifically, Margot and Kettler (2019) observed that the specialised knowledge connected with 3D modelling and printing may not align with all subjects and all teacher skill sets. Equally, Ralls et al. (2018) echoed Margot and Kettler (2019) by indicating that such digital CPD would extend teachers' workload. As a solution, McLean and Roswell (2020) proposed industry collaborations to overcome subject-specific and skill-set learning curves.

From an international perspective, Santos et al. (2018) have discussed how 3D printing could be integrated into STEM subjects to develop students' spatial reasoning skills and key transferrable skills across subjects. Santos et al. (2018) suggestion connects with the Irish Department of Education's Digital Strategy for Schools (Department of Education and Skills, 2015), which emphasised the value of embedding technologies, specifically technologies that encourage key transferrable skills, across all subjects. Also, Avanzini et al. (2019) proposed including 3D printed musical instruments as a novel approach to music education in this context. Avanzini et al. (2019) approach indicated that 3D printed musical instruments could promote instrument access and encourage an interactive learning environment. Although Avanzini et al. (2019) suggestion remains

within its theoretical stage, this literature evidences its potential application. Furthering Avanzini et al. (2019) suggestion, Tanabashi (2021) contended that 3D printed instrument integration within education would not only begin to address instrument provision challenges, but it would activate practical learning experiences in instrument making, and bring industry experiences into the classroom. In contrast, Alevizou (2007) argued that although educational policy frameworks promote the integration of technologies, the gap between policy and practice challenges their systematic integration. This indicates to the researcher that in order for 3D printing to be a fully integrated tool within Irish education, specific curriculum guidelines, infrastructures, and subject-specific pedagogical supports are needed. Equally, any subject integration proposals must complement existing educational standards (Department of Education and Skills, 2016). This finding suggests that, in order to develop Togou et al. (2018) and O'Reilly and Barry's (2021) research beyond isolated educational interventions, curriculum alignment and teacher training across all subjects are needed.

2.4.2 Role of 3D Printing in Cross-Disciplinary Education

By discussing the role of 3D printing across subjects, the researcher seeks to create a context for how 3D modelling and printing could enrich and complement existing subjects. Research from Santos et al. (2018) evidenced how developing skills in 3D modelling could be applied to art in order to enhance students' experiences in making virtual sculptures. This learning experience could be applied to the Leaving Certificate Visual Art practical guidelines under the sub-heading of digital art (Chárthaigh & O'Sullivan, 2021). Similarly, research from Ali and Khine (2020) explored how developing skills in 3D modelling could be applied to science in order to enrich students' understanding of human organs. This educational experience enriched students' comprehension and provided educational resources for future development.

Although cross-disciplinary projects that encompass music and 3D printed musical instruments for performance purposes have yet to be practically implemented in an Irish educational context, internationally, Bucur (2016) explored the benefits of 3D printed instruments for the teaching of acoustics and physics principles within a STEM curriculum. Like Santos et al. (2018), Bucur (2016) viewed 3D printing as a visualisation tool that can promote more in-depth learning of a topic. In another study, Hoskins (2018) argued that 3D printing technology enables students to engage with technical and creative aspects of music production, which are distinct from forms of recording and notation. However, Santos et al. (2018) astutely pointed out that sustained research incorporating these technologies requires both a level of technical proficiency and access to 3D printing infrastructures. In these instances, Hoskins (2018) made clear distinctions between digital tools that support student learning and digital tools that enable new ways of learning. While Santos et al. (2018) realised the limitations of attempting to integrate digital technologies without the physical infrastructural support necessary for sustained development.

The gap in standardised curriculum models outlined by Santos et al. (2018) is in line with the work of Campbell and Lum (2019), who called for the establishment of a more structured integration framework. They indicated that 3D printing may only fully benefit students with proper guidance. This literature demonstrates its capacity to enhance traditional modes of creation and learning and underscores the urgent need for the structured incorporation of 3D printing technology into the curriculum to nurture cross-disciplinary creativity while ensuring that foundational skills are not overshadowed.

2.4.3 The Impact of Previous Case Studies on Music Curriculum and Pedagogy

By discussing the impact of previous case studies within music education, the researcher seeks to establish existing methodological approaches. Although there are

currently no case studies exploring the impact of 3D printed musical instruments in an Irish educational context, three recent case studies from Italy (Calvani et al., 2011), Lithuania (Girdzijauskienė & Šmitienė, 2020), and the United Kingdom (Kelley & Knowles, 2016) are outlined in this section in order to establish how the use of 3D printed musical instruments has begun to be incorporated into music curriculum and pedagogy.

In the first case study, Calvani et al. (2011) explored the integration of 3D printing technology into an educational context by designing and leading a digital instrument modelling course for Australian high school students based on constructivist learning theories that focus on developing creative research in STEAM. Calvani et al. (2011) field research took place over one academic year and used student observations and teacher interviews to assess students' technical abilities in the physics of sound. The authors generated scaffolded teaching resources for use by music teachers. Although the research was limited by the participant sample size and the relatively short duration of the intervention, Calvani et al. (2011) were successful in incorporating 3D modelling into students' lessons, extending the notion of music technology beyond sound recording and composition.

In the second case study, and using collaborative project based learning frameworks, Girdzijauskienė and Šmitienė (2020) explored how 3D modelling could support STEAM integration in middle school music. Girdzijauskienė and Šmitienė's (2020) research took place over six months, and used surveys, focus groups, and performances to assess learning outcomes. The practical applications of STEAM in music education were advanced by focusing on the technical and performative potential of 3D printing. Research from Girdzijauskienė and Šmitienė (2020) on modelling and playing 3D printed instruments in interdisciplinary STEAM frameworks advanced music pedagogy by integrating innovative technology and design principles into music education. Although

this research was limited by the shorter timeframe and the reliance on 3D printing infrastructural support from the school, it provides a model for music and STEAM integration for teenagers.

In the third case study, Kelley and Knowles (2016) explored how 3D modelling could enhance primary school music education through inquiry-based and technology-enhanced learning. Over a period of three months, the researchers used action research, which involved iterative cycles of planning, observation, and reflection, as well as teacher reflection journals and student surveys, to develop a curriculum for integrating digital skills into a primary music curriculum. This new curriculum drew from the existing curriculum but included additional technology sections. Kelley and Knowles' (2016) research on the development of a curriculum for 3D modelling in primary school advanced music pedagogy by improving students' spatial awareness. However, its limitations included a short timeframe of three months, which affected its generalisability, and the comparatively younger age group of student participants, who may have had limited responses. Although their study provided a curriculum model, it did not provide details on teacher CPD that might enable general primary school teachers to integrate 3D printing into an existing curriculum.

Despite their limited sample size, timeframe, technical challenges, infrastructural demands, and potential bias, these three case studies demonstrate how researchers have integrated 3D modelling and printing practices into existing curriculum and pedagogy. Although they had a modest impact on students' learning, they suggested that incorporating 3D modelling and printing practices into music education can develop physics and engineering principles in relation to STEM and promote collaborative and iterative learning. In the Irish music education context, these outcomes suggest similar

research could occur with appropriate interdisciplinary collaboration, teacher CPD, 3D printing infrastructural support, and pedagogical support.

2.4.4 Advantages and Disadvantages of 3D Printed Musical Instruments in Education

Assessing the advantages and disadvantages of 3D printed musical instruments in education is central to understanding their potential influence on learning outcomes and access. Although the literature has identified advantages such as cost effectiveness and accessibility (Buehler et al., 2016; Cano, 2015), customisation and personalisation (Calignano et al., 2017; Hankammer et al., 2018; Peppler et al., 2016), and the development of technical and artistic skills (Hoskins, 2018), it is equally important to consider the material, sonic (Manapat et al., 2017), and pedagogical disadvantages of 3D printed musical instruments (Santos et al., 2018). Achieving a balanced view of their advantages and disadvantages can ensure that the integration of new technologies enhances rather than diminishes the educational process, thereby creating a safer, more effective, and more enriching educational environment for students.

Some studies have highlighted that 3D printing musical instruments, such as flutes, claves, and trumpets, has the potential to lower costs and make musical instrument provision more accessible, specifically in underfunded schools (Cano, 2015). For instance, Buehler et al. (2016) reported the initial and sustained financial cost of providing a traditionally constructed instrument and lessons for a student, citing these as a prime barrier to access for socioeconomically disadvantaged families. In addition, Peppler et al. (2016) estimated that the low cost of 3D printing materials and the ability to customise student instruments offer increased accessibility prospects. Similarly, Cano (2015) discussed the democratising power of file-sharing musical instruments for 3D printing, which decreases the cost barrier. However, solely focusing on the cost-effectiveness of 3D printed musical instruments provides a limited understanding of access to musical

instruments, as the latter involves more than simply affordability (Buehler et al., 2016). Moreover, Cano (2015) and Peppler et al. (2016) focused on instrument modelling and its theoretical application in educational contexts. However, Cano's (2015) research does not extend to 3D printed instruments' physical modelling and transferability into an educational context. Buehler et al. (2016) acknowledged that, while "technically feasible ... the [3D printed instrument] design would not be suitable for an education instrument" (p. 145), citing the quality of models on file-sharing websites such as Thingiverse as inferior to their traditionally constructed counterparts. These findings suggest a technical ability gap between researchers as modellers and researchers as music educationalists, which indicates the need for collaborative research, and a disconnect between research on the theoretical application of models, the practical acquisition of file-sharing models, and the potential application for musicians. This demonstrates the need for research that involves the practical testing of high-quality models tailored to a specific user group.

Recent literature (Huang et al., 2014; Olsson et al., 2019) discussed the durability and sound comparability limitations as key deterrents to using 3D printed musical instruments in educational contexts. While this echoes prior discussions from Fletcher and Rossing (2012), Manapat et al. (2017), Karana et al. (2015) and Shaer (2009) in Section 2.3.5, in this instance, the visual and sonic difference described by Huang et al. (2014) affects student engagement in educational ensemble contexts. This finding indicates that performing on an instrument with inbuilt limitations, whether mass-produced or 3D printed, creates limitations for musical progression by students. Likewise, Olsson et al. (2019) contended that, although early 3D printing costs are comparatively low in relation to traditionally constructed musical instruments, the unforeseen additional maintenance costs of producing a plastic instrument outweigh the initial price point. This finding shows that long-term infrastructural considerations must be taken into account to make the

integration of 3D printed instruments into educational contexts structurally and ethically viable. Similarly, Blok et al. (2018) found that the layering process inherent in 3D printing can produce structural weaknesses that compromise the durability of 3D printed instruments. This result indicates that instrument quality should be prioritised over cost-effectiveness when discussing an instrument's educational value. However, this undermines the cost-effectiveness of 3D printed instruments relative to their traditionally constructed counterparts; issues with sound fidelity further compound this limitation. As Bucur (2016) noted, 3D printed instruments can produce less resonance than traditional materials; this affects their educational effectiveness, given the importance of accurate sound representation. This finding indicates that more research on the sonic comparability of traditionally and non-traditionally constructed instruments is needed before integrating 3D printed instruments into an educational context.

Additionally, Li et al. (2018) viewed the integration of 3D modelling and printing in an educational setting with scepticism. They cited it as both an opportunity to engage students in hands-on learning and interdisciplinary engagement, but conceded that a lack of infrastructural support for all schools could widen the socio-economic divide. The underlying issue in the above perspectives is a tendency to either overstate the ease of instrument access or underestimate its nuanced challenges, such as the need for specialised knowledge to integrate these tools into curricula effectively (Peppler et al., 2016) and the uneven distribution of resources in educational contexts (Neimann et al., 2021). Although Li et al.'s (2018) findings indicate that studies on the integration of 3D printed musical instruments into educational contexts may have greater access benefits for students from socioeconomically disadvantaged schools, Neimann et al. (2021) argued that existing digital infrastructural provisions can dictate and perpetuate the environments in which research takes place. This finding implies that public-private partnerships, grants, and

funding can enable equitable systematic integration and that, while future research in schools with existing 3D printing infrastructures may provide data specific to instrument testing rather than instrument modelling, researchers should be cognisant of its future replicability in socioeconomically disadvantaged educational contexts. This partnership could involve inter-school collaborations to share resources, thus connecting with socioeconomically disadvantaged schools (Neimann et al., 2021).

From outlining the above research perspectives (Li et al., 2018; Neimann et al., 2021; Pepler et al., 2016), it would appear to the researcher that the limitations of these research perspectives include (i) the lack of comparative data on other cost-effective musical instruments as a gauge of instrument expectations and limitations, as well as (ii) the limited research involving collaborative stakeholders in the instrument design process, which may have developed the research beyond an affirmation of literature from Section 2.3.5. The integration of 3D printed instruments into educational contexts requires careful consideration of these nuanced factors and underscores the need for thoughtful decision-making in research involving 3D printed instruments. Therefore, a deeper understanding of access to musical instruments must account for durability and cost. Without addressing durability, a focus on cost effectiveness alone may overlook critical barriers and drivers of accessibility, which highlights the crucial role of educators, researchers, and policymakers in adopting 3D printed instruments.

Although recent literature has discussed the customisation and personalisation advantages of producing 3D printed instruments for education purposes (Blair & McCord, 2016; Calignano et al., 2017; Freedman, 2017; Khosrow-Pour, 2018), a key disadvantage is that it has remained a dominantly theoretical application to date. For example, Blair and McCord (2016) and Khosrow-Pour (2018) highlighted the potential pedagogical advantages of building customisable instruments for differentiated learning. While

Calignano et al. (2017) and Freedman (2017) suggested that engaging students in the design of musical instruments could increase student investment and extend the spaces in which acts of musicking could occur. This aligns with Small (2012), discussed in Section 1.4. However, in opposition, Celentano et al. (2016) expressed trepidation for introducing designs that promoted student personalisation of musical instruments. In this instance, Celentano et al. (2016) viewed instrument personalisation as a less authentic and more stylised representation of a musical instrument, thus undermining the act of reproduction. Moreover, Santos et al. (2018) underscored that the novelty and perceived "toy-like" (Santos et al., 2018, p. 21) nature of 3D printed instruments affect student retention. This perspective reinforces Celentano et al. (2016) notion that altering the instrument too much can undermine its historical and cultural symbolism. Hankammer et al. (2018) astutely pointed out that the ability to customise and personalise an instrument is based on the premise of teacher and student prerequisite knowledge and infrastructural support to enable students' visions to be actualised. Hankammer et al. (2018) perspective echoes concerns voiced in Section 2.4.3 regarding the lessons learned from previous case studies.

By contrast, Serdyukov (2017) suggested that the novelty of developing skills related to the design and 3D printing of instruments can initially engage students, but differences in sound quality between 3D printed and traditionally constructed instruments present significant challenges for musical progression, viability, and student retention. These differences raise questions about how developing technical and artistic skills related to 3D printing can advance the resultant instruments' sonic equivalence to traditionally constructed instruments. They also indicate that an overemphasis on process-driven designs can affect musical performance tools and undermine the skill development process. These challenges underscore the crucial need for a balanced approach to integrating 3D printed instruments into music education, which should be guided by

careful planning, execution, and reflexive action, as these are essential for successful implementation.

2.4.5 Education Stakeholders' Perceptions of 3D Printed Musical Instruments

By discussing education stakeholders' perceptions of 3D printed musical instruments, the researcher seeks to establish the instruments' practical and educational viability within an education context. Prior sections of this chapter have discussed luthiers (Bills, 2015) and musicians' (Sharma & Pandey, 2022) perspectives of 3D printed musical instruments being connected to innovation, cost-effectiveness, and a lightweight structure, but lacking in sonic and material comparability. However, in contrast, Plakitsi and Barma (2024) asserted that students and teachers may be more likely to prioritise instrument cost-effectiveness over musical instrument compatibility. This worrying perspective perpetuates a narrative of aesthetic access over a student's development potential. These contrasting viewpoints challenge the integration of 3D printed instruments as a viable counterpart to existing models of instrument provision. These viewpoints also perpetuate the novelisation narrative that was referenced through Freedman (2017) in Section 2.3.2. However, as Mesquita (2011) contended that the limited examples of 3D printed musical instruments, as well as a lack of longitudinal studies assessing the long-term durability of 3D printed instruments within education contexts, have affected education stakeholders' perceptions of 3D printed musical instruments, it would appear that more critical research must be undertaken to develop the instruments' technical and sonic comparability.

2.4.6 Existing Models of Musical Instrument Provision in Ireland

Comparing existing models of musical instrument provision in Ireland is necessary for identifying potential gaps and assessing the feasibility of integrating new technology into music education. The Music Capital Scheme and the Music Instrument Fund of Ireland are two existing models of instrument provision. The Music Capital Scheme

supports musicians at both the individual and institutional levels by funding the purchase of instruments, which helps address barriers to involvement in music-making (Deloughry, 2014). By contrast, the Music Instrument Fund of Ireland focuses on expanding access to musical instruments for schools and community groups and emphasises inclusion and equity (Deloughry, 2014). Although both programmes share the common objective of improving access to music education through instrument access, their implementation approaches and audiences differ. Literature from Deloughry (2014) and Moscardini et al. (2012) have been critical of the funding allocations and geographic inconsistencies of these two provision models. This challenges the existing instrument provision models in Ireland. Although 3D printed musical instruments are not currently represented in the Music Capital Scheme or the Music Instrument Fund of Ireland, international literature from Bacciaglia et al. (2019) Simian (2023) and Zoran (2011) indicates that 3D printed musical instrument files could decentralise provision and provide an alternative model of instrument provision.

2.5 Gaps in Research and Future Research Opportunities in Education

This literature review has evidenced gaps in existing research and the potential for future research opportunities in the areas of:

- (i) Collaborative interdisciplinary research between luthiers, musicians, and teachers (Sections 2.2.1, 2.3.1, 2.3.5, 2.4.3).
- (ii) Further comparative sound and material research based on iterative prototyping (Sections 2.3.2, 2.3.5).
- (iii) Longitudinal studies of 3D printed instruments within an educational context (Sections 2.4.3, 2.4.5).
- (iv) Short and long-term digital infrastructural provision and support (Sections 2.4.2, 2.4.3, 2.4.4).

- (v) Practical application of 3D printed instruments in an educational context
(Sections 2.4.3, 2.4.6).

As Burton and Snell (2015) contended that effective musical instrument interventions are designed with both short and long-term support for their participants, it would appear that further research must encompass short and long-term strategies for instrument maintenance and student support beyond the timeframe of an intervention. Future research based on the identified gaps in the existing literature is necessary to increase our understanding of the potential educational impact of 3D printed musical instruments within an educational context.

2.6 Conclusion

This literature review presented musical, technical, and educational aspects of 3D printed musical instruments and contextualised the research questions presented in Chapter 1. Section 2.2 viewed the distinction between luthier-crafted, legacy, and mass-produced musical instruments and highlighted their sonic and material differences. This section aided in contextualising the historical and social evolution of the violin and outlined the desirable and less desirable characteristics of these instruments. Two case studies, the Paris Experiment (Fritz et al. 2012, 2014) and the Stradivarius Sound Bank (Kiefer, 2021), aided in critically contrasting user perceptions of the sound of the Stradivarius. These case studies offered contrasting perspectives on the evaluation and replication of instrument sounds; while the Paris Experiment's empirical approach emphasised the value of double-blind testing in assessing sound quality, the Stradivarius Sound Bank highlighted the value of preserving the sounds of historical instruments beyond their physical life. Together, section 2.2 underscored a diverse approach to studying musical instruments. It provided a context for discussing the potential role of 3D printed musical instruments within this field in the following section.

Section 2.3 outlined the technical aspects of 3D printing, and key patent expirations that have led to recent market growth across diverse subjects. Making distinctions between luthier legacy, mass-produced, DMIs and 3D printed musical instruments aided in rationalising 3D printed musical instruments as a logical extension of a historically rich design process. Literature from Yao et al. (2016), Vasina et al. (2020), and Pei et al. (2023) evidenced the sonic and material limitations of existing 3D printed musical instruments. Cooper et al. (2014) five-step criteria for interaction design and Miranda and Wanderley's (2006) five-step process for DMI design provided comparable frameworks for assessing user-centred musical instrument design. Assessing the advantages and disadvantages of 3D printing and the sonic and material challenges of instrument replication provided a context for discussing the potential role of 3D printed musical instruments within an educational context in the following section.

Section 2.4 explored the educational viability of 3D printed musical instruments. By rehearsing existing case study examples of 3D printing in music contexts from Italy (Calvani et al., 2011), Lithuania (Girdzijauskienė & Šmitienė, 2020), and the United Kingdom (Kelley & Knowles, 2016) the researcher sought to show methodological approaches and gaps for future development. By incorporating Irish case studies using 3D printing interventions in the subjects of art (Togou et al., 2018) and maths (O'Reilly & Barry, 2021) at primary school level, the researcher sought to locate their research in relation to existing curricula and identify existing methodological gaps for further development. Discussing the advantages and disadvantages of 3D printed musical instruments in education provided evidence for their access benefits and material limitations. Synthesising literature based on education stakeholders' perceptions of 3D printed musical instruments aided in establishing the educational barriers to instrument integration. Referencing existing models of musical instrument provision in Ireland, which

focus on traditional instrument manufacturing and distribution methods, highlighted research gaps that merit further exploration.

Chapter 3 Methodology

3.1 Introduction

This exploratory, mixed-methods study took place over three years in three phases. In summary, it investigated the perspectives of five instrumental teachers (years one and three of this fieldwork), five luthiers, and 10 musicians (year two) on their experiences using 3D printed violins. Years one and two involved meetings with instrumental teachers and performance professionals in Cork, Offaly and Dublin. The interviews in year three took place with instrumental music teachers. As prefaced in Chapter 1, these instrumental teachers had trialled the 3D printed violins alongside a small cohort of their students for an academic year. Although the student data was omitted from the final thesis due to its progression towards more technical aspects of instrument making, the teacher's interviews discuss student examples in this section. This chapter critically discusses the conceptual framework of this research paradigm. It discusses the design of this research, data collection methods, analytical procedures, ethics, and limitations.

3.2 Research Aim

This research aimed to describe, evaluate and combine the perspectives of 20 participants on using 3D printed violins. It aimed to use postdigital tools of production (Berry & Dieter, 2015) to explore the problematised role of musicking, a term predicated on social commonality (Reily & Brucher, 2018) when physicality, geographical placement and communality were no longer integral to the social parameters of musical performance.

3.3 Research Questions

The literature review highlighted themes related to issues of accessibility and affordability (Buehler et al., 2016; Cano, 2015; Horvath, 2014; Lammert, 2016), customisation and adaptability (Birchnell & Urry, 2016; Lipson & Kurman, 2013; Yin et al., 2017), durable quality and sound production (Bucur, 2016; Fritz et al., 2012, 2014;

Gough, 2000), perception and acceptance (Duerinck et al., 2020; Fletcher & Rossing, 2012; Fritz et al., 2012), and long-term pedagogical integration (Blair & McCord, 2016; Campbell & Lum, 2019). These themes led to the following research question that framed this section: What are the conservation, adaptation, and performance potential and limitations of 3D printed violins within music education? The literature review findings and initial fieldwork revealed that although 3D printing comprised some musical instrument fabrication, they remained novelties due to either their incompatible playing logic (Santos et al., 2018), substandard materials (Bucur, 2016) or once-off fabrication (Kantaros & Diegel, 2018). The gaps in the literature review emphasised the need for further collaborative interdisciplinary research between luthiers, musicians, and teachers (Sections 2.2.1, 2.3.1, 2.3.5, 2.4.3), and additional comparative sound and material research based on iterative prototyping (Sections 2.3.2, 2.3.5). This led to the formation of research questions related to (i) conservation and making, (ii) perceptions and value, and (iii) performance, as outlined in Chapter 1. This research was necessary for understanding the potential viability of 3D printed violins for multiple stakeholders.

3.4 Methodology

This section outlines the methodological choices for data generation, analysis, and interpretation.

3.4.1 Positioning the Research Epistemology

The epistemological orientation of the study follows the overarching constructivist paradigm, informed by Atkinson (2017) and Greene (1994). As mentioned in Section 1.4, Small's (2012) concept of musicking is based on social constructivist epistemology (McPhail et al., 2024), which connects with Atkinson (2017) because both stress the role of social actions in the formation of meaning. As rehearsed in Section 1.4, Small (2012) views musicking as a collaborative social action framed through the act of music making.

Similarly, using an ethnographic approach, Atkinson (2017) emphasises how social constructs are continuously formed by their participants. In relation to this research, the researchers' use of a social constructivist epistemology enables the possibility of exploring the social interactions and rituals that emerge from the production of a musical instrument that facilitates musical interactions by participants. This, in turn, enables the possibility of exploring instrument making through 3D printed violins as a socially constructed action that contributes to collective musicking and the formation of musicians' relationships with their instruments.

Small's (2012) musicking and Atkinson's (2017) ethnographic approach can be viewed in an educational context through Greene (1994). Where Small (2012) views musical activities as the stimulus for enabling participant interactions and the resulting construction of meaning, and Atkinson (2017) views knowledge production as co-constructed by its participants, Greene (1994) emphasises the subjective and experiential interactions that shape knowledge production in education research. With regard to this research, the researcher viewed Greene's (1994) perspective on the important role of participant interpretation in educational research as an entry point to exploring teacher perceptions of 3D printed violins as a pedagogical tool.

Knowledge within this methodological research involved sound measurements, as well as the practical skills of violin making. Gaining knowledge involved empirical research through digital scanning, modelling, printing and iterative testing, based on Cooper et al. (2014) and Miranda and Wanderley's (2006) instrument design process. Quantitative data provided comparable snapshots across the luthier and musician user groups. Qualitative data provided contextual information about teacher user groups. Using an iterative process (Green, 1994) aided in addressing potential biases and limitations inherent in techno-positivistic research. Through using a mixed methods design, the

researcher sought to balance objective measurement with subjective experience.

Trustworthiness was ensured through trialling the 3D printed violins with multiple participants across a three-year period.

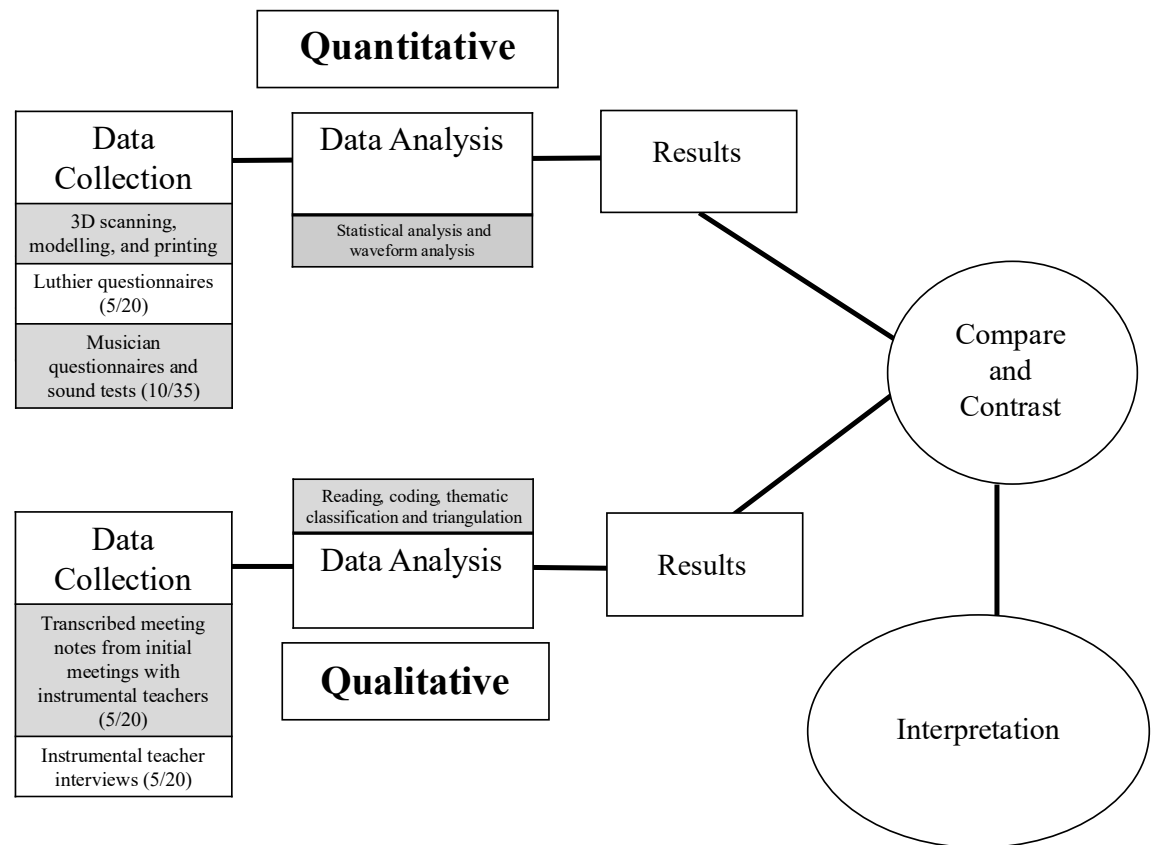
3.4.2 Research Paradigm

This research was based on a constructivist paradigm (Howell, 2013). Through this paradigm, the production and interpretation of knowledge occurred through shared interactions and processes between participants and the researcher. This perspective is connected with Howell (2013), who focused on how knowledge can be constructed through both individual and collective experiences. The paradigm contains an iterative design, analysis and testing process, which promotes cyclical learning for the researcher. This paradigm is connected with a pragmatic research philosophy (Clarke & Visser, 2018), which enabled the researcher to use multiple strategies to engage with and answer the research questions. The results evidenced the real-world advantages of research interventions (Creswell & Poth, 2023).

3.4.3 Research Design

Table 3.1

Mixed methods research design approach, adapted from Creswell (2012)



This study employed an interpretive perspective within a constructivist paradigm to capture participants' viewpoints. As outlined in Table 3.1, it adopted a mixed-methods sequential design (Creswell, 2012). The research was participatory (McIntyre, 2008) and framed within the context of performance and 3D printing literature. Quantitative data was statistically assessed, and qualitative data was thematically classified and triangulated. Initial teacher meetings informed many facets of the research design process. For example, instrument scanning and modelling influenced musician questionnaires and sound tests, musician responses shaped luthier questionnaires, and musician and luthier data informed teacher interviews. Johnson and Onwuegbuzie (2004) contended that mixed methods

design is time-consuming and challenging to interpret. Although this research design was time-consuming, triangulating teaching, making, and performance professionals' voices was necessary to produce a viable user-centred design for the 3D printed violin.

Regarding participation and co-authorship, Beetham and Sharpe (2019) note that contemporary education module design has shifted from the individual teacher to a co-authored structure that transcends disciplines. This shift indicates the level to which disciplines can complement, diversify, and develop existing models. However, by adopting this approach, research transparency, bias, intentionality, and ethical accountability should be continuously revised, rationalised, and justified as reflexive components throughout the research progression (Alvesson & Skoldberg, 2012). Audio and visual documentation tools capture this research. The main challenges in working this way included COVID-19 restrictions in ensemble performance, understanding the groups involved, the ranges of data this approach yielded, and the extended duration of engagement needed to ensure that the potential for new knowledge could be actualised.

Bloomberg and Volpe's (2018) understanding of qualitative research, comprising observation, interviews, and document analysis, enabled the possibility of building themes, categories, and patterns based on the data generated. Field notes, observations, content analysis, and semi-structured interviews, documented through developing and trialling musical instruments, comprise the primary qualitative data. The quantitative data, generated via 3D scanning and design, acoustical sound testing, and participant questionnaires (Hammersley & Atkinson, 2007), informed the final musical instrument designs. Data from interviews, questionnaires, and researcher actions aided in triangulating the research problem. This pattern-based qualitative data analysis method aligns with Bloomberg and Volpe (2018).

3.4.4 Research Approach

This study took an emic, ethnographic approach, using ethnographic methods of semi-structured interviews (Spradley, 2016) and researcher field notes (Emerson et al., 2011). Although aware of the limitations of generating data this way (Navas, 2014), the methodology required specific participants and contexts to engage with the research questions. These included professional violinists and luthiers with prior experience of playing, making or conserving musical instruments; instrumental teachers working in an environment with an existing instrumental programme, ensuring that the research focus remained on musical instrument evaluation rather than lesson provision; the technological infrastructures and ethos to support and continue instrument production; and instrumental teachers from an existing programme willing to integrate 3D printed violins into their teaching pedagogies.

Pre-audit meetings and informal conversations with instrumental music teachers quickly revealed that participant perceptions, values, and acceptance of musical instruments and musicking had deeper connections to their learning journeys' historical, cultural, and social aspects. This demonstrated that personal and professional participant perspectives needed sociohistorical contextualisation, which shaped the subsequent approach and design of the research methods. The researcher used convenience sampling within their school, a fee-paying, post-primary, inner-city school in Dublin. The pilot parameters matched the school because of its established instrumental programme, a student user base for full-size violins, its existing 3D printing infrastructure, and its ethos about social diversity. Regarding the school ethos, based on a Social Diversity Programme established thirty-five years ago to address social inequality and access issues, the pilot school accepts 15% of students from local feeder schools. It provides fees for socio-economically disadvantaged families for the total duration of a student's education. As

Conaghan (2022) contends that musical instrument access is connected to cultural, geographic, and socioeconomic factors (outlined in Chapter 1, 1.1), conducting research in this school enabled engagement with the infrastructural support previously mentioned.

Although the researcher's position as a post-primary teacher introduced a practical bias that shaped methodological choices (Cohen et al., 2011), the post-primary setting provided a specialist-driven environment for instrumental learning, to practically engage with the research (Hallam & Himonides, 2022). Deloughry (2014) deems instrument provision a structural extension of specialised instrumental tuition, and the research questions focused on using 3D printed instruments as innovative objects for musical engagement rather than establishing a teaching programme. Although innovative co-teaching collaborations between pre-service music teachers and primary schools reveal elevated teacher confidence levels and musical vocabulary (Kerin & Murphy, 2015), it is important to emphasise that it was the instrument rather than the pedagogy which was the focus of this research.

The researcher collaborated with instrumental music teachers, luthiers, and musicians. Collaboration took the form of instrument design pre-audits, informal feedback, comparative sound tests, and questionnaires, which were all beneficial to critically evaluating the instrument. As the scanned violin was full-sized, the full-sized violin necessitated a user base of eleven years or older (Kempter, 2003), indicating late primary or early post-primary students as the earliest viable cohort. Although future research envisages fractional-sized violins, this extended the parameters of a comparative sound study. Despite the advantage of earlier musical exposure (Schellenberg, 2004), the practical constraints and the researcher's professional context rationalise a post-primary context.

As this research occurred in 2021, it is critical to note that COVID-19 restrictions were still in place for music ensembles and in-person instrumental classes (Fallowfield & Gomez, 2022). This restriction affected the possibility of broader research across schools. However, undertaking ethnographic research in the researcher's school and employing reflective practices to maintain objectivity permitted Hammersley and Atkinson's (2007) concept of researcher immersion to occur. However, there were other challenges, such as maintaining objectivity throughout the research (Hammersley & Atkinson, 2007), managing role conflict between participants (Fetterman, 2010), and navigating ethical issues between participants and the researcher (Dwyer & Buckle, 2009).

3.5 Summary of Participants, Data Sources, Frequency, Format, Number, Emerging Themes, and Usability-Data Alignment

Table 3.2 summarises the participants, data sources, and frequency. Table 3.3 summarises the data sources, format, and number. Table 3.4, adapted from Pauwels and Mannay (2019), aligns the research questions with data sources and emerging themes.

Table 3.2*Overview of the Participants, Data Sources, and Frequency*

Year one – 2019-2020: Conservation and making		
Participants	Data Source	Frequency
5 post-primary instrumental music teachers	Pre-audit meetings with instrumental teachers to establish needs	
	Teachers at the pilot post-primary school in Dublin.	2 group meetings, lasting approximately 40 minutes each.
1 museum curator [George]	3D scanning	
	Researchers' handheld 3D scanner.	1 3D scanning session took place at the Museo del Violino in Italy, lasting approximately 2 hours.
Researcher generated	Modelling and 3D printing	
	STL files	5 modelling sessions lasting approximately 2 hours each (refined mesh, imported mesh to CAD, extracted critical surfaces, integrated new objects, and 3D printed the form using PLA, resin, and carbon fibre).

Year two – 2020-2021: Perceptions and value		
Participants	Data Source	Frequency
5 luthiers [Brian, Isaac, Josh, Julia, Matthew]	Questionnaires and sound tests	
	Luthiers	5 testing sessions took place in the participants' workshops in Cork, Dublin, and Offaly, lasting approximately 30 minutes each
10 musicians [Alice, Dean, David, Derek, Eleanor, June, Jessica, Maeve, Maria, Philip]	Questionnaires and sound tests	
	Musicians	5 testing sessions took place in Dublin, lasting approximately 40 minutes each
Year three – 2021-2022: Performance and musicking		
Participants	Data Source	Frequency
5 instrumental teachers [Anna, Alex, Dylan, Declan, Laura]	Interviews	
	Teachers	5 semi-structured interviews took place in the pilot school at the end of the study, lasting approximately 30 minutes each.
Researcher generated	Instrument maintenance checkups	
	3D printed violins	The researcher completed 2 instrument maintenance checkups.

Table 3.3*Summary of Data Sources, Format, and Number*

Data source	Format	Number
Pre-audit meetings	Transcribed MP4	N=2
3D scanning	STL	N=3
Modelling and 3D printing	STL, CAD, STEP	N=1
Luthier questionnaires	MS Forms	N=5
Violinist questionnaires and sound tests	MS Forms	Questionnaires (N=5)
	MP4	Sound tests (N=5)
Teacher interviews	Transcribed MP4	N=5
Instrument maintenance checkups	MS Word	N=30

Table 3.4

The Research Questions, Data Sources and Emerging Themes (adapted from Pauwels & Mannay, 2019)

Primary data sources	Pre-audit meetings	3D scanning	Modelling and printing	Questionnaires and sound tests	Interviews
RQ1: What technical specifications and material properties are required for comparable sound quality and durability between traditional and 3D printed violins?	X	✓	✓	✓	✓
Material composition and properties	✓	✓	✓	✓	✓
Acoustic performance	✓	X	✓	✓	✓
Structural integrity and durability	✓	X	✓	✓	✓
Manufacturing techniques	✓	X	✓	✓	✓
RQ2: What are the perceptions and values of musicians and luthiers who use 3D printed instruments, and how do these affect instrument viability?	✓	X	✓	✓	✓
Sound quality and performance	✓	X	✓	✓	✓
Durability and maintenance	✓	X	✓	X	✓
Cost and accessibility	✓	✓	✓	✓	✓
Customisation	✓	✓	✓	✓	✓

RQ3: What are the implications of integrating 3D printed instruments into music performances for teachers?	✓	X	✓	X	✓
Accessibility	✓	✓	✓	✓	✓
Innovation and creativity	✓	✓	✓	✓	✓
Digital literacy development	✓	✓	✓	X	✓

The use of purposive sampling rationalised the involvement of experts with the “information-rich” (Patton, 2002, p. 46) technical, performative, and educational knowledge to critically assess the 3D printed violins. Luthiers, musicians, and instrumental teachers addressed this criterion. Participants were identified through their high degree of experience in their field. Priority was given to luthiers specialising in violin-making, musicians performing in professional orchestras, and instrumental teachers involved in instrumental programmes. Although a larger sample of professionals and non-professionals could have been considered, purposive sampling enabled the 3D printed violins' technical and musical viability to be critiqued by professional standards, providing rigour to the sample.

The recruitment process took place via email, through professional networks and relevant gatekeepers. The researcher was cognisant of generating demographic diversity through age, gender, and geographic positioning. The usability testing aligned with data generation processes to ensure a thorough evaluation and the trustworthiness of the results (Mannay, 2019). Pre-audit meetings with music teachers established initial instrument needs, guiding the process towards 3D-scanning and digital modelling of a historic violin (Galantucci et al., 2015). This is connected with the instrument conservation literature

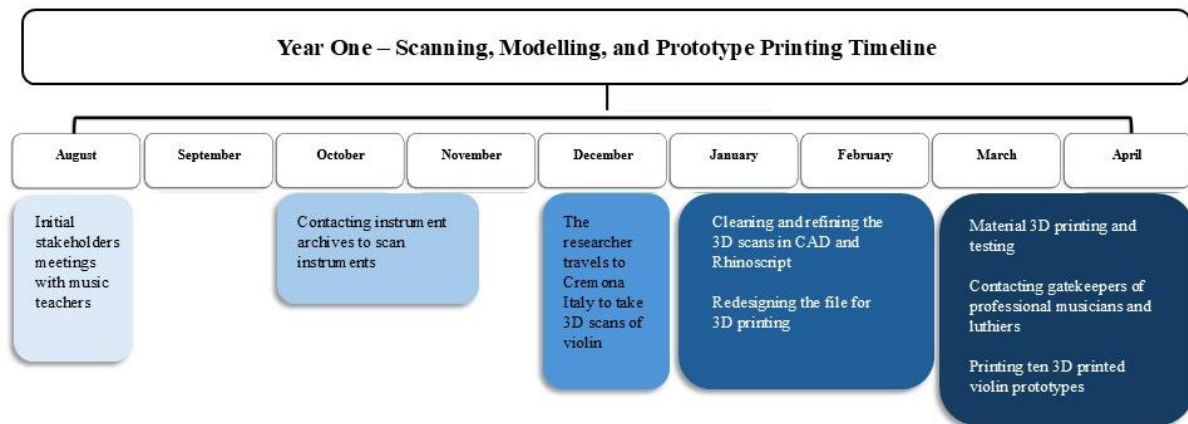
discussed in Section 2.3.6 (Burgess, 2018). Based on Nielsen's (1994) recommendation to include expert voices, the researcher undertook questionnaires and sound tests with musicians and luthiers prominent in their field to generate feedback on the 3D printed violin's sonic and material properties. Based on Creswell and Poth's (2023) advice to incorporate qualitative methods to elicit informal contextual data, the researcher completed instrumental teacher interviews to capture their perspectives. Researcher instrumental maintenance check-ups supported the findings, which aided in developing a robust connection between usability testing and data collection (Geisen & Bergstrom, 2017). In the next sections, the researcher will consider the three stages through which the research developed. As set out in Table 3.2, these followed a chronological order, starting with Year One.

3.6 Year One – 2019-2020: Conservation and Making of the Violins

This section presents transcripts from two group meetings with five instrumental music teachers, three data sets of unedited 3D scans, and one rendered data set showing design and print additions. This predominantly conservation and making stage enabled the researcher to produce a 3D printed violin prototype.

Table 3.5

Year One – Scanning, Modelling, and Prototype Printing Timeline



3.6.1 Pre-Pilot Meetings

The pre-pilot meetings (Appendix H) were a crucial step in assessing the needs of educational professionals and ensuring the validity and applicability of this research, a principle endorsed in the literature (Cohen et al., 2011; Creswell & Creswell, 2017). These meetings also highlighted practical concerns, echoed in the literature review. Importantly, they helped to align the research objectives with the perspectives of music educators (Omodan, 2024), demonstrating the role of their input in the research.

The pre-teaching audit focused on teachers' prior experience with DMIs, how using 3D printed instruments might support their pedagogical approach and a student's potential for engagement in music performance (Appendix F). Five teachers participated: two violin teachers, one string orchestra conductor and two classroom music teachers. Although the classroom teachers would not have direct contact in weekly instrument lessons, they provided a broader view of the school environment. The early involvement of a string orchestra conductor assisted in prefacing the 3D printed violins within the existing orchestra. The violin teachers were the main point of contact and provided technical feedback on all aspects of the research.

