A NEW KIND OF SCORE: RETHINKING THE RELATIONSHIP BETWEEN COMPOSER, PERFORMER AND TECHNOLOGY

by

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Abstract

This portfolio comprises compositions utilising new score-reading technologies. The research primarily investigates the role that technology can play in the performance and composition of polytemporal music, with a particular focus on tempo canon. This led to the development of two new software applications: a score viewer and a composition environment. The commentary discusses the impact that these tools have had on my work, while also touching on broader technical, aesthetic and philosophical themes. These include considerations of time, the balance of freedom and control, and the impact of technology on creative work.

ACKNOWLEDGEMENTS

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CONTENTS

MEDIA CONTENTS

COMMENTARY

commentary.pdf Commentary

commentary-graphs.html Interactive versions of commentary graphs

ELUVIUM

eluvium-recording.wav *Eluvium* recording (Heather Roche – clarinet)

eluvium-score.pdf *Eluvium* reference score

STUDY 1

study-1-recording.wav *Study 1* recording (Apartment House: Mira Benjamin – violin; Gordon Mackay – violin; Bridget Carey – viola; Anton Lukoszevieze – cello)

study-1-score.pdf *Study 1* reference score

STUDY 2

study-2-recording.wav *Study 2* recording (Apartment House: Mira Benjamin – violin; Gordon Mackay – violin; Bridget Carey – viola; Anton Lukoszevieze – cello)

study-2-score.pdf *Study 2* reference score

STUDY 3

study-3-recording.wav *Study 3* recording (Apartment House: Mira Benjamin – violin; Gordon Mackay – violin; Bridget Carey – viola; Anton Lukoszevieze – cello)

study-3-score.pdf *Study 3* reference score

BRACKEN

bracken-recording.wav *Bracken* recording (Apartment House: Mira Benjamin – violin; Gordon Mackay – violin; Bridget Carey – viola; Anton Lukoszevieze – cello)

bracken-score.pdf *Bracken* reference score

bracken-score-graph.html *Bracken* score as interactive graph

NYMPHAEA

nymphaea-recording.wav *Nymphaea* recording (GBSR Duo: George Barton – Percussion; Siwan Rhys – Piano)

nymphaea-score.pdf *Nymphaea* reference score

DRIFT

drift-recording.wav *Drift* recording (GBSR Duo: George Barton – Percussion; Siwan Rhys – Piano)

drift-score.pdf *Drift* reference score

SCORE VIEWER

score-viewer-demo.mp4 Score viewer demonstration video

score-viewer-macos Score viewer for macOS

score-viewer-windows.exe Score viewer for Windows

score-viewer-linux Score viewer for Linux

score-viewer-code.zip Score viewer source code

COMPOSITION ENVIRONMENT

composition-environment-extension.vsix Composition environment extension installer for Visual Studio Code

composition-environment-code.zip Composition environment source code

SCORE TIMING DATA FORMAT

score-timing-data-format.zip JSON Schema, documentation and type definitions for score timing data format

LIST OF FIGURES

LIST OF DEFINITIONS

Arithmetic sequence a sequence of numbers in which the difference between consecutive values is constant.

Convergence period the hypermeasure that exists between (potential) simultaneous attacks in voices moving at different tempos.[1]

Echo distance the temporal gap between an event in one voice and its corresponding recurrence in another.[2]

Five-limit lattice a two-dimensional lattice in which the axes derive their pitches from primes three and five (i.e. perfect fifths and major thirds).

HTTP Hypertext Transfer Protocol – a client-server protocol for fetching resources.

JavaScript a programming language and one of the core technologies of the World Wide Web.

JSON JavaScript Object Notation – a file format used for data interchange.

Just intonation a system of tuning in which the frequencies of notes are related by integer ratios (i.e. rational numbers).

Linearity a principle of composition and of listening under which events are understood as outgrowths or consequences of earlier events.[3]

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[1] Kyle Gann. *The Music of Conlon Nancarrow.* Cambridge University Press, 1995, p. 21.

[2] Gann, *The Music of Conlon Nancarrow*, p. 21.

[3] Jonathan D. Kramer. *The Time of Music.* Schirmer Books, 1988, p. 453.

MEI Music Encoding Initiative – a system for representation of musical documents in a machine-readable structure.