Instrumental teachers communicated that younger musicians would benefit from access to instruments. As noted in Section 3.4.4, the full-sized violin required a user base of eleven years or older (Kempter, 2003), which justified this choice. One teacher expressed that the timeframe of an academic year was too short for a "noticeable change" in student playing (Pre-pilot participant 1). The instrumental teacher's concern echoed prior literature on the limitations of short-term interventions using 3D modelling and printing in education. This was outlined in Section 2.4.1 (Togou et al., 2018; O'Reilly & Barry, 2021) from a national perspective and in Section 2.4.3 (Calvani et al., 2011; Girdzijauskienė & Šmitienė, 2020; Kelley & Knowles, 2016) from an international perspective. The researcher stated that the research sought to explore the sonic and material viability of the 3D printed violins in an educational context, with the hope of expanding beyond its initial scope. Another teacher expressed that they were doubtful that older students who had already played the violin would seek involvement, as they had "already found their voice" (Pre-pilot participant 2). This teacher trepidation connected with prior literature regarding musicians' preferences for recognised brands (Cottrell, 2013), instrument reliability (Murphy, 2014), as well as the emotional attachments that musicians attribute to instruments (Schmid, 2017), which influence musicians' instrument choice, outlined in Section 2.3.5. The pre-pilot meetings aided in shaping the methodological design and enabled Cooper et al. (2014) and Miranda and Wanderley's (2006) design process to be collaboratively constructed.

3.6.2 Rationalising What to 3D Scan

As part of the process of creating the 3D printed violins, 3D scanning was chosen over alternative physical measurement methods because it provided accurate, high-resolution digital replicas of existing instruments, which served as the initial model for further design. Unlike traditional calliper measurement techniques, which can help

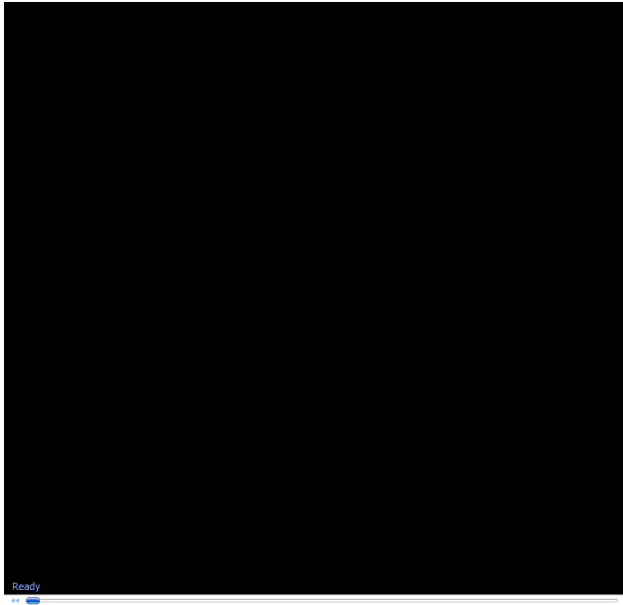
establish the exterior dimensions but create limitations when attempting to develop variations in interior dimensions and distinguishing between the parameters of objects and finishes, 3D scanning captured interior surface geometry, which preserved essential acoustical properties (Melde, 2020). Unlike more invasive physical methods, 3D scanning produced a 3D digital equivalent without physically touching an object. From a conservation perspective, this made measuring more ethically favourable.

The researcher initially considered several instruments of note. Violins, flutes, and saxophones, which were particularly popular in the pilot school, assisted in focusing the exploration. While Moloney and McCrea's *Report of a feasibility study into the establishment of a national musical instrument fund* (2014), aided in connecting this smaller research sample of instrument need to the broader national context. Specifically, Moloney and McCrea (2014, p. 37) evidenced that classical instruments were the dominant applicants (53%) and awardees (62.5%, with 27% for violins/fiddles), with the majority of funding (84.2%) allocated to this genre. These statistics reflected a larger demand and higher instrument costs for classical instrumentalists in this study. Although Moloney and McCrea's report (2014) indicated that only 27% of requests for violins were granted (p. 42), the most significant award of €40,000 was allocated for a historic violin (p. 45). These figures supported a connection between gaps in the existing instrument provision for violinists in Ireland and an acknowledgement that historical violins were still a valuable investment. In relation to instrument selection for this research, it justified the exploration of alternative forms of violin provision that built upon historical design. As outlined in the literature review (Fritz et al., 2012, 2014), distinctions between remarkable players and instruments that were in themselves remarkable were vital distinctions that refined and justified this research enquiry.

In Chapter 2, literature from Bucur (2016) and Santos et al. (2018) outlined the material limitations of contemporary 3D printed instruments. Instead, Kantaros and Diegel (2018) suggested hybrid methods of construction, which require hybrid infrastructures. Hybrid printing proved infrastructurally costly. Concerning the saxophone, the pitfalls of instrument choice based on players rather than instruments prevailed. Adolphe Sax's archive reveals the inventor's iterations before finalising the design (Cottrell, 2013). It has been an instrument in progress through the twentieth century (Ozdemir et al., 2021). The violin fulfilled most of the criteria for addressing the research. It was old enough to reflect design variations but still maintained haptic logic. Many reputable brands were predominantly known for their sonority (Faber, 2012). These historical brands were deteriorating and would benefit from digital conservation and replication. The violin was a model that cherished tradition (Hart, 2019). Traditionally, Stradivarius instruments used a mould for their construction (Beament & Beament, 2000). This implied the implementation of technologies to ensure essential features. As the violin was a popular instrument within the pilot school, and support structures already existed for teaching, this methodology sought to explore how 3D printing violins could enhance opportunities for musicking. The researcher contacted a curator from the Museo del Violino in Cremona, Italy, to seek access to historical violins in their collection. The researcher travelled to Cremona in December 2019 to make digital scans of Stradivarius violins, instruments known for their exceptional sonic properties (Figure 3.1).

Figure 3.1

Video Showing Images Taken During the 3D Scanning Process



Based on literature from Pollens (2015), the researcher identified the instrument as an exemplary form and function model with relatively unchanged parts from its original construction. The researcher used a Peel 2 3D scanner to capture the object and CAD 3D software to visualise, edit and export the form. 3D scanning enabled the original to be captured within 0.01mm of the original without touching the instrument and generated a digital blueprint for subsequent development. This permitted the reconceptualisation of the design print as integrated parts rather than following the original design based on separate components. The researcher cross-referenced the 3D scans with prior manual measurements taken of the instrument in previous research by Bissinger (2008), located in Chapter 4. Although the design underwent significant modelling and material revisions to ensure that it would meet its users' material and sonic needs (Sullivan, 2015), creating a digital trace from a prominent instrument enabled the possibility of comparative studies.

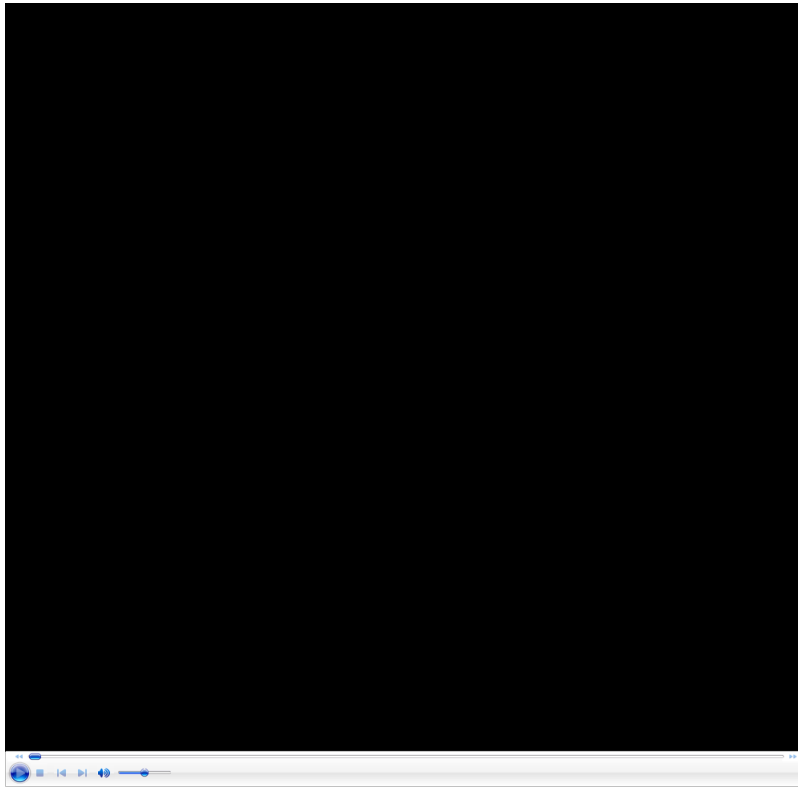
3.6.3 Modelling and Printing

Building on the instrument design processes outlined by Cooper et al. (2014), Miranda and Wanderley (2006) in Section 2.3.3, the researcher developed a similar five-step iterative design process consisting of (i) concept development, (ii) material and printing process selection, (iii) post-processing and assembly, (iv) testing and evaluation,

(v) refinement, iteration, and production. Using these methodological steps enabled a user-centred design to be followed (Cooper et al., 2014). Developing from instrument fabrication techniques discussed in Section 2.3.4 (Vasina et al., 2020), the researcher chose 3D scanning, modelling and Selective Laser Sintering (SLS) printing over traditional luthier techniques due to this process's ability to replicate the violin's internal and external geometry. From a production and efficiency point of view, the researcher chose 3D printing methods due to their relatively efficient printing time, which is referenced in Section 2.3 (Martinelli et al., 2020). Santos et al. (2018) viewed these methods as necessary in educational contexts where customisability and cost-effectiveness may be prioritised. The redesigned and rendered two-part print comprised the violin neck and body (Figure 3.2). This design decision to fuse multiple sections connected with Pearse (2020), who discussed prior musical instruments printed using this method, which was outlined in Section 2.3.1. Although Pearse (2020) noted the neck tension challenges of 3D printed musical instruments made using this method, by eliminating the need for excessive joining over larger surface areas, the researcher sought to reduce the possibility of misalignment during and after construction. This mode of construction also made the neck and body interchangeable, connecting with Santos et al. (2018) and Yin et al. (2017) recognition of the customisability potential of 3D printing, referenced in Section 2.3. Although cognisant of Birtchnell and Urry (2016) and Lipson and Kurman's (2013) hesitancy to overemphasise the customisability of 3D printed musical instruments, discussed in Section 2.3.5, the researcher justified this mode of design, modelling and printing because it provided the possibility of replacing instrument sections. This printing choice aided in addressing longer-term maintenance challenges, referenced by Olsson et al. (2019) in Section 2.4.4.

Figure 3.2

Video Showing a Visualisation of the 3D Modelling Components



3.6.4 Material Selection

With Lipson and Kurman's (2013) recommendation of composite materials to enhance instrument functionality and Brezas et al. (2024) establishment of a direct link between material and acoustic properties of 3D printed instruments, the researcher was aware of the pivotal role of material selection in 3D printing musical instruments that match the sonic quality of their traditional counterparts. Table 3.6 below compares the durability (Tanikella et al., 2017) and sonic properties (Faruque et al., 2016) of 10mm thick printing filaments. The filament comparison reveals the highest tensile strength in PLA (65MPa), the highest structural integrity in carbon fibre (10/10), the highest durability in nylon (10/10), the highest density in PLA (1.24 g/cm³), and the highest sound absorption in carbon fibre (85.75mm). Based on the data from Table 3.6 (Tanikella et al., 2017; Faruque et al., 2016), coupled with the filament studies discussed in Section 2.3.4

(Yao et al., 2016; Vasina et al., 2020; Pei et al., 2023), the researcher completed filament tests. Using PLA, nylon, wood filament, and carbon fibre, the researcher assessed the sonic and durability potential of these materials for violin making. In alignment with Tanikella et al. (2017) and Faruque et al. (2016), PLA provided strong tensile strength, and carbon fibre provided strong sound absorption. Although the researcher undertook surface colouration tests during the early prototyping stages, the design decision to ultimately print using natural wood effects was influenced by Santos et al. (2018) observation of the perceived "toy-like" (Santos et al., 2018, p. 21) quality of some 3D printed instruments, outlined in Section 2.4.4.

Table 3.6

Print Filaments' Durability (Tanikella et al., 2017) and Sonic Properties (Faruque et al., 2016). Comparison Based on 10mm Thickness

3D printing materials:	ABS	PLA	PETG	Nylon	Wood filament	Polycarbonate	Carbon fibre
Thickness t=10mm							
Strength	40 MPa	65 MPa	53 MPa	40 MPa	46 MPa	72 MPa	45-48 MPa
Stiffness	5/10	7.5/10	5/10	5/10	8/10	6/10	10/10
Durability	8/10	4/10	8/10	10/10	3/10	10/10	3/10
Density	1.04 g/cm ³	1.24 g/cm ³	1.23 g/cm ³	1.06-1.14 g/cm ³	1.15-1.25 g/cm ³	1.2 g/cm ³	1.3 g/cm ³
Sound absorption coefficient	Air gap size a=30mm	a=0.9mm	a=0.01-0.05mm	a=19.75	a=27.21mm	-	a=85.75mm

3.6.5 Technical Considerations and Post-Processing

Further 3D printing considerations, such as the print precision, material choice, layer resolution and directionality, significantly impacted the instrument's acoustic properties and structural integrity (Buehler et al., 2016; Zoran, 2011). Additionally, the time-intensive post-processing steps like sanding, assembly, and stringing prompted an iterative reassessment of the digital model. This iterative process was crucial to fully exploit the design potential and ensure the file's continued suitability for educational contexts beyond the timeframe of researcher engagement (Yin et al., 2017). Although stringing the instrument remained a manual post-processing step, as they were not 3D printed, sanding and assembly time were reduced by iterative design. Not addressing these technical aspects during the modelling and post-processing stage would result in material and sonic limitations, undermining the possibility of assessing 3D printed instruments as a viable alternative in music education.

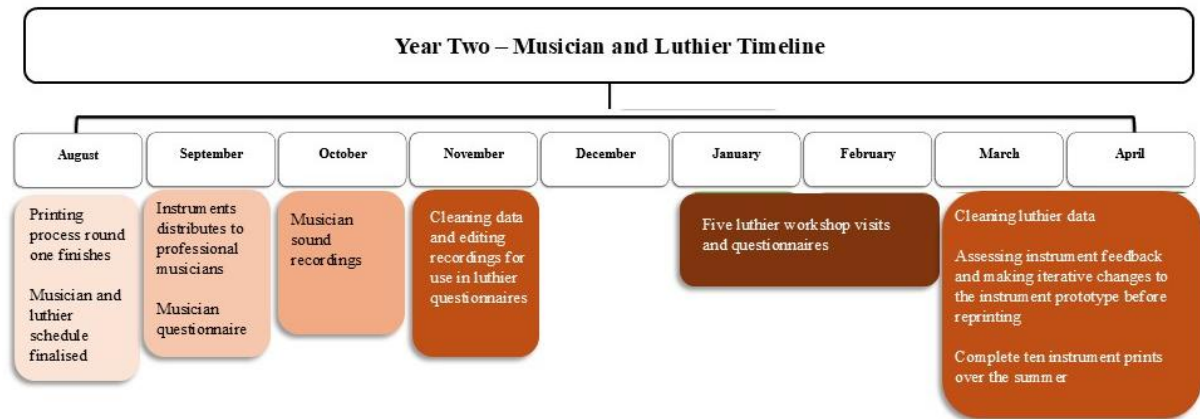
Each print required 480g of fibre substrate, a maximum layer height of 3mm, an infill of 30% and five parameters. Violin replicas were constructed using the G-Create G-max 1.5xt plus printer and Kodak PLA filament, and later printed on the researchers' Bambu Lab X1 Carbon 3D Printer to accommodate carbon fibre printing. A large printing bed enabled printing larger sections and fewer seams. The redesigned instrument maintained the internal cavity of the original design but was printed in two parts, eliminating seam maintenance issues. More ambitious designs enabled printing the instrument in one form; however, physically printing the virtual design posed several practical problems that troubled this final product. Printing the body and the neck as one required excessive substrate to align, making it more time-consuming and costly.

3.7 Year Two – 2020-2021: Exploring Perceptions and Value

Literature from Kantaros and Diegel (2018) contends that a collaborative approach to designing and manufacturing 3D printed instruments was necessary for their development and integration. Therefore, to develop this design from the original, the researcher sought perspectives from luthiers and professional violinists. These perspectives aided revisions to the instrument design – see Table 3.7 below for the timeline. This stage produced three data sources: ten questionnaires on professional violinists' experiences using the 3D printed instrument, twenty-six comparative audio recordings of the violinists trialling the instruments, and five luthier questionnaires based on comparative sound tests. The questionnaires are in Appendix A, and E. Chapter 4 contains sound samples and related waveform visualisations. Chapters 4 and 5 present the results and findings from both data sources.

Table 3.7

Year Two – Musician and Luthier Timeline



3.7.1 Musician Questionnaires and Sound Tests

The questionnaire method was used to explore the influencing and impeding factors that shaped professional violinists' instrument choices. Musician questionnaires were chosen instead of interviews because they quickly captured participant perspectives,

enabled greater generalisability of findings (Bryman, 2016), and reduced researcher bias (Creswell & Creswell, 2017; Fowler, 2013). Furthermore, as some technical questions may have required re-engagement with the 3D printed instrument for clarification, questionnaires allowed participants to reflect at their own pace (Robson & McCartan, 2016). The musician's questionnaire (Appendix A) comprised three sections: participants' early experiences learning the violin, current experiences, and their experiences with the 3D printed violin. Directed by Kempter's (2003) writing on the influence of early instrument acquisition on students' learning and choices, data on their early playing helped create a picture of their prior teaching and learning. Although data on early playing experiences was ultimately cut from the findings due to a lack of relevance to the research questions, the professional violinists' answers enriched the researchers' understanding of their musical journeys and musical instrument preferences. Generating data on current performance practices sought to understand what participants are comparing. Generating feedback on participants' use of the 3D printed instruments helped gain a snapshot of the current instruments and revisions needed. Although interviews had initially been considered a richer contribution to this section, defining the research objectives and drafting the instrument clarified the questions and format.

For this section, the researcher considered several participant groups, including music teachers, university music students, and industry performers. However, the decision to contact professional musicians from national orchestras to evaluate the violins before integrating them into a music education context was rationalised by the literature review (Fritz et al., 2012, 2014; Kiefer, 2021). Specifically, Fritz et al. (2014) sound recording and blind listening tests, discussed in Section 2.2.4, cited the importance of involving professional violinists in both the performance and evaluation stages of instrument tests. As earlier research from Fritz et al. (2012) had come under criticism for recruiting amateur

musicians and recording in hotel rooms rather than more acoustically ideal spaces, the researcher was cognisant that participants, recording quality, and the recording venue were important for the integrity of this section of the research. This perspective was echoed by Freytag et al. (2024), who reference the use of questionnaires to elicit quick responses from industry professionals. Equally, Kiefer's (2021) discussion of the Stradivarius Sound Bank, referenced in Section 2.2.5, emphasised the need for high-quality musical recordings that maximise the performance potential of musical instruments. Although Section 2.3.5 evidenced the social, cultural, technical and personal preferences that challenged the integration of 3D printed instruments with professional violinists (Cottrell, 2013; Murphy, 2014; Schmid, 2017), the researcher recognised the importance of involving critical, collaborative perspectives in advancing existing 3D printed instrument designs. The researcher sought professional violinists' perspectives on the sonic and material properties of the 3D printed violins to ensure the instruments had transferability beyond an educational scope.

Ten participants from national orchestras took part in this research. The participants represented a broad age and gender demographic. After two weeks of prototype testing, the researcher distributed questionnaires to the professional violin participants via a QR code and link (Appendix A). All ten participants responded to all but one question, and the average time spent on the questionnaire was twelve minutes, as evidenced by MS Forms analytics. In alignment with Fritz et al (2012,2014), the sound tests were completed in tandem with questionnaires in order to provide objective acoustic measurements to participants' written responses. Robson and McCartan (2016) argue that sound tests are a valuable research data point that connects objective sound measurements with subjective experiences. Therefore, sound tests were crucial for generating sonic data that could not be obtained through questionnaires alone.

Repertoire selection was informed by violin pedagogy, performance practice, and comparative studies of musical instrument literature (Galamian, 2013; Kellogg, 1975; Ramey, 1976; Van Dyke Bingham, 1914) spanning from beginner to advanced levels, as endorsed by Dooling and Hulse (2014), to display instrument viability across a range of performance standards. Ramey's (1976) pedagogical approach involved comparisons of technical demands to repertoire by Tchaikovsky and Lalo, which justified its use for comparative purposes in this methodology. Van Dyke Bingham's (1914) historical analysis of violin repertoire, which focused on the technical and musical qualities that specific repertoires reveal, aided in formulating a repertoire that reflected the violin's dynamic and timbral range. Galamian (2013) discussed Bach's concertos and Massenet's "Meditation" as essential repertoire for recognising technique and expression, which were extended to comparative analysis contexts. Kellogg (1975) referenced Bach's Violin Concertos and Tchaikovsky's Violin Concerto with technique and interpretation, indicating its suitability for a comparative analysis.

In alignment with Fritz et al. (2012, 2014) sound recording recommendations, a sound level meter was used in studio conditions to measure the sound intensity of the 3D printed violins. This process of objective measurement enabled the violinists to perform sound tests using both their violins and the 3D printed violins. This recording process enabled sonic comparisons of established and new violins to be captured with the same sonic parameters and performer mannerisms. On discussion with the studio sound engineer about the Stradivarius Sound Bank recording process, discussed in Section 2.2.5, the recording setup used for the comparative recordings between 3D printed and musician violins drew from the recording practices outlined by Kiefer (2021). This alignment ensured that the sound quality was prioritised (Fritz et al., 2014), and inconsistencies in recording techniques were minimised (Giraldo et al., 2019). Adhering to a standardised

recording setup used in prior research ensured that scholarly practices were followed. Sound tests provided high-quality audio documentation that displayed the instrument's possibilities and limitations. They enabled participants to communicate in a familiar language and provided the source material for informal conversations regarding sonic compatibility and ergonomic design. Chapters 4 and 5 present the results and findings from both data sources.

3.7.2 Luthier Questionnaires and Sound Tests

Similarly to the musician questionnaires and sound tests discussed in 3.7.1, the use of luthier questionnaires and sound tests was justified for the same reasons, based on similar literature (Bryman, 2016; Creswell & Creswell, 2017; Fowler, 2013; Robson & McCartan, 2016). Based on Huber and Runstein's (2012) discussion on the importance of aural tests in audio engineering, the sound recordings conducted with professional violinists were subsequently used in aural tests with luthiers to assess the acoustic qualities of 3D printed violins. This provided an instance where data from one instrument informed that of another. This iterative method is connected with Fraenkel et al. (2015), who discussed how initial findings can shape the following data collection phases. As Davidson (2017) was critical of aural tests being too subjective, echoed by critics of Fritz et al. (2012) in Section 2.2.4 (Bucur, 2016), the researcher correlated participant responses with separate audio measurements in Chapter 4.

Nine luthiers working in Ireland were contacted via email, and five participated. Echoing Freytag et al. (2024), the value placed on industry professionals in enriching research outcomes, the researcher visited participants' workshops in Cork, Dublin, and Offaly to test the instruments. Higgins and Willingham (2017) emphasised the importance of engaging with music practitioners in their environments, indicating that physical and gestural interactions were authentic. This environmental engagement was pertinent for

increased participant engagement. However, engagement in a workshop environment also elicited informal comparative instrument conversations that may not have occurred if workshop visits had not taken place.

The comparative sound tests involved data from sound measuring software and five luthier participants' feedback. As evident in Appendix E, five questions were formulated around comparative sound quality, tone quality, timbre, playability, and bowing. These questions stemmed from Duerinck et al. (2020) listener evaluation tests of violins, as well as Buxton (1997) and Whitney (2016) instrument evaluation assessments for luthiers. The first question asked luthiers to assess the 3D printed violins' comparative sound quality based on the two instrument recordings generated by the professional violinists. Based on a Likert scale from weak to excellent, luthiers were asked to rate the 3D printed violin tone clarity, projection, warmth, sustain, response, dynamics, articulation, balance, playability, and versatility. All these characteristics are related to luthier perceptions of musical instrument sound quality, as outlined by Buxton (1997) and Whitney (2016). The second question asked luthiers to assess the 3D printed violins' comparative tone quality. Luthiers were asked to rate the 3D printed violin tone, projection, resonance, response, clarity, warmth, brightness, sustain, evenness, dynamics, articulation, intonation, and playability. All these characteristics are related to listener perceptions of musical instrument tone quality, as outlined by Duerinck et al. (2020). The third question asked luthiers to assess the 3D printed violins' comparative timbre quality. Luthiers were asked to rate the 3D printed violins' brightness, warmth, richness and resonance. All these characteristics are related to musical instrument timbre, as outlined by Duerinck et al. (2020). Moving from comparative sound tests towards the luthier's experience playing the 3D printed violin, the fourth question asked luthiers to assess the 3D printed violins' comparative playability. Luthiers were asked to rate the 3D printed violins' comfort, ease of bowing, fingerboard,

string action, response, sound projection, and overall playability. Finally, the fifth question asked luthiers to assess the 3D printed violins' comparative bowing. Using a traditionally constructed and 3D printed violin, luthiers were asked to rate the bow response, clarity of sound, articulation, projection, evenness of tone, resonance, string sensitivity, dynamic range, sustain, and bow control. These characteristics are related to musical instrument playability and bowing as outlined by Buxton (1997) and Whitney (2016). The full questionnaire for luthier participant feedback is in Appendix E. Chapter 4 presents the results and findings from both data sources, highlighting the significant role of the luthiers in this research.

3.8 Year Three – 2021-2022: Performance and Musicking

This stage of the study involved five semi-structured interviews concerned with teachers' pedagogical experiences integrating the instruments within a post-primary context. The interview questions are in Appendix B. The decision to use this method stemmed from Spradley (2016), Angrosino (2007), and Emerson et al. (2011). The rationale for using instrumental teacher semi-structured interviews is outlined in Sections 3.8.7, 3.8.8, and 3.8.9. Chapters 6 and 7 present the results and findings from this data source.

3.8.1 Research Participants and the Recruitment Stage

Research participants were sought from the researcher's school. The decision to source participants from the researcher's school stemmed from the need to have infrastructural and pedagogical support in the literature, outlined in Section 2.5. Specifically, the need for short and long-term digital infrastructural provision and support (Sections 2.4.2, 2.4.3, 2.4.4), as well as the practical application of 3D printed instruments in an educational context (Sections 2.4.3, 2.4.6), which may not have been possible without an existing instrumental programme. In relation to the student age demographic,

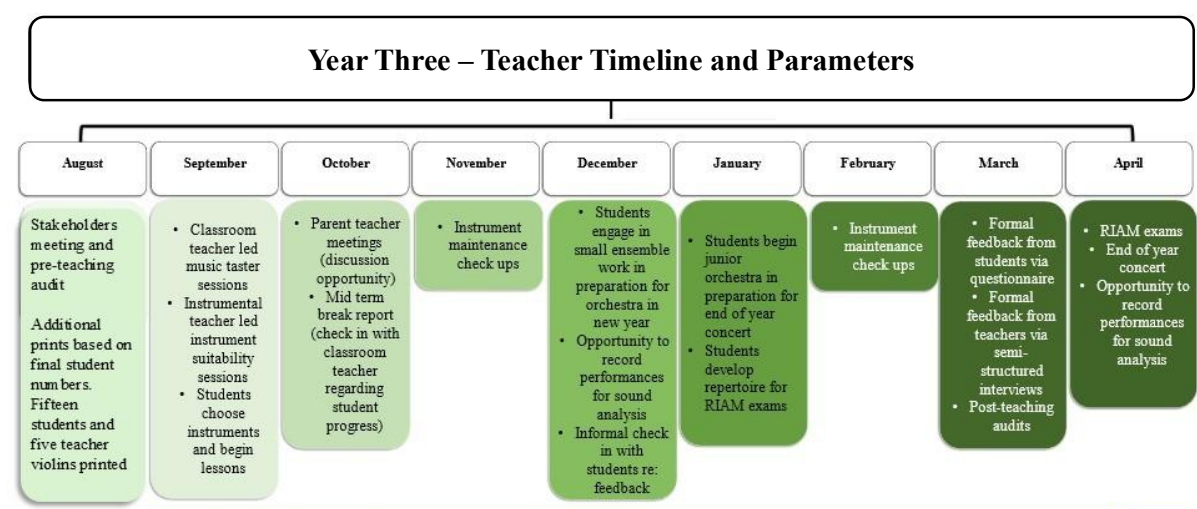
while local primary schools were also considered, Kemper's (2003) age recommendation of eleven or older for full-sized violin players, mentioned in Section 2.4.4, justified this age demographic. Also, the pilot schools' Social Diversity Programme, outlined in Section 3.4.4, addressed Buehler et al. (2016)'s concerns about the short and long-term challenges of music performance, outlined in Section 2.4.4. Although Gray (2018) would support this research approach, emphasising the need to access appropriate contexts to undertake educational research, Creswell and Creswell (2017) would argue that undertaking research in the researcher's school would introduce biases. To address this bias, the researcher anonymised the data, established clear roles, and maintained reflexivity throughout the research process. However, the potential for bias remains a limitation. While research from Calvani et al. (2011) focused on developing the technical aspects of student digital modelling skills, and Kelley and Knowles (2016) developed pedagogical resources to support teachers using 3D modelling in the classroom, this research specifically focused on teacher experiences of using 3D printed violins. Through this perspective, Girdzijauskienė and Šmitienė (2020) exploration of STEAM integration would be furthered by focusing on the technical and performative potential of 3D printing. Five teachers were recruited based on their involvement with the existing instrumental programme. Teachers agreed to monitor students' progress using the instruments and to participate in an interview at the end of the project that extrapolated emergent themes based on their perspectives.

3.8.2 Timeline and Parameters

The timeline took place over one academic year, outlined in Table 3.8. As part of the existing instrumental structures set out by the school, students had one individual instrumental lesson per week and attended orchestra in January in preparation for an end-of-year concert in April. Although cognisant that Creswell and Creswell (2017) recommended structured planning to enable effective time management during research,

the research plan was impacted and reshaped by COVID-19 restrictions for music performance during this time, previously articulated in 3.4.4 (Fallowfield & Gomez, 2022). The timeline and parameters of this research were also shaped by existing class timetabling structures, which Mertens (2019) conceded were necessary when undertaking research within educational contexts. The pilot timeline (Figure 3.8), spanning September 2021 to April 2022, aligned with scheduled music lessons, orchestra rehearsals, examinations, recording sessions, performance recitals, and end-of-year examinations. Participants agreed that introductory music taster sessions would incorporate the 3D printed instruments alongside existing instruments. This approach would normalise the instrument's integration.

Table 3.8
Year Three – Teacher Timeline and Parameters



All violin teachers agreed to perform with 3D printed violins while undertaking instrumental lessons. This enabled teachers to model the instrument. This modelling practice was justified through literature from Williams and Kladder (2019), who identified the influence that music teachers impart on student styles and instrumental preferences. Although instrumental teachers indicated variations in comfort levels when performing

with instruments that were not their own, this limitation aligned with Williams and Kladder's (2019) observation that the integration of new instruments can be shaped by both physical and social factors.

3.8.3 The School's Existing Music Structures, Programmes and Practices

In putting the above into a more fine-grained context, the school's music department features a comprehensive range of music editing and composition programmes, yet it has yet to integrate 3D modelling and printing into its skill set. Although the school possesses two 3D printers donated by local businesses to encourage technological integration, these tools remain underutilised, primarily serving as novelties for technocurious staff and students. This novelisation of technology connected with prior literature from Alevizou (2007), previously outlined in Section 2.4.1, indicated the challenges of meaningfully integrating technologies within existing educational practices. Within the school, music performance is formally and informally promoted through state examinations, grades, musical evenings, competitions, and charity events to student-led popular music groups and *YouTube* channels. While the school's music programme is strong in traditionally constructed instrumental offerings, the methodological choice to study existing structures and their potential development into technology-enhanced practices is grounded in the recognition that interdisciplinary approaches can enrich students' learning experiences (Vink et al., 2017) and promote STEAM education (Harris & de Bruin, 2017).

3.8.4 Access to Instruments

The school has an instrument bank containing a range of orchestral, rock, and traditional instruments that music students can access. However, as prefaced in Section 1.1 (Moscardini et al., 2012), instrument popularity limits lending or lending based on a student's second or third instrument choice. Limited availability of musical instruments

undermines the individual assessment process undertaken by the specialist instrumental and class teacher to establish student suitability to a specific musical instrument (Hallam & Himonides, 2022). Although Section 2.4.6 mentioned the Music Capital Scheme and the Music Instrument Fund of Ireland as existing models of instrument provision in Ireland, and Section 1.1 indicated that the financial cost of instrument purchase could affect parental investment (Conaghan, 2022), the school instrument bank provides a model of provision for development. As Kaufman and Scripp (2019) contended that early instrumental engagement was critical for sustained interest in music making, it would appear to the researcher that access to instruments provides a crucial tool for musical engagement.

3.8.5 Observation Field Notes

Emerson et al. (2011) viewed field notes as an essential qualitative research tool for capturing moments that interviews or surveys may not. Emerson et al. (2011) discussed the use of field notes in music education ethnographic research to capture participants' physical, social, and cultural "lived experiences" (p. 150). They allowed the researcher to observe nonverbal interactions, participants' evolving needs (Angrosino, 2007), and researcher biases (Monahan & Fisher, 2010). Taking the position of observer as participant (Gold, 1958), three hundred and fifteen lesson observation sessions took place between September and April. Although this was useful to generate data initially, the frequency and repetition of notes proved repetitive. Following this reflection, the researcher attended fifteen monthly lesson observation sessions, one observation session with each student every four classes for the remainder of the project. This permitted space for relationships to develop naturally (Kaler & Beres, 2016). "Thick description" (Lincoln & Denzin, 2001, p. 83) field notes were time-consuming to document and analyse. Although video samples were initially considered, instrumental teachers' feedback indicated that it might prove

intrusive within a lesson context for a shy beginner instrumentalist. Audio recording aided in balancing observations and note-taking. It was essential to maintain a sense of distance (Bernard, 2011), openness to conflicting perspectives (Musante & DeWalt, 2010), and to align with the research questions to avoid feeling "like a ship adrift" (Fetterman, 2010, p. 116). Chapters 4 and 5 present the results and findings from these data sources.

3.8.6 Informal Feedback from Classroom and Instrumental Music Teachers

Merriam and Tisdell (2015) contended that informal feedback that was rooted in practical teaching experiences could be a useful indicator when trying to understand and decipher practical educational challenges. While Flick (2018) viewed informal feedback from student engagement in research in a similar capacity. However, Patton (2002) would assert that this reliance on participant subjectivity introduces bias and limitations to research in educational contexts. In an attempt to address these limitations, the researcher combined informal participant feedback relating to teacher experiences using 3D printed violins with more formalised metrics. Creswell and Poth (2023) indicated that this data approach would reinforce research findings.

Informal feedback from teachers during this research revolved around the violin's sonority and tactility, the instrument's durability, and student progress rates based on teachers' prior experiences. These feedback concerns are connected with prior literature outlined in Sections 2.3.2 and 2.3.5 of the literature review. Instrument-related progress and challenges were discussed bi-monthly with the violin teachers and monthly with the classroom teachers. This process of establishing informal feedback from users and stakeholders connected with Cooper et al. (2014) and Miranda and Wanderley (2006) criteria for instrument design, outlined in Section 2.3.3. The next section provides a rationale, description, indication of data collection methods, and an analysis of each research instrument used.

3.8.7 *The Instrumental Teacher Semi-Structured Interviews*

Cohen et al. (2017) viewed semi-structured interviews as an effective instrument when undertaking educational research, because they enabled the interviewer to adapt based on each participant's engagement. Undertaking semi-structured interviews with teachers regarding their experiences and their students' experiences using 3D printed violins provided rich insights into the challenges of integrating 3D printed violins in an educational context. Although the subjective nature of this instrument affects the generalisability of the findings, semi-structured interviews provided a qualitative counterpoint to the quantitative data. Spradley (2016) informed the structure and language of these semi-structured interview questions. Regarding interview question structure, Spradley's (2016) advice to balance rapport with eliciting participant information required the researcher to reflect on how the interview questions informed the research questions and when to refine superfluous information. Furthermore, Spradley's (2016) use of "native language questions" (p. 89), where terms are reformulated to reflect words more commonly used by participants, influenced the researchers' wording of the SDP, 3D printed instruments, and traditionally constructed instruments.

At the end of the pilot, semi-structured interviews lasting approximately forty minutes provided an emic perspective (Angrosino, 2007) that emphasised the teacher's involvement and viewpoint. Interviews took place in the school at a time convenient to the interviewee, respecting their schedules and commitments. Interviews were recorded and transcribed. Before each interview, the researcher clarified that the objective was to establish individual teacher perspectives and values regarding the study, showing respect for their unique experiences. Cognisant of researcher-interviewee bias (Denscombe, 2017), response bias (Gomm, 2008), and interviewee subjectivity (Spradley, 2016), sequential questions were formulated based on pre-pilot audits, informal feedback from classroom

and instrumental teachers, lesson observation sessions, instrument maintenance checkups and audio recordings.

This iterative process, where one instrument informs another, provided the context for richer data collection (Bell, 1993) based on user experiences with 3D printed violins. Through this process, researcher prompting was minimised (Kemmis et al., 2013; Ryan & Deci, 2000). The interview questions are in Appendix B. Questions one to five addressed student progression and technique development using the 3D printed violins during the pilot study. Questions six to eight focused on the potential impact of 3D printed violins on student access and student engagement in orchestral settings. Questions nine and 10 concentrated on perceptions of difference when using 3D printed violins, whether visual, sonic, or language-based. Finally, questions 11 to 14 focused on the future potential and limitations of producing 3D printed violins in an educational context. The results and findings are in Chapters 6 and 7.

3.8.8 Musical Instrument Maintenance Checkups

Instrument maintenance checkups took place in November and February to identify instrument faults that might impede musicians' progress or could inform future designs. Maintenance checkups allowed for real-time identification and adjustment of structural or acoustic issues that could have affected musicians' learning experiences. This approach is advocated by Visvizi et al. (2018), who emphasise the need for iterative assessment of new technologies in educational contexts. Similarly, Pollens (2015) noted the importance of regular instrument maintenance in maintaining musicians' engagement, even in traditional violin pedagogy research. As the 3D printing process leaves a series of lines across the surface, it may be easier for dirt to accumulate on the surface. Surface sanding could aid in easily cleaning future designs, providing a practical solution. An instrument maintenance checklist used by the researcher is located in Appendix G, and a pamphlet for musicians to

maintain their 3D printed violins is situated in Appendix I. The results and findings are in Chapters 6.

3.9 Data Analysis

This section presents the steps which led to the data analysis. The data preparation involved transcribing teachers' semi-structured interviews, cleaning, organising and categorising the interview data, and removing repetition. The researcher used Braun and Clarke's (2021) six-phase process for the Reflexive Thematic Analysis approach to identify themes within this research. Although Braun and Clarke (2013) contended that subjective data did not yield a single 'correct' answer (Braun & Clarke, 2013, p. 4), this method ensured that the data analysis was indicative of both the participants' perspectives as well as the researcher's interpretations. Returning to Section 3.4, by using an interpretative and constructivist paradigmatic framework, the researcher was able to examine the research questions. As the research aimed to capture the participants' perspectives, it used an experiential orientation for data interpretation. The researcher primarily employed an open-coding inductive approach to illustrate participant experiences. Both semantic and latent, or explicit and implicit coding facilitated reflection on participant perspectives and researcher interpretation. Nvivo was used to interpret the qualitative interview data. This tool was useful for organising, coding, and visualising the data.

Using comparative and factor analysis, the researcher assessed comparative waveform analysis for sound tests (Miksza & Elpus, 2018). It identified participant preferences and numerical variables between instruments and sound samples. These techniques aided in establishing themes and differentials (Miksza & Elpus, 2018). To make the findings more accessible, tables and waveform imaging visualised sonic data. Presenting data in this way enabled a range of data to be presented and patterns and themes

to emerge, making the research more engaging and comprehensible. In the following section, the researcher will map Braun and Clarke's six-phase process for reflexive thematic analysis (2021) to this research.

3.9.1 Phase One: Familiarisation With the Data (Braun & Clarke, 2021)

The data was transcribed and read multiple times for familiarity. Based on Braun and Clarke's direction (2021), pauses and inflections were delineated to provide greater context, and equal time was given to the data to avoid researcher bias (Braun & Clarke, 2021). The researcher highlighted initial data trends. Table 3.9 shows the initial analysis of the data sources. This table shows a sequential development from research questions, categorisations, descriptors, and emerging sub-themes based on the collected data. Following on from this, Table 3.10 shows an indicative sample sub-theme, violin ergonomics and sound quality, and its recurrence throughout the research data sets. This phase produced twenty-seven sub-themes. Repetition was deleted and emergent themes were established.

Table 3.9

Initial Analysis of Data Sources

Investigating the Potential of 3D Printed Violins in Instrumental Teaching and Learning Contexts: Perspectives from Luthiers, Musicians and Instrumental Teachers.								
RQ1: Confidence in post-digital practices			RQ2: Relevance to broader community			RQ3: Impact on musicking and performance practices in an educative environment		
Category 1			Category 2			Category 3		
Technical specifications and material properties			Perceptions and values of musicians and luthiers			Musicking implications for teachers		
Descriptor	Descriptor	Descriptor	Descriptor	Descriptor	Descriptor	Descriptor	Descriptor	Descriptor
Planning	Scanning and modelling	Comparative sound tests	Expert perspectives	Technical proficiency	Instrument viability	Collaboration	Access	School values
Sub-themes	Sub-themes	Sub-themes	Sub-themes	Sub-themes	Sub-themes	Sub-themes	Sub-themes	Sub-themes
Historical and cultural significance of digital preservation	Emulating material properties	Comparative sound quality metrics	Perceptions of material quality	Ergonomics and sound quality	Cultural and social impact	Educational function	Resource availability	Pedagogical approaches
Ethical and environmental	Material composition and choice	Design prototyping and customisation	Aesthetic and emotional connection	Precision and accuracy	Craftsmanship and artistry	Durability, longevity, and maintenance	Cost and accessibility	Support and Sustainability
Economic and accessibility	Manufacturing precision	Comparative durability	Acceptance and adaptation	Economic and accessibility	Repairability and modifiability	Learning curve	Musicking from design to performance	Ethical considerations and digital citizenship
1. Environmental sustainability impact			Cross-cutting themes:					
			• Resource efficiency					
			• Evaluation of the accuracy					
			• Feedback on playability, sound quality, and performance					
			• Short and long-term challenges					

2. Cultural impact	• Preservation of tradition -v- innovation • Acceptance and adaptation • Quality and authenticity • Accessibility and democratisation of music • Perception and acceptance in the music community
3. Affordability and accessibility impact	• Comparative cost of production, market accessibility, long-term financial viability • Infrastructural investment and maintenance, viability for luthiers and accessibility for musicians • Impact on brands • Sustainability and economic efficiency
4. Educational impact	• Education utility • Technical proficiency • Learning curve • Ethical considerations and digital citizenship • Extending music technologies • New pedagogical approaches • Collaboration and community building

Table 3.10

Sample Based on Ergonomics and Sound Quality Across the Data Sets

RQ2: Relevance to the broader musical community					
Category 2: Perceptions and values of musicians and luthiers					
Descriptor:	Technical proficiency				
	Ergonomics and sound quality				
Sub-theme:					
Data source	Pre-pilot meetings	3D scanning	Modelling and printing	Luthier and musicians' questionnaires and sound tests	Teacher interviews
Material properties	Types of materials and significant brands	Researcher-museum correspondence: reproduction for research, education, and demonstration purposes only	Researcher-Intellectual Property Office of Ireland: Production Design Intellectual Property	Luthier and musician compare differences in weight distribution and handling Musician: playability, comfort, ease of movement, and the effect of weight on posture and technique	Violin longevity: balance, weight, durability, and maintenance
Projection and volume	Instrument quality Digital integration	What are the specific acoustic properties of 3D printed violins, and how can they influence musical performance?	Material properties and their impact, comparative analysis, layer resolution, and surface finish	Luthiers: how 3D filaments affected sound production Musicians: gaps in projection and volume capacity, compared to traditional instruments	Comparison between traditionally made instruments and 3D printed instruments Comparisons to older students playing traditionally fabricated instruments

Sound quality	Usability and practicality	Equal emphasis on interior dimensions and resonant material properties	Structural integrity and durability	Luthiers and musicians: comparative resonance and tonal quality Musicians: Loss of richness in tone	More revisions: Tonal range and projection issues
Response and sensitivity	-	-	Material property resonance prints	Luthiers: Differences in the violin's ability to produce a dynamic range, bow pressure and speed response Musicians: Difference in bowing technique, dynamics, and sensitivity to gestural nuances	Not an issue for students at present
Weight and balance	Can physical and sonic characteristics be altered by using 3D printing?	-	Printing with less support material, using honeycomb trajectories to decrease weight	Luthiers: comparative weight distribution Musicians: comfort and ease of handling	Weight, balance, and fingerboard tactility
Accessibility adjustments	-	-	Original and two-part design adjustments	Luthiers: Ease of assembling parts Musicians: adjustability for the best playing	Challenges in adopting recent technology
Durability	Sustained involvement in access	Scans for future development	Durable carbon fibre	Luthiers: Longevity of filaments Musicians: resistance to environmental factors	Concerns about long-term use
Resonance and tonal quality	-	-	Material testing through multiple iterations	Luthiers and musicians: tonal characteristics, resonance and sustain, and response feedback	Improvements before continuing

3.9.2 Phase Two: Generating Initial Codes (Braun & Clarke, 2021)

The researcher generated initial codes throughout the data. Although this was a non-linear and recursive process (Braun & Clarke, 2013), these codes eventually aided in establishing distinct patterns and themes. Tables 3.11-3.13 present the sub-theme coding legends.

Table 3.11

Sub-Theme Coding Legend for Category One, Conservation and Making

Descriptor:	Descriptor:	Descriptor:
Planning	Scanning and modelling	Comparative sound tests
Sub-themes	Sub-themes	Sub-themes
- HCC: Historical and cultural context - EEL: Ethical and environmental impact - EPC: Economic and practical considerations	- SMP: Sound and material properties - MCS: Material composition and selection - MPCT: Mechanical properties and construction techniques	- CAPM: Comparative analysis and performance metrics - DPE: Design prototyping and enhancements - CD: Comparative durability

Table 3.12

Sub-Theme Coding Legend for Category Two, Perceptions and Value

Descriptor:	Descriptor:	Descriptor:
Expert perspectives	Technical proficiency	Instrument viability
Sub-themes	Sub-themes	Sub-themes
- PQS: Perceptions of quality and sound - AA: Adoption and acceptance - PQP: Perceived quality and performance	- PSQ: Playability and sound quality - PA: Precision and accuracy - EPC: Economic and practical considerations	- CSEI: Cultural, social, and environmental impact - CA: Craftsmanship and artistry - ERM: Ergonomics, repairability and modifiability

Table 3.13*Sub-Theme Coding Legend for Category Three, Performance and Musicking*

Descriptor:	Descriptor:	Descriptor:
Colloboration	Access	School values
Sub-themes	Sub-themes	Sub-themes
• SECI: Student engagement, customisation, and innovation • DLM: Durability, longevity, and maintenance • LC: Learning curve	• PTEA: Physical, technological, and educational access • CA: Cost and accessibility • MDP: Musicking from design to performance	• CCBEO: Collaboration and community building through engagement and outreach • SS: Support and sustainability • ECDC: Ethical considerations and digital citizenship

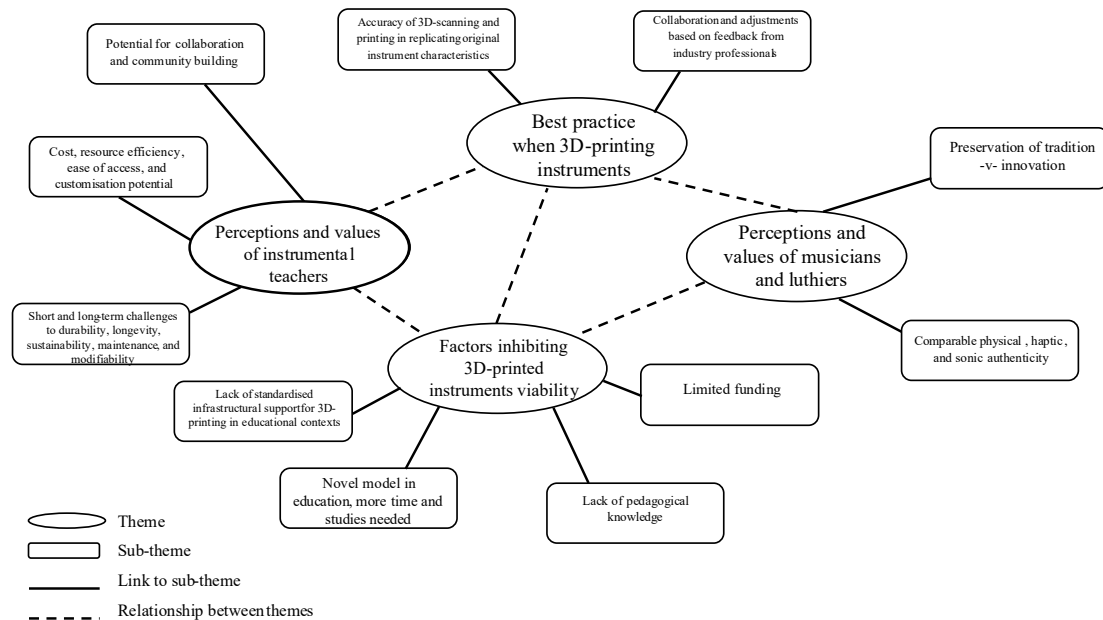
3.9.3 Phase Three: Generating Themes (Braun & Clarke, 2021)

The researcher reviewed and consolidated the coded data into themes and sub-themes based on shared relational meaning (Braun & Clarke, 2013). Aware of distinctions between theme salience and quantity of occurrence, the researcher focused on code patterns that directly addressed the sub-research questions (Braun & Clarke, 2013). The researcher formed a miscellaneous theme category. This category was removed later in the analysis due to its peripheral relevance to the sub-research questions (Braun & Clarke, 2013). Table 3.14, adapted from Braun and Clarke (2021), presents the thematic map indicating four candidate themes and eleven sub-themes.

Table 3.14

Initial Thematic Map Adapted from Braun and Clarke (2021) Indicating Candidate

Themes and Sub-Themes



The theme "best practice when 3D printing instruments" is definable, with coded data evidencing two parallel sub-themes. One emphasises the technical proficiencies needed to replicate and fabricate an object. In contrast, the second emphasises the importance of collaborative dialogue from industry professionals to sustain the viability of the design beyond an isolated pilot study. It addresses research question one (Table 1.1). The theme "perceptions and values of musicians and luthiers" is equally clear. It recognises a distinct contrast of narratives between industry and educational participants' instrument values and two equal sub-themes, more closely related than theme one. One identifies factors that may inhibit participants' engagement with 3D printed instruments, while the second examines factors that may enhance engagement. It addresses research question two (Table 1.1).

The theme "factors inhibiting 3D printed instruments' viability" collated data referencing more prominent infrastructural factors influencing sustained longevity. These

factors were divided into four sub-themes, reflecting a lack of funding, pedagogical knowledge, prior studies, and standardised infrastructural support for 3D printing in educational contexts. This theme is connected with prior literature outlining the short and long-term digital infrastructural provision and support necessary for the effective provision of 3D printing in educational contexts (Sections 2.4.2, 2.4.3, 2.4.4). Although sub-themes initially emphasised instrumental limitations, multiple revisions indicated that the more pertinent inhibiting factors resided in the model's iterative sustainability, which refers to the ability of the model to adapt and improve over time. This concept, which resonates with gaps in the research regarding longitudinal studies of 3D printed instruments within an educational context (Sections 2.4.3, 2.4.5), was identified in Section 2.5.

The theme “perceptions and values of teachers” focused on the influencing and deterring factors of using 3D printed violins in an educational context. These factors were further subdivided into three sub-themes, highlighting (i) the potential for industry and education collaboration, (ii) addressing the cost challenges of instrument provision, and (iii) the possibility of addressing long-term durability challenges. All three of these sub-themes, collaboration (Section 2.3.6), cost (Section 2.4.5), and durability (Section 2.4.4) connected to prior literature. Themes three and four addressed research question three, affirming the infrastructural challenges and user potential (Table 1.1). This concept, which resonated with gaps in the research regarding the practical application of 3D printed instruments in an educational context (Sections 2.4.3, 2.4.6), was identified in Section 2.5.

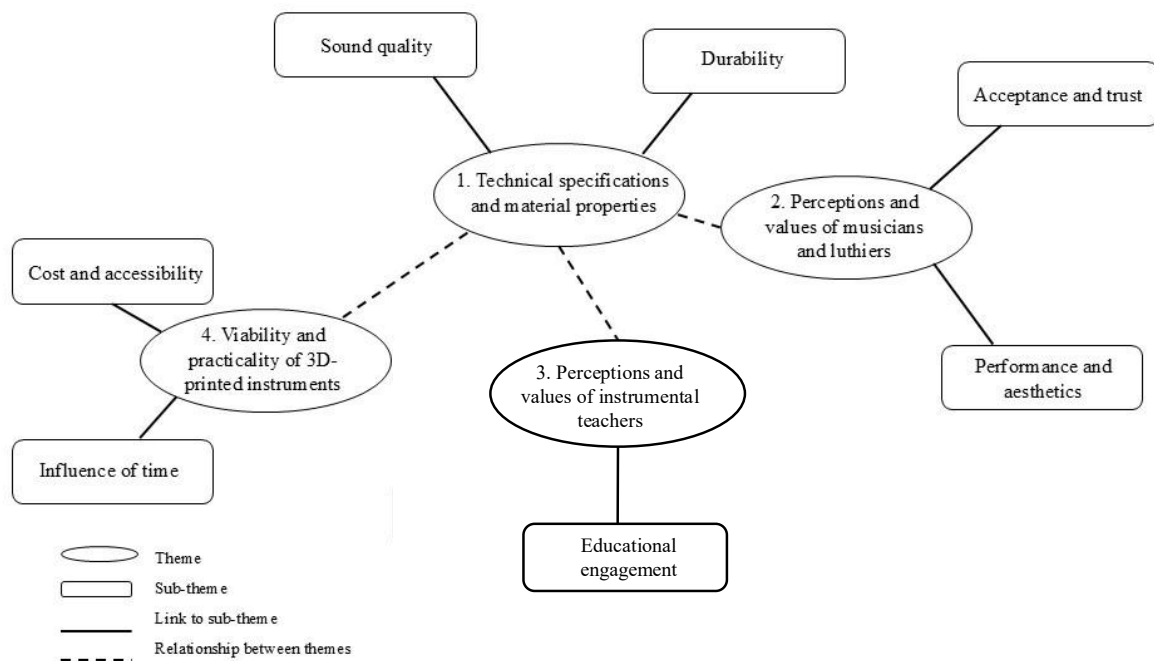
3.9.4 Phase Four: Reviewing Potential Themes (Braun & Clarke, 2021)

Phase four sought to generate a revised thematic map based on the first themes and sub-themes relevant to the sub-research questions. The researcher recursively reviewed the first themes relative to the coded data and dataset (Braun & Clarke, 2021). The researcher viewed codes concerning the research questions and removed incongruent data items to

refine the results and findings. For instance, an initial reading of the literature deemed musicians' starting age as a determining factor in professionalisation and brand alignment. Therefore, the musician questionnaires reflected this. However, through the code refining process, the researcher found that this needed to be more relevant to the research questions. Using Braun and Clarke's critical questions for assessing themes (2013, p. 65), the researcher differentiated themes from codes, relationally orientated themes to the research questions, generated an inclusion and exclusion criterion for themes, assessed the thick or thinness of the themes, and assessed the coherence of the data. Using two levels of review (Braun & Clarke, 2013), the researcher refined themes, evaluated the codes' relationships to the theme and sub-themes and evaluated relative to interpretations of the data set. As recommended by Braun and Clarke (2013), Patton's *dual criteria for judging categories* (2002) based on internal and external heterogeneity aided in ascertaining how codes informed themes and themes informed an interpretation of the dataset. Table 3.15, adapted from Braun and Clarke (2021), presents the final thematic framework with four themes and eight sub-themes.

Table 3.15

The Final Thematic Framework Adapted from Braun and Clarke (2021), Indicates the Final Themes and Sub-Themes



The theme development was guided by Braun and Clarke's key questions (2013). In order to address research question one, theme one developed from 'best practice when 3D printing' to 'technical specifications and material properties.' This aided in directing focus away from general practices towards replication and reproduction. Similarly, the sub-themes also developed, with the 'accuracy of 3D scanning and printing in replicating original instrument characteristics,' and 'collaborations and adjustments based on industry professionals' feedback,' changing to 'sound quality' and 'durability.' This theme and sub-theme development, when viewed in relation to Patton's dual criteria (2002), connected with research question one.

Theme two, 'perceptions and values of musicians and luthiers,' largely remained unchanged. However, as the original sub-theme of 'preservation of tradition -v- innovation' progressed, it ultimately did not accurately reflect the data, research question two, or the

“quality” of the theme (Braun & Clarke, 2013, p. 65). As a result, this theme was revised to 'acceptance and trust' to capture participant perspectives more accurately. The descriptive nature of 'comparable physical, haptic and sonic authenticity' was integrated into 'performance and aesthetics' to offer a more complete view of the theme.

Based on revisions to the six phases (Braun & Clarke, 2013), the researcher switched the positions of themes three and four to enable a logical flow between industry and educative perspectives. The revised theme three, 'perceptions and values of teachers', remains unchanged. However, sub-themes changed from 'cost, resource efficiency ease of access, and customisation potential' and 'short and long-term challenges to durability, longevity, sustainability, maintenance and modifiability' to 'educational engagement' to accurately reflect the intent of research question three and that there was “enough data to support this theme” (Braun & Clarke, 2013, p. 65).

On review, theme four, 'factors inhibiting 3D printed instruments viability,' changed to 'viability and practicality of 3D printed instruments' to recognise that the codes were not solely representative of inhibitive factors. Returning to Braun and Clarke's key questions (2013) to identify data that was too diverse, dense sub-themes significantly changed from 'limited funding,' 'lack of pedagogical knowledge,' 'novel model in education,' and 'lack of standardised infrastructural support' to 'cost and accessibility' and 'influence of time' because the initial sub-themes elicited topical instead of thematic aspects of the data, and informative of isolated narratives within the data. This theme allowed data relating to research questions two and three to interweave, enabling participant group commonalities to the evidence and a richer comprehension of the data hidden by the first, domain-based sub-themes. The 'influence of time' developed from simply illustrating time as an inhibiting factor in 3D printed instrument integration. Through engagement with the data, the researcher focused on the bi-directional nature of time limitations, which conceded that

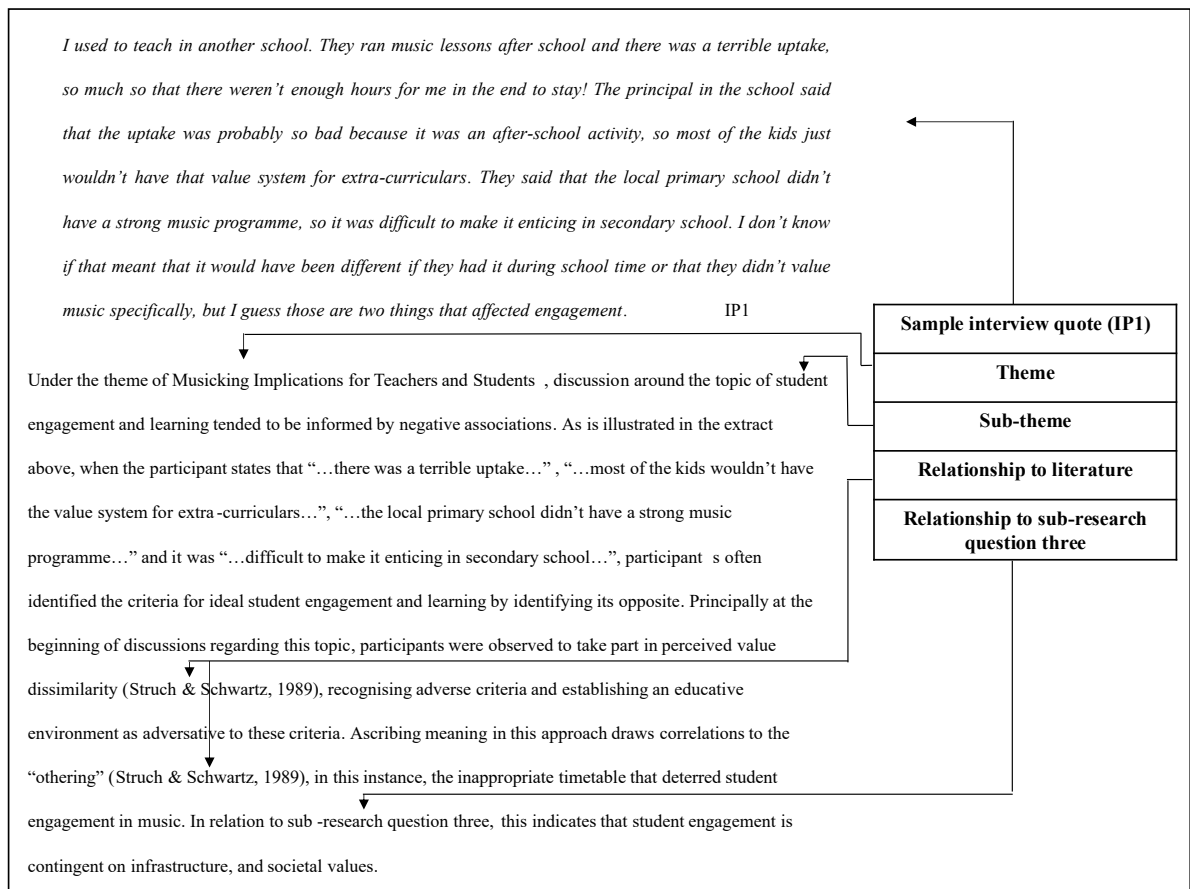
previously existing time limitations affected instrumental performance, while instrument provision deepened time limitations. More generally, the influence of time featured in dataset codes to describe short and long-term challenges to the continuation of this provision model and the potential for community building between industry professionals and teachers. Appendix K shows a categorisation of the sub-themes.

3.9.5 Phase Five: Defining and Naming Theme (Braun & Clarke, 2021)

Phase five examined the thematic framework. Aligning with Patton's dual criteria (2002), each theme must show a coherent data report. To generate an analytic narrative (Braun & Clarke, 2013), the researcher found data items that functioned thematically, with the research questions, and with a context to the literature (Braun & Clarke, 2013) to use in the results and findings chapters. Table 3.16 shows a sample of the defining and naming process, identifying the quote, theme, sub-theme, relationship to the literature and research question three.

Table 3.16

The Defining and Naming Process

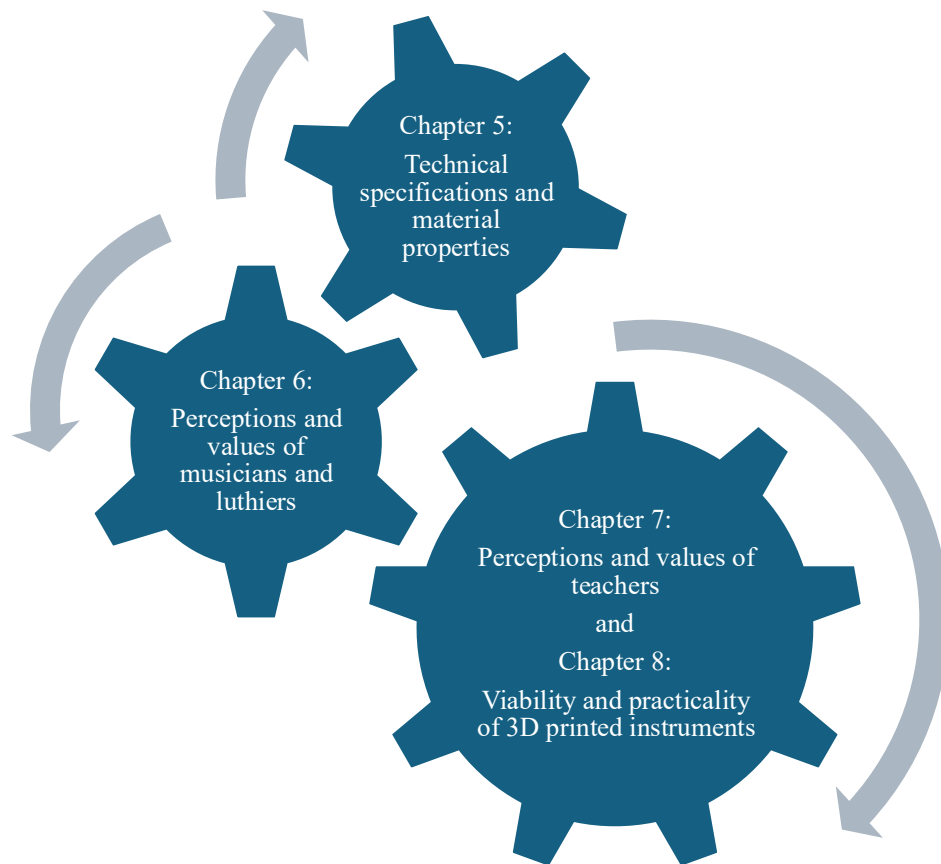


3.9.6 Phase Six: Producing the Report (Braun & Clarke, 2021)

Producing the report involved iterative revisions before presenting the results and findings in Chapters 5, 6, 7, and 8. Although thematically presented, the chapter divisions also connected to the order of the research questions. The researcher sought to provide structural logic and ease of readership throughout. To avoid repetition, it moved from a sequential to a thematic presentation. The researchers' writing style changed from an illustrative to an analytic narrative to prevent overly descriptive results. The researcher edited the quantity of data presented to enable deeper engagement and analysis. Table 3.17 visualises the order in which the themes are reported.

Table 3.17

Visualising the Order in Which the Themes are Reported



The researcher first reported 'technical specifications and material properties' because it provided the foundational sonic and material data necessary to review the technical and material properties of the 3D printed violin. This theme's placement was essential to a technical understanding of the violin because it signposted the technical and sonic criteria that would inform the following themes. This theme used quantitative data from 3D scanning and sound tests of the 3D printed violins. The results were communicated numerically and visually using comparative manual measurements of the original instrument. Presenting the data in this way enabled a quantifiable dataset confirming the sonic and material strengths and limitations of 3D printed violins used in this research. 'Perceptions and values of musicians and luthiers' provided a logical

transition from the technical aspects of replicating and generating a violin to engagement with industry professionals who could critique technical and performance challenges at a prominent level. This theme introduced the truth that, for this participant group, instrument choice is influenced by a range of historical, social, cultural and personal variables that problematise a discrete understanding of perceptions.

The researcher sought to coherently transition from industry professionals' perceptions to teachers' perceptions and values to streamline data points and avoid repetition. The qualitative nature of this section enables a deeper analysis of the theme and sub-themes. Finally, assessing the 'viability and practicality of 3D printed instruments' structurally enabled a synthesis of perspectives regardless of participant categorisation. Chapters 7 and 8 have a more significant visual representation because they address two themes related to research question three. Their representation in this format emphasises the theme's logical connection. Although addressing distinct aspects of the study (Braun & Clarke, 2013), themes hold permeable signifiers that enable a greater understanding of the viability of alternative modes of instrument making and provision.

3.10 Ethical Considerations

Ethical issues and a duty of care exist when undertaking research within the researcher's school. Including multiple stakeholders in the research design and implementation lessened the researchers' bias. This research aligns with the ethical standards outlined by the Trinity College Dublin handbook and was approved through the School of Education's ethical approval procedures. The researcher contacted relevant gatekeepers, seeking permission to complete the research (Appendix C, G). Gatekeepers and participants received consent forms and participant information leaflets (PIL) (Appendix D). The consent form language was simple. It indicated the research purpose, the proposed role of the participant, the research instruments, and the expected duration of

participation. Participants knew that participation involved providing formative feedback on the use of 3D printed instruments. Participants recognised that the study was part of a Doctorate in Education at TCD, that participant and school data would be anonymised and stored in a GDPR-compliant manner, that involvement was voluntary, that they could withdraw at any time, and that a copy of the data could be made available. As outlined by TCD recommendations, seven days of reflection were allocated. Consent was obtained in written format, indicated with an original signature. The 3D printed violins were distributed to professional musicians and luthiers two weeks in advance of administering the instruments, while instrumental teachers had a more extended timeframe of an academic year for them to test and observe student use.

Historical, copyright, and preservation ethics shaped this study. Historically, the Stradivarius is a seventeenth-century instrument (Faber, 2012). Consequently, simply emulating a beloved model would neglect over three centuries of instrument design literature and discoveries (Hopkin, 1996). As approximately 650 Stradivarius instruments survive (Faber, 2012), they are deemed instruments of the elite. Therefore, promoting access to these instruments was ethically essential and a moral imperative. Adesope and Rud (2018) outline the ethical issues when using disruptive technologies. The main challenge lies in constantly updating policy to reflect the fast-changing nature of these technologies. Regarding copyright, replica patterns of several Stradivarius instruments currently exist. However, they differ from this research due to their expense and traditional panelled construction. The researcher is approaching the incorporation of disruptive technologies from an arts and music perspective. Although the researcher has upskilled to reflect this, expertise in this area is utilised throughout this research to maximise its potential shared value, offering promising outcomes for the field of arts and music.

3.10.1 Researcher Bias

As a practising teacher in the pilot school, the researcher was cognisant that bias can consciously or unconsciously impact conclusions. The researcher was aware of insider bias (Sikes & Potts, 2008), which can affirmatively shape conclusions; selection bias (Sikes & Potts, 2008), where participants may be selected to affirm success; the observer expectancy effect (Rosenthal, 1976), which influences participant responses; and confirmation bias (Klayman, 1995), which unequally favours data that support the research hypothesis. Omodan (2024) emphasised trustworthiness through openness with participants, which was enacted by initial meetings with instrumental teachers, which aided in identifying specific areas of need for participants and a co-constructed design. The instrument design process was externally moderated by documenting sound tests, design tests, and iterations based on feedback from professional luthiers and musicians. Using data from expert voices, pre-pilot audits, teacher informal feedback, instrument maintenance checkups, and teacher semi-structured interviews, the researcher sought to diversify voices and create a robust framework. Triangulation through multiple data points sought to diminish the possibility of misrepresentation (Flick, 2018).

3.10.2 Research Trustworthiness

During the three-year study, luthiers, professional violinists, and instrumental teachers tested the instruments to ensure a comprehensive and unbiased approach. Integrating multiple data instruments demonstrated reliability. External validity was measured through sound tests and questionnaires with expert voices. Inviting expert musicians to test and critique the instruments sought to incorporate multiple stakeholders within the design decision-making process. Making design modifications based on expert voice suggestions exemplified communication, analytical, collaboration, adaptability, and critical thinking transferability skills (Foster, 2015). Internal validity was measured

through instrumental teacher pre-pilot audits and interviews, and involving instrumental teachers to co-construct from the beginning aided in trustworthiness. Triangulation and variation of data sources (Bloomberg & Volpe, 2018) aided in trustworthiness.

3.10.3 Research Transferability

Using the concept of "thick description" (Lincoln & Denzin, 2001, p. 83), this study aimed to provide a digital blueprint that future musicians, luthiers and educators could use as a starting point for further exploration and innovation. For instrument makers, this allowed the integration of traditional knowledge into new fabrication processes. For professional violinists, it enabled them to voice their opinions on sonic and haptic design changes. For instrumental music teachers, this research promoted the use of violins within an educational environment. Regarding research transferability, the 3D files generated throughout this research could be transferable to other instrumental music contexts. This connects with Cano's (2015) assertion of the democratising power of file-sharing, discussed in Section 2.4.4.

The 3D printed violin provision model may be applicable to other instrumental music contexts seeking an alternative mode of instrument provision. Despite being a small sample study, the depth of digital files produced and the expert voices' perspectives have enriched the research. In alignment with Bijker's (1995) theory of the social construction of technology, outlined in Section 2.3, this instrument and its geometry can be shaped by both social and cultural factors. However, in recognition of Mendonça et al. (2004) diffusion of innovations theory, referenced in Section 2.3, this model of alternative provision is highly contingent on collaborative skill sets and infrastructural provision.

3.11 Limitations of This Research

This research has limitations based on the participants, digital and educational infrastructures, and the short research timeframe. This research explored the viewpoints of

twenty luthiers, violinists, and instrumental teachers. Although the research incorporated multiple voices, which was called for in Sections 2.2.1, 2.3.1, 2.3.5, and 2.4.3 of the literature review, and addressed gaps in existing 3D printing literature, noted in Sections 2.3.2 and 2.3.5, it has only been evaluated by industry professionals and instrumental teachers. Consequently, the researcher acknowledges that the subsequent findings may only be generalisable to instrumental music contexts with access to similar digital and instrumental music teaching infrastructures. Therefore, further studies, specifically involving the establishment and development of industry professional collaborations with music departments, as mentioned in Sections 2.4.3 and 2.4.6, are recommended. This will aid in exploring how foundational infrastructures can be established and built upon. Equally, longitudinal studies, as outlined in Sections 2.4.3 and 3.4.5, are recommended. This will aid in addressing the long-term instrument durability and infrastructural viability of such interventions.

3.12 Conclusion

Sections 3.1, 3.2 and 3.3 contextualised the research problem, intention and approach. Section 3.4 articulated the research epistemology, paradigm, design and approach. This section justified using a mixed-methods sequential design, a constructivist paradigm, an emic, ethnographic approach, and an interpretive perspective for this research. Pre-pilot audits (Appendix F) assessed teachers' expectations. 3D scans established the technical specifications. Luthier questionnaires (Appendix E) and musician sound tests confirmed the material properties necessary for comparable sound quality and durability between traditional and 3D printed violins. Engaging professionals in music education provided insights on time management, sonic variations, and economic considerations. It also allowed for the customisation of the instruments based on the

anticipated users' needs, identification of the most effective user base, and testing of the potential to expand musicking possibilities within an instrumental music context.

Teacher interviews (Appendix B) and industry professional questionnaires (Appendix A & E) provided insights into user perceptions, values and viability of 3D printed instruments. Teacher interviews addressed the educational implications of integrating 3D printed instruments into instrumental music contexts. Formal feedback from teachers via semi-structured interviews enabled teachers to comment on its viability for the future and assess the new instrument's sonic relationship with older instruments. The teacher interviews provided a qualitative perspective to the data and enabled the researcher to seek clarification on some of the emerging themes from the industry professionals' data. Finally, this chapter outlined the data analysis, preparation, coding, categorisation, and interpretation process, providing a transition from data generation to an analysis of the findings in the following chapter.

For the data analysis, the researcher discussed using comparative waveform and factor analysis to show themes and differentials for Quantitative data (Miksza & Elpus, 2018). Regarding qualitative data, using Braun and Clarke's (2021) RTA approach to find themes and their six-phase process for reflexive thematic analysis, this chapter presents the data analysis process. This analysis method ensured that the participants and the researcher were reflected. Chapters 4, 5, 6 and 7 thematically present and synthesise the results and findings, assess their relationship to the sub-research questions and evaluate their convergence or divergence from the literature.

Chapter 4 Results and Findings of Technical Specifications and Material Properties

4.1 Introduction

Based on the theme of technical specifications and material properties, this chapter discusses the results and findings of two sub-themes: (i) sound quality and (ii) durability. As indicated in Section 3.7.1, the audio data was produced from instrument comparison tests with professional violinists, while the sound visualisations provide a graphic counterpoint to reinforce differentials. In addition, this chapter presents the results of the luthier questionnaires, which provided practical insights into the material properties of the 3D printed violins. These results are thematically presented, and each sub-theme synthesises the findings in relation to the literature.

Providing a context for understanding the sound acoustics, resonance, sustain, and frequency response of 3D printed violins in relation to traditionally made counterparts is important when addressing gaps in the research, as outlined in Sections 2.3.2 and 2.3.5. While the importance of undertaking collaborative interdisciplinary research between luthiers, musicians, and instrumental music teachers to establish instrument viability has been outlined in Sections 2.2.1, 2.3.1, 2.3.5, and 2.4.3. The technical specification of violin sounds detailed in this chapter were grounded in acoustic and instrument design principles used by Fletcher and Rossing (2012). These authors stressed the importance of material and structural fidelity to the construction of stringed instruments. Based on this literature, nine sound tests were conducted to assess the violins comparative performance. Factors included sound, tone, sustain, timbre, volume, playability, frequency, resonance and bowing ability. These factors serve to determine both the instruments functionality and its potential pedagogical potential.

Dooling and Hulse (2014) championed the preservation and educational potential of digitally replicating musical instruments. However, Section 2.2.1 evidenced that the

material properties of instruments directly affected both sound and durability, while Section 2.3.4 discussed how small variations in 3D printing filaments and print directionality affected material resonance and robustness. Combined, Buehler et al. (2016) would contend that all these factors influence the violin's sound, performance, and durability. However, as Andrés et al. (2022) concede, changing the material composition of an instrument introduces long-term viability questions. This finding emphasises the fine balance between the material properties and the sound quality when designing using alternative construction and material methods.

4.2 Sub-Theme: Sound Quality

The sub-theme of sound quality emerged as a foundational indicator of instrument comparability for this research. This sub-theme became a key benchmark when addressing the violin's technical specifications. In this research, sound quality is used to refer to the violin's tonal values, richness, and projection in comparison to traditionally constructed violins. As evidenced in the literature review (Day, 2000; Morton, 2006), there are mixed reviews of the sound quality of new musical instruments. Specifically, while Morton (2006) believed that technological advancements have the potential to customise and shape sound quality, Day (2000) maintained that new construction techniques cannot replace craft, skills, and understandings of sound developed over centuries. Therefore, as reinforced by McPherson and Welsh (2018), it would appear that comparable sound quality is a key influencing factor to the integration of new musical instrument designs. In relation to this research, the measure of good sound quality is based on its comparability to traditionally constructed violins.

The following section presents the results and findings from three data points relating to the sub-theme of sound: comparative sound samples performed by professional violinists, researcher-led sound tests, and luthier feedback on the comparative sound tests.

The sub-theme of sound is thematically subdivided into comparative acoustic properties, structural design and sound resonance to reflect how sound functions comparatively and how the instrument structure influences sound. The findings show the results of the professional musician's performances, the Quantitative sound measurement tests, and the luthier's feedback on the comparative sound recordings. The findings are connected to relevant literature, ensuring that the methodology connects with prior practices.

4.2.1 Comparative Acoustic Properties

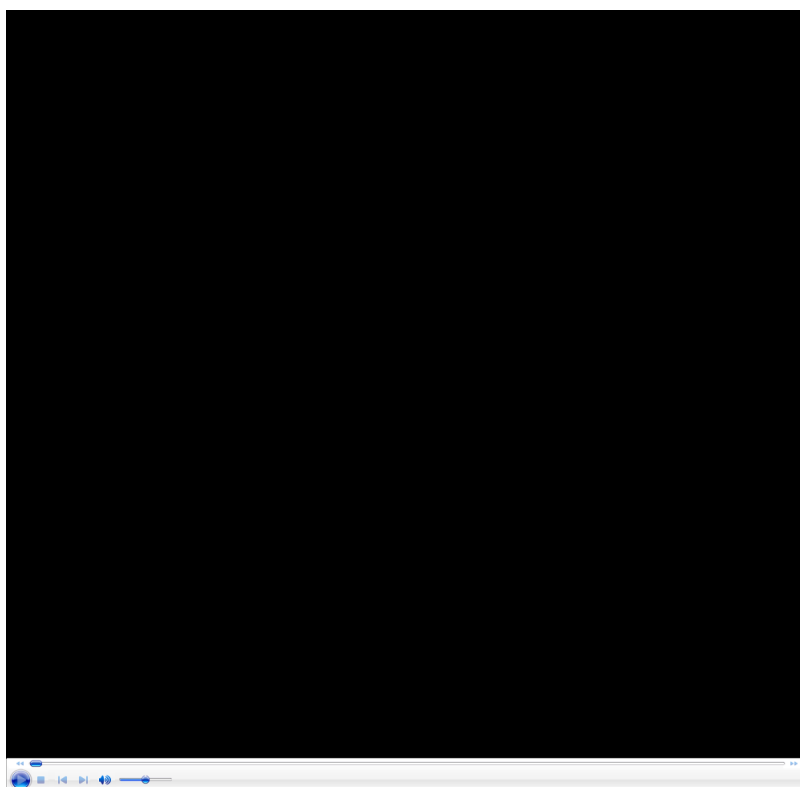
The professional violinists' sound sample data enabled the sonic comparison of traditionally constructed and 3D printed violins. Eight comparative performance tests were conducted, and the tests were designed in recognition of lessons learned by Fritz et al. (2014) about removing variables. In this context, variables included using the same bow, recording space, professional musicians, and pieces spanning from beginner to advanced, as Dooling and Hulse (2014) suggested. These sound recordings, which ranged from twenty-two seconds to one minute and thirty seconds, enabled the sonic characteristics of the violins to be profiled and assessed. By using a recommended repertoire (Dooling & Hulse, 2014) and controlled recording conditions (Fritz et al., 2014) it increased the reliability of the instrument comparisons. Although the violinist's performance capacity added credibility to the resulting tests and findings, there are limitations within this methodology. Specifically, the small sample size of participants may limit the finding's generalisability. Equally, the repertoire selection, although diverse in performance ability, is limited to a predominantly classical genre. Finally, as violinists use their own instrument as well as the 3D printed instrument in the sound tests, musicians will have an assumed comfort level with their own instrument that is difficult to replicate on other instruments, creating comparability limitations in the findings. This transparency regarding the research limitations is crucial for the research integrity.

To analyse the sound samples, Audacity sound editing software was used for its ability to compare the recordings of Violin A (traditional) and Violin B (3D printed) visually and aurally. Using waveform multi-view and spectrogram analysis allowed the research to identify and illustrate variations in five key sonic parameters: attack, sustain, decay, overtones, and noise. Although these tools offer a detailed visual indicator of the sound samples, Fletcher and Rossing (2012) would contend that sound visualisation software can simplify complex acoustic data. To address Fletcher and Rossing's (2012) critique, the visual data in these findings are juxtaposed with an auditory analysis in an attempt to fully represent the specific instruments' sonic profiles.

The following results show the differences between Violins A, the violinists traditionally constructed violin, and Violin B, the 3D printed violin, across a range of musical pieces. For example, in the first video from Figure 4.1 (Twinkle Twinkle Little Star), Violin A displayed a more pronounced attack and sustained resonance, while Violin B evidenced softer articulation and a quicker decay rate profile. This finding suggests that the traditionally constructed violin offers a richer, more dynamic tonal palette. This finding reinforces Andrés et al. (2022), who contended that traditional, cured woods provided superior attack and deterioration rate profiles that could not be duplicated. It also affirms Yao et al. (2016) comparative acoustic experiments using PLA, outlined in Section 2.3.4. In this example, 3D printed instruments diminished resonance and affected listener perceptions. However, Violin B's smoother attack could be advantageous in specific musical contexts, such as ensemble performances, where the instrument's attack and decay may not be as prominent. Although the visuals from Figure 4.1 show that the attack and decay differentials between both instruments are relatively small, this finding indicates that more research on the resonance potential of 3D printing filaments are necessary for 3D printed instruments to align with their traditionally made counterparts.

Figure 4.1

Video Showing the Comparative Audio Test of Twinkle Twinkle Little Star



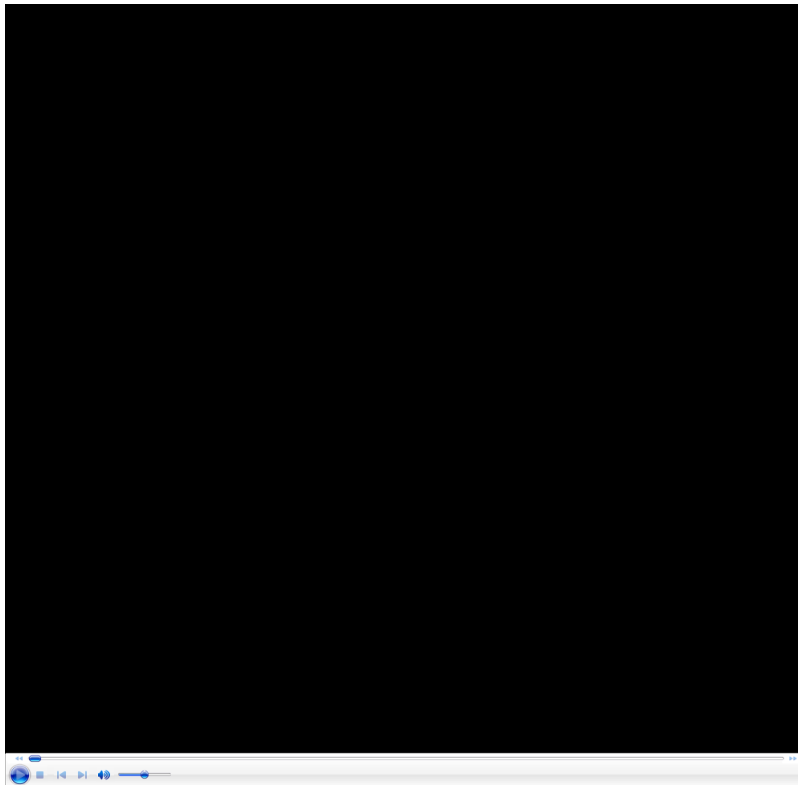
The video from Figure 4.2 (Bach Violin Concerto in A minor), displayed the sustain and decay capabilities of the instruments. Violin A displayed more pronounced bowing regarding the attack, highlighting each note's clarity. In contrast, violin B presented with a softer attack, producing legato phrasing. The introductory four notes exhibited longer sustained notes by Violin A than Violin B. Concerning decay, Violin A decayed more gradually, enabling longer phrasing. However, in contrast, Violin B decayed faster, but, due to the repertoire choice, this decay was masked by the quicker musical passages. From Figure 4.2, it is evident that Violin A displays a profile consistent with well-defined overtones, that reverberate throughout the recording. However, Violin B's more muted overtones produced cleaner scale passages, producing a cleaner profile that may be more easily audible. In relation to the noise profile, Violin A presented minimal contextual noise, while Violin B presented some noise. Although Fletcher and Rossing

(2012) would attribute this noise to string abrasion, it is worth noting the small variables.