MIDI Musical Instrument Digital Interface – a music technology protocol that connects digital music instruments and devices.

MusicXML an open format for sharing digital sheet music files between applications.

Nonlinearity a principle of composition and of listening in which events are understood as outgrowths of general principles that govern entire pieces.[4]

SVG Scalable Vector Graphics – a language for describing two-dimensional vector graphics.

Tempo canon a type of canon in which the same material is superimposed at different speeds.

TypeScript a superset of the JavaScript programming language that adds static types.

Superparticular ratio a ratio of two consecutive integers.

WebSockets a protocol that enables two-way interaction between client and server.

[4]Kramer, *The Time of Music*, p. 435.

1 OVERVIEW

1.1 INTRODUCTION

This commentary accompanies a portfolio of works composed between 2018 and 2021. My research explores the intersection of composition, performance and technology and is centred around the development of a new score-reading application. My primary focus has been the role that technology can play in the performance and composition of polytemporal music, a theme that emerged naturally from my prior compositional work. This has led me to reevaluate many aspects of the creative process, the performance situation and our relationship with machines.

1.2 SCORE VIEWER

In recent years the tablet computer has become increasingly prevalent on the concert stage. Many musicians are now using score-reading applications as a convenient replacement for sheet music, much as e-readers have become a popular substitute for books. Advantages include greater portability and silent hands-free page turning. Popular apps include *forScore*,[5] for iOS, and *Newzik*,[6] for iOS and the web. Despite this widespread adoption, the performer's relationship with the score has remained much the same. A static file is imported, typically in PDF format, with the pages corresponding to those in the printed score. The potential uses for tablet-based score-reading, how-

[5]https://forscore.co/ (visited on 18/02/2022)
[6]https://newzik.com/ (visited on 18/02/2022)

ever, extend far beyond this and offer many new possibilities to the composer. Several tools have emerged in this field, including *INScore*,[7] developed at the Grame Computer Music Research Lab, *Drawsocket*,[8] developed at the Hamburg University of Music and Theatre (HfMT), and *Decibel ScorePlayer*,[9] developed by the Decibel New Music Ensemble. These each have their own particular use cases, including real-time score generation and scrolling display of graphic notation. My own interest as a composer, however, is in using technology to aid the performance of music containing simultaneous divergent tempi. This is an area that is not well served by existing tools and my technological focus has therefore been the development of a new score-reading application for this purpose.

1.3 COMPOSITION ENVIRONMENT

While the score viewer aids the performance of my music, technology also plays an important role in the compositional process. Polytemporal music is not natively supported in score writing applications, such as *Dorico*,[10] *Sibelius*[11] and *Finale*,[12] and therefore requires significant workarounds. The

[7]Dominique Fober et al. 'Distributing Music Scores to Mobile Platforms and to the Internet using INScore'. In: *12th Sound and Music Computing Conference (SMC15)*. 2015, pp. 229–233.

[8]Rama Gottfried and Georg Hajdu. 'Drawsocket: A Browser Based System for Networked Score Display'. In: *Proceedings of the International Conference on Technologies for Music Notation and Representation – TENOR'19*. 2019, pp. 15–25.

[9]Cat Hope et al. 'The DECIBEL Scoreplayer - A Digital Tool for Reading Graphic Notation'. In: *Proceedings of the First International Conference on Technologies for Music Notation and Representation – TENOR'15*. 2015, pp. 58–69.

[10]https://www.steinberg.net/dorico/ (visited on 18/02/2022)

[11]https://www.avid.com/sibelius (visited on 18/02/2022)

[12]https://www.finalemusic.com/ (visited on 18/02/2022)

way that I work with musical material—expanding, contracting and shifting it in time—also benefits from the use of the computer as a compositional aid. These factors led to the creation of my own compositional environment, which comprises a JavaScript library and an extension for the *Visual Studio Code*[13] editor. As well as facilitating notation rendering, playback and export, it allows me to work with fragments of material to build larger structures. Rather than acting as a replacement for manuscript paper and the piano, this has become a complementary tool that I use alongside them. Finding the right balance and incorporating technology in a way that is conducive to creativity is a significant and ongoing part of the research.