In summary, Figure 4.2 evidenced that Violin A produced clear, sustained notes, with a gradual decay, while Violin B showed more suitability for legato playing due to its faster decay rate.

Figure 4.2

Video Showing the Comparative Audio Test of Bach Violin Concerto in A minor

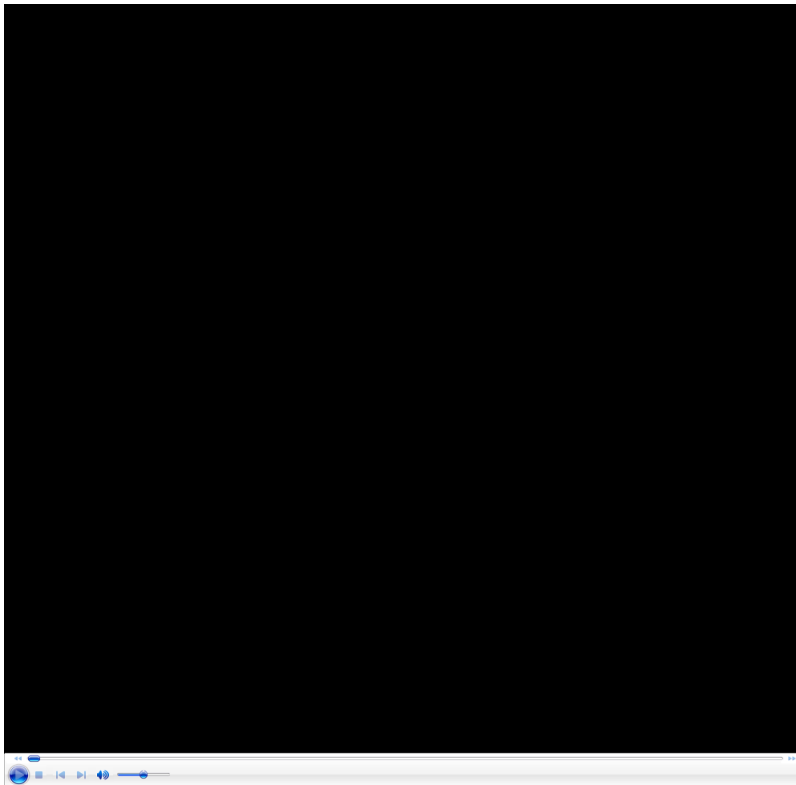


The video from Figure 4.3 (Bach Violin Concerto for Two Violins), displayed the attack and sustained capabilities of the instruments. Violin A produced a sharp and precise attack, creating a seamless connection between the action and the resulting sound. In contrast, violin B's softer attack resulted in a slower response time. The recording indicates that the variation in the attack time between both instruments impacted the overall tonal character of the piece. In relation to the instruments sustain rate, Figure 4.3 shows that Violin A produced longer resonant frequencies, and a more controlled decay rate than Violin B. This softer attack and shorter sustain gives Violin B a lighter overall effect. In

this recording, Violin A produced a broader harmonic palette, while Violin B's overtones were narrower. Despite these differences in harmonic palette, the noise levels produced by both violins were relatively small. However, this finding indicates that a slower attack and response time may affect the overall tonal character of the piece.

Figure 4.3

Video Showing a Comparative Audio Test of Bach Violin Concerto for Two Violins

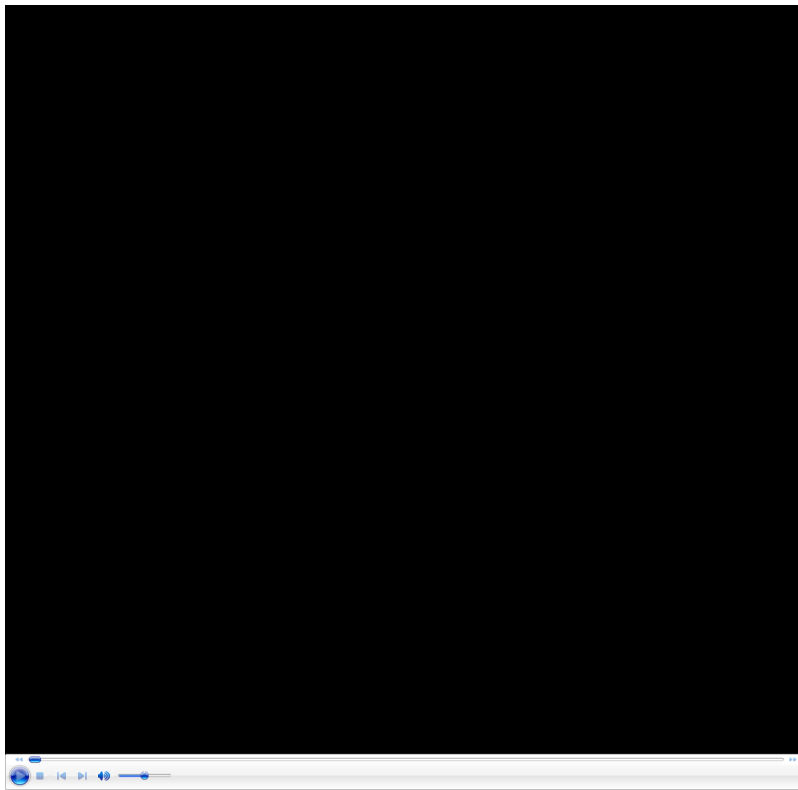


The video from Figure 4.4 (Massenet Meditation de Thais), highlighted the sustained capabilities of the instruments. Violin A's sharp initial attack added a sense of immediacy to the rubato notes, while Violin B's softer initial response was visible and audible. Violin A's longer sustain and decay rate allowed the performer to focus on the musical nuances. In contrast, Violin B's shorter sustain capabilities reduced the intensity of the performance. Violin A's richer overtones provided a highly resonant sound sample, while Violin B's narrower overtones created limitations in the intensity of performance. While both violins presented minimal noise, the sonic limitations of Violin B become more

evident as the repertoire becomes more demanding. This finding indicates that the sonic disparities of 3D printed violins may affect their use for professional musicians.

Figure 4.4

Comparative Audio Test of Massenet Meditation de Thais



This comparative disparity is evidenced further in Figure 4.5 (Lalo's *Symphonie Espagnole*), where the piece is even more complex than the previous example. In this example, Violin A consistently outperformed Violin B in relation to the instrument's attack, clarity, sustain, and harmonic profile. These results support the use of traditionally constructed violins when seeking to produce a denser sonic profile, particularly when performing an advanced repertoire. However, Violin B's lighter and narrower tonal output, although not as robust as Violin A, could be an alternative option for performers seeking clarity for faster passages. However, returning to Section 2.4.4 of the literature, it would appear that Buehler et al. (2016) acknowledgement that, while “technically feasible ... the [3D printed instrument] design would not be suitable for an education instrument” (p. 145)

resonates with this specific design iteration. Therefore, the researcher suggests that further design iterations must take place to minimise the discrepancies between conventionally made and 3D printed violins before it reaches an educative context. Seeking participation and feedback from industry professionals through this process has enabled the gap between researchers as modellers and researchers as music educationalists to diminish.

Figure 4.5

Video Showing a Comparative Audio Test of Lalo Symphonie Espagnole (1st Movement)

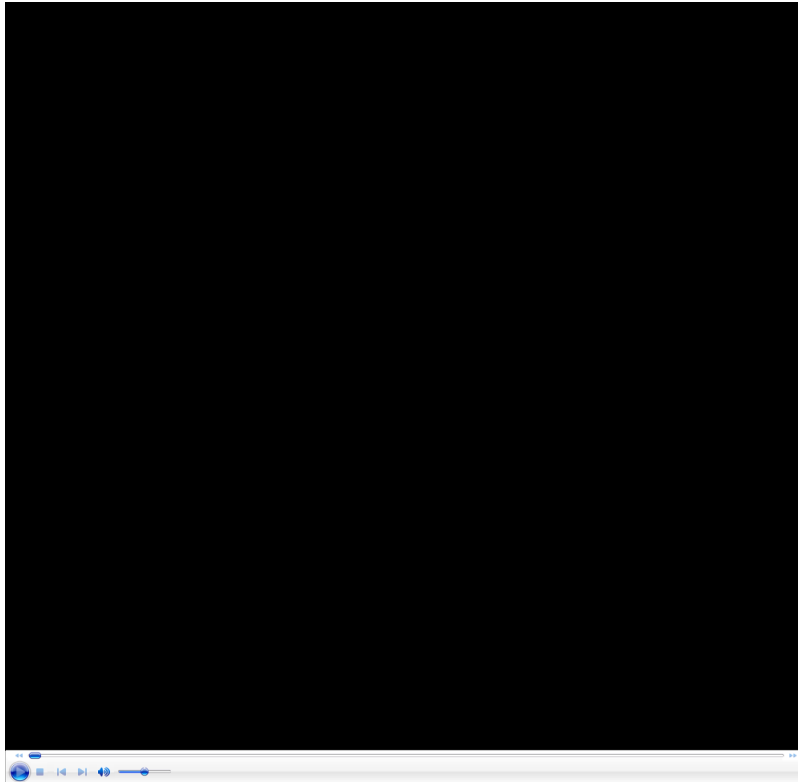


The video from Figure 4.6 (Tchaikovsky Violin Concerto, 3rd Movement) evidenced the sonic attack abilities of both instruments. In this example, Violin A's more pronounced attack produced a more vibrant and energetic performance. However, in contrast, Violin B presented a slower response time, leading to a less vibrant performance. While Violin A evidenced clear, sustained passages, similarly to Figure 4.2, the quicker musical passages masked Violin B's sustain limitations. While Violin A displayed a gradual decay rate, resulting in coherent musical phrasing, Violin B decayed faster and

required more frequent bowing action for its continuation, as evidenced in the sound recording. Violin A displayed a harmonically rich overtone profile, while Violin B's less complex harmonic palette provided more simplicity.

Figure 4.6

Video Showing a Comparative Audio Test of Tchaikovsky Violin Concerto (3rd Movement)



The video from Figure 4.7 (Tartini-Kreisler Devil's Trill, Cadenza) presented the overtone capabilities of the instruments. Violin A's attack was incredibly responsive, a crucial element for the cadenza. In contrast, Violin B's attack could have been more immediate and precise. Violin A's sustained passages were intense, contributing to an emotive recording. Violins B's sustain was comparatively less pronounced, affecting the note response as they jumped between octaves and posing a challenge to the fluency of the performance. Violin A's decay rate was tapered, which suited the musical style of the piece. However, in contrast, Violin B's faster decay rate produced less controlled dynamic variation, affecting the comparative impact. As evidenced in Figure 4.7, Violin A's

overtone profile was harmonically reverberant, which enhanced the octave leaps, while Violin B's overtone profile was less rich, leaving overtone gaps based on the specific composition structure. Although Violin A displayed more noise in this recording than Violin B, this may have been due to the recording parameters, the violins limitations, the performers style, or the reduced overtone possibilities for a piece that requires the performer to have a strong control of overtones.

Figure 4.7

Video Showing a Comparative Audio Test of Tartini-Kreisler Devil's Trill (Cadenza)

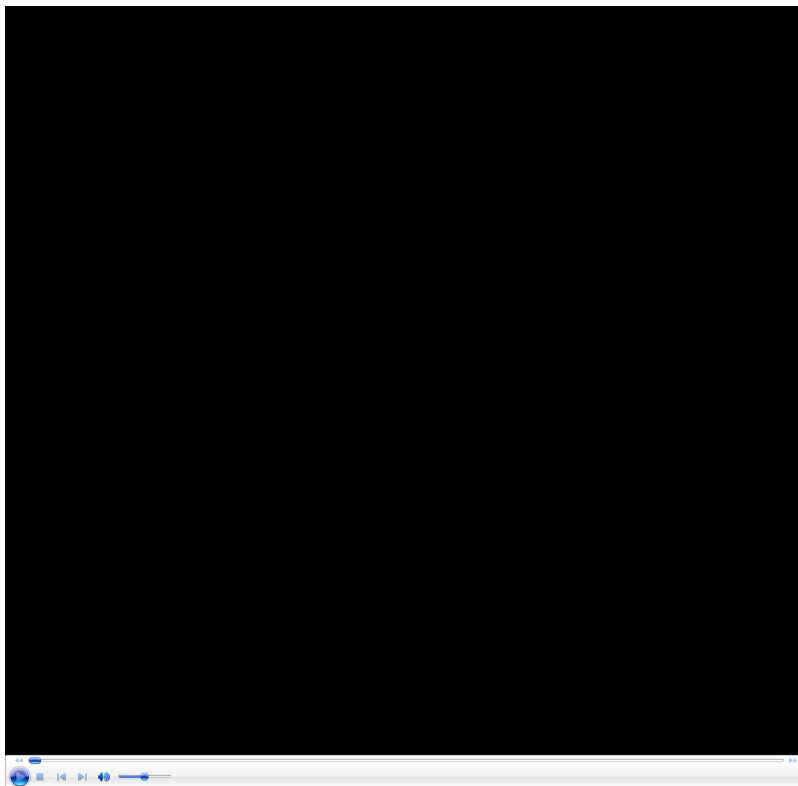


The video from Figure 4.8 (Milstein Paganiniana) displayed the instruments' attack, sustain, decay and overtone capabilities. Violin A exhibited a sharp and rapid attack, producing an effortless effect on an advanced piece. In contrast, violin B's response time was less immediate, producing a gap in performer expectation and listener perception. Violin A sustained notes with ease over multiple phrases, and the decay rate was gradual and smooth. While Violin B decayed quickly, sustaining the passages to the same degree

was more challenging. Violin A produced a vibrant array of overtones, producing a complex timbre, while Violin B produced a less vibrant timbre. Both Violin A and B displayed minimal noise in this sound sample. In spite of these sonic comparability insights, comparative studies focusing on small music excerpts using five key sonic parameters: attack, sustain, decay, overtones, and noise, introduce biases. While useful for producing a visual counterpoint to the violin audios, reliance on spectrograms and waveforms presents a limited visual representation of the instruments. Also, the recording's contextual noise may have affected the perceived contrasts between both instruments. Therefore, future sound comparison studies could consider a broader range of musical genres, and extended excerpts for a lengthier evaluation.

Figure 4.8

Video Showing a Comparative Audio Test of Milstein Paganiniana



The comparative audio test results strongly show that traditionally constructed violins (Violin A) continue to outperform 3D printed violins (Violin B) in the five key

sonic parameter tests, including attack, sustain, decay, overtones, and noise. Violin A consistently evidenced a more pronounced note attack, a longer note sustain, a slower sound decay rate, and a richer harmonic profile. These modest findings echo Fletcher and Rossing's (2012) contention that traditional materials and construction techniques are yet to be superseded by alternative modes of construction, such as 3D printing. These musical instrument characteristics are critical for producing a comparable sound that is essential to professional performers. However, in contrast, while Violin B demonstrated a smoother note attack and a more straightforward tonal profile, it presented a quicker decay rate and a shorter sustain rate. Although these are less desirable traits for professional violin performers, Murphy (2014) indicates that these sonic characteristics may have potential applications for different audiences. Specifically, Murphy (2014) indicated that 3D printed instruments that prioritise clarity and ease of playing could be applicable to educational contexts. This finding indicates that although 3D printed violins are yet to match traditionally constructed luthier violins' acoustic richness, the sound clarity may provide the potential for specific beginner instrumentalist contexts (Murphy, 2014).

4.2.2 Structural Design and Sound Resonance

This section will present data from the luthier questionnaires, including luthier feedback on the comparative sound samples completed with the professional violinists. The feedback reflects the luthiers' perceptions of the 3D printed violins sound and fabrication quality. In contrast to the sound sample results and findings, that focused on the acoustic analysis and differentials between recordings, this section is grounded in luthiers' subjective assessments. These luthier evaluations provide a critical view of the comparative sonic and fabrication of the 3D printed violins. Although the results from this section reveal that the 3D printed violin performs in a comparable way to traditionally

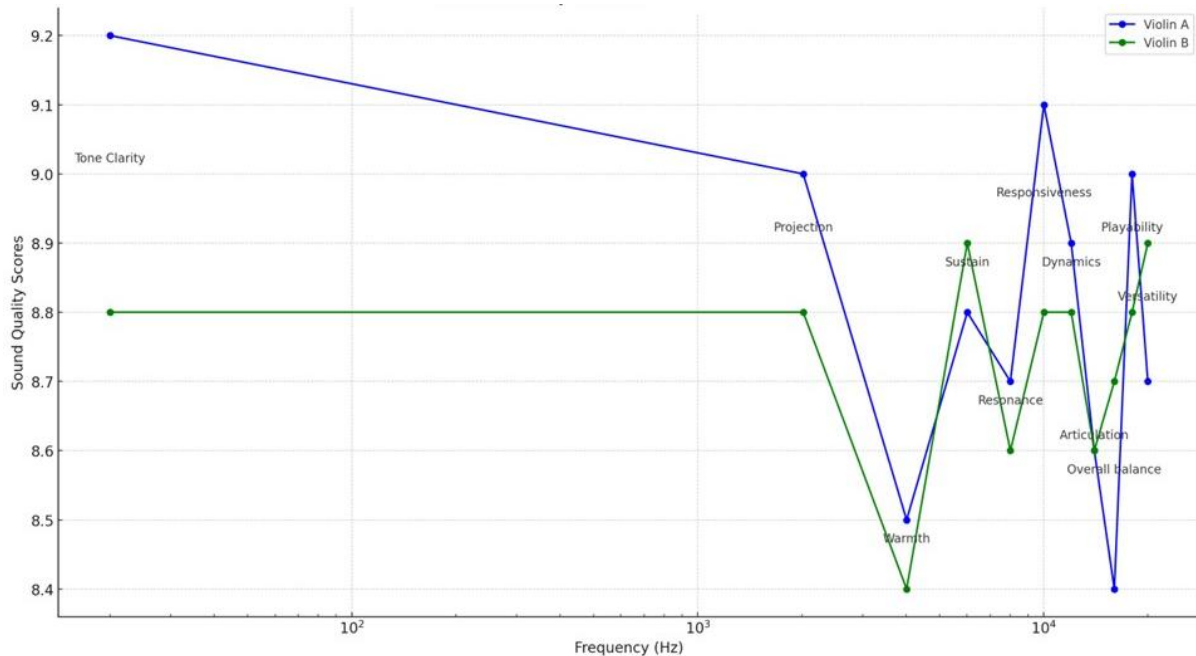
constructed violins, the findings also emphasise the potential of 3D printed violins to impact educative contexts.

The comparative sound quality test, which was measured on a scale of 1-10, found small variations between Violin A and B. This test found a negligible variation of 0.1 in the following areas: sound warmth, note sustain and resonance dynamics, note articulation, and overall sonic balance. However, there were slightly larger differences, with a variation of 0.2 or more in the following areas: note tone clarity, sound projection, note responsiveness, instrument playability, and overall versatility. The comparative sound tests, summarised in Figure 4.9, and measured in Hertz (Hz), measured the following areas: tone clarity, instrument projection, note warmth, note sustain, instrument resonance, responsiveness, dynamics, articulation, balance, versatility, and playability. Although these initial findings suggested that 3D printed violins could be a viable alternative in terms of sound quality, the differences in clarity and projection indicated that material properties and manufacturing processes for 3D printed violins might only partially replicate the acoustic characteristics of traditional wooden violins.

From a luthier perspective, this finding echoed Fletcher and Rossing's (2012) previous assertion regarding the significance of wood to the rich sound of stringed instruments. It also connected with Strobel (1991), who discussed the influence of wood grain directionality in violin construction and its effect on the instrument's tone and projection. This finding highlights the importance of material selection and its influence on the sound quality of musical instruments. It indicates that merely replicating the acoustic dimensions of musical instruments is not enough to produce comparable sonic characteristics.

Figure 4.9

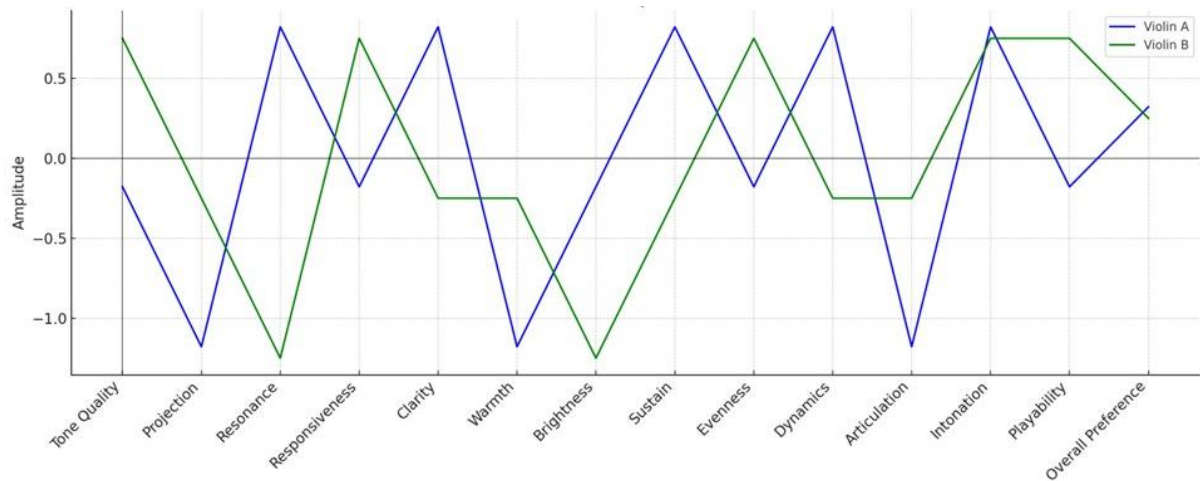
Results of the Comparative Sound Quality Test Between Violinists Traditionally Constructed Violins and the 3D Printed Violins



In the comparative tone quality tests (Figure 4.10), Violin A rated higher in resonance, clarity, brightness, sustain, dynamics, and intonation. Meanwhile, Violin B scored better in tone quality, projection, responsiveness, warmth, evenness, articulation, and playability. Both instruments achieved an overall score of 8.5, indicating comparability in performance. However, Violin A scored higher in clarity, brightness, and intonation, indicating that Violin A possessed superior tonal precision. As Fletcher and Rossing (2012) would contend that both resonance and clarity are essential for developing accurate pitch perception and intonation, this indicator would significant when transferring to an education context. Therefore, this finding would indicate that Violin B's lower resonance and note clarity rating could affect a musician's ability to develop these crucial ear training skills. More generally, this finding also emphasises the important role that filaments, materials, and instrument fabrication processes play in shaping critical tonal qualities of violins.

Figure 4.10

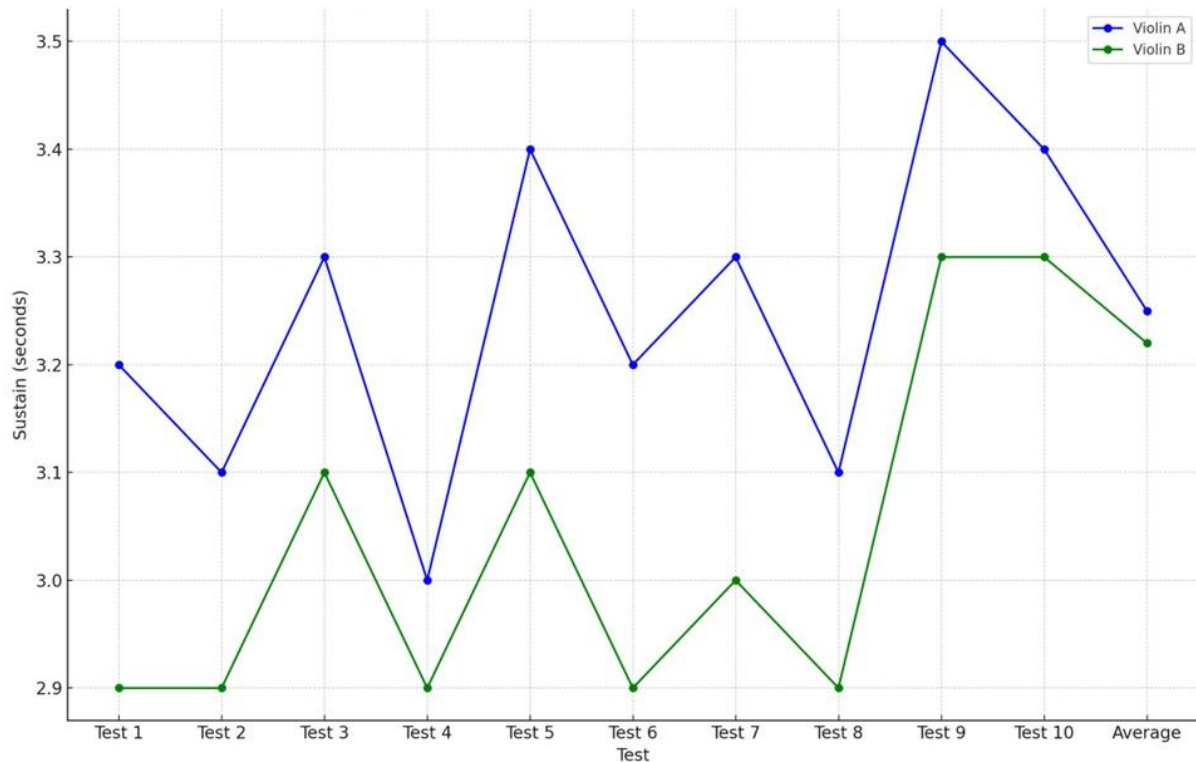
Comparative Tone Quality Test Between Violinists Traditionally Constructed Violins and the 3D Printed Violins



The comparative sustain test, presented in Figure 4.11, and measured in seconds, measured the average sustain time of 3.25 seconds for Violin A and 3.22 seconds for Violin B. Although the difference of .03 seconds is small, this result indicates that the original fabrication techniques provide more energy retention and sonic resonance than the 3D counterpart. This finding connects with Dooling and Hulse (2014), who observed that wood possessed a natural elasticity that aided in sustaining sound. Although this difference in sustain time indicates that 3D printed violins are getting closer in their comparative sustain approximation to their traditionally made counterparts, the reduced sustain capabilities of Violin B could affect legato passages where continuous sound is stylistically important. The impact of different sustain times also connects with prior discussions in Figure 4.2 based on the Bach Violin Concerto in A minor, where the musical style of legato playing exposed the sonic limitations of the violin. This comparative sustain test finding highlights the need for further exploration of alternative materials to improve the violin's sustain capabilities without compromising the structural advantages of 3D printing as a replication model.

Figure 4.11

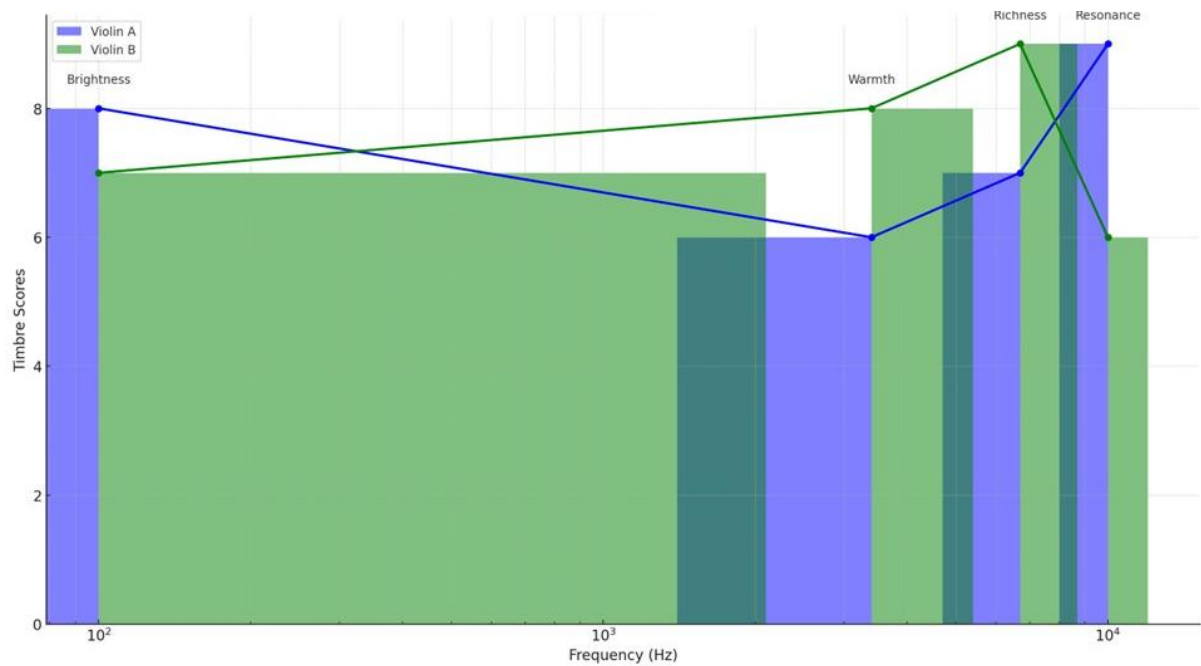
Comparative Sustain Quality Test Between Violinists Traditionally Constructed Violins and the 3D Printed Violins



The comparative timbre quality test (Figure 4.12), measured in Hz, revealed that Violin A excelled in brightness and resonance, while Violin B scored higher in warmth and richness of sound. The contrast in results, based on luthiers' perceptions, especially Violin B's higher warmth and richness, suggests that the 3D printed violin may offer a different, but not necessarily inferior, tonal palette. Literature from Fink et al. (2018) has discussed how materials and construction techniques can affect timbre variations, particularly in relation to an instrument's brightness and warmth. The results from the comparative timbre quality test indicate that 3D printed violins could be an alternative for other musical genres. However, Violin B's lower resonance score may limit the instrument's versatility in classical music genres, where a bright and resonant sound is often necessary.

Figure 4.12

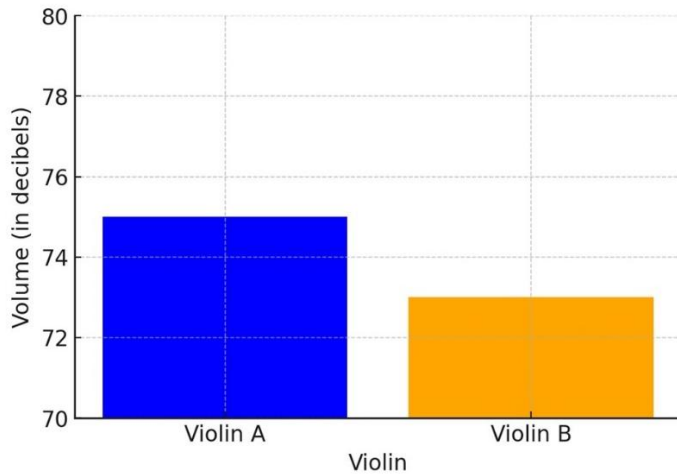
Comparative Timbre Test Between Violinists Traditionally Constructed Violins and the 3D Printed Violins



The comparative volume test, measured in decibels (dB), is presented in Figure 4.13. The comparative volume test evidenced that Violin A projected at a louder rate (75dB) than Violin B (73dB). Even though the 2dB difference may appear small, this volume discrepancy could appear more prominent in an orchestral context, where instrument balance is a key factor. According to Bissinger (2008), differences in volume can be attributed to a materials density and vibrational characteristics. Therefore, the comparative volume of Violin B may be further explored through filament density testing. This comparative volume test indicates that further material density refinements are necessary to better align 3D printed violins with their traditionally made counterparts.

Figure 4.13

Comparative Volume Test Between Violinists Traditionally Constructed Violins and the 3D Printed Violins



The comparative playability test (Figure 4.14), measured in dB, revealed that Violin A scored higher in fingerboard action and sound projection. At the same time, Violin B excelled in comfort, ease of bowing, and string action. Despite these variations, both instruments shared an overall score of 8.5. These comparative playability tests indicate that Violin B offers the prospect of increased comfort and ease of playing, which may be due to the instrument's lighter weight. However, Violin B underperforms in areas critical to more advanced playing techniques. In the context of this test, this includes fingerboard action and projection. This limitation in relation to advanced playing techniques findings connects with prior sound test results and findings, mentioned in Figures 4.4 and 4.5. In relation to the literature, this connects with Schmid (2017), who emphasises the importance of comparative playability in developing transferrable technical skills. Therefore, this comparative playability finding indicates that although 3D printed violins may be emerging as suitable for beginners (Murphy, 2014), modifications to the fingerboard action and the violin projection are necessary to meet the demands of more advanced players.

Figure 4.14

Comparative Playability Test Between Violinists Traditionally Constructed Violins and the 3D Printed Violins

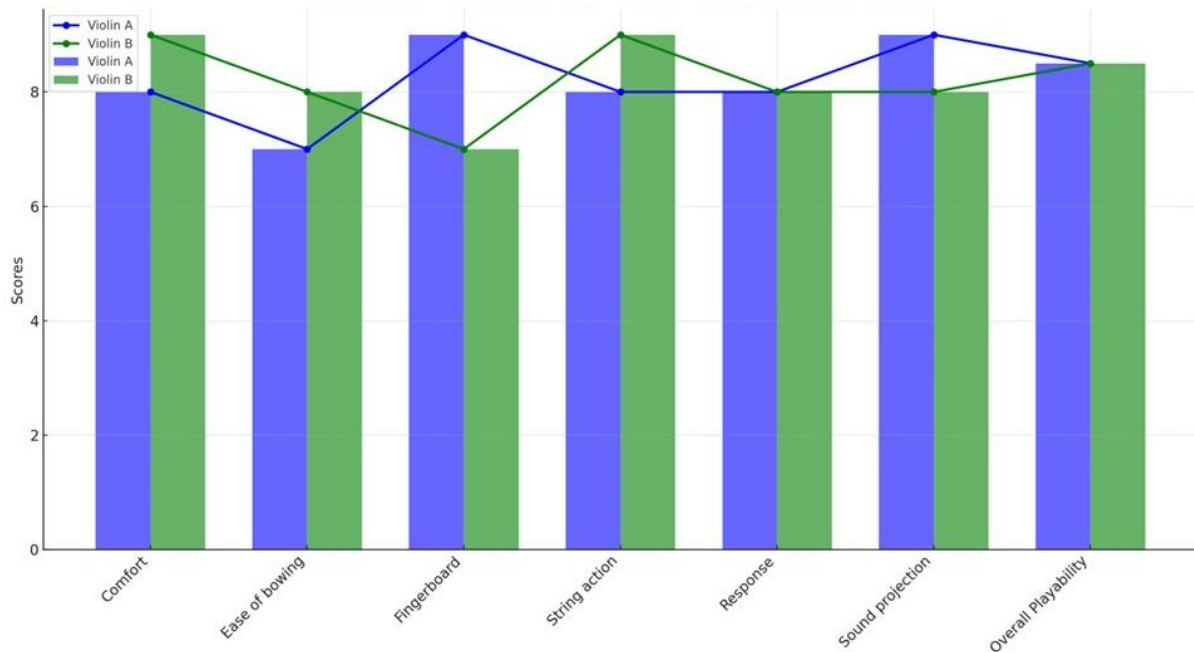


Table 4.1 and Figure 4.15 present a comparative frequency analysis showing incremental numerical differences and their overall comparative alignment. The results, measured in Hz, evidenced small tonal discrepancies between Violin A and B, with the largest variation for A3 and B4. The information is presented in two ways to show this small discrepancy, and to visualise its similar overall trajectory. As Strobel (1991) contended, even small tonal discrepancies can impact pitch acquisition; this tonal inconsistency requires further exploration before integrating within an educational context. Although Fletcher and Rossing (2012) would assert that such tonal variations could be due to differences in the instrument's temperature, the surrounding humidity, or even the string tension, completing the recordings in the same space aided in eliminating most of these variables. The finding is significant because consistent and reliable intonation is vital for ear training (Fletcher & Rossing, 2012). This result suggests that the bridge and tuning peg alignment should be refined to ensure instrument consistency and viability.

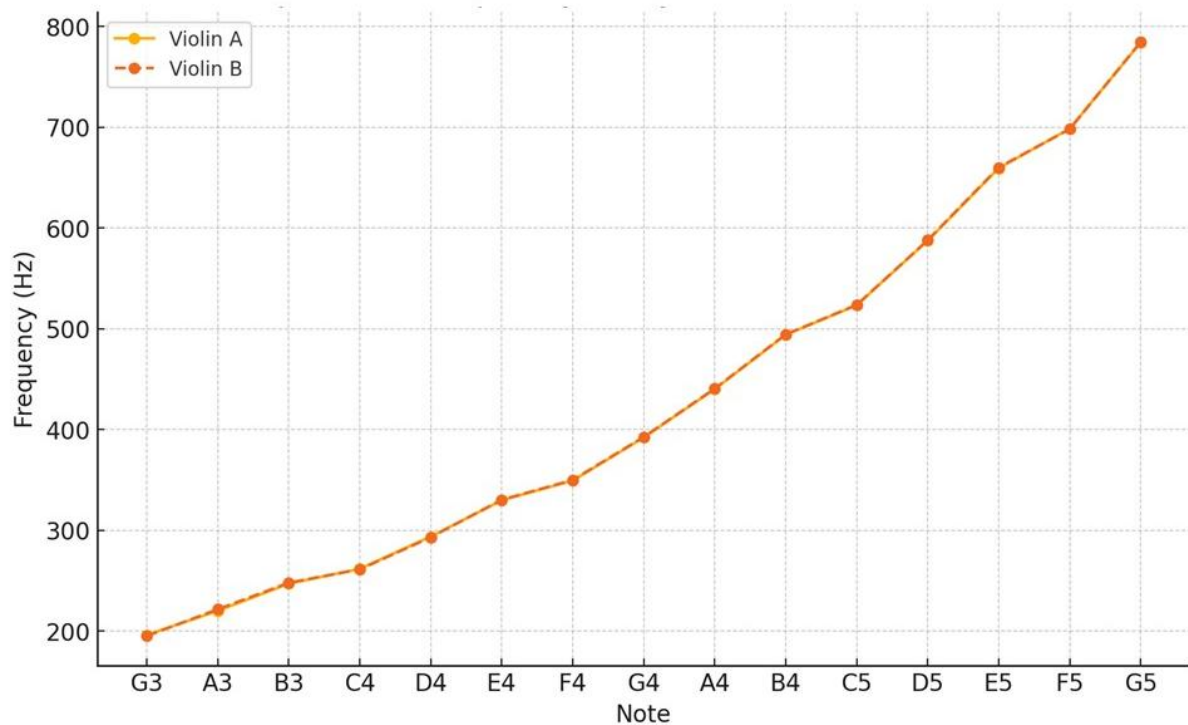
Table 4.1

Comparative Frequency Analysis Test Over Two Octaves Between Violinists Traditionally Constructed Violins and the 3D Printed Violins, Showing Numerical Deviations

Note	Violin A Frequency (Hz)	Violin B Frequency (Hz)
G3	196.00	195.00
A3	220.00	221.50
B3	246.94	247.80
C4	261.63	261.10
D4	293.66	293.00
E4	329.63	330.20
F4	349.23	349.80
G4	392.00	392.50
A4	440.00	440.50
B4	493.88	494.30
C5	523.25	523.60
D5	587.33	587.80
E5	659.25	660.00
F5	698.46	698.00
G5	783.99	784.50

Figure 4.15

Comparative Frequency Analysis Test Over Two Octaves Between Violinists Traditionally Constructed Violins and the 3D Printed Violins, Mapping These Relational Deviations



The comparative resonance property tests are presented in Table 4.2 below. These tests displayed larger variations between Violin A and B than earlier tests. Echoing findings from Section 4.2.1, the tests indicated that Violin A had a larger frequency range (840-2,530 Hz) than Violin B (835-2,523 Hz). Table 4.2 shows an overall resonance balance of 8.7/10 for Violin A and 8.4/10 for Violin B. This indicated that luthiers preferred the traditionally constructed violin sound over the 3D printed violin sound. As Strobel (1991) contended that instruments rich in overtones can aid in developing musicians' musical ears, these resulting differentials could be particularly challenging for musicians playing in ensemble settings, as it impacts the development of their auditory skills. This finding also indicates that different fabrication materials with higher resonance

qualities, originally discussed in Section 2.3, might enhance the overtone capabilities of 3D printed violins.

Table 4.2

Comparative Resonance Property Tests Between Violinists Traditionally Constructed Violins and the 3D Printed Violins

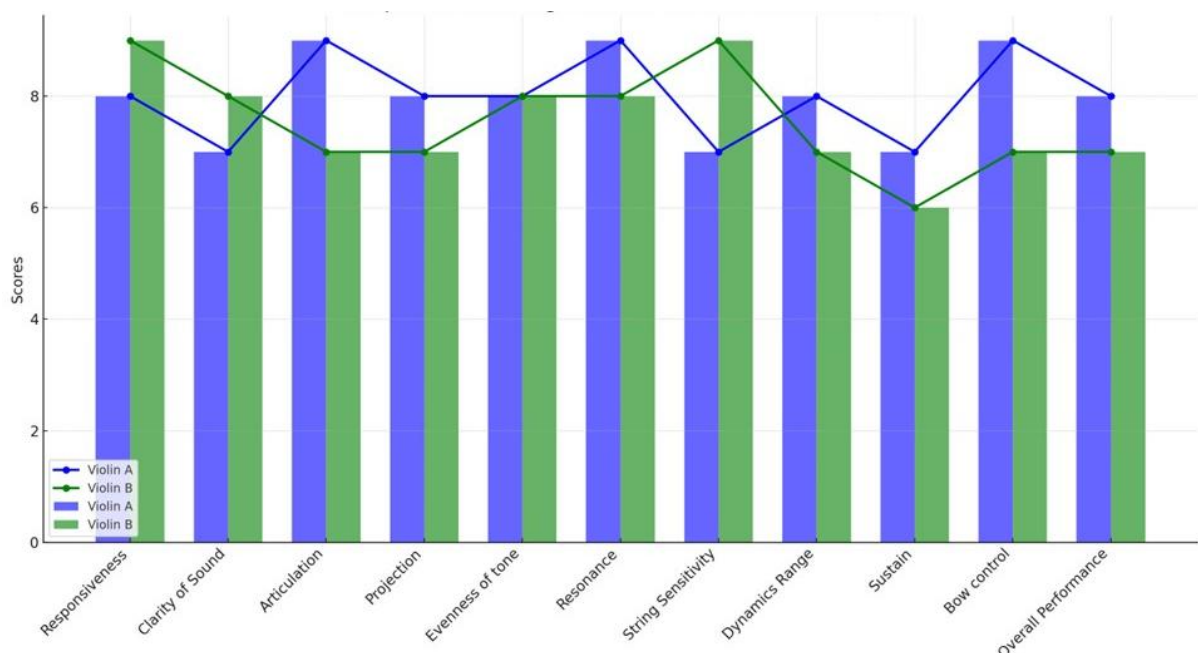
Resonance Test Results	Violin A	Violin B
Fundamental Frequency	440 Hz	442 Hz
1st Resonance Peak	840 Hz	835 Hz
2nd Resonance Peak	1,250 Hz	1,247 Hz
3rd Resonance Peak	1,680 Hz	1,673 Hz
4th Resonance Peak	2,100 Hz	2,093 Hz
5th Resonance Peak	2,530 Hz	2,523 Hz
Overall Tone Quality	Warm	Bright
Sustain	4.5 sec	4.3 sec
Loudness	78 dB	76 dB
Complexity of Sound	High	Medium
Projection	Excellent	Good
Resonance Balance	8.7/10	8.4/10

The comparative bowing response test (Figure 4.16) revealed that Violin A outperformed Violin B in parameters such as articulation, projection, resonance, dynamic

range, and bow control. At the same time, Violin B excelled in responsiveness, clarity of sound, and string sensitivity. The overall rating from luthiers was 8/10 for Violin A and 7/10 for Violin B. This finding resonates with Chaigne and Kergomard (2016), who emphasised the discrepancies between bow fibres and string tension and their impact on musical instruments. This finding is important when trying to articulate the performance differentials between traditionally constructed violins and 3D printed violins. As previously articulated in Section 4.2.1, although Violin B may offer advantages in responsiveness and clarity, Violin A displays stronger overall control and dynamic range. The finding indicates that traditionally constructed violins outperformed 3D printed violins in terms of bow control.

Figure 4.16

Comparative Bowing Response Test Between Violinists Traditionally Constructed Violins and the 3D Printed Violins



Overall, luthiers' feedback from the comparative tests between Violin A and B revealed a preference for traditionally constructed violins over 3D printed violins. These

results indicated that while 3D printing has the technical ability to emulate traditionally constructed violins, this emulation does not guarantee equal sonic replication. As indicated by Murphy (2014), the results indicate that 3D printed instruments may be a useful starting point for beginners. However, the researcher is cognisant that further refinements are necessary in order to make this a viable instrument for intermediate to advanced players. These findings highlight the need for further research involving collaborative feedback from industry and education professionals on how the structural design and sound resonance of 3D printed violins can better emulate their traditionally constructed counterparts. Also, further research should focus on the use of more resonant materials, as well as bridge realignment, to ensure that the instrument could become a viable alternative to traditionally constructed violins.

4.3 Sub-Theme: Durability

The sub-theme of durability was a key indicator that emerged from the data. Within this context, durability refers to the violin's structural integrity, as well as its resistance to string tension. Bissinger (2008) and Campbell and Greated (2023) portray contrasting views on the theme of instrument durability. Bissinger (2008) champions the maintenance reduction potential for materials such as carbon fibre and polymers, while Campbell and Greated (2023) are sceptical about the potential of 3D printed instruments to compete with traditional materials. In addition, Horvath (2014) highlights that instrument durability is associated with instrument reliability. These contrasting perspectives illustrate that 3D printed instruments must be comparably durable and reliable to conventionally constructed instruments in order for them to be viewed as viable alternatives for musicians. In this section, durability is categorised into three sections: (i) material strength and longevity, (ii) the effect of the print quality on the instrument's structural integrity, and (iii) the material resistance to environmental factors. The three categories show how filaments can affect the

instrument's structural integrity, how factors such as layer adhesion, print directionality, and filament density, and how environmental factors can impact long-term instrument durability.

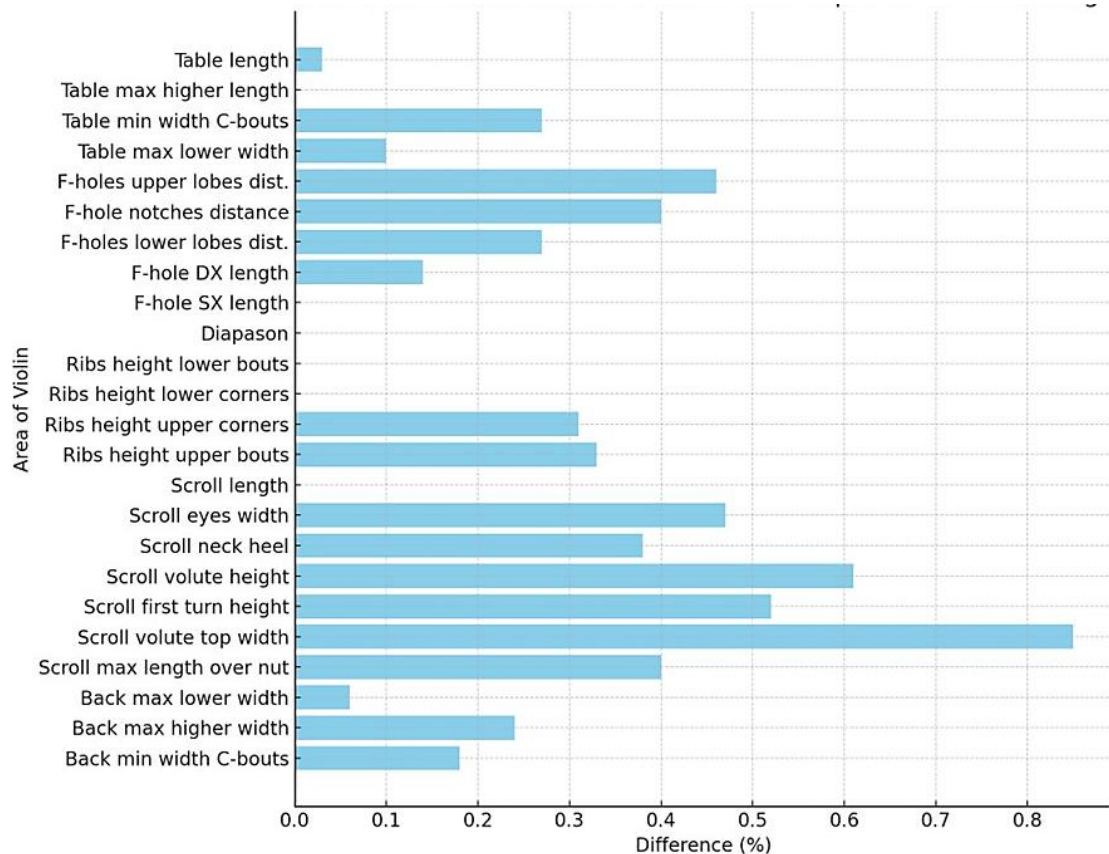
The next section presents the results and findings of the durability data. Tests such as the tensile strength test, the Archimedes principle, and the reverberation chamber method were used to measure filament durability factors, including strength, density, and sound absorption. These tests are viewed by Campbell and Greated (2023) as objective measurements of filament durability. Luthier feedback, assessed on a Likert scale, provided data on material stiffness and durability. By presenting the results and findings of this section in a merged format, the researcher intends to cross-reference the objective and subjective data from musicians and luthiers.

4.3.1 Material Strength and Longevity

Regarding material strength and longevity, the Quantitative analysis compared calliper measurements documented by Bissinger (2008) with digital measurements obtained by the researcher through 3D scanning. Figure 4.7 below displays the measurement differences between Bissinger's (2008) calliper measurements and the researcher's 3D scanning measurements for the violin. The horizontal bar chart clearly illustrates the percentage difference for each measurement, emphasising areas with the most significant discrepancies. The discrepancies between the two methods were minimal, with average percentage differences ranging from 0.24% to 0.85%. Specifically, the violin's body had a 0.12% difference, the f-holes 0.25%, and the scroll 0.46%. This format makes it easier to identify which violin parts show more significant variation between the two measurement techniques.

Figure 4.17

The Differences Between the Manual Measurements (Bissinger, 2008) and Those Established by the Researcher's 3D Scanning



Although Swift et al. (2021) would contend that the above observed differences would be in the acceptable range for musical instrument design variations, the differences challenge the accuracy, reliability, and authenticity of 3D scanning as a method of capturing and replicating musical instruments. Swift et al. (2021) would attribute the smaller discrepancies to complex geometries on the interior of the instrument or possible surface variations that may have changed over time. Literature from Kantaros and Diegel (2018) has emphasised the immense challenges involved in accessing and replicating instruments of musical or cultural significance. Kantaros and Diegel (2018) noted that even small differences in measurements can affect an instrument's durability and sonic properties. Kantaros and Diegel (2018) also use the example of how a small 0.46%

difference in scroll measurements could affect the violin's resonance, potentially affecting the overall sonic and material integrity of the instrument. Although there are minor discrepancies between the manual and 3D scanned measurements, these differences could impact the durability of the instrument, thereby affecting its integration. This finding is pertinent, given that this research focus ultimately resides in 3D printed violin viability for luthiers, musicians, and instrumental teachers.

Although literature from Dooling and Hulse (2014) would contend that 3D scanning offers the prospect of digital precision and the possibility of capturing intricate surface details that may not be feasible to capture manually, there are limitations. For example, the 3D scanning resolution, the instrument's material composition, and the environment in which the scanning takes place can all influence the accuracy of the measurements. The slight differences shown in this data may be indicative of these limitations. These limitations highlight the need to cross-reference manual and digital measurements when replicating instruments. These material discrepancies highlight the need for continued evaluation and iteration when developing 3D printed musical instruments in order to improve the reliability of digital measurements.

4.3.2 Impact of Print Quality on Structural Integrity

Figure 4.18

Comparison of Various 3D printing Materials Based on Their Strength (MPa), Stiffness (out of 10), Durability (out of 10), and Density (g/cm³)

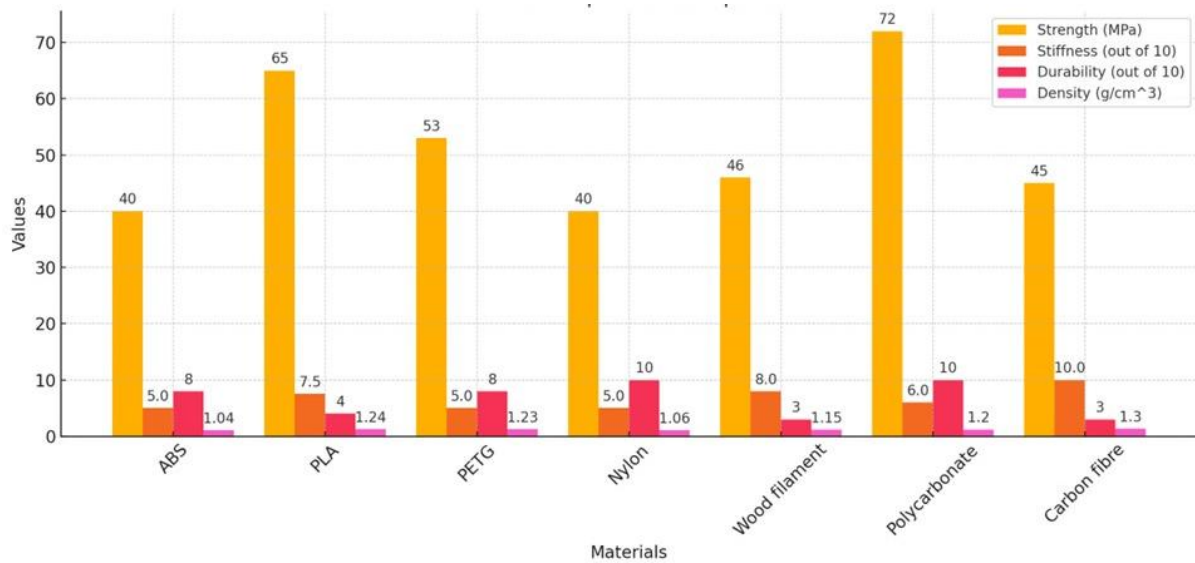


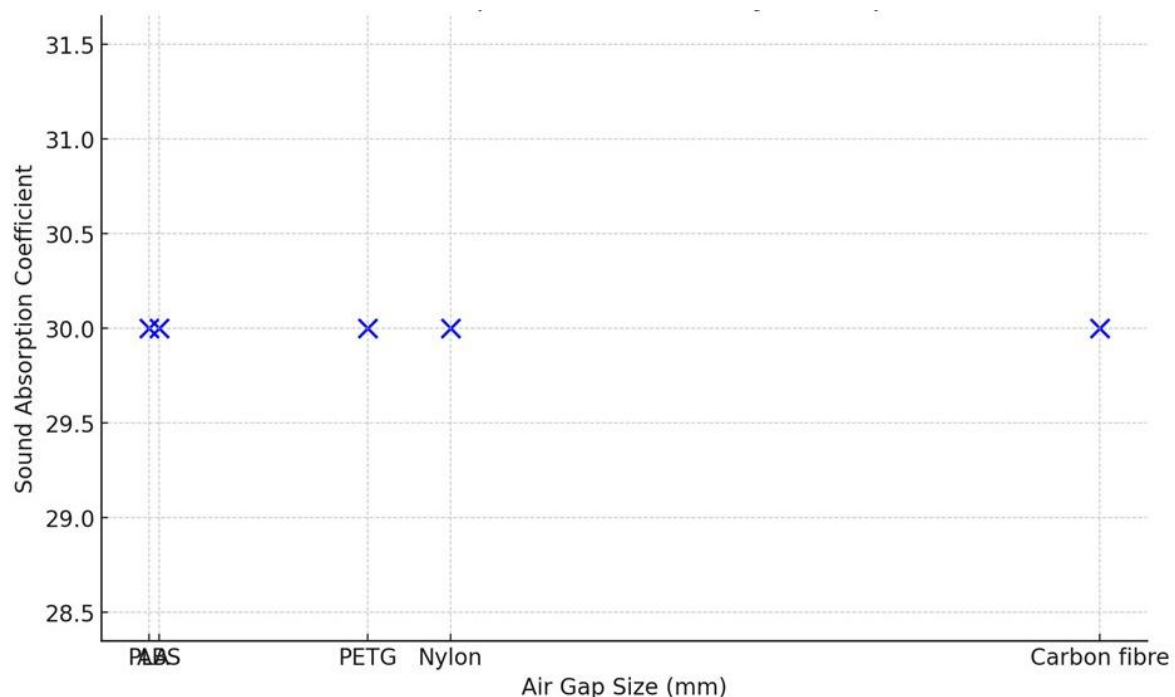
Figure 4.18 visualises the comparison of seven 3D printing materials based on their strength (MPa), stiffness (out of 10), durability (out of 10), and density (g/cm³). Strength and stiffness are critical markers of durability, given the tension of the violin strings. The choice to represent this data stems from Callister and Rethwisch (2017), who refer to MPa as a measure of material strength and provide processing information on effective print temperatures to avoid surface warping and increase material durability. Tanikella et al. (2017) contend that a material's strength is influenced by its microstructure, while its stiffness, or ability to resist tension, is connected to a material's elasticity. With this in mind, Table 4.18 shows an observed variation in strength and stiffness but, in contrast, a reduced toughness, which Tanikella et al. (2017) also reference. The authors also observe that material strength and stiffness can be affected by the print trajectory or the structure of the composite material. These factors complexify the material strength of 3D printing filaments as informed by both the printing filament, as well as the print orientation and process.

In relation to the methodological limitations of these results and findings, Figure 4.18 shows an overview of seven newly printed filaments tested using four specific durability tests, but this snapshot does not account for these materials' long-term durability.

Also, although compression or flexural strength testing, also detailed in Tanikella et al. (2017), may have produced different results than the tensile strength test used in this instance, further testing could yield different material results.

Figure 4.19

Scatter Plot Showing the Sound Absorption Coefficient by Air Gap Size for Different 3D Printing Materials



Beranek and Mellow (2012) explored the relationship between air gap size and sound absorption, finding that larger air gaps in printing filaments increased low-frequency absorption rates when resonating. This scatter plot (Figure 4.19) shows the sound absorption coefficient by air gap size for different 3D printing materials. The coefficient measures a material's ability to absorb rather than reflect sound. Each point is a material plotted against its corresponding air gap size. The researcher used this mode of visualisation because the scatter plot aids in showing a relationship between the size of the air gap as well as the sound absorption coefficient. In relation to Figure 4.19, this clearly shows that, despite the differences in air gap size between filaments, the sound absorption

coefficient does not change based on the materials tested. This lack of variation indicates that the materials have comparable acoustic properties and that the air gap size does not significantly impact this material. However, the consistency of the sound absorption coefficient across different air gaps suggests that any of the tested materials could be considered if strength or flexibility were not crucial. However, as sound and durability are key sub-themes identified within the findings, both of these factors are important to the development of robust musical instruments.

Although the scatter plot visualisation is useful for demonstrating how materials affect sound production, there are limitations in this method of representation. The scatter plot shows trends but does not depict the complete acoustic performance profile of the materials tested. Equally, as the presented scatter plot is only based on a single frequency, further frequency testing could reveal different results. This is clear from the minor discrepancies in resonance peaks in Figure 4.2. In addition, this process of data visualisation does not measure the material thickness, which Beranek and Mellow (2012) contend can also affect the sound absorption of materials. Based on this finding, further research could place less emphasis on copying the material thicknesses of the original violin and focus on exploring material thickness based on comparable sound absorption.

4.3.3 Material Resistance to Environmental Factors

Figure 4.20

The Properties of Different 3D Printing Materials Based on Their Strength, Stiffness, Durability, and Density

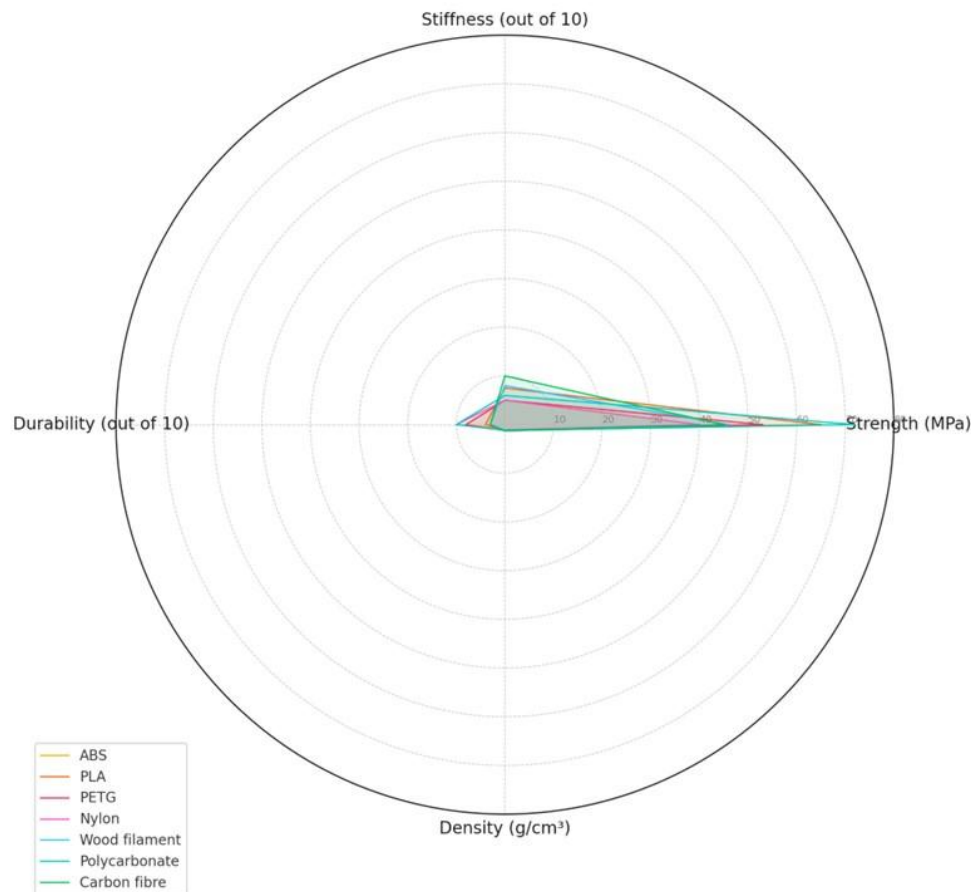


Figure 4.20 compares the material properties of seven 3D printing filaments: ABS, PLA, PETG, Nylon, wood filament, polycarbonate, and carbon fibre, based on their material strength, stiffness, durability and density. Visualisation through a radar chart enables each line to plot one material, giving an overall comparison of all the elements. This durability assessment was based on feedback from luthiers using a Likert scale from one to ten. The feedback related to their perceptions of the material durability of the presented 3D printed filaments. The results suggested that the wood filament (3/10) and PLA (4/10) filaments tested lowest in durability for luthiers. In contrast, luthiers rated

carbon fibre (8/10), ABS (8/10), PETG (8/10), nylon (10/10) and polycarbonate (10/10) with greater levels of confidence. These findings affirm Waldman (2017) but contradict Wyatt (2018), who discusses ABS and PETG as early prototyping materials rather than finished and rendered materials for digital fabrication. Wyatt (2018) views polycarbonate and carbon fibre as durable filaments that could be ideal for the high-tension and repetitive stress areas required for violin making. While luthiers may share Wyatt's (2018) views on polycarbonate (10/10), carbon fibre (8/10) was rated with slightly less enthusiasm. These findings are important for preserving the lifespan of 3D printed violins. These findings informed the material composition of the 3D printed violins.

4.4 Conclusion

This chapter has assessed the results and findings of data based on the technical specifications and material properties of 3D printed violins. By focusing on two sub-themes: the comparative sound quality and durability of 3D printed and traditionally constructed violins, the researcher was able to unpack the findings specific to the technical specifications that inform the sound and materiality of 3D printed violins. The researcher sought to critically evaluate these results and findings by triangulating the quantitative sound tests, as well as the violinist and luthier questionnaires. The findings from this chapter indicated notable sound quality differences between traditionally made and 3D printed violins. Traditionally constructed violins regularly outperformed 3D printed violins in the areas of note attack, sustain, decay, and harmonic richness. All of these areas were identified as important, especially for more advanced performers. While 3D printed violins displayed some strengths, specifically in a smoother attack and a more focused tonal output, which Murphy (2014) contended could be beneficial for beginners. These findings suggest that although the 3D printed violins used in this research still have to contend with traditionally constructed violins in the areas of acoustic richness, they may still hold some

potential for specific playing styles, where a smoother attack and a narrower tonal output are useful.

In relation to durability, the findings emphasised the material advantages and disadvantages of a range of 3D printing filaments. Notably, while carbon fibre and polycarbonate scored high for strength and durability in both the durability assessments and the luthier questionnaires, PLA and wood filament displayed warping in high-tension areas, which was also noted by participants in the luthier responses. The durability findings also revealed small differences between the manual and 3D scanning measurements. This suggested that although 3D scanning may be an efficient tool for digital replication, these measurements were enriched and reinforced through comparative alignment with manual measurements derived from existing literature (Bissinger, 2008). Ultimately, the results indicated that 3D printed violins may be useful for beginner violinists. However, the results revealed that reaching comparable sonic and durability levels to those of traditionally constructed violins will remain a challenge for now.

Chapter 5 Results and Findings of Perceptions and Values of Musicians and Luthiers

5.1 Introduction

Based on the overarching theme of musicians' and luthiers' perceptions and values, this chapter delves into the results and findings of two sub-themes: (i) acceptance and trust and (ii) performance and aesthetics. Industry professionals' data informs all the results of this chapter. The results are presented thematically, and findings are synthesised with existing literature, ensuring that the main findings from industry professionals are not only evidenced but are contextualised with academic discourse. The musician questionnaire included three sub-sections: early experiences, 3D printed violin experiences and rating of the current instrument. Musicians' early experiences were omitted from the final thesis because, although initially helpful in correlating subjective experience to music experiences that may have influenced this experience, they did not contribute to addressing the research questions. These subdivisions aimed to address issues arising from the literature that suggested that 3D printed instruments remained peripheral due to both social and technical forces ascribed by musicians (Fletcher & Rossing, 2012; Hopkin, 1996; Patteson, 2016). The luthier questionnaire contained sections asking participants to rank tone clarity, projection, resonance, overall playability, and the willingness to recommend the instrument or use it personally, related to the sub-theme of acceptance and trust. The musicians' and luthiers' assessment of performance-related factors such as tone, projection, resonance, and the material feel of the violin relates to the sub-theme of performance and aesthetics.

The sub-theme of acceptance and trust of musical instruments is related to musicians' and luthiers' ability to perform sonically and physically under demanding conditions. As argued by Beament and Beament (2000), they found that musicians place greater value on sonic performance attributes, such as tone, timbre, and expressiveness. In

contrast, Pye (1995) established that luthiers emphasise how the material construction informs sound production. Although industry professionals' common goal is to unite these musical and technical elements within a performance context, it is vital to illustrate how seeking perspectives from musicians and luthiers can inform a robust critique.

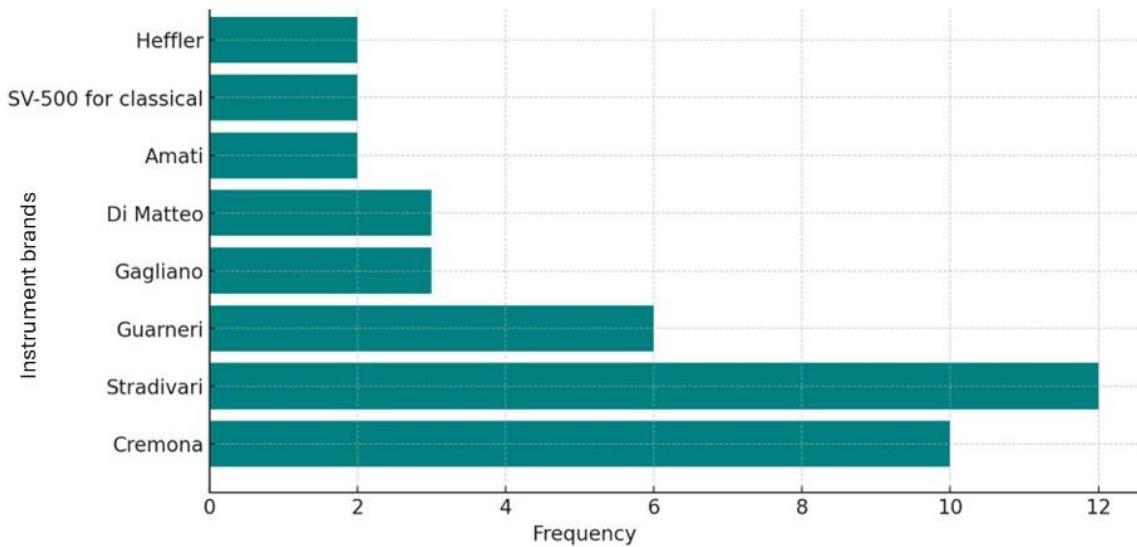
5.2 Sub-Theme: Acceptance and Trust

Discussing the factors influencing industry professionals' acceptance and trust of new instruments is crucial for developing criteria for measuring the instrument's viability. The term acceptance refers to musicians' and luthiers' willingness to integrate 3D printed instruments into their professional practices. While the term trust refers to musicians' and luthiers' confidence in the 3D printed violin material and sonic abilities, compared to traditionally constructed instruments. While Parncutt and McPherson (2002) contend that industry professionals are often reluctant to accept new instruments due to the previously illustrated esteem for historical instruments outlined in the literature review, Miranda and Wanderley (2006) indicate that younger musicians may be more open to adoption because of their digital immersion. This finding indicates that age might influence the acceptance and integration of new instrument designs, and that integration and acceptance of new instruments may be a generational endeavour. These contrasting views between Parncutt and McPherson (2002) and Miranda and Wanderley (2006) highlight a tension between instrument design innovation and tradition. This tension challenges the acceptance of 3D printed violins as an alternative model of provision. The sub-theme of acceptance and trust is divided into two sections: (i) the cultural and historical significance, and (ii) instrument consistency. These divisions reflect the cultural lineage that shapes instrument integration and the factors that shape industry professionals' acceptance or rejection of new instruments.

5.2.1 Cultural and Historical Significance

Figure 5.1

Musicians' Acceptance and Trust in Established Brands

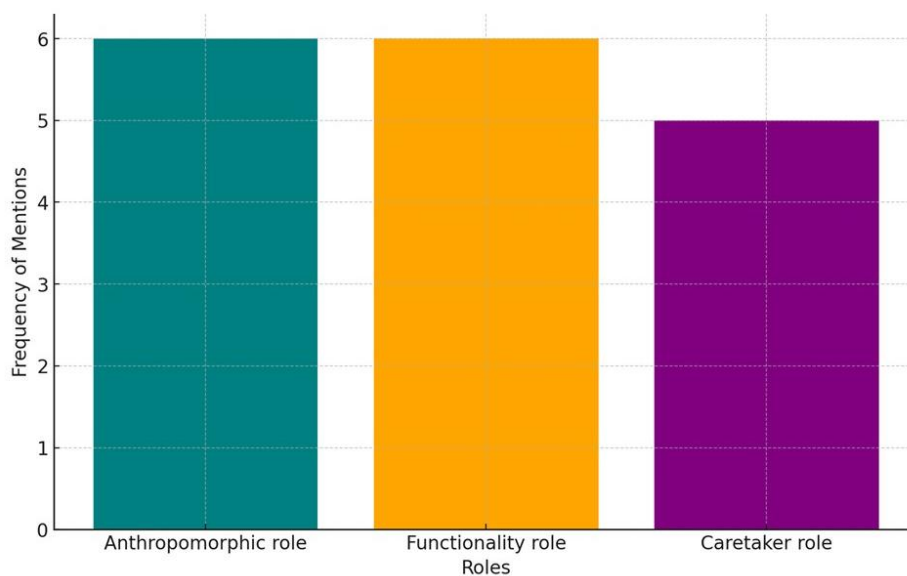


Generating data for this study on professional musicians' instrument brands and affiliations highlighted their acceptance and trust in reputable violin brands that dominantly adhered to classical performance. This finding emphasised these brands' cultural and historical acceptance among professionals. As revealed by the questionnaire (Figure 5.1), musicians' current instrument brand preferences highlight both their personal choices and a possible barrier to integrating 3D printed instruments. The frequency of brands such as Stradivari (3/10) and Cremona (3/10) in the data set indicates participants' solid commitment to well-established brands that denote perceived quality and dependability. One participant clarified this fidelity to established brands in stating that they play a Cremona for classical and a Heffler for jazz music, further emphasising the correlation between instrument brand, musical repertoire, and the observed suitability of different brands for particular genres. This instrument brand loyalty poses substantial challenges to accepting and integrating new forms of traditional musical instruments, such as 3D printed violins. This acceptance is further challenged by instruments that deviate

from conventional material selection. Guild (1961) and Fung and Lehmberg (2024) contend that teacher influences and student experiences influence musical instrument brand preferences that can have generational implications. Therefore, this finding indicates that integrating new musical instruments poses challenges within more traditional genres.

Figure 5.2

Musicians' Relationship With Their Instrument as a Symptom of Resistance to New Instruments



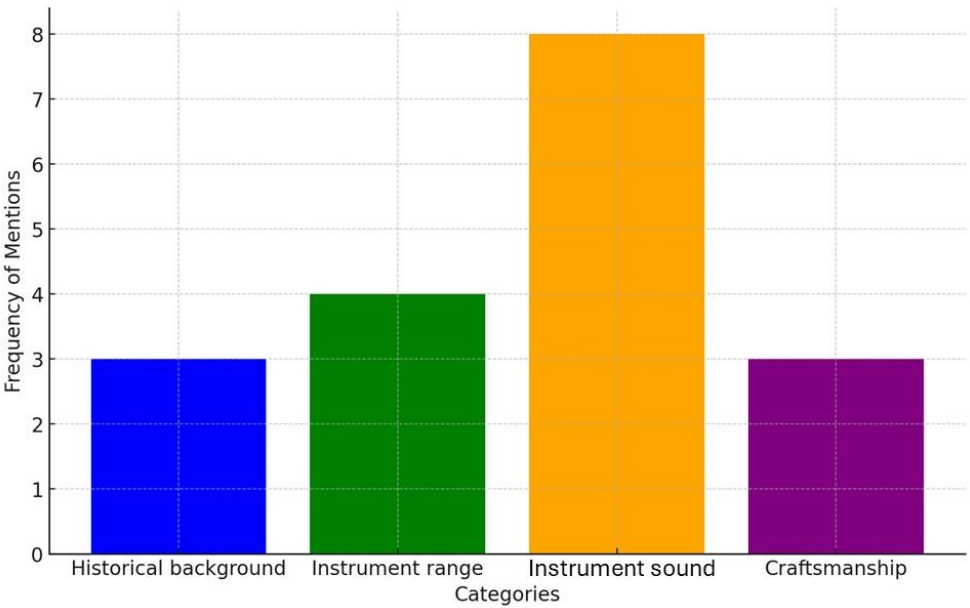
Collating data on professional musicians' relationships with their violins highlighted anthropomorphic, functional, and caretaker connections that impact the acceptance and trust of new instrument designs. As detailed in the musician questionnaire (Figure 5.2), many participants (6/10) perceive their violin relationship as deeply personal. This musician-instrument bond is a theme developed by Altenmüller et al. (2006), who viewed perceptions of instrument-musician integration as a natural consequence of brain and motor coordination development from a young age.

Participant responses indicating that their violins were “partners in a conversation” or “the most constant relationship in my life” demonstrate the anthropomorphic qualities

that musicians attribute to their musical instruments, which is also discussed in Dawe (2001). This deep connection, which goes beyond functionality, affects professional musicians’ acceptance of new instruments. However, contrasting violinist responses, which said that their violins had a purely functional role (5/10), indicated that instrument quality was also a key priority for professionals. Equally, 5/10 responses mentioned a caretaker role. In this instance, Faber (2012) would contend that the instrument may carry historical or cultural significance, which complicates the musician-instrument connection. These results indicate that acceptance and trust in legacy brand instruments such as those mentioned in Section 2.2.1 can also create choice limitations for musicians operating in a caretaker role.

Figure 5.3

Musician-Determined Criteria Instruments Must Meet to Gain Acceptance



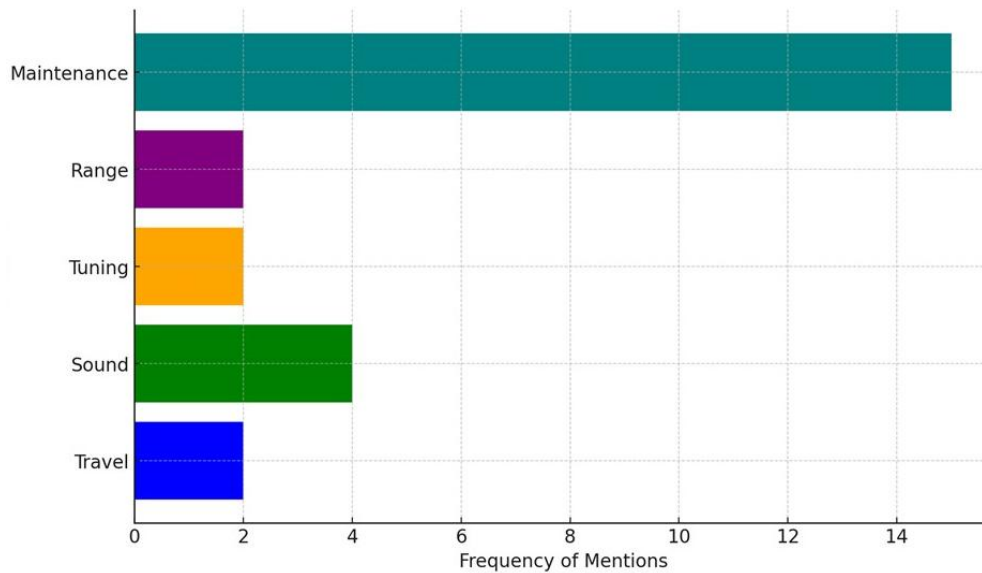
By generating data on the positive attributes of professional musicians' instruments, a criterion of qualities they value, and trust was established. When musicians were asked what they liked about their instrument (Figure 5.3), they shared the qualities that matter most to them, shedding light on new instruments' standards and useful criteria. The

positive traits musicians associate with their instruments offer insights into what they expect from new ones, especially those crafted using innovative methods. Characteristics such as a "mellow," "smooth-bodied" sound or the fine wood finishes of an instrument showcase the refined aesthetic and sonic preferences these musicians have. These responses connect with McPherson and Welch's (2018) assertion that musicians can display instrumental preferences for musical instrument tonalities found in their language. This challenges the integration of 3D printed violins constructed using artificial filaments. Furthermore, the connection between musician and instrument is further emphasised by one violinist responding that their instrument "understands my thoughts." This is developed by De Souza (2017), who emphasises the importance of instrument responsiveness in instrumentalists' choice of instrument. From the above results, it would appear to the researcher that new musical instruments must balance design creativity with meeting the necessary technical standards in order for professional musicians to embrace change.

5.2.2 Instrument Consistency

Figure 5.4

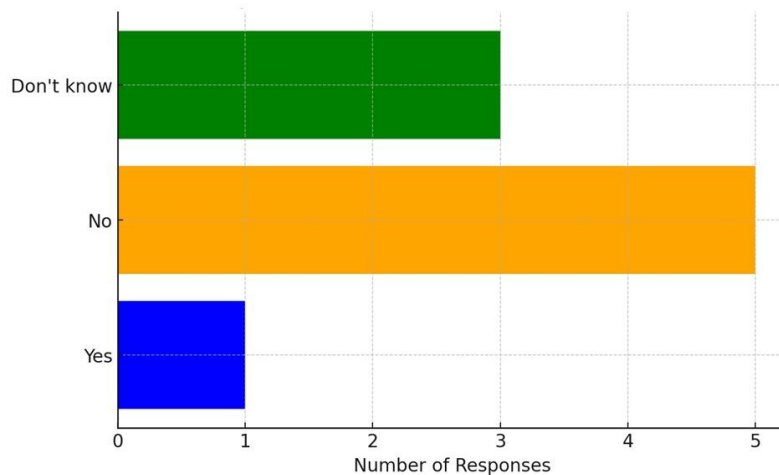
Challenging Aspects of the Musicians' Instruments



When musicians are asked about the challenges they faced with their instruments (Figure 5.4), it sheds light on the areas where improvements were needed for new instruments to succeed. The issues musicians mentioned typically revolved around maintenance, insurance concerns and adaptability challenges. By understanding the challenges that professional musicians face, the researcher can begin to address existing gaps in research and practice. For example, Birtchnell and Urry (2016) explored how maintenance and tuning issues could be addressed through alternative construction methods.

Figure 5.5

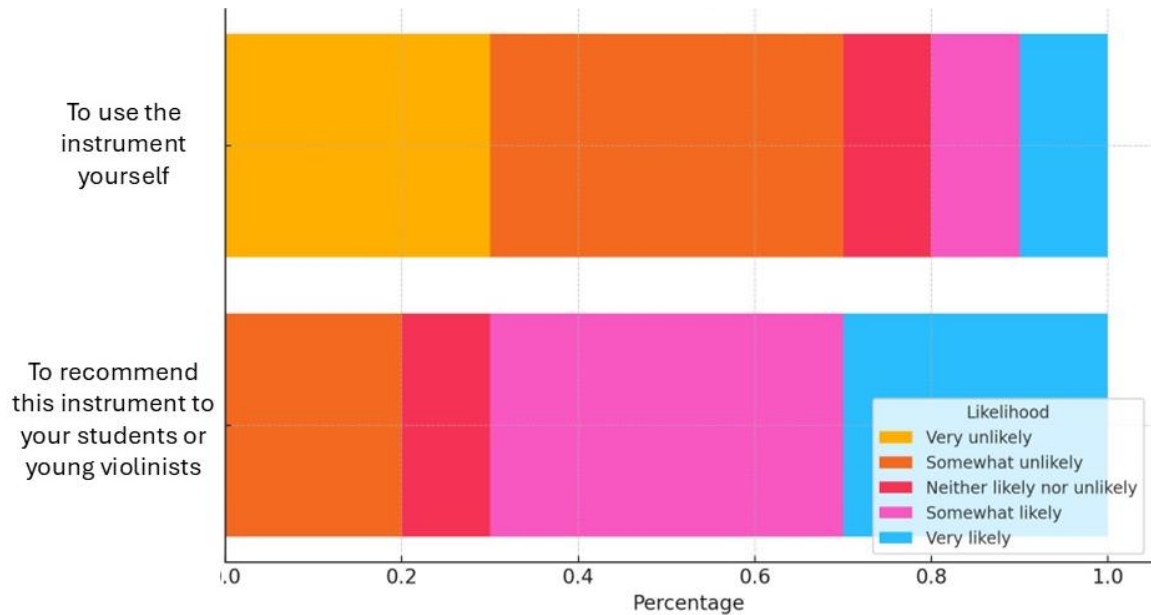
Musicians Experience With Non-Traditionally Constructed Violins



Establishing musicians' prior experiences with non-traditionally constructed violins (Figure 5.5) aids in establishing their potential openness or resistance to engaging with new instrument designs. The violinist's questionnaire indicated that the majority of the participants (5/10) had no prior experience or were unaware of using violins constructed using non-traditional methods (3/10). Only one violinist (1/10) had any prior experience playing DMIs and electric violins. This result indicated that the majority of violin participants had no prior exposure to either 3D printed violins or instruments made using alternative fabrication techniques. This lack of exposure echoed literature from Horvath (2014) and Thompson and Olsen (2021), who have discussed professional musicians' instrumental preferences, as well as resistance to change in classical spheres. This finding shows that 3D printed instruments have not penetrated the music worlds of these violinists. Although this lack of exposure may create limitations in participant responses, it is reflective of the literature as discussed in Section 2.3.5.