1.4 TEMPO CANON

Several of the included works are examples of tempo canon. This is a type of canon in which the same material is superimposed at different speeds. As a form, it poses particular challenges to an ensemble as each performer must maintain their own unique pulse, which is nevertheless in a precise relationship to the other players. Individual performers may also be required to shift suddenly to distant tempi with a high degree of precision. The score viewer, developed as part of my research, seeks to overcome these obstacles through network synchronisation and an embedded visual metronome.

The historical precursor of the tempo canon is the prolation canon (or mensuration canon), a musical form that first became popular in the early Renaissance. Leading exponents of this style included Johannes Ockeghem

[13] https://code.visualstudio.com/ (visited on 18/02/2022)

and Josquin des Prez. The *Missa Prolationum* by Ockeghem is the most rigorous exploration of this form and it has been said that it 'may well be the most extraordinary contrapuntal achievement of the 15th century'.[14] A section of the original manuscript is included in Figure 1 and a transcribed excerpt is shown in Figure 2. A single voice is written out for each canon and the mensuration markings indicate the respective alterations of the written durations. Figure 3 translates this into modern notation, revealing the intricate ways in which the parts overlap and intertwine. It should be noted that the mensuration markings do not alter all the note values and it is this that distinguishes prolation canon from tempo canon. In a tempo canon, all the durations within each tempo are scaled by the same ratio. The Agnus Dei from Josquin des Prez's *Missa L'homme armé* maintains a 2:1:3 ratio throughout and can therefore be considered a tempo canon as well as a prolation canon.[15]

During the 20th century, tempo canon was used extensively in the compositions of Conlon Nancarrow. In his works for player piano, the relationships between tempi reached ever greater levels of complexity and included rational, irrational and even transcendental numbers. An excerpt from the piano roll for *Study 49c* is shown in Figure 4. A defining characteristic of this music is that it demands performance by machines. Though there have been significant attempts to perform some of these works in recent years,[16] the

[14]Leeman L. Perkins. *Ockeghem [Okeghem, Hocquegam, Okegus etc.], Jean de*. 2001. URL: https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-0000020248 (visited on 18/02/2022).

[15]Gann, *The Music of Conlon Nancarrow*, p. 111.

[16]A key example is *Nancarrow: Studies and Solos — Bugallo-Williams Piano Duo*

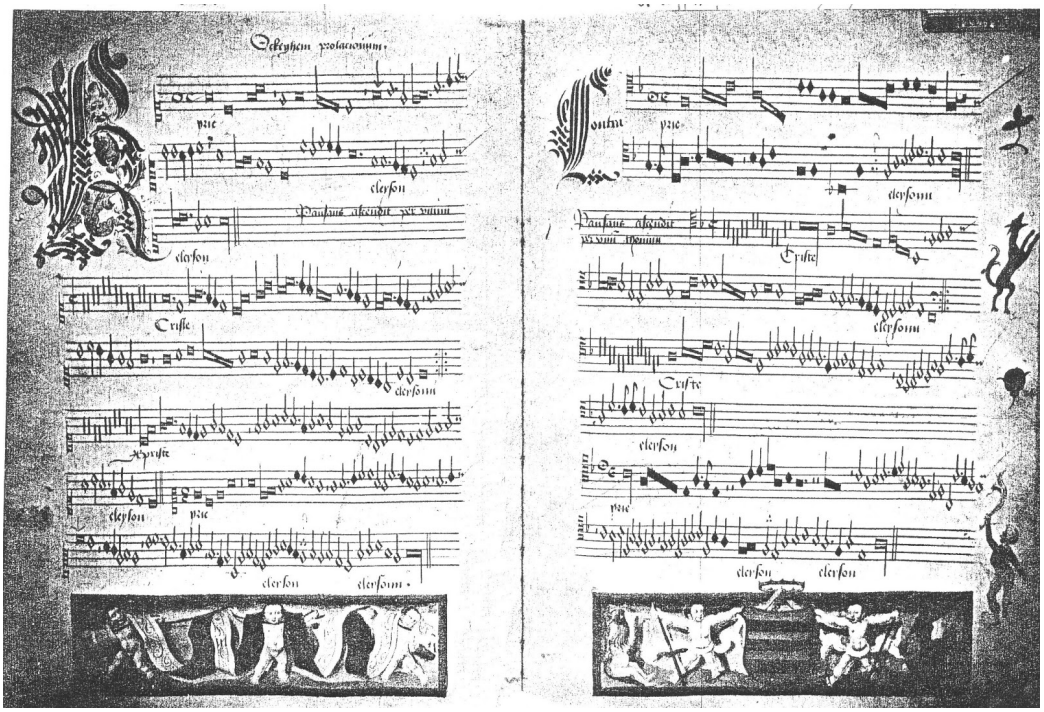

Figure 1: Original manuscript of the first *Kyrie* from the *Missa Prolationum* by Johannes Ockeghem