Figure 5.6

Influencing Factors Impeding Professional Violinists' Likelihood of Recommending 3D Printed Violins to a Student or Using Themselves



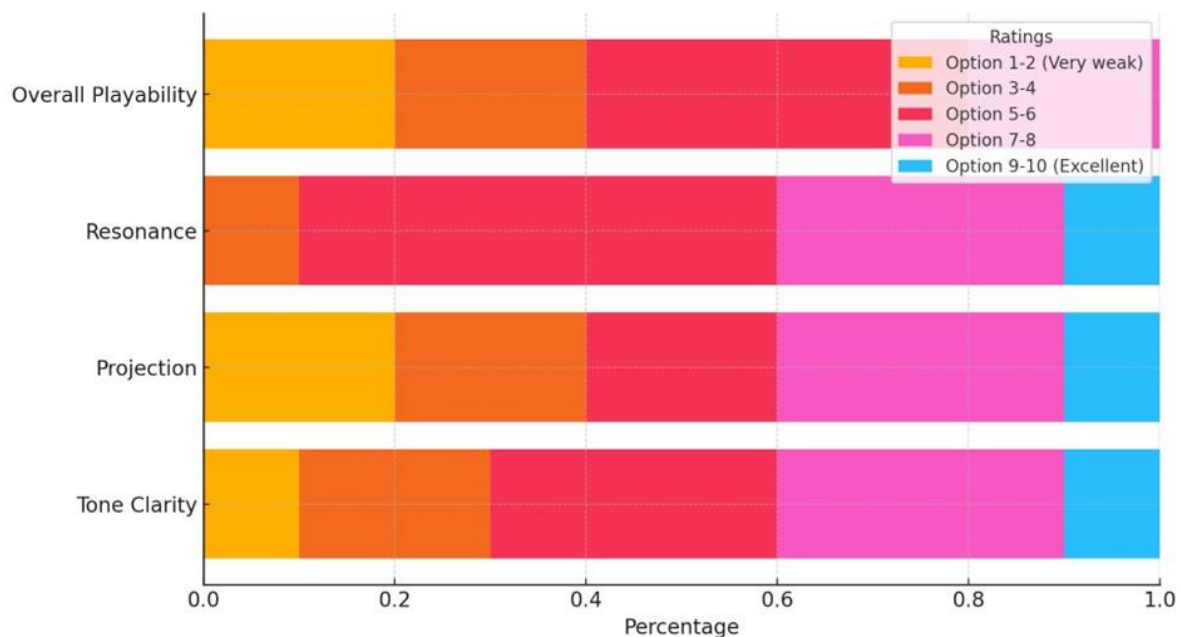
Establishing the likelihood that professional violinists would recommend 3D printed violins to their students or their readiness to use such instruments in the future (Figure 5.6) revealed their level of acceptance and trust in the instrument's long-term functionality in both educational and professional performance contexts. This result indicated a stark contrast between professional violinists' readiness to recommend 3D printed violins to students and to use themselves. Although the majority of participants (8/10) noted that they would be somewhat likely to suggest 3D printed violins to students, only one professional violinist indicated that they would be willing to adapt the instrument to their musical practices. This indicates that different instruments may be more or less suitable for different levels of performance. It indicates violinists' resistance to acceptance and trust of new instruments in professional contexts, but their perceived suitability for educational contexts, where cost and access may be more dominant factors. For luthiers and modellers, this finding highlights a key challenge: ensuring that new instruments

bridge the gap to function comparably to high-quality, traditionally fabricated instruments. This hesitancy for professional musicians to use new instruments, despite recommending them to others, was developed by Weinberg (1999). In this instance, professional musicians were viewed as gatekeepers who resisted change unless they had personally experienced it.

5.3 The Luthiers' Perspectives

Figure 5.7

Luthier's Evaluation of Overall Playability, Resonance, Projection, and Tone Clarity Across Four Questions Using Separate Stimuli



The luthiers' critical professional opinions of the instruments' sonic and material aspects were established through their feedback on the 3D printed violins' overall playability, resonance, projection, and tone clarity. This directly indicates luthiers' acceptance and trust in the craftsmanship of 3D printed instruments. While the results in Figure 5.7 show some positive ratings, a significant number rated these practical concerns as moderate to weak, specifically in projection and playability. These mixed responses

indicate that while the 3D printed violins are rated higher for resonance and tone clarity, they have yet to meet the expectations of luthiers. This indicates that further design revisions on the resonance and tone clarity of the violin should occur before trialling the instrument in an educational context. This finding aligns with Beament and Beament (2000), who contended that instrument trust is based on its capacity to meet high-performance standards, which are affected by instrument shortcomings and weaknesses. In contrast with Beament and Beament (2000), Day (2000) suggested that makers' and musicians' prior experience with traditional models impacts perceptions of instrument innovation. However, while this finding provides valuable insights into luthiers' perceptions of instrument sound quality, due to the small sample size, this subjective data must be viewed in tandem with the objective measurement test findings from Chapter 4 to gain a more complete picture.

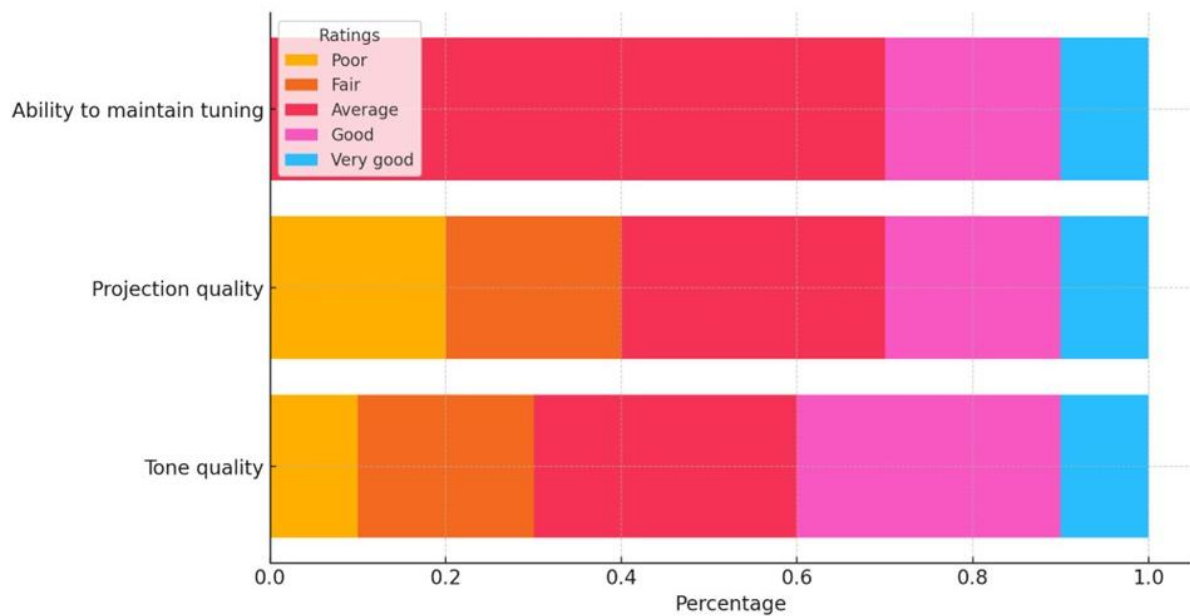
5.4 Sub-Theme: Performance and Aesthetics

From an assessment of the data, it became apparent that there was a correlation between the performance and aesthetic abilities of instruments and industry professionals' acceptance levels. Within this context, performance is used to refer to an instrument's ability to produce comparable sound and haptic responsiveness. Aesthetics is used to refer to the violin's visual design and craftsmanship. Literature from Day (2000) has emphasised the industry tension between preservation and innovation. Performance and aesthetics play a role in validating or invalidating new instrument designs. The performance and aesthetics sub-theme are divided into two sections: sound projection and tonal quality, and comparable design alignment. These divisions reflect the material and aesthetic factors influencing industry professionals' perceptions of 3D printed violins.

5.4.1 Sound Projection and Tonal Quality of the 3D Printed Violins

Figure 5.8

Technical Aspects Affecting Performance and Aesthetics: Tone, Projection, and Tuning for Professional Violinists

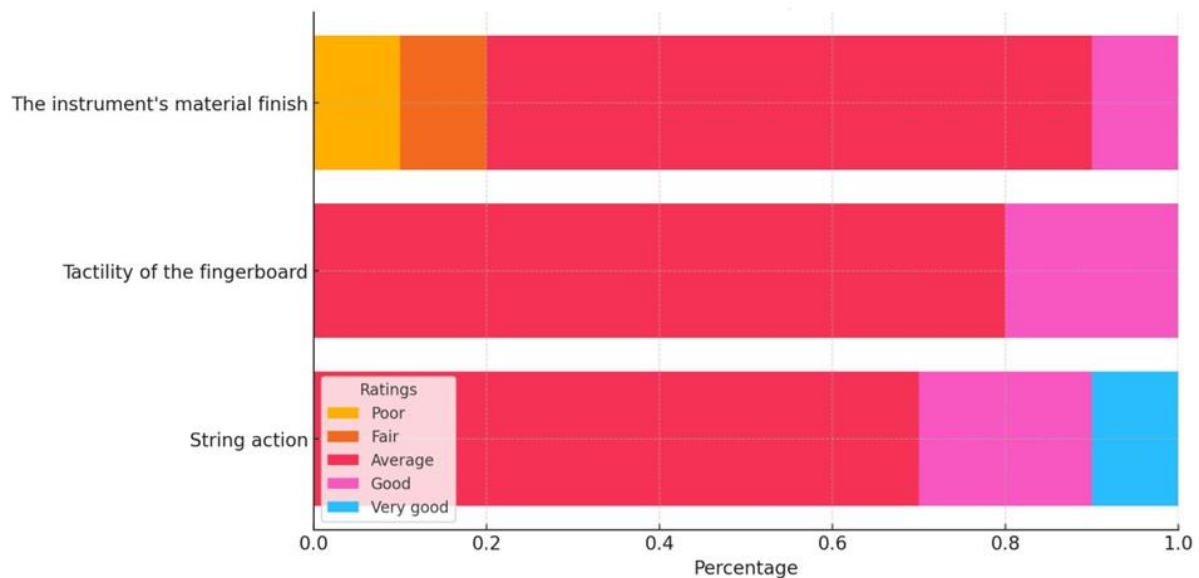


The professional musicians were asked to rate the tone, projection, and tuning when assessing instrument quality. The specific rating of these features directly reflects the 3D printed violin's performance potential and limitations. The questionnaire findings (Figure 5.8) reveal that most professional musicians rated the instrument's ability to maintain tuning as average (7/10), with the remaining responses as good (2/10) and very good (1/10). This finding indicates that the 3D printed instrument is balanced with participants' expectations, and material concerns, such as peg slipping, align with expectations. However, as Hart (2019) would contend, an average tuning rating does not meet expectations for violinists working in a professional context, who can be affected by minor discrepancies in intonation. This finding indicates that tuning of 3D printed violins may limit their use in a professional context.

Musicians rated the tone quality as average to very good (7/10), while the remaining participants rated it poor (1/10) to fair (2/10). This result reveals that the majority of these musicians viewed tone quality as predominantly on balance with the musicians' expectations. However, the poor (1/10) to fair (2/10) rating resonates with prior discussions on the disadvantages of 3D printed musical instruments, outlined in Section 2.4.4. This concern is elevated in the projection quality results, which found that although the majority of professional musicians rated the projection quality as average to very good (6/10), the rating of poor (2/10) and fair (2/10) indicates that the sonic resonance of the materials used, or the position of the sound post is causing the instrument to underperform, thus limiting the instrument's resonance potential. Although based on traditional instrument fabrication, this scenario of a misaligned sound post affecting resonance is detailed in Thompson and Olsen (2021). This finding suggests that material limitations affect the instrument's sonority, echoing literature from Horvath (2014). Moreover, Thompson and Olsen's (2021) focus on projection as a critical indicator of an instrument's capability to perform competently in diverse musical contexts indicates the importance of resolution for 3D printed violins to gain acceptance within a performance context. This indicates that further iterative testing is needed before integrating 3D printed violins into an educational context, where younger students may not have a prior reference point for instrument quality and expectations. These findings indicate that although the 3D printed violins meet the basic standards of professional musicians, the limitations in projection and tonality, which were qualities previously associated with high-quality violins (Section 4.2.1), affect their acceptance as an alternative provision model at this level.

Figure 5.9

Design Aspects Affecting Performance and Aesthetics: Action, Tactility, and Finish for Professional Violinists



Establishing how string action, tactility, and finish affect sound quality revealed industry professionals' perceptions of the physical craftsmanship and aesthetics of the 3D printed violins. It is arguable that these critical aesthetic factors influence the haptic aspects of performance. As Figure 5.9 shows, participants' experience of the instrument's material finish was highly variable, with the majority rating it as average (7/10) and peripheral variations ranging from poor (1/10), fair (1/10), and good (1/10). This dominant average indicates to the researcher that although the instrument may be functional for a beginner instrumentalist, it does not meet professional violinists' higher aesthetic and ergonomic material finish requirements. This echoes Romdhane (2020), who highlights the importance of refining the surface quality of 3D printed musical instruments to improve the ease of performance, as well as user tactility. In this finding, the material finish and resulting aesthetic directly impact the participant's rating.

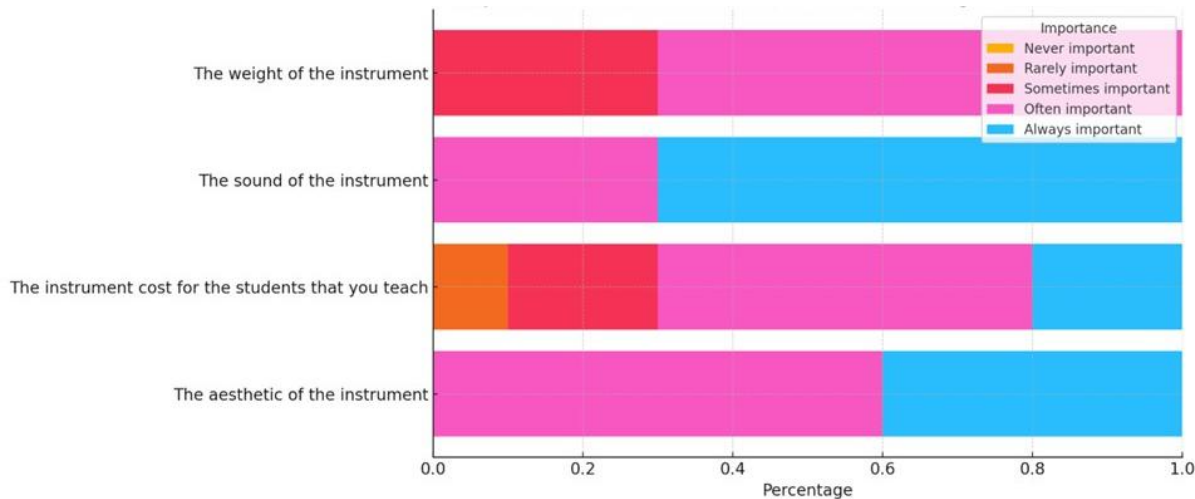
However, participants' experiences of the violin's tactility as good (8/10) or very good (2/10) indicate a contrast in how participants view the instrument's appearance in

relation to its feel. In this instance, this result suggests that aesthetic instead of tactile factors have affected participants' choices. The majority of participants (7/10) rated the string action as average, with the remainder rating it as good (2/10) or very good (1/10). This participant feedback indicates that even though the string action was deemed functional by participants, it may require more refinement to enhance the string's tactility. This refinement could take the form of bridge and fingerboard realignment and string tensioning, as previously outlined in Section 4.2.2. This recommendation to adjust the tension in order to improve the string action aligns with Moro (2018), who states that even though higher string action does not impact the instrument's sound, it does impact the player's effort required to play the instrument.

5.4.2 Comparable Design Alignment between Traditionally Constructed and 3D Printed Violins

Figure 5.10

Aesthetic, Sound, Cost, and Weight Considerations for Professional Violinists



Establishing industry professionals' perspectives on the aesthetic, sound, cost, and weight considerations of 3D printed violins revealed how they consolidate visual aesthetics with performance acoustics. The findings from these four categories (Figure 5.10) indicate a strong preference for instruments that can balance cost-effectiveness with quality.

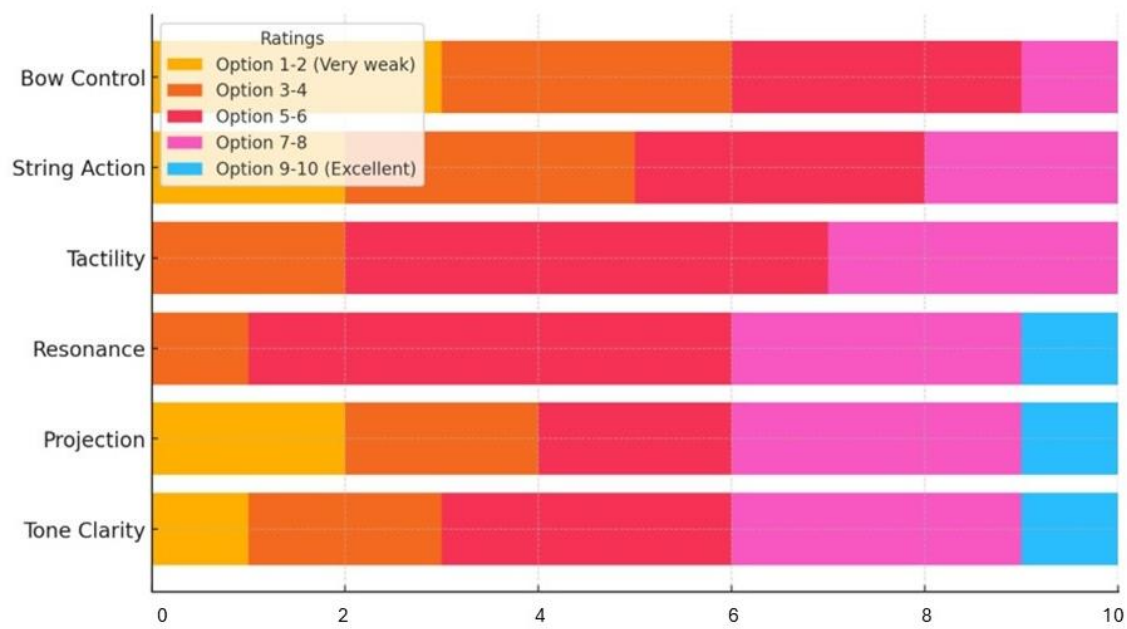
However, although half of the participants (5/10) said that the instrument cost for students they teach is often important, the broader responses that it is rarely (1/10), sometimes (2/10), and always (2/10) important conflicts with the literature and may reflect the particular socioeconomic contexts that these professionals teach in. This finding highlights that cost should not be the only influencing variable when designing and integrating new instruments.

Most participants noted that the instrument's aesthetic is often (6/10) or always important (4/10). Although this might be attributed to an instance of neophobia, it could also suggest that, even with non-traditional materials and designs, musicians place a substantial value on the visual components of the instrument. This brings into question the potential level of acceptance of new instrument designs. This finding connects with literature from Goto (1999), who contended that the aesthetic components of musical instruments impact a musician's connection to them, affecting the adoption of new instruments. Participants rated the instrument's sound as often (3/10) or always important (7/10). This highlighted the sonic expectations that 3D-printed instruments must meet to gain acceptance and compete with traditionally made instruments. It aligned with Murphy (2014), who cited sound disparities as a barrier to 3D printed musical instrument integration with conventionally constructed instruments. Participants rated the instrument's weight as sometimes (3/10) and often important (7/10), indicating that a light and ergonomic design is preferable even as an adult or professional musician. For this set of participants, although the 3D printed violin is lighter than its traditionally constructed counterpart, without sonic comparability, this will not be a deciding factor in its adoption.

Regarding sound quality, the comparative acoustic properties tests revealed that traditional violins outperformed 3D printed instruments in the categories of attack, sustain, decay, and harmonic richness. As these are significant attributes for forming resonance,

this finding indicated that more resonant 3D printed materials were needed to ensure instrument compatibility. Although Murphy (2014) contended that a softer attack and focused tonal output, evident in the 3D-printed instruments, can be useful in ensemble settings, the design intention was to be as compatible as possible with its traditionally constructed counterpart. These sound quality discrepancies were noted to a lesser extent in the luthier questionnaires, with greater criticality placed on instrument durability. This de-emphasis on the sound quality of the instrument connects with Bissinger’s (2008) description of musicians' and makers' skill sets influencing their focus and critique of instruments.

Figure 5.11
Professional Violinists’ Evaluation of the Tone, Projection, Resonance, and Physical Feel of the Instrument (Tactility, String Action, Bow Control) Across Four Questions Using Separate Stimuli



As shown in Figure 5.11 above, factors such as the tone, projection, resonance, and physical aspects of the violin articulated professionals' perspectives on the balance between acoustic and ergonomic design. These are significant factors when assessing

performance and aesthetic appeal. The results presented in Figure 5.11 display a range of perspectives from very weak to excellent. The results show that while some professionals found aspects of the 3D printed violins' resonance, projection and tone clarity acceptable, with a 4/10 rating from very good to excellent, most participants rated these aspects as average or below (6/10). This highlights tone, projection, and tactility design limitations, which directly affect performance. This finding connects with Beament and Beament (2000), who contended that the performance of an instrument was directly linked to aesthetic characteristics such as tactility and projection, which affect the musical expression abilities of the instrument. This finding from Beament and Beament (2000) contrasts with Campbell and Greated (2023), who discussed the significance of ergonomic design in the acceptance of contemporary designs. Although the small sample size and lack of further qualitative details create limitations for further interpretation, this finding indicates that the 3D printed violin does not meet the professional's expectations for instrument ergonomics.

5.5 Conclusion

This chapter has outlined the results and findings of professional musicians and luthiers based on the sub-themes of acceptance and trust and performance and aesthetics. The findings were contextualised with existing literature and affirmed that 3D printed instruments remain peripheral to industry professionals due to social and technical forces ascribed by musicians and luthiers. This finding aligns with previously discussed literature in Chapter 2 (Fletcher & Rossing, 2012; Hopkin, 1996; Patteson, 2016). The technical and cultural challenges of attempting to integrate 3D printed musical instruments are shown in the professional violinists' ingrained trust in established instrument brands, as well as their deep connections with their current violins. This finding aligns with Beament and Beament's (2000) assessment of the barriers to new instrument integration. For luthiers,

inconsistencies in the instrument's tone, projection, resonance, and playability affect their acceptance and trust of the 3D printed violins. This finding resonates with Pye (1995), who indicates how such inconsistencies affect luthiers' willingness to recommend new instruments. Although the results suggest that the professional musicians involved in this study may be willing to recommend new instrument fabrications for younger students, they are reluctant to adopt them personally. This indicates a gap in professional user acceptance and trust of 3D printed violins. Issues related to music professionals' acceptance and trust of 3D printed violins may be addressed by undertaking iterative designs that seek to improve the new instruments' quality and comparability.

Regarding performance and aesthetic components, the results indicate that while the instrument is functional, they do not meet the tone, projections, tuning, and tactility expectations set by traditionally constructed instruments that professional musicians and luthiers are accustomed to. Similarly, professionals' critique of the sound quality and aesthetic components of the 3D printed violin further challenges this new design's ability to penetrate the professional musician market. Through seeking musicians' and luthiers' perspectives, this chapter has built a critique based on the performance and construction aspects of the instrument design. To gain broader acceptance, future instrument iterations need to address performance and aesthetic design components that specifically influence tone, projection and instrument tactility, in order to increase the possibility that 3D printed instruments could become viable alternatives to traditionally constructed counterparts. There are limitations in sample size, demographics, profession, and the instruments used. Further studies could explore larger sample sizes, international demographics, professional and amateur musicians from different genres, and questions.

Chapter 6 Results and Findings of Perceptions and Values of Teachers' Results

6.1 Introduction

This chapter outlines the results and findings of educational engagement based on the theme of the perceptions and values of teachers. Teacher interviews inform this chapter. In keeping with the format of the previous two chapters, the results are presented thematically, and findings are compared with relevant literature, ensuring that the main findings from teachers are articulated. It is important to recognise that these findings are not exclusive to 3D printed violins, but are reflective of broader technical and practical challenges associated with the fabrication and performance of both luthier-constructed and mass-produced violins, as discussed in Chapter 2 (Section 2.2.3).

6.2 Sub-Theme: Educational Engagement

Kelly (2009) uses the term "educational engagement" to discuss the existing physical and social infrastructures in place to support and enable students' progression. The researcher uses the term educational engagement to refer to the physical and social infrastructures needed to integrate 3D printed violins into existing instrumental practices. For music teachers, educational engagement was contingent on four factors: (i) resource allocation and access, (ii) teacher training and pedagogical support, (iii) curriculum alignment and educational goals, and (iv) socio-cultural perceptions and acceptance. These factors form four distinct sections of this chapter and help to align the findings with the educational and social structures necessary for educational engagement. Existing literature reveals a tension between instrument innovation (ThéBerge, 1993) and the established conventions within music education (Hallam & Himonides, 2022). ThéBerge (1993) is critical of technological integration that fails to consider its effect on its audience. In this instance, the authors are critical of the concept that technological newness alone will

produce learning outcomes. Similarly, Hallam and Himonides (2022) suggest that embedded technologies are more successful when they align with teachers' existing goals. These authors' perspectives indicate that educational engagement is successful when it builds on and contributes to existing provisions. The educational engagement sub-theme is divided into four sections: resource allocation and access, teacher training and pedagogical support, curriculum alignment and educational goals, and sociocultural perceptions and acceptance. These divisions reflect the practical, pedagogical, educational, and societal factors influencing education integration.

6.2.1 Resource Allocation and Access

Resource allocation and access are critical structural challenges affecting access to technological integration. As evidenced by Selwyn (2011), the digital divide can heighten these structural challenges and inequalities. Integrating 3D printed violins within an instrumental music context was greatly influenced by 3D printing resource availability. Although the researcher could have sought to establish resource allocation for instrumentalists with no prior musical or technological infrastructures, integration within an existing musical framework, where instrument cost was not a dominant influencing factor for some students, ensured that the instruments were more critically evaluated, and the research questions were critically addressed.

Interviews from music teachers two, three, and five revealed substantial variations in educational support for instrumental music provision. This can directly shape the integration of new musical instruments in educational environments. Instrumental teacher two recognised their “point of privilege,” highlighting their understanding of the inequalities between schools with dedicated instrumental programmes and schools lacking this support. For instrumental teacher two, educational success in terms of music performance and instrumentation was deeply connected to instrumental teacher

availability, funding and school infrastructures. The instrumental teacher two's point of view connects with Hallam and Himonides (2022), who emphasise the crucial role of environmental support when designing, developing, and implementing sustainable educational interventions. In this instance, the challenges related to engaging with instrumental music education programmes gesture towards a larger equity gap in instrumental education provision. For instance, instrumental teacher three observed that “an instrument programme should be the norm for every school, but it’s not,” capturing the continuing instrumental music education debate regarding performance provision and access (Deloughry, 2014). However, this gap in access creates additional concerns about the capacity for 3D printed instruments to strengthen existing inequalities instead of addressing them.

Equally, it emerged from the interview data that successfully integrating 3D printed violins into an instrumental music context heavily relied on the supporting educational and technological infrastructures. This challenged the generalisability of these research findings in relation to other educational settings. This finding is connected with Section 2.4.4, which Li et al. (2018) used to illustrate that lack of infrastructural support can widen the socioeconomic divide. This finding also aligned with Neimann et al. (2021), who recognised that researchers may be more inclined to undertake research in infrastructurally rich contexts. Building on the relevance of school context in supporting educational engagement, instrumental teacher five mentioned the school ethos, specifically the commitment to “inclusion” and “equity”, as exemplified through the school's Social Diversity Programme. This programme has been previously mentioned in Section 3.4.4. Equally, instrumental teacher five mentioned the established instrumental programme as a key infrastructure that facilitated the integration of 3D printed violins. Instrumental teacher five indicated that a similar instrumental intervention might not have been so successful

without such school values combined with the infrastructural support. By astutely recognising this methodological limitation, instrumental teacher five echoes Avanzini et al. (2019). Specifically, Avanzini et al. (2019) question the reproducibility and scalability of educational research that is too reliant on specialist infrastructural support for its implementation. As an extension of Avanzini et al. (2019), this finding also connects with Selwyn (2011), who maintains that the unequal distribution of educational resources lends itself to unequal educational outcomes for students. However, the researcher posits that without adequate digital and educational infrastructures, future research may continue to be limited to highly resourced educational environments. This finding perpetuates instrumental teacher five, Avanzini et al. (2019) and Selwyn's (2011) points.

Furthermore, instrumental teachers three and five referenced the significance of teachers' support in building trust in the intervention. In particular, instrumental teacher three mentioned that students' trust in the 3D printed violins was reinforced by instrumental teacher modelling, while instrumental teacher five noted that existing infrastructural teaching provisions assisted in building students' trust. These participant observations emphasise how existing infrastructural provisions can enhance trust in new interventions. As an extension, these participants' perspectives also highlight that 3D printing as an alternative provision model could remain short-term, novel, and isolated without sufficient infrastructural provisions for continuation. This infrastructural dependence limits the replicability in other educational contexts.

The results from the teacher data found that the perceived relevance of 3D printed violins to a musician's musical journey was connected to the level of school provision. This, in turn, can affect engagement. Instrumental teacher two's reflection on the perceived relevance of 3D printed violins to a musician's musical journey indicates a change in pedagogical strategies. This change, in instrumental teacher two's words, focused on

“empowering musicians from the start rather than addressing issues when they fail.” This anticipatory approach, which focuses on addressing existing instrument deficiencies and deviations, seeks to aid in reshaping the musician's musical journey. It connects with Zimmerman's (2002) study exploring the role of students' self-regulation in their early progression in education contexts, echoed by student participant three. However, in this instance, the success of this approach is based on the educational context's willingness to promote new instrumental educational practices. Without this willingness, the relevance of 3D printed violins to the students' musical journeys could remain hypothetical. This reliance on school infrastructures raises concerns regarding scalability and transferability in different educational settings. As noted by Brennan and Naidoo (2008), this can perpetuate existing educational inequalities.

Instrumental teacher two also mentioned the Social Diversity Programme, a scholarship programme run by the school to promote social and cultural representation within the student body, previously mentioned in Section 3.4.4. Instrumental teacher two discussed how financial support can make instrumental music more accessible for families of students who wish to avail of IME, but stated its low participation rates to date as an indicator that funding alone is not a determining factor in musical engagement. This finding connects with Hallam and Himonides (2022) contention that early experience, cultural significance, familial encouragement, and financial support are necessary to promote students' musical journeys.

6.2.2 Teacher Readiness and Engagement

Teacher readiness and engagement were vital to the educational integration of the 3D printed violins. However, even though all the teachers who were interviewed displayed a willingness to discuss the integration advantages and challenges of these instruments, it was evident that there were different levels of engagement. For example, instrumental

teacher four conveyed some limitations in understanding the adjusted stringing process, exposing a gap in the pedagogical support necessary to integrate the new designs into their teaching practices. This reveals a larger design and usability issue that Pikkarainen and Piili (2020) echo. This finding suggests that although instrumental teachers may be ready and willing to engage in new technological means of producing musical instruments, without adequate CPD to engage education professionals at an earlier stage of the design process, their ability to synthesise these practices will be reduced. This point connects with McLean and Roswell (2020), previously discussed in Section 2.4.1. These authors propose industry collaboration as a potential solution to this learning curve challenge. Similarly, instrumental teacher four's further critique of the intuitive aspects of the violin design indicates that effective integration and acceptance are not merely about teacher readiness and willingness to engage in the process, but also involve enabling the necessary tools and knowledge to be used by participants. This finding resonates with Margot and Kettler (2019), also discussed in Section 2.4.1. In this instance, the authors recognise 3D printing skill sets that extend beyond a music teacher's general toolkit. Although this research specifically focused on user perceptions of 3D printed violins and their potential for educational integration, rather than teacher CPD, these findings indicated that the integration of any new technology or instrument design should be accompanied by clear guidelines and educational resources.

In relation to teacher readiness, the teacher interview data also evidenced that instrumental lessons and student progression can be affected by inferior or damaged instruments. Specifically, instrumental teacher three mentioned their readiness to loan students their own instruments as a short-term solution to overcoming tuning, intonation, and construction differences, as well as damage to instruments. This practice highlights deficiencies in the construction of student instruments and provision. In this instance, it

places excessive responsibility on instrumental teachers to mitigate instrument technical problems and creates further inequalities based on the resources of individual teachers. This instance aligns with Wright (2017), who discusses the social dynamics of music education, specifically in ensemble contexts, where tuning, intonation and material differences may be more prominent.

Furthermore, due to a lack of familiarity or possibly the fear of undermining the performing process, the teacher's careful approach to integrating new instrument brands reflects broader educational challenges. Instrumental teacher five noted the personal challenges that they experienced with the redesigned 3D printed violin scroll, pegs and pegbox. This instance demonstrates how design innovations can create user challenges that affect usability and challenge acceptance. This finding highlights the value of developing new designs with the intended users, especially when this design diverges from iconic iterations of such a historic instrument (Taylor et al., 2021). It also highlights that teachers will remain peripheral to engaging with the design process and in deeper educational outcomes without more systematic integration of the processes involved in developing new musical design components. This finding resonates with Pikkarainen and Piili (2020), who correlate teacher CPD and resulting teacher confidence levels with the meaningful integration of new educational technologies.

What also came from the teacher interviews was some interviewees' nostalgia for traditionally constructed instruments. This challenged the acceptance of new designs and practices. Instrumental teacher two described the emotional and familial significance that they had to their traditionally made violin and how this made them resistant to embracing the change of new technologies. This emotional attachment to musical instruments was also evident in the industry professionals' data, mentioned in Section 5.3. This perspective is reflective of literature from DeNora (2017) that discusses the hierarchy of historical

luthier traditions. Equally, these perspectives resonate with Taylor et al. (2021), who contend that in order to effectively integrate new educational practices, interventions must be sympathetic to the social, emotional and psychological factors that shape a teacher's readiness to change.

6.2.3 Curriculum Alignment and Educational Goals

So far in this thesis, curriculum alignment has been used to connect STEAM processes with existing literature. Specifically, Section 1.5 references policy documents that highlight the important role of industry professionals in developing educational practices that reflect real-world work practices (Department of Culture, Heritage and the Gaeltacht, n.d.; Department of Education and Skills, 2015, 2017, 2023). While Section 2.4.1. outlined CPD challenges associated with integrating 3D printing into the curriculum (Margot & Kettler, 2019; McLean & Roswell, 2020; Ralls et al., 2018). Section 2.4.2 outlined the cross-disciplinary potential of 3D printing in the education curriculum (Bucur, 2016; Hoskins, 2018; Santos et al., 2018). The researcher uses the term curriculum alignment to refer to the degree to which the 3D printed violins support and complement the instrumental teachers' intended learning outcomes and educational goals.

In relation to curriculum alignment and educational goals, the data affirmed the contextual challenges involved in integrating new technological practices within an education context. Instrumental teacher two suggested that the design and construction of 3D printed violins could be aligned with musical literacy, skill development, and creativity goals, in order to be more educationally aligned. Although this research used 3D printing educational goals, its misalignment with musical goals creates conflicts between existing performance pedagogies. Similarly to Herring et al. (2016) Technological Pedagogical Content Knowledge (TPACK) framework, successfully integrating technology must effectively balance pedagogy and content with technology. Instrumental teacher three

discussed the relationship of the pilot to curriculum and educational goals. They made correlations between industry professionals, and instrumental music teachers, and instrument relationships and their integration into the existing educational framework. Instrumental teacher five's discussion on the possibility of 3D printed violins to promote access shows the potential alignment with equity educational objectives. However, as interviewees also noted disparities between the 3D printed violins' weight and balance to their traditionally constructed counterparts, it is crucial to question the longer-term educational value of an instrument without addressing the recognised structural limitations. Returning to Herring et al. (2016), who contended that new technologies are successful when they complement existing educational structures, it is conceded that this limitation is the belief that new technologies can harmoniously be integrated into existing educational structures without the need for substantial modifications. Further research on how such tools can address the music curriculum and educational goals and what significant modifications are necessary to balance pedagogy and content with technology would aid in furthering this narrative.

In relation to educational goals, instrumental teachers two and three expressed that instrument integration most appropriately aligned with first-year students. In particular, instrumental teacher two maintained that an early instrument intervention, regardless of fabrication, would help students' individual and collective growth and development with their instruments. While instrumental teacher three noted that this would provide students with a "standardised starting point" for development. These perspectives connect with Simian's (2023) call for a move beyond technological novelty towards longer-term alternative provision models. Although the suggestion to make instruments available to older years as well as local primary schools and music communities shows teachers wish

to develop this project beyond the immediate school environment, this suggestion exposes the scalability, replicability, and sequenced sizing challenges of such an endeavour.

The teacher interview results also revealed a gap in this school's instrument provision practices. Instrumental teachers two and five conveyed that they often loan their own instrument resources in order to overcome student instrument challenges. This informal network of instrument resourcing creates inequalities among teachers who do not have a personal "instrument bank" to loan to students. In this instance, the instrumental teacher is addressing the gap in the quality of instrument provision, mitigating the immediate challenge of inferior quality instruments but masking the consequences of purchasing such an instrument, thereby masking the perceived gap in curriculum provision and how teachers achieve these educational goals. Conaghan (2022) recognises this systematic issue as having overwhelming implications for educational access and equity. This instance emphasises the need for a more formalised approach to musical instrument provision in schools.

Finally, the teacher interview findings showed that new instrument integration must be both technically and pedagogically trustworthy. It found that new instrument integration involves much more than the technical competencies in scanning, modelling and 3D printing instruments. It involves a more nuanced understanding of instrumental music teacher expectations, access to digital infrastructures, as well as a broader understanding of how industry professionals could shape and inform design in order to begin addressing curriculum alignment and educational goals. Returning to Herring et al. (2016) TPACK framework, it would appear that while 3D printed violin integration may be technically possible, provided the necessary digital infrastructures are utilised, the pedagogical and content of such integration is still to be fully actualised in relation to curriculum and educational goals.

6.2.4 Socio-Cultural Perceptions and Acceptance

Acknowledging the socio-cultural perceptions and acceptance of new musical instruments is vital for effective educational integration because they shape users' motivations for using such instruments. The recurring motif of sameness as a positive attribute, used within this research when referencing shared sonic or material attributes to traditionally constructed violins, arose in two of the interviews. This included comparability of technique, intonation, and tuning. Instrumental teachers four and one observed how the new instruments “blended” and “layered” in an ensemble context. This highlights the potential for 3D printed violins to expand musicking practices, which, in turn, contributes to positive socio-cultural perceptions, instrument acceptance, as well as ensemble cohesion, which has been discussed by Hallam (2010). However, instrumental teacher two astutely noted that changes in perceptions and acceptance of 3D printed instruments are shaped by infrastructural provisions for periodic maintenance, as well as design development. Instrumental teacher two points challenges the notion that short-term changes in perceptions and acceptances of 3D printed instruments are possible without longer-term infrastructural support. This finding connects with Cascio and Staiger (2012), who emphasise that the acceptance of new technologies within education can be contingent on the design and support structures put in place during and beyond the timeframe of research interventions.

Although the concept of equivalence to traditional instruments may not appear as a major finding initially, when juxtaposed with literature from Cano (2015) and Santos et al. (2018), it is evident that sonic blending and materiality of 3D printed instruments have been historically challenging to emulate. As prior literature established (Cano, 2015; Santos et al., 2018), producing inferior-quality instruments or viewing these instruments in isolation limits their potential for integration. While Montagu (2007) would contest that

this issue of integration is particularly relevant when established models of instrument production already exist. Although the research focus on emulating comparable instruments may limit the sonic and material possibilities of such instruments, in this instance, instrument comparability has led to effective educational assimilation.

The concept of sameness as a positive attribute could be extended to the positive influence that teacher and older student modelling had on the perceptions and acceptance of 3D printed violins. In alignment with Bandura (1977), modelling the instrument's potential shifted the emphasis from the technical aspects of musical production toward student-appropriate pedagogical practices. Similarly, echoing Fonseca (2023), observing the role of student instrument modelling within an orchestral context aided in highlighting the influence of sociocultural aspects of performance on students' acceptance of new instruments. This action extended the 3D printed violin function beyond an alternative model of provision. In this instance, the instruments became tools that enabled student engagement in acts of musicking.

In relation to postdigitalism, unpacked in Section 1.5, this creates an instance where the technological processes used to produce the instrument begin to become more invisible, leading to the possibility of greater focus on performance outcomes. This shift from technological novelty towards embeddedness resonates with Cassone's (2000) notion of effective postdigital integration because the discussion shifts from the technological means of production towards the opportunities for music-making that alternative provision models might afford. This shift also connects with Jandrić et al. (2023) concept of integrated postdigital practices because it places an emphasis on users' relationships with digital technologies, rather than viewing them as discrete and detached entities. Regarding musicking, the socio-cultural perceptions and acceptance of the new instruments have widened the music-making circle. Connecting with Section 1.4, this enables the informal

music processes involved in musicking-in-any-which-way (Small, 2012) to be formalised. In relation to social constructivism, Small's (2012) musicking-in-any-which-way infers that social interactions aid in the construction of meaning. In relation to the sub-theme of sociocultural perceptions and acceptance, these results indicate that shared social practices that can occur both virtually and physically (Reily & Brucher, 2018) and have both social and individual potential for change (Sanford, 2017). Therefore, in relation to the concept of sameness as a positive attribute, the notion of postdigital musicking begins to emerge. This is made visible by focusing on developing technologies that enable users to engage with acts of music-making (Savin-Baden, 2021) rather than just theorising its future use (Jandrić et al., 2023).

In contrast, Instrumental teachers two and three noted differences in weight and balance. Although data from industry professionals viewed weight and balance as challenging aspects of their own early playing and viewed these design differences as potentially useful features for younger students, Instrumental teacher two noted how such features could affect instrument legitimacy. Specifically, Instrumental teacher two noted that the lightweight body created a “toy-like” feel, based on the comparative weight and balance of their own instrument. This perspective challenges the potential successful integration of new instruments that seek to problem-solve existing design features while seeking to maintain comparable legitimacy with existing instruments. It aligns with literature from ThéBerge (1993) which asserts that a musical instrument’s cultural value affects its integration and acceptance. It also resonates with Norman’s (2013) argument that effective technology design must address the usability and adaptability needs of its users. Instrumental teacher two also noted differences with the stringing process. This further highlights the tension between innovative design and user expectations. This

finding connects with Selwyn (2011), who contends that new design technologies that deviate from user expectations can create new problems that affect user acceptance.

However, instrumental teacher three also noted how design differences such as weight, balance, and customisation provide an opportunity for new students to develop performances practices independent from teachers' experiences. In this instance, instrumental teacher three recognises that their experience of playing the new instrument is framed through a comparative lens, a lens that students may not have. Although the instrumental teacher perspective has been invaluable for providing a comparative framework and a professional assessment of performance milestones, this does reveal the perceptions and acceptance limitations of 3D printed violins that structurally deviate from existing models.

Additionally, instrumental teacher one observed that the instruments were initially viewed as a beginner or “entry-level” tool by older students, possibly due to the age group with which they were piloted for this research. This created limitations in socio-cultural perceptions and perceived acceptance of the 3D printed violins. This limitation connects with Rogers (2003) assessment of the diffusion of innovations theory in education, which specifically references how integrating technologies for specific age groups can marginalise its greater acceptance. As an extension of Rogers (2003), instrumental teacher three envisaged making 3D printed violins available to older students with the aim of reinforcing student acceptance. In these instances, the researcher accounted for the potential perceptions of othering due to differences within a specific year group but did not account for how this focus might affect non-user perceptions and acceptance of said instruments outside this year group. Consequently, this finding indicates that to promote the acceptance and effective integration of 3D printed violins within an educational context, these instruments must be open to all age groups. This connects with Fonseca’s

(2023) notion of student modelling within orchestral settings as an effective marker of both instrument integration and student acceptance levels.

The instrumental teacher interview data indicated that sound and material differences in violins affected an ensemble performance. Instrumental teacher one expressed that as students develop their musical ear, they become more aware of differences in intonation. According to Yao et al. (2016), previously referenced in Section 2.3.4, these differences were more evident in an ensemble setting, where age, musical experience, and instrument construction influenced students' intonation perception and performance capacity. As Section 5.2 found that material and sonic variations affect industry professionals' trust in new instruments, based on the instrumental teacher's perspective, it would appear that this also extends to the 3D printed violins. Instrumental teacher one's perspective connects with Fitzgerald and O'Flynn's (2016) assertion that musician identity is a crucial self-motivator in their musical engagement and progression. Although other factors such as age, shifting student interests, and perceived progression may also affect student enthusiasm and motivation towards musical engagement, the resulting data evidenced perceived differences between instruments as a motivating factor towards engagement.

In an example of sociocultural perceptions affecting new instrument integration within an ensemble context, Instrumental teacher five recalled their own experience as a student playing a Clarineo, a plastic clarinet brand, in a school ensemble context. The teacher recalled how the sonic and material variations between the Clarineo and traditionally constructed instruments affected their musical development in an ensemble context, resulting in them stopping the instrument. This participant's reflection connects with research question three. In this instance, their personal experience of playing a non-traditionally constructed instrument affected their trust in, and progression on that

instrument. The potential for musicking was impacted by instrument fabrication. This example connects with literature from Khan (2021) regarding the unintentional marginalisation of student demographics that new instrument designs may seek to integrate. Although Instrumental teacher five's experience refers to a separate new instrument design, it provides an example of marginalisation due to sonic and material instrumental differences.

Separately, the results also indicated that the terms 'innovation' and 'violin' attracted two distinct audiences. Instrumental teacher four questioned whether violins needed to be innovative or whether a musician's prior experience with the instrument was enriched by its historicism. This aligns with literature from Van Epps et al. (2015) who contend that technological innovation can broaden opportunities for access. However, this comment conflates engagement with technological novelty, a concept that Cascone's (2000) postdigitalism, and this research sought to move beyond.

6.3 Conclusion

This chapter outlined the results and findings of the sub-theme of educational engagement based on the theme of the perceptions and values of teachers. The instrumental teacher results and findings showed that the effective integration of 3D printed instruments in educational contexts is based on addressing infrastructural and contextual issues. Infrastructural issues, such as digital software investment, CPD, and curriculum placement, could be addressed and supported in order to establish a more meaningful context for the integration of 3D printing technologies in post-primary music education. Equally, contextual issues such as socio-cultural observations and teacher participation are crucial to the future of such initiatives. The teacher findings indicated that without a comprehensive method that considers these aspects, the introduction of new technologies will remain marginalised. The teacher results indicated that the incorporation

of 3D printed violins into this post-primary music education context was influenced by factors such as resource provision, teacher training, relevance to the curriculum, as well as participants' sociocultural perspectives. Although this study shows some promise in promoting access and engagement for violinists, its success is reliant on addressing these structural and background challenges.

Chapter 7 Results and Findings of Viability and Practicality of 3D Printed Instruments

7.1 Introduction

This chapter outlines the results and findings of two sub-themes: (i) cost and access and (ii) the influence of time, based on the viability and practicality of 3D printed instruments. This chapter was informed by musician and luthier questionnaires, and teacher interviews. In alignment with the previous results and findings chapters, data is presented thematically, and findings are synthesised with the literature.

Cost in relation to 3D printed violins refers to the financial and logistical aspects that shape instrument readiness and affordability for teachers and industry professionals. This includes filament, 3D printers, digital infrastructures and incremental maintenance costs. The term access is used within this chapter to refer to the potential availability of 3D printed violins to other instrumental music contexts. As noted in Section 2.3.5, systematic access is influenced by technical expertise. In Chapter 2, contrasting literature viewed the democratising potential of 3D printed musical instruments (Cano, 2015) alongside concerns about the long-term viability of constructing in this novel way, which had the potential to marginalise users that this process sought to provide access to (Hallam & Himonides, 2022). Education and technology literature from Norman (2013) and Rogers (2003) highlighted how barriers such as cost and access can impact the integration and acceptance of new technologies. This literature indicates that while 3D printed violins promote increased access due to cost, this is only beneficial to musicians in the long term if it adheres to comparable sonic and material principles.

The influence of time refers to results and findings that gesture towards tracking a musician's journey with their 3D-printed violin over a sustained period of time. This encompasses the instrument design, development, testing, iterative design changes, and

sustained maintenance stages. As initial design and printing occurred in year one, iterative design changes based on industry professionals' feedback occurred in year two, and teacher interviews occurred in year three, time was a crucial factor in determining the final form of the instrument. The influence of time also encompasses the potential learning curve for musicians, instrument maintenance and durability over a sustained period, and the potential for acceptance over a sustained period. Norman's (2013) discussion on product design development indicates that time management is a key factor in the meaningful integration of new technologies. Norman's (2013) perspective emphasises the need to view the influence of time as a significant factor in the development and integration of new products and tools, such as 3D printed violins. Equally, Bongomin et al. (2020) emphasise a tension between the rapid evolution of 3D printing and the slower pace of adoption for musicians. Bongomin et al. (2020) perspective highlights the hesitancy with which 3D printing has been adopted in instrumental music contexts to date. This has been previously referenced in Section 2.4 of the literature review.

7.2 Sub-Theme: Cost and Access

Cost and access are divided into four sections: (i) material costs and availability, (ii) printing technology and equipment, (iii) distribution and scalability, (iv) training and expertise. These divisions reflect the sustainability, infrastructural, replicability, and learning challenges associated with cost and access.

The material costs and availability are key factors in the practicality of the sustained use of 3D printed violins beyond the timeframe of this study. As instrumental teachers one and three noted, calibration and standardisation of the 3D printing and finishing process could potentially lower costs by ensuring that the design is optimised for musicians' use and that print filaments are robust and hard-wearing for long-term use. Although this file and instrument calibration could offer an alternative to musical

instrument access, enabling musicians to print and generate their own instruments, the findings from this research indicate that filament selection was crucial to instrument material standardisation. This is evident through the industry professionals' comparison of the 3D printed violin to “lesser brand” instruments, which emphasises the sonic and physical problems associated with using cheaper and lower quality materials. Therefore, this industry professional finding indicated that material viability should always be prioritised over cost-effectiveness to ensure that instruments are fit for purpose. For musicians, creating sonic and material limitations in musical instruments can result in disengagement, as evidenced by the instrumental teacher five student experience of using the Clarineo plastic clarinet. In this instance, this instrumental teacher finding indicated that access to an instrument that did not align with other clarinet counterparts directly impacted their disengagement with the instrument. This resonates with literature from Beament and Beament (2000), who highlight the significance of instrument quality in maintaining student engagement and drive, reinforcing that the sub-themes of cost and access are only valuable to a musician if they do not undermine instrument quality.

Regarding 3D printing technology and equipment, using 3D printing technology in the production of musical instruments presents opportunities and problems. Although the technology offers the prospect of consistency in production, the initial infrastructural investment, steep learning curve and training challenge the notion of 3D printing, promoting ease of access and file democratisation. The consistency in production is particularly evident in interviews with instrumental teachers two and five, who highlight the benefits of having a “stable model” to build from, and the potential for developing a “protocol [for] standardisation” and accessing models in the future. In these instances, future development and growth are contingent on access to 3D printers, as well as the skillsets involved in developing digital models for new instruments. Without continued

infrastructural resources, the scalability of this method is restricted. This resonates with Baines (2008), who argues that the integration of new technologies in the classroom is made possible through balancing technological innovation with practicality. Baines (2008) infers that while 3D printing presents theoretical benefits, these benefits can only be unpacked through sustained support and training of teachers.

The findings from instrumental teachers one, two and five indicate that an added focus on the scalability and distribution of 3D printed violins is crucial for their development and acceptance. Instrumental teachers one and five suggested developing fractional-sized violins for engagement with local schools or catchment areas. The research approach outlined in this thesis (3.4.4) justified that a full-sized violin necessitated a user base of eleven years or older (Kempter, 2003), indicating late primary or early post-primary students as the earliest viable cohort. However, based on literature from Schellenberg (2004) that cited the advantages of earlier musical exposure, scalability for younger audiences may promote increased access. Instrumental teacher two discussed transitioning from teacher-driven provision models to a more systematic approach. This presents a gap in instrumental education provision for potential standardisation based on 3D printing. This resonates with Khasawneh and Darawsheh (2023), who view open-source software and file-sharing platforms as crucial spaces for digital collaboration.

Integration of 3D printed violins into education contexts requires teacher training and expertise. Instrumental teachers three and five noted that the ability to adjust the violin's action made the instrument more customisable, specifically for more experienced musicians. However, this benefit is only possible for those who are equipped with the training to complete this with confidence and competence. This potential shift from luthier adjustments to user customisations requires musicians and educators to develop new skill sets. Atkinson (1997) stipulated that the introduction of new educational technologies must

be supported with the necessary skill development for teachers and educators to maximise its pedagogical integration. This indicates that providing a 3D printed instrument without a digital blueprint and skill set for replication limits the possibility for educationalists to engage with and envisage its future possibilities. Although this perspective may be attributed to neophilia or techno positivism, Ching and Foley (2012) might contest that this perspective is indicative of maker and creator trends that view the relationship between identity and technology for young people. Nevertheless, involving musicians in more aspects of the musicking process enables 3D printed violins to be viewed as an extension of Small's (2012) musicking concept.

7.3 Sub-Theme: Influence of Time

The influence of time sub-theme is divided into four sections: (i) development and iteration time, (ii) the user learning curve, (iii) durability and longevity of materials, and (iv) market adoption timeframe. These divisions reflect the practical and logistical challenges of sustaining and replicating 3D printed instruments over time.

Development and iteration time are vital for the successful integration of 3D printed violins within an instrumental music context. As emphasised in instrumental music teacher interviews one and five, although the iterative process of identifying, scanning, designing, printing, testing, refining and retesting has significantly refined the 3D printed violin, more development time is needed in order to observe how these instruments behave longitudinally. Specifically, instrumental teacher one rehearsed the benefits of the new tuning design, and instrumental teacher five mentioned the benefit of the instrument's reduced weight, which made it easier for students to hold and perform for longer periods. The professional violinist questionnaires indicated that iterative testing for sound enhancement would elevate the instrument. While luthiers indicated that a great focus on the materiality of the instrument would improve its structural integrity and aesthetic

alignment with traditionally constructed instruments. However, the iterative nature of this research indicates that continuous alterations are necessary to address user comments.

While Norman (2013) advocates for iterative designs as imperative for developing the instrument in relation to its audience, this continual iteration presents time and resource challenges, and it can also undermine older models. The cyclical design and iteration process highlights the significance of allocating the appropriate time and resources for the development and refinement of a final instrument that addresses the practical needs of industry professionals and instrumental teachers.

The user learning curve was a factor influencing the viability of 3D printed violins. Although the research approach in Chapter 3 (3.4.4) outlined that the instrument rather than the pedagogy was the focus of this research, as the pilot progressed, it became evident that providing an instrument with an adjusted design without the infrastructural knowledge to maintain such an instrument was not considering the musicians future with the instrument. Although the two maintenance checks conducted by the researcher during the educational context pilot predominantly aligned with the process undertaken for traditionally constructed instruments, for professional luthiers, the learning curve could be extended to encompass 3D printing techniques to extend or replace instrument parts. Therefore, to position 3D printed instruments as viable alternatives for luthiers, adequate training must be provided to reposition them as active makers. Instrumental teacher four commented on the ease of tuning and maintaining the 3D printed violins. This perspective highlights the potential for 3D printing and iterative testing to reduce technical barriers that can affect engagement for beginner musicians. However, new features such as the machine heads and the adjustable action, more common in guitars, necessitate the development of new skills. In particular, instrumental teachers three and five highlighted the convenience of these design adjustments, while also recognising that the successful integration of these

designs is contingent on the musician's capacity to adapt to the new designs. In this instance, the learning curve involves both technical proficiency and design acceptance in order to accept the 3D printed violins as viable alternatives. Rogers (2003) views the learning curve as a significant barrier to the adoption of new technologies. Consequently, to address the learning curve linked to the production of 3D printed violins, further pedagogical support may be necessary. To address the user learning curve, Appendix J provides proposals for an instrument maintenance and modelling short course and post-primary Lutherie programme. Appendix L provides a link to 3D printing files of the 3D printed violin in stereolithography, Standard Triangle Language (STL) format, including a step-by-step software, hardware, print and assembly manual for users. Both build on the foundation set out by the JCT4 3D printing for Junior Cycle because they provide scaffolded learning towards the acquisition of knowledge in 3D printing and digital modelling. Although the resources in Appendix J and L extend beyond the data captured during this research, they act as a useful resource for future research development in the area of 3D printed violins.

Discussing the durability and longevity of filament materials over time is fundamental to assessing the lasting viability of 3D printed violins. Beament and Beament (2000) noted that instrument longevity is a key factor that can determine the educational value of an instrument. In this instance, maintenance and time-consuming replacements can interrupt and impede student development. Although the instrumental teachers noted a decline in maintenance and sonic issues during the pilot study, the researcher would contend that the timeframe of this study has been insufficient to establish how these instruments may degrade over time, and how this degrading compares to traditionally constructed violins. Instrumental teacher three stated that the students "start with brand new instruments with no difficult brands that will make their progress more challenging,"

indicating that they are satisfied with the instrument's construction. However, due to its new material construction, it would appear that more time is needed to assess how the 3D printed violins react to rosin build-up, moisture, temperature changes, travel, and daily deterioration.

As outlined in the literature review, the market adoption timeframe for 3D printed instruments has been influenced by both social and technical issues, yet it remains peripheral to traditionally constructed instruments (Murphy, 2014). The sustained use of 3D printed violins is contingent on their acceptance and integration by teachers and industry professionals. The professional violinist and luthier data indicated that this is affected by their perceived sonic and material quality, and alignment with traditionally constructed violins. Rogers' (2003) outline for innovation adoption indicates that gaining the momentum of users is integral to the success of a new technology. This indicates that increased promotion of 3D printed violins may condense the market adoption timeframe and enable 3D printing to be viewed as a viable alternative to traditionally constructed instruments. However, Instrumental teacher two astutely voiced concerns about the sustained promotion of a single instrument within an education environment, which could lead to instrument oversaturation, and increased competition for orchestral positions. In this instance, the instrumental teacher recognised the consequence of prioritising one instrument over another and the balance necessary for musicians to grow within an orchestra. As this year was the highest uptake of the violin (15) in this school, with the flute (8) and saxophone (7) as the nearest contenders, it is important to consider the repercussions of prioritising instruments. With traditionally twenty violins in an orchestra, a long-term continuation of this project may undermine the act of musicking, restricting some musicians to solo playing or creating a highly competitive performance environment. Providing instruments in this somewhat unlimited way also forces teachers and conductors

to consider future provisions such as additional instrumental teachers, orchestras, and violin ensembles to facilitate increased performance needs as musicians advance. This concern echoes literature from Girsberger et al. (2014) that urges music educators to build instrument families in tandem with considerations for future repertoire. In contrast, instrumental teacher twos comparison of the short pilot study to Music Generations' "isolated interventions" highlights the need for sustained infrastructures beyond the timeframe of the pilot study. Through sustained support, 3D printed instruments can begin to move from novelty to an integrated instrumental provision practice.

7.4 Conclusion

This chapter outlined the results and findings of the sub-themes of cost and access, and the influence of time, based on the theme of the viability and practicality of 3D printed instruments. The dominant findings relating to the cost and access of 3D printed violins focus on viability and feasibility. Although the affordability and reproducibility of 3D printing technologies were outlined as key factors that can shape access to instrument provision, the initial infrastructural costs of purchasing, learning and maintaining machines remain an initial barrier. Also, the scalability and dissemination of 3D printed violins beyond making the file accessible for potential future users has yet to be explored beyond the parameters of the pilot school. Although the results and discussion have outlined that the musical instruments have sonic and material potential, without strategic investment from other educational institutions, it may remain an alternative model of localised provision.

The dominant findings relating to the influence of time on the feasibility of 3D printed violins emphasised the following aspects. The modelling, rendering, testing and iteration time were a crucial aspect of developing comparability to traditional models. Equally, the learning curve for teachers to engage with 3D printing beyond instrument

acquisition needed to be addressed through training and units of learning, outlined in the appendices. Also, the material durability will inform the viability of these instruments over time. Finally, the market adoption timeframe is contingent on user acceptance, sustained use, and greater visibility. These time-related factors affect the viability and sustainability of these instruments.

Chapter 8 3D Printed Violins as an Alternative Instrument Provision Model –

Synthesis of the Findings

8.1 Chapter Outline

This research sought to develop iterative prototypes of 3D printed violins based on industry professionals' and educationalists' feedback and to test the viability of 3D printed instruments within a post-primary context. An assessment of the data indicated two general findings:

- i. A sense of increased support for teachers, specifically regarding the provision of musical instruments (Chapter 6).
- ii. A perception amongst professional violinists and luthiers that although 3D printed violins contain sound and material variations based on the filament used (Chapter 4), they could still be viable instruments (Chapter 5).

The findings, when amalgamated, differentiate 3D printed violins as a potential alternative instrumental provision model for musicians. This chapter develops two aspects unique to this research:

- i. The impact of 3D printed violins in the new context of post-primary music education.
- ii. The significance or insignificance of iterative testing with music professionals over the three years.

This chapter discusses the connection between collaborative, iterative testing and user investment in 3D printed violins. Participant perspectives citing opportunities for increased musicking are explored, and the possibility of 3D printing as an alternative form of instrument provision is discussed. Returning to sociocultural theoretical frameworks discussed in Chapter 3 provides the prospect of gaining a deeper understanding of the findings. Table 8.1 gives a synopsis of the findings.

Table 8.1*Summary of the Findings*

Increased provision and teacher agency		Viability as instruments
• Collaborative framework • Shift from overreliance on teachers for instrument provision • Enthusiasm for extending the musicking process towards creation and fabrication		• Variation in design and materials • Iterative testing • Infrastructural supports
Philosophy	Mechanism	Development model
• Researcher and instrumental teachers • Researcher and professional musicians • Researcher, professional musicians and luthiers • Researcher and instrumental teachers	• Plan • Test • Remodel • Reflect • Test • Remodel • Reflect	• Pre-participation meetings • Modelling and development • Iterative testing with industry professionals • Participation and iterative testing with teachers • Feedback and contribution

8.2 Potential for Increased Provision and Teacher Agency Through 3D Printing

The results from this study are connected with findings from similar studies conducted in educational contexts (Calvani et al., 2011; Girdzijauskienė & Šmitienė, 2020; Kelley & Knowles, 2016), which have been previously discussed in Chapter 2 (see Section 2.20). Both of these examples reported cross-curricular connections, with the increased potential for instrument access, although they have either been theoretical or based on shorter pilot studies. Similarly to these studies, working collaboratively enabled informed and precise feedback based on participants' skills. Additionally, the findings from this research study also indicated the need for informal instrumental teacher provision. Although initially discussed in Chapter 3, it has been addressed and reduced, with findings in Chapter 6. Cognisant of contrasting literature from Chapter 2 that viewed 3D printing as both a model of democratisation (Cano, 2015), as well as a potential model of further marginalisation (Hallam & Himonides, 2022), the dominant perspective from instrumental teachers in this study was that this mode of production enabled the prospect of increased

provision and teacher agency through decreasing reliance on teachers personal instrument banks (Chapter 6). This shift from an overreliance on teachers for instrument provision towards a replicable model of provision based on musicians' needs created a positive shift in responding to user needs.

Most teachers began the research study citing issues with instrument provision, with little knowledge but a curiosity for processes related to 3D scanning, modelling and printing as they pertained to musical instruments. As a consequence of the collaboration between the researcher and teachers, a majority of teachers reported comparable sonic and material experiences with the instruments, aligning with Bourell's (2016) recommendation. This finding aligned with Negroponte's assertion that "being digital [would] be noticed only by its absence, not its presence" (2015, p. 4), developing Cascone's (2000) concept of postdigitalism, discussed in Chapter 1 (1.5). In this instance, the musical object functioned in a manner that directed focus to the action of playing rather than the action of comparability. This resonated with Small's (2012) musicking-in-any-which-way, as discussed in Chapter 1 (1.4), which emphasised personal exploration within an educational context.

8.2.1 Collaborative Framework

From a conservation perspective, exploring how instruments of historical prominence may benefit from digital replication and study raises questions regarding the validity of the instrument's evolution that is not reflected in emulating an artefact. This is connected with Wilson et al. (2017) regarding the relationship between the original and the replica when 3D printing. From a comparative perspective, the instrument maker's context provided a prospect for critiquing the fabrication. The professional musician context allowed reflection on the main design obstacles that prevented new instruments from becoming viable alternatives for musicians and the variables that shaped instrument

choice. The school context allowed instrumental teachers to reflect on the instrument's potential viability for different audiences.

The overall findings from the post-primary intervention resonated with Foster's (2015) notion that collaboration breeds the potential for democratising spaces. The findings indicated the immense areas of specialisation that were required to bring an instrument from its infancy to critical stakeholders such as luthiers, musicians, and instrumental teachers. The power of collaboration has been re-emphasised in the conclusion as a method of incentivising industry and education partnerships. However, the applicability of such interventions in other schools necessitates teacher CPD. The need for continued digital skill workshops has been outlined in the STEM Education Policy Statement 2017-2026 (Department of Education and Skills, 2017), Digital Strategy for Schools 2015-2020 (Department of Education and Skills, 2015), the Action Plan for Education (Department of Education, 2023), and The Creative Ireland Programme (Department of Culture, Heritage and the Gaeltacht, n.d.). The findings from the post-primary intervention emphasised the crucial need for inter-department collaboration when undertaking research and when mobilising an ensemble comprised of a range of instruments. However, this responsibility may fall to a single teacher in some schools. This problematises the notion that such an intervention applies to every educational environment. This perspective correlates with Weinberg (1999), who grappled with curriculum hours and expectations for music educators.

The overall findings from the violin modelling evidenced that co-authorship and customisation of new instruments were strong factors that informed participants' perception of their potential collaborative role within the instrument-making process. Although the prospect of customisation based on a student's size has previously been addressed in Sections 3.5.4 and 7.8, further research focused on addressing user-led design

could aid in building a collaborative framework. The role of collaboration in building participant engagement has been previously explored by Togou et al. (2018). Although Togou et al. (2018) focused solely on students' roles in digital fabrication, it illustrates the potential spaces that musicking could extend (Small, 2012).

8.2.2 Shift From Overreliance on Teachers for Instrument Provision

The access possibilities of 3D printed musical instruments include increased engagement and participation in music making, co-authorship and the ability to modify based on user needs, its retrievable format, a common language, maintenance and providing a standardised starting point, discussed in Chapter 6. However, the researcher concedes that, in its current iteration, the research study provides a limited instance of engagement.

8.2.3 Enthusiasm for Extending the Musicking Process Towards Creation and Fabrication

The data demonstrates evidence that this model of instrumental provision has the potential to promote sustained engagement, but an engagement with little to no reliance on the Irish curriculum. Therefore, this would appear as a long-term solution for the sustained engagement of students with access to private music education, but a short-term solution to issues of inclusion and diversification within this field. This develops literature from Freedman (2017) but conflicts with techno-positivistic literature from Cano (2015). 3D printing musical instruments presents the possibility for customisation, increased accessibility, sustainability through reduced material waste, design innovation possibilities, replication and preservation, educational opportunities, cost reduction, repair and maintenance. The findings reveal that technologies that play with the liveness and togetherness of the musical performance trouble Small's (2012) notion of musicking. This aligns with Kaschub and Smith (2014) but contrasts with Hall (2014), who acknowledges

that although digital technologies permeate modern musicking, they primarily appear to be used as a learning tool rather than a component for integration within a performance. Similarly, the findings resonate with Prior (2018), who views technology as a springboard for reflective musicking but acknowledges that social etiquette regarding performance parameters prevents it from being anything more. Finally, the findings match Bauer (2020), who argues that in an age where digital footprints and living archives frame our digital presence, the relationship between the medium and the message has never been more pertinent. The message, in this instance, is individuals. For music and education, this indicates new parameters from which musicking can be discussed and explored.

8.3 Potential as an Alternative Instrument Model

Regarding conservation and instrument making, the findings indicate that construction for preservation versus construction for sound are two vastly separate design activities. Although reproducing an instrument's sonic properties is contingent on mathematical calculations and equivalent physical materials, 3D printing still has material limitations for projection. This was evidenced in the modelling and rendering data (Chapter 4) of professional violinists and luthiers (Chapter 5). Regarding perceptions and values, the findings from Chapters 5 and 6 indicate that although 3D printing may fulfil many of the technical requirements of musical instruments, luthiers, professional musicians, and teachers' perceptions of it as an exterior force to real instruments mean that they will remain peripheral for now. Contrary to Schmid (2017), Fletcher and Rossing's (2012) association of inferior price reflecting inferior quality, in this instance, technological advancements have extended the message of the medium, whereby the functionality, usability and ultimate possibility for engaging in the act of musicking is made possible for all students, regardless of socio-economic status. The instruments were printed using approximately one roll of carbon fibre, with approximately 35 instruments

produced throughout this research. Therefore, in opposition to Schmid (2017), Fletcher and Rossing (2012), an inferior price does not indicate inferior quality. Instead, it potentially positions the 3D printed violin as a viable option that adheres to and aligns with both musicianship and monetary concerns.

In relation to the instrument design, Cooper et al.'s (2014) five-step criteria for interaction design and Norman's (2013) advocacy for human-centred design in technology are evidenced in this methodological process. While incorporating Miranda and Wanderley's (2006) focus on iterative prototyping enabled reflexive testing, remodelling, and reflecting, as outlined in Table 8.1. This process enables the development of Sullivan's (2015) concept that the musical creation process connects with the interaction between the musician and their instrument.

This research provides an instance where disruptive (3D printing) and sustained technologies (musical instruments) intersect. In contrast to Schmid (2017), it is posited that learning to play on a replica instrument might increase engagement and possible progression. In this instance, musicians can access a replica of a world-renowned form (Pollens, 2015). Coupling the instrument template with 3D modelling and printing has enabled maintenance issues that traditionally might have impeded progression to be reconceptualised, reconsidered, and resolved. Presenting the 3D file as an editable and customisable experience for users also aids in building a sense of instrument ownership and individuality that may promote longevity of use.

This research contributes to prior explorations of 3D instrument design and printing (Duerinck et al., 2020; Kantaros & Diegel, 2018; Zoran, 2011). It attempts to challenge Duerinck et al.'s (2020) notion that 3D printed instruments are not currently viable due to incompatible audible, physical and usability differences by focusing on these three components throughout the research. It has sought to address Zoran's (2011) belief that

new instruments have finite limitations due to their existence in isolation by generating a suite of violins that can grow and develop within an orchestral context. It has attempted to address Kantaros and Diegel's (2018) idea that a replica is never a substitute for the real object by maintaining as many dimensional and material characteristics as possible without replicating the inherent errors of the original. Although a substitute will never replace the real object, it is hoped that design issues and practical solutions have been critically assessed and tested within the timeframe of this research, providing viable solutions for future-proofing. This research concedes Kantaros and Diegel's (2018) view that 3D printing technologies are still in the formation process and may require more time to prove a viable substitute nationally and internationally.

8.3.1 Variation in Design and Materials

Concerning the characteristics of fine musical instruments, the findings indicate just how challenging it is to produce a highly responsive, sonically viable, ergonomically designed instrument. It indicates that making, modelling, and performing expertise are necessary to produce a viable model. This aligns with Montagu (2007). The results demonstrated that several additional considerations must be reflected on when building for communal playing. These include the ability to align with the family timbre concisely and to share standard techniques. This tests Fletcher and Rossing's (2012) hypothesis that maintaining shared sonic and technical compatibility is crucial to the success of new instruments. Findings from the teacher interviews regarding the progressive limitations of lesser brand instruments mirror literature from Blackshields et al. (2014). It posits a case for subsidised provision as outlined by Burton and Snell (2015).

Unlike Bucur's (2016) account of maintenance issues associated with inexpensive instruments, using carbon fibre made the instruments lighter, more durable and less prone to conservation issues than the original. Concerns regarding poor finishes and badly fitted

parts (Bucur, 2016) can be addressed and redesigned during the virtual modelling stage of the construction process. Although the initial research findings suggest that a longer duration is required to assess the physical longevity and long-term value placed on these instruments by their users, it is posited that the project's first year has been successful in using 3D scanning and rapid prototyping in making Stradivarius violin replicas.

Concerning the research question, this process has extended mediums for performance and engagement by using contemporary technologies. Regarding the literature, preliminary research findings suggest an inversion of the Deleuzian concept of a “body without organs” (Deleuze & Guattari, 2004, p. 9), whereby musicking has been activated through technology. The technology is editable, permitting the virtual file to exist as more than a “doubled” (Brown, 2016, p. 5) “voice” (Dolar, 2006, p. 3) but as an “organ without a body” (Žižek, 2016, p. 26). The findings have determined that an advantage of 3D printing is that musical instruments could be produced on the basis of need. Similarly, many 3D printing materials can be recycled, meaning prototype materials may be reused to produce newer models. From an economic perspective, this promotes 3D printing as a viable tool for construction. This links with literature from Kerr (2022). From an educational viewpoint, it demonstrates how consumers can be more environmentally conscious. From an individual perspective, it indicates that instruments could be tailored to suit specific musicians' needs. This resonates with Bongomin et al. (2020).

8.3.2 Iterative Testing

Although the feedback from professional musicians, luthiers, and instrumental teachers was predominantly positive, the need for continuous reflexivity was an initial theme. It was necessary to undertake material and file revisions after the expert musician consultation. Teacher feedback regarding usability also assisted in refining the instrument. More minor edits regarding file format and printing options were necessary to address

before making this file accessible for public consumption. This connects with Miranda and Wanderley's (2006) iterative and cyclical designs for instrument prototypes. As 3D printing is still a relatively emergent technology, this project required the researcher to question whether this medium was ultimately the most logical for the research question. This resonates with Alvesson and Sköldberg (2012), who recommend iterative cycles of design involving collaboration. From a literature perspective (Kantaros & Diegel, 2018), fabrication based on pre-existing methods was unlikely to produce new results. From a personal perspective, having designed and completed traditional luthier projects previously, 3D scanning and printing appeared as a more quantifiable means of designing and producing for sound fidelity. However, the results and findings from participants revealed the extent to which tradition continues to inform industry professionals' and instrumental teachers' choices and perceptions. This aligns with the literature from Bissinger (2008) and Guild (1961).

8.3.3 Infrastructural Supports

The findings indicate that time, resources, specialist instrumental teachers and access to standardised instruments are infrastructural supports that shape instrumental provision. Although the first three feature prominently within the IME literature (Weinberg, 1999), the fourth is an extension of this logic only made possible when the preceding infrastructures are in place. Therefore, supplying instruments to students is sadly not even conceivable for many. Regarding geographical access, the findings propose a model that has the potential to conflict with literature contesting the geographically exclusive literature by having files made available digitally (Roza, 2014). However, regardless of geography, the proposed model is still based on infrastructural support.

Regarding providing a national fund for musical instruments, the findings posit that 3D printing could be a viable solution to access and storage issues of physical banks;

however, files may need to be built with customer guarantees like their traditionally constructed iteration to build customer trust. The findings and related appendices propose another way of bringing technology into the music classroom, based on an integral rather than an “add-on” (Cantoni & Danowski, 2015, p. 23) way. Concerning existing musical instrument funds such as the Musical Capital Scheme and the Musical Instrument Fund of Ireland, findings indicate that a similar model of instrument provision could be initiated using this application model to promote the viability of 3D printing. However, this fails to utilise the decentralising power of the digital file. Echoing Burton and Snell (2015), the findings from the instrumental teacher interviews support the notion that the intervention will only have long-term viability for those involved if the infrastructural support remains after the timeframe of the research. Infrastructural support in the form of course content, and the proposed programme extensions in the appendices, have sought to address this issue. This connects with Blackshields et al. (2014) and Pollens (2015), who focus on file dissemination.

The influencing factors impeding musicians’ use of new instrument fabrications and brands include tradition, prior experiences, teacher perceptions, sonic and technical incompatibility, the relative novelty of the instruments and reliable infrastructure for sustained maintenance (Chapters 5 & 6). All these factors have been explored with the assistance of instrument makers, professional musicians, and instrumental teachers. It reveals that instrument choice is influenced by historical, social, cultural, and economic choices that are primarily decided upon by parents/guardians and IME teachers. This aligns with literature from Bovermann et al. (2016), who explore how social and cultural identity shapes and informs musical tendencies.

8.4 3D Printing as an Experiment in Postdigital Practices

The teacher's findings from Chapters 6 and 7 indicate that postdigital musicking allows musicians to conceive of 3D printed instruments within an ensemble context as more than a novel tool but a strategy for promoting socioeconomic and geographical equity. It resonates with Blikstein (2013), who calls for new music education pedagogies based on twenty-first-century learning. Some participating teachers expressed their tentativeness regarding the longevity of such instruments (Chapter 7), correlating with Doddamani et al. (2023).

Discussing the cyclical role of iterative prototyping and the role of critical thinking throughout Chapters 4, 5, 6, and 7 enabled postdigital practices to connect with STEAM principles. This research data extended the STEM Education Policy Statement (Department of Education and Skills, 2017) by developing learning outcomes that relate to student access. The findings related to teacher CPD (Chapter 6) and addressed the DSS (2015–2020), which called for meaningful interdisciplinary integration within the existing curricula to enrich learning outcomes. The funding findings, discussed in Chapter 7, connect with the Action Plan for Education (Department of Education, 2023), due to its provision of a road map outlining future infrastructural provision. The interdisciplinary findings, discussed in Chapters 4, 5, and 6, connect with the Creative Ireland Programme (Department of Culture, Heritage and the Gaeltacht, n.d.) by advocating for collaboration between teachers and industry professionals.

8.5 Postdigital Practices Extending the Role of Musicking

The findings indicate that contemporary musicking still bears a relationship to the other, but the other, in this instance, has been disembodied (Deleuze & Guattari, 2004), reflected and inverted (Cano, 2015). Therefore, a return to the origin is a return to an altered form distinct from the original. As an extension of Small's (2012) portrayal of

musicking as an action verb, today, societal engagement promotes participation with technology (Adesope & Rud, 2018). Therefore, luthiers and instrumental music teachers must look further than traditional methods of instrument fabrication and acquisition and consider the wider spaces in which musicking can occur. Equally, the research suggests that to reframe musicking practices, the fundamental meaning of performing, composing, and listening needs to be re-evaluated, considering technology as more than a medium but an entwined message. Regarding performance and musicking, the findings indicate that by promoting process over product, collaboration and community, role flexibility, iteration and evolution, engagement and participation, the educative value of 3D printed instruments is evidenced. This lens shows design and prototyping as a form of musicking, 3D printing sessions as performances, and feedback and iteration loops as improvisation.

8.6 A New Framework

The results of this study indicate that, through working collaboratively to provide feedback that informed iterative prototyping, most participants moved to a transformative activist point (Murphy & Carlisle, 2008), assuming the ontological and epistemological perceptions and socio-cultural practices of postdigital musicking (Trondalen, 2023). This changed the school culture of instrumental music provision from an informal or outsourced practice to a collaborative, cyclical, and iterative model of transformative engagement that extended musicking practices to encompass modes of production.

8.7 Limitations of the Study

COVID-19 limited research within schools, and music performance department communications were particularly strict regarding musical performance, as outlined in the methodology. There are limitations in the research scope, participant demographics, and participant scale. Although the original design had also encompassed an intervention with local primary schools, the data from this was not retrieved due to a combination of

COVID-19 restrictions, the volume of data produced already, as well as the decision to dedicate time to iterative testing as the research progressed. Although data was initially collected for post-primary students, the shifting focus towards the technical development of the musical instrument limited the data relevance to the research questions. Future research could involve engagement with these schools in instrument production or further data collection based on design edits.

There are limitations in the school type used in this study. This study took part in the researcher's own school: a private, city centre school with a well-established instrumentation programme already in existence and a strong ethos regarding social justice. It is acknowledged that adding structures to an already established system is much easier than starting from the beginning. However, it was rationalised that this research was not intended to establish a music instrumentation programme but to explore the viability of 3D printed instruments compatibility within an existing performance framework. Therefore, an existing instrument programme was a key component of the decision process. However, further research could explore these instruments within a public school, where the school's support may differ.

The timeframe of this study is limited. Music performance COVID-19 restrictions truncated the timeframe for participant engagement. Therefore, a post-COVID longitudinal study that studies the durability and maintenance challenges would be useful for answering questions regarding sustained engagement. The tools used to generate these violins are limited. Although 3D printing has become more mainstream in recent years, it would be unreasonable to assume that all Irish schools have access to a large 3D printing bed like that used in this research. Future designs have subdivided print sections to access the files from all 3D printers. Although the modest participant sample size, combined with the distinctive characteristics needed for this research, created research limitations, this

research has been a valuable endeavour for testing makers, musicians, and teachers' experiences with the instrument.

8.8 Conclusion

This chapter discussed the connection between collaborative, iterative testing and user investment in 3D printed violins and their relationship to existing literature.

Participant perspectives cited possibilities for increased musicking and 3D printing as an alternative form of instrument provision. The findings' relationship to sociocultural theoretical frameworks and the research limitations were discussed. The findings suggest that 3D printed instruments technically have the power to extend music instrumentation and performance practices in Irish post-primary education; however, viability will remain contingent on access to high-performance machines, cooperation from gatekeepers, and school investment in their continuation. As 3D printing becomes more domesticated, it is exciting to envisage this process becoming more democratised. However, it is unrealistic to suggest it at present without significant investment.

Chapter 9 Conclusion

9.1 Introduction

This research began with an interest in whether access to 3D-printed musical instruments could increase music-making opportunities for musicians. The literature review has outlined the challenges related to current instrument manufacturing and provision and documented its effect on musicians' access and musical experiences. However, despite prior feasibility studies identifying the need to develop musical instrument provision that is culturally, geographically, and socioeconomically more accessible (Moloney & McCrea, 2014; Music Network, 2003), this research found that there are still limitations to the current model of provision. Based on a pilot instrumental programme, this three-year mixed methods research aimed to explore if 3D printed violins could be developed as an alternative provision model for instrumental education. It sought to explore the technical skills, industry and education perspectives, and infrastructural and pedagogical support necessary for initial and sustained integration. This research sought to present 3D printed violins as an alternative model to support access for musicians (Cano, 2015), explore industry professionals' and educationalists' perceptions to ascertain instrument viability (Kantaros & Diegel, 2018), and explore opportunities for STEAM development through 3D printing (Ulbrich et al., 2024).

Based on three research questions, this research explored and synthesised the perspectives of twenty musicians, luthiers, and teachers on the challenges and opportunities that this alternative model presented. This concluding section summarises this research and assesses the overall findings in relation to the three research questions. This research is viewed in relation to the broader context of instrument-making and performance education. Future research recommendations are discussed. The findings

relate to luthiers and post-primary instrumental music teachers concerned with developing musical instrument provision and STEAM learning outcomes.

9.2 Overview of the Research

This research, which resulted from significant collaboration with a diverse group of professional musicians, luthiers, and music teachers, relied on their collective expertise, iterative testing, and critical reflection. The three-year timeframe was necessary for iterative prototyping based on participants' feedback. Year one was utilised to critically assess users' needs and develop high-quality scans, designs, and prints that addressed sound and material challenges outlined in the literature. It directly addressed research question one: What technical specifications and material properties are required for comparable sound quality and durability between traditional and 3D printed violins? Year two was used to undertake iterative comparative sound and material testing with industry professionals to establish instrument limitations and user perceptions indicative of the literature. It focused on research question two: What are the perceptions and values of musicians and luthiers using 3D printed instruments, and how does this affect instrument viability? Year three was used to pilot the violins in a post-primary education context and ascertain integration's infrastructural, pedagogical, and perceptual challenges. It addressed research question three: What are the implications for teachers integrating 3D printed instruments into music performances? Although time spent in an education context was comparatively small, comprising one-third of the research methodology, prior literature indicating the sonic and material limitations of 3D printed instruments to date (Wilson et al., 2017) justified dedicating more time to the research's design, iterative prototyping, and industry feedback stage. This dual prototyping with industry professionals and education participants enabled the performance potential and limitations of the instrument to be

critically explored with multiple stakeholders. Testing the instruments in a professional and entry-level context explored their viability beyond musical education.

Data was sourced from pre-audit meetings (N=2), 3D scanning (N=3), modelling and 3D printing (N=1), violinist (N=10) and luthier questionnaires (N=5), violinist sound tests (N=26), teacher interviews (N=5), and instrument maintenance checkups (N=30). Questionnaires and maintenance checks were collated via MS Forms, interviews were recorded and transcribed, and recordings were compared and visualised. This research sought to explore how 3D printing could inform music instrumentation and performance practices (Chapters 6 & 7). The literature revealed that although discussing music education concerning technology is not a new concept (Adesope & Rud, 2018; McPherson & Welch, 2018), its early adoption in the curriculum has primarily not been reflected in its advancement, with existing literature mainly focusing on technology as a visualisation and compositional tool and its effects on existing educational practices. This continued separation between traditional educational practices and disruptive technologies forced an analysis of music-making that needed to consider tools and content, or the medium and the message (McLuhan, 2016) as integrated and mutually functional modes of thought.

3D printing provided the opportunity to capture the original structure of the Stradivarius and provided a blueprint for its agency beyond the instrument's lifespan. Furthermore, digital music reproduction challenges the concepts of originality that cultural industries are built upon (Roza, 2014). In this instance, there is the option to accept the anti-commodity position as a social critique (Plakitsi & Barma, 2024) or to visualise new methods for commodifying and enacting music (Simian, 2023). This research demonstrated a method to capture the instruments from which future sounds may be generated. By exploring the key challenges and opportunities when designing, producing, and performing 3D printed musical instruments, this research has provided practical

insights for teachers, violinists and luthiers regarding enhancing accessibility and engagement. By examining the literature, practical testing, and mapping the experiences of industry professionals and instrumental teachers, this research has contributed to existing practice in music performance, education, and 3D printing.

9.3 Synthesis of Salient Findings

The salient findings indicate that 3D printing technologies can play a vital role in producing instruments that promote social communality, as evidenced by the increased uptake of instruments in Chapter 7 (7.10). However, although 3D printing presents an alternate model that encompasses user agency (6.3.3), the costly nature of these infrastructures ensures that this construction mode is still subject to gatekeepers (6.2.1). This resonates with Neimann et al.'s (2021) acknowledgement that access to provisions will continue to shape the spaces in which research occurs, thus perpetuating inequalities (2.21).

The salient findings from Chapter 4 indicated minor differences between manual and 3D scanning measurements, indicating that a dual measurement methodology may minimise human and computer error (4.6.1). It also indicated that carbon fibre filament responded to the sonic and material requirements for instrument production (4.6). The industry professional questionnaire findings from Chapter 5 revealed that although they will remain peripheral to industry professionals due to social and technical forces ascribed by musicians and luthiers (Fletcher & Rossing, 2012; Hopkin, 1996; Patteson, 2016), the majority of participants viewed 3D printed violins as potentially viable instruments for students (5.4). The teacher interview findings from Chapters 6 and 7 revealed that 3D-printed violins were helpful for increasing instrument provision, instrument access, and instrument standardisation (6.2.3). Violinists (4.5.1) and luthiers (4.5.3) commented on the

comparable sonic variations, while teachers commented on the benefits to a musician's progression when using instruments without significant sonic variations (6.3.1).

Although not all participants in the study reported experiencing the same levels of instrument comparability, overall, as the iterative testing timeline progressed, participant confidence in the instruments increased. However, regarding structural design and resonance, the comparative acoustic properties test findings revealed that although luthiers reported broadly comparable sound results between violin A and B, their materiality rating was critical of 3D printed materials. This indicates that, for luthiers, fabrication techniques are still not comparable with traditionally constructed instruments, suggesting that further research is needed to make these materials viable to makers. This echoes educational engagement literature from Herring et al. (2016), referenced in 6.2.3. An unanticipated outcome was the relative invisibility of this new method of instrumental construction for musicians adopting the violins (6.2.4). In relation to postdigitalism, this demonstrated the degree to which the digital medium has been consolidated with the physical object (6.2.4). It also demonstrated a shift in user perception beyond novelisation towards integration, which connects with the interdisciplinary STEAM framework (1.5). Initial research challenges involved justifying 3D printing as a viable instrument production and provision model. Long-term challenges included foreseeing sustainability without collaboration.