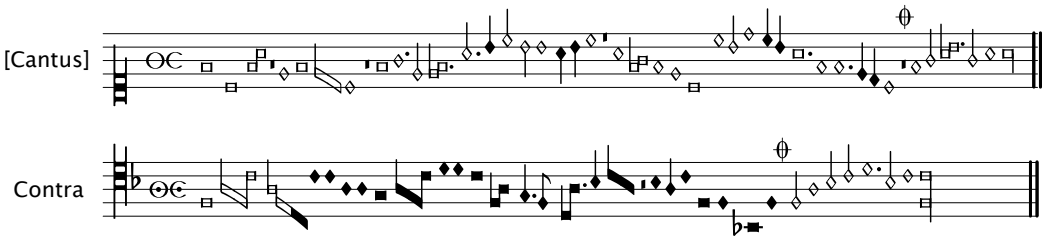

Figure 2: Excerpt from the *Missa Prolationum* in mensural notation

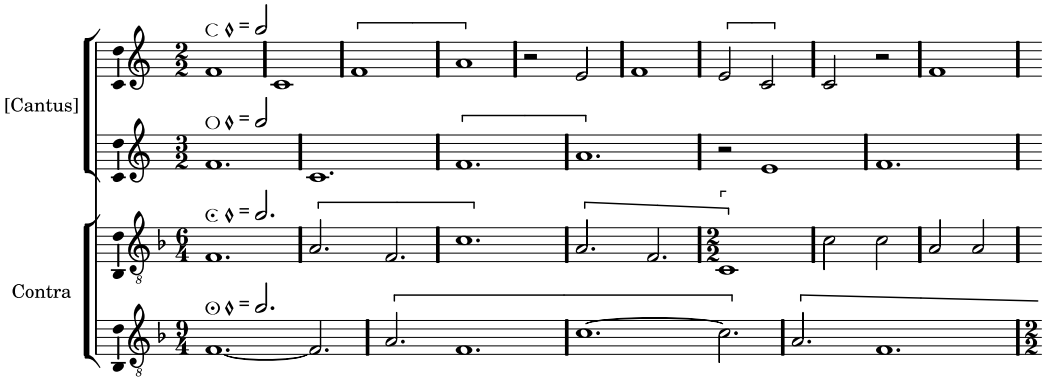

Figure 3: Excerpt from the *Missa Prolationum* in modern notation

extremely intricate layering of tempi is difficult to perform accurately and Nancarrow's music for ensembles therefore favoured simpler relationships. Nancarrow did, however, theorise about the possibility of using synchronised video conductors to assist ensemble performance:

> And I've got the idea of each performer having a small television screen, with something imitating a conductor that comes to the beat, so they can see it coming, whatever it is. I don't think it would be too complicated. It would probably be expensive, each one having his own screen.[17]

This provides important historical context for my research. I have been able to realise and extend Nancarrow's vision at a time when the idea of each performer having their own screen is now commonplace.

[17]Gann, *The Music of Conlon Nancarrow*, p. 274.