The most commonly reported findings by industry professionals related to the technical specifications and material properties required for comparable sound quality and durability between traditional and 3D printed violins. These included:

- Sonic and technical incompatibility, experienced through the comparative sound tests, completed with professional violinists and critiqued by luthiers.
- Access to standardised instruments, evidenced in the violinist and luthier questionnaires.

The most commonly reported findings related to perceptions and values of musicians and luthiers using 3D printed instruments included:

- The learning curve associated with 3D printing, the current deficit of reliable infrastructures for sustained maintenance, and the unknown durability of 3D printed instruments, as evidenced in the luthier questionnaires and teacher interviews.
- The relative novelty of 3D printed violins, as reported by professional violinists and luthiers' questionnaires.

The most commonly reported findings focused on opportunities for musicking conveyed by teachers included:

- The increased provision opportunities afforded by 3D printed violins are evidenced in the increased annual uptake of violin students.
- The standardised starting point was produced through the availability of a suite of violins, as evidenced in the teacher interviews.
- The sonic comparability of 3D printed violins to their traditionally made counterparts, played by the older students, as evidenced in teacher interviews.
- The need for further collaboration and training in aspects of 3D printing for skills to be transferred and sustainability to be enacted was voiced in the teacher interviews.

9.4 Research Limitations

While the results and findings from Chapter 4 aligned with design-based research addressing comparative instrument sounds (Barab & Squire, 2004), it had limitations. The sample size of professional musicians was small. Their expertise was vital in providing quantitative feedback, but Patten and Newhart (2017) would assert that the size limited the

findings' generalisability. Andrés et al. (2022) also outlined that individual performance style creates a subject bias. Furthermore, although varied, the repertoire selected for testing only covered a classical music genre. While beginner to advanced-level excerpts provided a broad overview, they covered only a portion of the violin's repertoire. As Dooling and Hulse (2014) contend that repertoire selection significantly shapes the outcome of comparative sound studies, this suggests that expanding the genre selection could yield different results about the violin's profile. Equally, from a visual representation perspective, although useful for representing visual differences between instruments, Fletcher and Rossing would contend that using waveform and spectrogram analysis simplifies sound production. Therefore, in order to acknowledge these limitations, future research could involve a broader sample size, diverse musical genres, and alternative modes of visualisation.

Under the heading of structural design and sound resonance, Chapter 4 also presented the professional luthier's assessment of the comparative sound quality tests conducted by professional musicians through questionnaires. These questionnaires gathered expert opinions on the preferred sonority of traditional instruments (Violin A) compared to 3D printed instruments (Violin B). While luthier perspectives provide valuable insights into the tonal qualities of the violins, this approach has limitations. The generalisability of the results and findings is shaped by the small sample size (Patten & Newhart, 2017). Moreover, relying on subjective opinions rather than objective acoustic measurements raises concerns about generalisability, echoing Andrés et al.'s (2022) methodological critiques. To address these limitations, it is crucial to consider the nine subjective comparative sound quality results and findings in conjunction with the objective acoustic data presented in the sound samples results and findings, ensuring a comprehensive evaluation of sound quality. While the durability tests from Chapter 4 were

valuable in incorporating luthier perspectives, they have their limitations. Objective measurements such as tensile strength, compression, or impact tests could have provided a more objective assessment of durability rather than relying on subjective perspectives. Callister and Rethwisch (2017) have pointed out that humidity can significantly affect durability, a factor not considered in this test. Future studies should aim for more standardised testing parameters, considering added factors such as environmental durability, fatigue resistance, and sound analysis through chromatic frequencies. Tanikella et al. (2017) caution against equating density with durability, suggesting that print fillers and design reinforcements can enhance strength without adding weight. These findings highlight the shared role of print material and pattern in determining material durability and the need for further research.

Chapter 5 findings emphasise that established brand loyalty and deep connections to musicians' instruments substantially impact professional musicians' levels of acceptance and trust in 3D printed instruments. The professional musicians favoured long-established brands such as Cremona and Stradivari. These brands denote traits of quality and tradition, which can create barriers to the introduction of new instruments which lack this historical lineage. These barriers are further strengthened by the anthropomorphic attributes that some musicians place on their current instruments. Through this anthropomorphic lens, musicians' instruments are a reflection of self rather than merely a tool for communication. This humanisation of musical instruments complicates the integration and acceptance of 3D printed instruments. Furthermore, the findings show that while professional musicians may be willing to recommend 3D printed violins to students, most would not play them themselves. This resistance reflects the sonic and material gap between 3D printed and traditionally constructed violins. Violinists' resistance is rooted in recognising differences in quality, rather than neophobia. These findings highlight the iterative sonic and material

changes needed to produce comparable instruments. It also emphasises the challenges to trust and acceptance that designers and modellers encounter when integrating new instruments within a historically rich field.

Chapter 5 findings of the performance and aesthetic aspects of 3D printed violins expose critical challenges that could impact instrument acceptance and integration for professional violinists and luthiers. Rating the 3D printed violin tone and projection as average indicates that the rich and resonant tonalities of traditional violins are not being emulated through this construction process. The tactility and material finish rating of average further evidence a deficiency between the 3D printed design and its traditionally made counterparts. These findings indicate that further iterative design modifications are necessary before this instrument is used in any other context. While professionals rated the tuning and string action of 3D printed violins as comparable to traditionally constructed violins, the findings indicated that playability was not optimised for professionals' expectations. This finding indicates that although the participants found aspects of the instruments comparable, they will continue to prioritise tried-and-tested instruments for performance within professional contexts. Finally, while aesthetics and sound quality were viewed as crucial for professionals, instrument weight and cost were collectively deemed more important for younger players, indicating that weight and cost are not influencing factors for professionals. This finding indicates that 3D printed instruments need further performance and aesthetic refinement to increase the viability and acceptance within the wider musical community.

Chapter 6 limitations include the reliance on availability of digital infrastructures, the assumption of teacher ability and willingness, the assumption that the possibility of increased access to instruments engages with curriculum goals, as well as the socio-cultural challenges which could affect integration and adoption. The research sample size,

duration, and instruments used also created limitations on this research. In order to address these limitations, further research should involve a longitudinal study with a larger sample size, with additional questions that have been developed from these interviews and questionnaire findings.

For Chapter 7, although the prospect of reduced cost and increased access presents opportunities for enhancing IME, there are limitations in this approach. Although the methodological preference for carbon fibre printing over cheaper alternatives such as PLA was justified for sonic and structural integrity reasons in Chapter 3, this creates limitations for desktop printers using this digital file. Although the methodological preference for printing the model in two parts, rather than smaller subdivisions that would weaken the structural integrity of the instrument, was rationalised in Chapter 3, it creates limitations on the size of 3D printers that can be used. Finally, although the prospect of reduced cost and increased access would appear to address the literature discussing these factors (Hopkin, 1996), there are limitations in this small-scale study. Future dissemination with a focus on making the digital files publicly accessible will aid in addressing this challenge.

Although the integration of 3D printed musical instruments has presented benefits, it also has limitations. Although the iterative design and prototyping process was a crucial methodological step in this research, it required significant time and prototyping resources. This prolonged time spent on developing and redeveloping the instrument could affect wider use, and could affect the development of other instruments based on this time-consuming process. Equally, the learning curve related to the new design features of the instrument could affect the growth of the instrument, unless it is addressed through training. The long-term durability of the 3D filaments, although positive in the short term of the pilot study, is untested in the long term. This challenges the economic feasibility of the 3D printed violins. Finally, as referenced in Section 2.5, moving from a localised

instrument provision model towards market adoption is contingent on social and technical challenges. In order to view this research as more than a response to localised instrument provision models, but as a viable alternative to provision, this research must be transferred to other educational contexts.

9.5 Contribution to the Field of Instrument Making

Methodological, practical, and creative contributions to the field of instrument making are evident in this research. Firstly, this research provides a methodological contribution by exploring interdisciplinary approaches to instrument design. This has been contextualised within the research through Sections 1.5, 2.4.4, 2.5, 3.8.3, and 8.4. This approach incorporates methods from digital design, traditional luthier practices, and STEAM education. By using this interdisciplinary approach to the fabrication and integration of 3D printed violins, a hybrid methodology, informed by traditional and novel approaches to musical instrument making, occurs. Secondly, this research provides a practical contribution by developing 3D printing applications for the construction of new violins. Finally, this research provides a creative contribution to the field of instrument design and performance through proposing a novel production alternative to the existing provision of musical instruments.

This is the first application of 3D printed violins in an Irish education context. This research contributes to the field of instrument making by developing 3D printing filament studies (Pei et al., 2023; Vasina et al., 2020; Yao et al., 2016) with a key focus on their application to developing musical instruments' sonority. Regarding contribution, the researcher argues that this research moves beyond the physics of sound towards its application to 3D printed violins. For luthiers, this research affirms Birtchnell and Urry's (2016) and Lipson and Kurman's (2013) contention that the material variations in print filaments and printers restrict their meaningful integration in the broader context at

present. However, this research has shown that, with collaborative input from industry professionals and teachers, a comparable model of provision can be initiated. This collaborative input ensures that research builds on, rather than replaces, existing luthier and provision models, ensuring research sustainability. This research offers practical insights and equips future researchers and luthiers with sonic and material templates. It moves beyond engagement with modelling programmes towards physically testing musical instruments.

9.6 Contribution to the Literature

Regarding instrument design, this research was built on Cooper et al.'s (2014) criteria for designing new musical instruments by seeking participant feedback at all stages of the prototyping process. It developed Miranda and Wanderley's (2006) DMI design approach by focusing on the acoustic, rather than digital potential of 3D printing as a mode of production. Through this, Cascone's (2000) concept of postdigitalism (Section 6.2.4) was enacted. The filament testing has contributed to existing 3D printing filament studies (Pei et al., 2023; Vasina et al., 2020; Yao et al., 2016). As evidenced in Sections 2.3.4, 3.6.3, and 3.6.4, these authors explored the sonic potential of printing filaments. In particular, this research sought to focus on the practical application of carbon fibre to 3D printed violins.

In relation to alternative musical instrument provision models, this research explored Pranadani's (2023) claim that 3D printed musical instruments could provide a cost-effective and accessible alternative to existing models of provision (Section 2.15). This research contributes to the literature, with the caveat that 3D printing only meets the above criteria if luthiers are trained and willing to incorporate 3D printing technologies into their existing fabrication processes, or if industry professional collaborations occur. While for musicians, the prospect of 3D printing as a cost-effective and accessible

alternative remains reliant on access to 3D printing infrastructural support and industry professionals' knowledge. Although this research confirmed the comparative sonic (Manapat et al., 2017) and material limitations of 3D printed instruments (Shaer, 2009), through iterative testing with industry professionals and teachers, the researcher has sought to explore how these challenges could be addressed.

9.7 Contribution to Instrumental Education

Returning to Chapter 1 (1.3), Feldman and Contzius's (2020) assertion that access to high-quality instruments is the foundation of effective music-making permeates the research. Despite the research limitations, it is argued that the iterative testing and modelling that this research provides a blueprint for future research around the access potential of 3D printed instruments to be developed. Although this is a geographically localised model (Moloney & McCrea, 2014), with replicable infrastructural support for 3D printing, this model of provision could transcend site as a digital file. This research contributes to producing and testing instruments for access in education. The research demonstrates that, with a luthier-informed approach to digital modelling and material fabrication, combined with a musician and teacher-informed sequence of iterative testing, 3D printed instruments can begin to be conceived of as a functional and cost-effective alternative to traditional methods. This study's originality lies in its innovative approach to integrating modern digital practices with historical instrument design. This research digitally maps, analyses, and presents original data on the efficacy of 3D printed musical instruments in an Irish post-primary context and extends the musicking process to encompass digital competencies related to instrument fabrication.

This study also addresses the STEAM framework by integrating digital competencies into arts education through interdisciplinary research, providing an avenue for customisation and personalisation influenced by industry professionals and teachers.

This user-centred design approach, a core principle of the study, ensures the customisability of 3D modelling is actualised, and participants' voices are reflected in iterative designs. Although modest, the pilot study, conducted within a post-primary educational context, paves the way for further longitudinal studies that could further validate the replicability of these findings. By effectively addressing the challenge of making 3D printing a practical and intuitive tool for creating musical instruments, this study shifts the perception of 3D printing from a novelty or "a cure in search of a disease," as Freedman (2017, p. 27) termed it, to a viable alternative, with the appropriate digital infrastructure. The findings inform educational policy by demonstrating the viability of integrating 3D printing into the arts curriculum. This research advances educational outcomes by providing a high-quality digital model that is a cost-effective and innovative method for instrument creation.

9.8 Replicability, Sustainability, Funding and Curriculum Recommendations

To test this research's replicability, a pilot programme could be trialled across various schools to consider the instruments' viability in different contexts. Comparative studies on instrument usage between schools, with variations in public or private, single gender or mixed gender, urban or rural, national or international, could yield a range of different data sets that could aid in ascertaining whether 3D printed instruments could promote access and inclusion in a school context. Further recommendations include longitudinal studies across multiple instruments to assess their long-term impact on musicians' learning outcomes and skill development. Studies exploring such technologies' collaboration and community engagement possibilities would also speak to the literature and promote local interests (Thompson, 2014). Education, local industry and partnerships could support this expansion. The resulting data could inform future instrument provision decisions.

School funding for infrastructural and technical support, CPD and periodic maintenance would ensure that 3D printing becomes a naturalised tool within the classroom. Specific CPD could include subject-specific pedagogical integration, facilitation of 3D scanning, modelling, and printing principles, and collaborative models to incorporate multiple stakeholders. Training workshops could develop design and AutoCAD skills, progress material knowledge skills, provide access to resources, and provide ongoing developmental support. To ensure cost-effectiveness, recommended safety protocols, material choices and sustainable recycling procedures should be established and followed.

At the post-primary level, recommendations include school or department investment in a 3D printer in tandem with, or as an alternative to, an instrument suite. From a music department perspective, recommendations include collaboration with industry professionals to bridge the learning gap and empower music teachers to adopt 3D printing practices within their instrument provision. Providing digital files as open source enables users to engage with the process democratically. It also allows files to be edited and updated based on future users' needs.

Regarding curriculum development, curriculum guidelines, units of learning, and learning objectives that develop the existing music education curricula should be undertaken collaboratively between policymakers, educators, and industry professionals. Echoing the limitations mentioned in this research, future research could develop curriculum and STEAM education within primary and post-primary music education. Ethical considerations should involve IP rights for instrument designers, ensuring ethical licensing is attained. Consumer quality assurance rights and regulations, maintenance agreements, warranties and support options should be established to protect consumers. Education recommendations include providing violins via 3D printing methods. At the

primary level, recommendations include introducing instrumental programmes beginning at a younger age. At a performance level, recommendations include continuing to perform 3D printed instruments aimed at showcasing and normalising them.

9.9 Suggestions for Future Research

As new instrument designs historically stem from a perceived user need or instrument deficit (Dabin et al., 2016), future instrumental studies should build on this research by replicating and editing files based on their intended users. This will assist in maintaining relevant file formats and maintaining files that reflect the interests of its user base. Future design studies could use existing files to develop new instrument hybrids that address current timbre and maintenance issues. By building on existing files, prior knowledge can be continually revised. Future studies could redesign the 3D models to produce model variations specific to the intended user base in connection with prior literature. Future studies could trial these instruments in public and DEIS schools to assess their transferability in different contexts and communities. Future music education studies could trial these instruments in an early primary context to assess if increased access to instruments at a younger age can promote sustained engagement beyond the primary years.

Conservation studies focused on accessing and scanning instruments of historical or cultural significance could prove viable for constructing a database for future musicians and promoting greater visibility of such collections. Dissemination online could address issues of access and inclusion. Comparative instrument studies assessing the specific access and affordability of traditional and 3D printed musical instruments within Ireland could provide initial data that would influence the provisions of 3D printing infrastructures. Infrastructural support in the form of collaborations could prove economically and promotionally viable for educational and commercial parties.

Comparative instrument studies between musicians learning traditional and 3D printed musical instruments, focusing on indicators such as increased enrolment, attendance, engagement in performances, cultural and socioeconomic diversity, and musicians with disabilities, could provide data on the inclusive potential of 3D printed musical instruments. Relative assessments of technical skill and musical proficiency could determine equivalent progression rates. From a conservation perspective, exploring how instruments of historical prominence may benefit from digital replication and study raises questions regarding the validity of the instrument's evolution that is not reflected in emulating an artefact. From a comparative perspective, this school context allowed new and developed musicians to consider the main design obstacles that prevent new instrument fabrications from becoming viable alternatives for musicians. The age group allowed new and current users to engage with and test the instrument's capabilities over an academic year.

9.10 Dissemination of Findings

The first step in disseminating these findings will be to provide a summary of the key findings for the participants, the school headmaster, and the school's Board of Management. The findings are relevant to the professional development services in the Department of Education and Skills, as well as luthiers and instrument providers. The findings also apply to post-primary school leadership, who may seek to develop opportunities for instrument provision in their schools. Equally, agencies such as the Musical Instrument Fund of Ireland, Music Network, Music Generation and Ceoltoiri Eirinn may seek to explore diversification alternatives for instrumental provision. More broadly, publishing through journals will be prioritised. Presentations based on aspects of this research have taken place at the International Society for Music Education in Azerbaijan (17/07/18), the Society for Music Education in Ireland (25/01/20), the Post-

Graduate Research Conference, Trinity College Dublin (15/12/21), and the Guild of American Luthiers in Washington (07/07/23).

9.11 Conclusion

This thesis explored the potential of 3D printing to promote access to violins. It used a mixed-methods approach, incorporating qualitative and quantitative data collection and analysis techniques. The literature review mapped key literature, policy, and initiatives concerning inclusive education and music, exposing prevailing gaps within the current provision. It offered an alternative to decentralise, democratise, and individualise musicians' experiences, ultimately fostering more diverse instrumental music access for future performers. All participants were co-designers, collaborating with the researcher to adapt the design based on their expertise. The research participants were luthiers, performance professionals, and instrumental teachers. Comparative instrument tests with luthiers tested the fabrication of the instrument. Factors such as fabrication, playability, and adaptability were considered.

Questionnaires and comparative sound tests with performance professionals ascertained the sonic and physical potential and limitations of 3D printed violins. Interviews with instrumental music teachers established the pedagogical and access possibilities of 3D printed instruments. The findings suggested that 3D printed violins provide a model to widen the music-making circle and promote opportunities for access. However, the findings also highlighted the sonic and material limitations of 3D printed violins and access issues related to 3D hardware and software. This research has proposed and tested a viable model for alternative provision based on 3D printing practices. The research aims and objectives have been met using a mixed-methods, participatory, interdisciplinary approach framed through 3D printing literature.

Framed through three research questions, the findings indicate that barriers such as resources and access to standardised instruments continue to challenge instrument provision. Factors such as tradition, prior experiences, teacher perceptions, sonic and technical incompatibility, the relative novelty of the instruments, and reliable infrastructure for sustained maintenance can affect the acceptance of new instruments. 3D printed instruments provide a model by which access can be developed towards educational models of musicking. The evolving nature of the medium necessitates the continued maintenance of such musical interventions involving 3D printed instruments, which is needed to maintain the long-term longevity of such instruments. Finally, when returning to the statement that becoming postdigital has the potential to make us more human, this research has endeavoured to explore how humanising digital practices has seeded the possibility of future musical equity.

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Appendices

Appendix A: The Professional Musician Questionnaires, Link and QR Code

<https://forms.office.com/r/wPpjbsJ2cW>



Even better than the real thing? Testing 1-2 NCO and NSO

Thank you for taking part in this project.

This questionnaire is focused on your experiences using your 3D printed violin. You have been asked to play and test the instrument for 2 weeks before filling in this questionnaire. This research is focused on finding ways to make musical instruments more accessible for Post-Primary Music students, by making instruments printable and editable by users. Studies have shown that access to instruments is an influencing factor to music engagement and instrument quality is a prime factor cited for disengaging with performance. This design is based on a Stradivarius violin, with the rationale that if we are going to build an instrument, we might as well base it on a good one!

Although the intended target audience for these instruments would be students, your expert knowledge on the violin will inform revisions and adjustments to these instrument. So your opinion is very important!

We will start with your early experiences learning the violin, move onto your current experiences and finish with your experiences with the 3D printed violin.

...

1. What age did you start the violin at?

Enter your answer

2. What brand was your first violin?

Enter your answer

3. What aspect of early playing did you find enjoyable?

Enter your answer

4. What aspect of early playing did you find challenging?

Enter your answer

5. Where did you receive your early musical education? (in the home, private teacher, conservatory, school of music, school, self-taught, other)

Enter your answer

6. How would you define yourself? (Soloist, Performer, Teacher, Composer, Artist, Other)

Enter your answer

7. What musical genre categories do you generally perform? (Avant-garde and experimental, Blues and Country, Classical, Electronic, Folk, Jazz and Latin, Popular, Religious, Rock and Punk, Metal, Other)

Enter your answer

8. What instrument brand do you play at present? (Cremona, Eastman, Höfner, Knilling, Mendini, Stentor, Stradivarius, Yamaha, Other)

Enter your answer

9. How long have you played your current instrument for?

Enter your answer

10. How would you describe your relationship with your instrument?

Enter your answer

11. Name a positive characteristic of your present instrument.

Enter your answer

12. Name a challenging characteristic of your present instrument.

Enter your answer

13. Have you ever played a non-traditionally constructed violin before this?

☐ Yes

☐ No

14. Please rate your experience testing the 3D printed violin:

	Poor	Fair	Average	Good	Very good
Tone quality	☐	☐	☐	☐	☐
Projection quality	☐	☐	☐	☐	☐
Ability to maintain tuning	☐	☐	☐	☐	☐
String action	☐	☐	☐	☐	☐
Fine tuners in relation to the tailpiece	☐	☐	☐	☐	☐
Tactility of the fingerboard	☐	☐	☐	☐	☐
Nut and bridge alignment	☐	☐	☐	☐	☐
The bow quality	☐	☐	☐	☐	☐
The instruments material finish	☐	☐	☐	☐	☐

15. How important is the following:

	Never important	Rarely important	Sometimes important	Often important	Always important
The instrument cost for the students that you teach	☐	☐	☐	☐	☐
The aesthetic of the instrument	☐	☐	☐	☐	☐
The sound of the instrument	☐	☐	☐	☐	☐
The weight of the instrument	☐	☐	☐	☐	☐

16. Please rate your likelihood of the following:

	Very unlikely	Somewhat unlikely	Neither likely nor unlikely	Somewhat likely	Very likely
To recommend this instrument to your students or young violinists	☐	☐	☐	☐	☐
To use this instrument yourself	☐	☐	☐	☐	☐

16. Please rate your likelihood of the following:

	Very unlikely	Somewhat unlikely	Neither likely nor unlikely	Somewhat likely	Very likely
To recommend this instrument to your students or young violinists	☐	☐	☐	☐	☐
To use this instrument yourself	☐	☐	☐	☐	☐

17. Have you got any other comments?

Enter your answer

Submit

Appendix B: The Instrumental Teacher Interview Questions

Instrumental Music Teacher Interview Questions

Thank you for participating in this semi-structured interview. As you are aware, this interview will aim to explore the potential of increased access to musicking using 3D printed violins. Your valuable insights as instrumental music teachers are crucial for the success of this research. Today you have kindly agreed to take part in an interview.

Progression and Technique Development

1. Have you noticed any progression changes in your students using the 3D printed instruments?
2. Have you noticed any techniques which are more or less challenging on the 3D printed violins?
3. Have you noticed any changes in your own playing of the instrument?
4. Have you noticed the fingerboard changing your own playing of the instrument?
5. What about the projection of the instrument?

Access and Engagement

6. Do you have any SDP students?
7. Do you think that instruments that sound different in an orchestral setting can affect student engagement?
8. Do you think that student engagement is similar to other years or different in any way?

Perceptions of Difference

9. Have you heard students discuss 3D and traditionally made instruments in different ways?
10. Do you feel that instrument difference is based on terminology, visual, or sonic aspects of the instrument?

Future Iterative Cycles

11. What age group or year do you think would suit best for future cycles?
12. Is this pilot generalisable or specific to this school?
13. Can you think of other musical instrument provision models in schools?
14. Can you think of any access challenges to using these instruments?

Appendix C: Sample Gatekeeper Letter



Dear Sir/Madam,

My name is Sarah Dunne, and I am currently pursuing a Doctorate in Music Education at the School of Education, Trinity College Dublin. As part of this programme, I am conducting research in the area of music technology that has the potential to increase access to music. My research is under the supervision of Dr Andrew Loxley and is titled *Investigating the Potential of 3D Printed Violins in Instrumental Teaching and Learning Contexts: Perspectives from Luthiers, Musicians and Instrumental Teachers*. This project seeks to question how mediums for musical performance might be extended through twenty-first-century technologies. To test this, I am seeking violin participants to participate in a questionnaire that will be completed in tandem with an instrumental test. I am specifically interested in professional musicians who can provide expert knowledge on the subject.

The questionnaire is anticipated to take no longer than 15 minutes. It is envisaged that the questionnaire be taken outside of rehearsal times so there will be no impact on the orchestral schedule. I would greatly appreciate your assistance in permitting staff members to participate in this research. I can foresee no risks associated with participation in this study. The information gathered will be anonymised, and it will be treated in a GDPR-compliant manner. No information about the participants will be identified in the research. All information about the participants will be stored safely with access only to the research team and examiners. Data will be destroyed after a period of seven years. The anonymised results will be included in a dissertation and may be discussed at conferences or published in academic literature. A copy of the results can be made available to you if requested.

Please note that participants involved are under no obligation to participate in this study. If, at any time, a participant wishes to withdraw from the study, they may do so. If you have any further questions regarding the research, please contact me using the email address listed below. Finally, I would like to thank you for taking the time to consider my research.

Kind regards,

Sarah Dunne

Researchers email: dunnes38@tcd.ie

Supervisors email: loxleya@tcd.ie

Appendix D: Sample Consent Forms and Participant Information Leaflets (PIL)



Dear Sir/Madam,

My name is Sarah Dunne, and I am currently pursuing a Doctorate in Music Education at the School of Education, Trinity College Dublin. As part of this programme, I am conducting research in the area of music technology that has the potential to increase access to music. My research is under the supervision of Dr Andrew Loxley and is titled *Investigating the Potential of 3D Printed Violins in Instrumental Teaching and Learning Contexts: Perspectives from Luthiers, Musicians and Instrumental Teachers*. This project seeks to question how mediums for musical performance might be extended through twenty-first-century technologies. To test this, I am seeking violin participants to participate in a questionnaire that will be completed in tandem with an instrumental test. You will be asked a series of questions pertaining to your experiences with a 3D printed violin that has been based on a scan of a Stradivarius violin, which will be given to you two weeks prior to the questionnaire. I am specifically interested in professional musicians who can provide expert knowledge on the subject.

The questionnaire is anticipated to take no longer than 15 minutes. It is envisaged that the questionnaire be taken outside of rehearsal times so there will be no impact on the orchestral schedule. If you are interested in participating, please contact me using the contact information below. The information gathered will be anonymised, and it will be treated in a GDPR-compliant manner. No information about the participants will be identified in the research. All information about the participants will be stored safely with access only to the research team and examiners. Data will be destroyed after a period of seven years. The anonymised results will be included in a dissertation and may be discussed at conferences

or published in academic literature. A copy of the results can be made available to you if requested.

Please note that you are not obligated to participate in this study. If, at any time, a participant wishes to withdraw from the study, they may do so. If you have any further questions regarding the research, please contact me using the email address listed below. Finally, I would like to thank you for taking the time to consider my research.

Kind regards,

Sarah Dunne

Researchers email: dunnes38@tcd.ie

Supervisors email: loxleya@tcd.ie



Declaration of Consent

Please tick the box for each statement and complete the details below.

I confirm that I have read and understood the information sheet about the above study, informing me about the aims and procedures involved.	
I understand that the study is voluntary, and if a person decides they do not want to take part, they can stop participating at any time without giving a reason.	
I have had the opportunity to consider the information, ask questions, and have any queries answered satisfactorily.	
I understand that I am entitled to a copy of the results of the research.	
I reserve the right to withdraw from the project at any stage.	
I understand that all personal data will be handled in compliance with GDPR.	
I understand that the information gained will be anonymous and that personal information will be removed from any materials used in the research.	

Name: _____

Signed: _____

Orchestra: _____

Appendix E: Luthiers Questionnaire, Link and QR Code

<https://forms.office.com/e/1fctB0VjRj>

Instrument makers and modellers

This questionnaire asks about your comparative experiences between conventionally constructed violins and a 3D-printed version. Please listen to the comparative sound samples attached to the questions. Thank you for your time and expertise in completing this.

1. Comparative sound quality test: After listening to the attached comparative sound file (Violin A and Violin B), please rank the following aspects of the violin (1=Very weak, 10=Excellent)



	Option 1-2 (Very weak)	Option 3-4	Option 5-6	Option 7-8	Option 9-10 (Excellent)
Tone Clarity	☐	☐	☐	☐	☐
Projection	☐	☐	☐	☐	☐
Warmth	☐	☐	☐	☐	☐
Sustain	☐	☐	☐	☐	☐
Response	☐	☐	☐	☐	☐
Dynamics	☐	☐	☐	☐	☐
Articulation	☐	☐	☐	☐	☐
Balance	☐	☐	☐	☐	☐
Playability	☐	☐	☐	☐	☐
Versatility	☐	☐	☐	☐	☐

2. Comparative tone quality test: After listening to the attached comparative tone file (Violin A and Violin B), please rank the following aspects of the violin (1=Very weak, 10=Excellent)



	Option 1-2 (Very weak)	Option 3-4	Option 5-6	Option 7-8	Option 9-10 (Excellent)
Tone	☐	☐	☐	☐	☐
Projection	☐	☐	☐	☐	☐
Resonance	☐	☐	☐	☐	☐
Response	☐	☐	☐	☐	☐
Clarity	☐	☐	☐	☐	☐
Warmth	☐	☐	☐	☐	☐
Brightness	☐	☐	☐	☐	☐
Sustain	☐	☐	☐	☐	☐
Evenness	☐	☐	☐	☐	☐
Dynamics	☐	☐	☐	☐	☐
Articulation	☐	☐	☐	☐	☐
Intonation	☐	☐	☐	☐	☐
Playability	☐	☐	☐	☐	☐

3. Comparative timbre: After listening to the attached comparative timbre file (Violin A and Violin B), please rank the following aspects of the violin (1=Very weak, 10=Excellent)



	Option 1-2 (Very weak)	Option 3-4	Option 5-6	Option 7-8	Option 9-10 (Excellent)
Brightness	☐	☐	☐	☐	☐
Warmth	☐	☐	☐	☐	☐
Richness	☐	☐	☐	☐	☐
Resonance	☐	☐	☐	☐	☐

4. Comparative playability test: After trying the two instruments, please rate your experience of the following (1=Very weak, 10=Excellent)



	Option 1-2 (Very weak)	Option 3-4	Option 5-6	Option 7-8	Option 9-10 (Excellent)
Comfort	☐	☐	☐	☐	☐
Ease of bowing	☐	☐	☐	☐	☐
Fingerboard	☐	☐	☐	☐	☐
String Action	☐	☐	☐	☐	☐
Response	☐	☐	☐	☐	☐
Sound projection	☐	☐	☐	☐	☐
Overall playability	☐	☐	☐	☐	☐

5. Comparative bowing test: After trying the two instruments, please rate your experience of the following (1=Very weak, 10=Excellent)



	Option 1-2 (Very weak)	Option 3-4	Option 5-6	Option 7-8	Option 9-10 (Excellent)
Response	☐	☐	☐	☐	☐
Clarity of sound	☐	☐	☐	☐	☐
Articulation	☐	☐	☐	☐	☐
Projection	☐	☐	☐	☐	☐
Evenness of tone	☐	☐	☐	☐	☐
Resonance	☐	☐	☐	☐	☐
String sensitivity	☐	☐	☐	☐	☐
Dynamics range	☐	☐	☐	☐	☐
Sustain	☐	☐	☐	☐	☐
Bow control	☐	☐	☐	☐	☐

Submit

Appendix F: Teaching Audit

Thank you for participating in this pre-pilot questionnaire aimed at assessing the potential for increased access to musicking using 3D printed violins. Your valuable insights as instrumental music teachers are crucial for this research. Please take a few minutes to complete the following questions. Your responses will be treated confidentially and will be used solely for research purposes.

Section 1: Teacher Information

1. Name: _____
2. School: _____
3. Contact email: _____
4. Contact phone: _____

Section 2: Experience and Background

5. How many years have you been teaching instrumental music? _____
6. What instruments do you primarily teach? _____

Section 3: 3D Printed Violins

7. Are you familiar with the distinction between 3D printed and traditionally constructed violins?

Yes, very familiar []

Somewhat familiar []

Not familiar []

8. In your opinion, what potential benefits could 3D printed violins offer in terms of access to music education? (Please provide your thoughts)._____

9. What challenges or concerns do you foresee in using 3D printed violins for teaching students? (Please provide your thoughts)._____

10. Would you be interested in incorporating 3D printed violins into your teaching practice?

Yes []

No []

Maybe []

11. Would you be willing to permit your students to participate in an upcoming research study involving 3D printed violins?

Yes []

No []

Maybe []

12. If you answered “Yes” or “Maybe” to the previous question, please indicate the number and year group that you would anticipate for this research_____

Section 4: Additional Comments

13. Please use this space to provide any additional comments, suggestions, or concerns that you may have regarding the use of 3D printed violins_____

Thank you for taking the time to complete this information. If you have any questions or require further clarification, please do not hesitate to contact me at dunnes38@tcd.ie

Appendix G: Maintenance Check

Instrument Maintenance Check

Regular care and maintenance are important for any instrument. Periodic maintenance checks can ensure its longevity. A student instrument maintenance checklist is below.

Daily Before Playing

- Inspect for Damage:** Check for any cracks, dents, or signs of damage before playing.
- Tuning:** Tune before playing, but try not to over-extend the strings, as this may affect the neck tension.
- Clean Hands:** Ensure your hands are clean before touching the violin. Wipe excess rosin that may have settled on the instrument while in its case.

After Playing

- Wipe Down:** Wipe down the instrument using a lint-free cloth.
- Loosen Bow Hair:** Loosen the bow tension before storing it in your case.

Weekly

- String Check:** Check for signs of deterioration or discolouration. Replace as needed, or every 9-12 months.
- Rosin Application:** Based on your practice frequency, apply rosin when needed.
Both over and under-use of rosin can affect bow movement and the resulting violin sound.
- Bridge Inspection:** The bridge is printed directly onto the violin body, so it will not become misaligned. However, as this is a particularly thin section, it may be useful to check that the bridge is not deteriorating.

Pegs	and	Fine	Apply peg chalk if the pegs are sticking.

Tuners:

Monthly

Clean Fingerboard: Clean the fingerboard to avoid resin buildup.

Nut and Saddle: Check the nut and saddle for excessive wear.

Soundpost Check: The soundpost is printed directly onto the violin body, so it will not become misaligned. However, as this is a particularly thin section, it may be useful to check this monthly.

Humidity Control: Use a hygrometer to ensure your violin is stored at a safe temperature (45-50% relative humidity).

9-12 Months

Replace Strings: Replace strings to maintain a consistent sound.

Professional Inspection: If you have noticed any changes or if your instrument has been dropped or damaged, ask your teacher to check it. They can advise you on local instrument maintenance professionals who can service or fix your instrument.

Bow Rehair: Based on your practice routine, bows may need to be repaired annually. Ask your teacher for advice before doing so to avoid unnecessary costs.

Appendix H: Pre-Intervention Music Education Meeting

Meeting with education stakeholders

Dear Music teachers,

I am writing to invite you to a meeting. I would like to discuss the possible implementation of 3D printed violins in a pilot instrument programme. Participation is voluntary, and it would last approximately 40 minutes. This is part of research for a Doctorate in Education at Trinity College Dublin. I want to gather valuable insights and opinions to ensure that this research aligns with teachers' and students' needs. Your expertise as classroom teachers, instrumental teachers, and conductors is crucial in shaping this research. Topics may include, but are not limited to, possible curriculum alignment, teaching methods, potential student engagement, logistical considerations, and performance and sound quality.

If you are interested in participating, please contact me using the information below. Based on your responses, I will schedule a meeting at a time that is convenient for all.

Regards,

Sarah Dunne

Email: dunnes@tcd.ie



Exploring Maintenance Differences: Traditional vs. 3D Printed Violins

Welcome to the world of violins, where craftsmanship meets innovation. Whether you are a seasoned musician or an enthusiastic beginner, understanding the maintenance differences between traditionally constructed violins and 3D-printed violins is essential for ensuring the longevity and optimal performance of your instrument. In this pamphlet, we delve into the distinctive care requirements of these two violin types.

Traditional Violins

Traditional violins are the embodiment of centuries of artisanal skill and dedication. Their organic materials and construction demand a particular approach to maintenance:

Humidity Management: Wood is sensitive to changes in humidity. Store your traditional violin in an environment with stable humidity levels (around 40-60%) to prevent cracks, warping, or changes in tonal quality.

String Adjustments: Periodically, tune your violin's strings and make small adjustments to the bridge, soundpost, and tailpiece. Consult a luthier (violin maker)

Bow Care: Rosin the bow hair regularly to maintain optimal friction between the strings and bow. Avoid excessive pressure on the bow hair, and loosen it after playing to preserve its curvature.

Cleaning: Use a soft, dry cloth to wipe off rosin and sweat from the instrument after each use. Occasionally, have your violin cleaned and polished by a professional luthier.

Restringing: Change strings every 6-12 months, depending on your playing frequency. This revitalizes the sound and playability of your violin.

Professional Maintenance: Engage a qualified luthier for periodic inspections, adjustments, and repairs to ensure your violin's health and sound quality.

3D-Printed Violins

3D-printed violins push the boundaries of innovation, introducing novel materials and construction methods. Here's how to keep your 3D-printed violin in optimal condition:

Material Considerations: Understand the specific material your 3D-printed violin is made from, as each may have unique maintenance requirements. Some materials are more resilient than wood but could react differently to temperature and humidity.

Humidity Awareness: While 3D printed materials are often less affected by humidity, it's still advisable to maintain a stable environment to prevent any potential deformities.

String Adjustments: Similar to traditional violins, regular string adjustments are necessary. Ensure the bridge, soundpost, and tailpiece are correctly aligned for the best sound and playability.

Bow Care: Bow maintenance remains consistent. Rosin the bow hair, maintain proper curvature, and release tension after playing.

Cleaning: Use a soft cloth to clean rosin residue and oils from the instrument's surface. Avoid using abrasive materials that might damage the 3D-printed texture.

Restringing: Follow string change recommendations provided by the manufacturer or consult with a luthier familiar with 3D-printed instruments.

Technical Expertise: Seek out luthiers or technicians with experience in 3D-printed violins for specialized maintenance and repairs.

Conclusion

Both traditional and 3D-printed violins offer unique benefits and challenges in terms of maintenance. Whether you own a masterpiece of craftsmanship or a modern marvel of technology, proper care and attention are essential to keep your instrument playing beautifully for years to come. Consult with experienced luthiers or professionals in the field to ensure you provide the best care for your violin, regardless of its construction type. **Happy playing!**

Appendix J: Proposals for an Instrument Maintenance and Modelling Short Course and Post-Primary Lutherie Programme

Scheme of Work: Instrument maintenance and modelling short course

Subject: Design and Technology

Grade Level: Post-Primary School, (1-3rd year)

Duration: 10 weeks (1 term)

Week 1-2: Understanding 3D Concepts

- Introduction to 3D concepts: difference between 2D and 3D, depth perception, spatial awareness.
- Exploring real-life examples of 3D objects and their applications.
- Introduction to 3D modelling software: navigating the interface, basic tools, and creating simple shapes.
- Assignment: Create a basic 3D model of an everyday object (e.g., mug, pencil).

Week 3-4: Basic 3D Modelling Techniques

- Exploring primitive shapes: cubes, spheres, cylinders, and cones.
- Learning to manipulate objects: move, rotate, scale.
- Introducing more advanced tools: extrusion, bevelling, Boolean operations.
- Assignment: Design a simple geometric sculpture using a combination of primitive shapes.

Week 5-6: Designing Functional Objects

- Introduction to designing objects with purpose: phone stand, keychain, pencil holder.
- Understanding measurements and dimensions: the importance of accuracy in design.
- Discussing ergonomics and usability in design.
- Assignment: Create a functional object and ensure it meets specific size and usability criteria.

Week 7-8: Texturing and Materials

- Introduction to materials and textures: applying colours, patterns, and textures to models.
- UV mapping basics: unwrapping a model for texturing.
- Using pre-made textures vs. creating your own.
- Assignment: Apply textures to the previously designed functional object.

Week 9-10: 3D Printing Basics

- Introduction to 3D printing: principles, types of 3D printers, materials.
- Preparing a 3D model for printing: checking and fixing common issues (overhangs, wall thickness, supports).
- Using slicing software: converting 3D models into printable instructions.
- Safety precautions and considerations when using a 3D printer.
- Assignment: Prepare a 3D model for printing, and print the functional object designed earlier.

Assessment:

- Formative assessments throughout the course, including in-class activities and quizzes.
- Summative assessment: Final project where students design and 3D print a functional object, considering all concepts learned.

Additional Considerations:

- Guest speakers: Invite professionals from the fields of design, engineering, or architecture who use 3D modelling and printing in their work.
- Field trip: Visit a local maker space, Fab Lab, or 3D printing studio to observe real 3D printers in action.
- Integration with other subjects: Explore opportunities to connect 3D modelling and printing with subjects like mathematics (measurement and geometry), science (material properties), and art (aesthetics).

Appendix K: Theme, Sub-Theme, and Category Map

Theme one: Technical specifications and material properties					Theme two: Perceptions and values of musicians and luthiers					Theme three: Perceptions and values of teachers					Theme four: Viability and practicality of 3D printed instruments				
Sub-theme:		Sub-theme:			Sub-theme:		Sub-theme:		Sub-theme: Educational			Sub-theme: Cost and		Sub-theme: Influence of time					
Sound quality		Durability			Acceptance and trust		Performance and aesthetics		integration			access							
Comparative acoustic properties	Structural design and resonance	Material strength and longevity	The impact of 3D printing on structural integrity	Material resistance to environmental factors	Cultural and historical significance	Instrument consistency	Sound projection and tonal quality	Comparable design alignment	Resource allocation and access	Teacher training and pedagogical support	Curriculum alignment and educational goals	Sociocultural perceptions and acceptance	Material costs and availability	Equipment and distribution scalability	Training and development time	Learning curve	Durability and longevity of materials	Market adoption	

Appendix L: 3D printing Files in Stereolithography, Standard Triangle Language (STL) Format, Including a Step-by-Step Software, Hardware, Print and Assembly Manual for Users.

The full violin file, video overview showing how the files look when open, and assembly manual can be accessed via the Google Drive link:

https://drive.google.com/drive/folders/1uT7I0g8jDbADdP9CORUJkehF1RYYU07Z?usp=s_haring