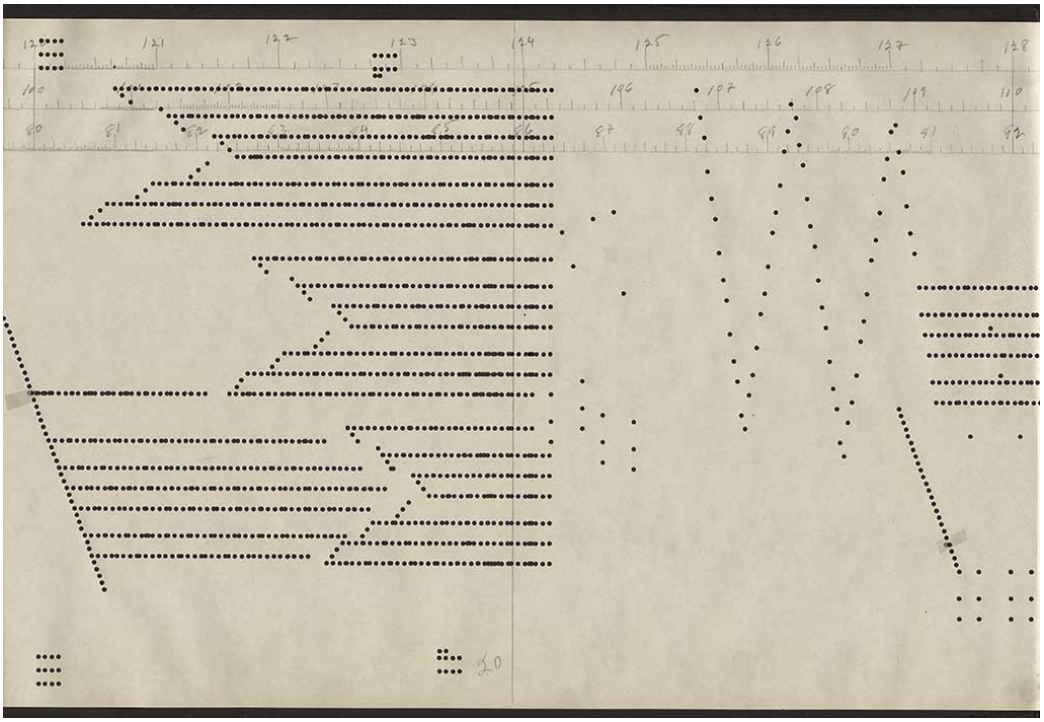

Figure 4: Excerpt from *Study for player piano no. 49c* by Conlon Nancarrow

1.5 NEW TOOLS, NEW FORMS

The historical developments of prolation canon and tempo canon demonstrate another important strand of my research. Both are examples of new compositional practices emerging as a result of new methods of notation. Mensural notation was introduced in France with the *Ars nova* movement of the 14th century and would later become the standard form of notation across Europe. For the first time, rhythmic durations could be precisely described in terms of the proportions between note values. Prolation canon then took this idea a step further by also applying proportions to the relationships between parts. Crucially, the new notation had enabled the kind of externalised musical thinking required for this idea to take seed. As Thor

Magnusson writes:

> The effect of externalised musical thinking through the instrument (organum) of notation quickly materialised: after polyphony, we begin to see counterpoint (*contrapunctum*, a term that relates to the neume notational practice), the musical techniques of the fugue (mirroring, transposing, inverting, retrograding, expanding, delaying, etc.), and polyphonic instrumentation for more than one instrument; all techniques that benefit from notation as a technology of composition and arrangement.[18]

Tempo canon, on the other hand, was made possible by the new notational technology of the piano roll. In *New Musical Resources*, first published in 1930, Henry Cowell writes:

> Some of the rhythms developed through the present acoustical investigation could not be played by any living performer; but these highly engrossing rhythmical complexes could easily be cut on a player-piano roll.[19]

This idea was later encountered by Conlon Nancarrow and would become the focus of his life's work.

In my own work I have been able to demonstrate that technology can now be used to aid the performer with tackling these rhythmic complexes. The possibilities of conventional notation are expanded by scores that now

[18]Thor Magnusson. *Sonic Writing*. Bloomsbury Academic, 2019, p. 80.
[19]Henry Cowell. *New Musical Resources*. Cambridge University Press, 1996, p. 64-65.

play an active rather than passive role in performance. Additionally, the computer has begun to play an active role in the compositional process, providing rapid visual and auditory feedback as well as flexible methods for transforming material.

1.6 PITCH AND DURATION

As a composer, I have come to conceptualise pitch and duration as being the constituent parts of a shared continuum. What we refer to as frequency in the pitch domain is analogous to tempo; both describe how many repetitions occur within a given unit of time. During the 20th century, composers increasingly drew parallels between pitch and duration. Henry Cowell, in *New Musical Resources*, sought a common theoretical basis for both and introduced *scales of rhythm* based on the pitches of just intonation. He writes, 'a parallel can be drawn between the ratio of rhythmical beats and the ratio of musical tones by virtue of the common mathematical basis of both musical time and musical tone.'[20] These ideas were to have a profound influence, not only on Conlon Nancarrow, but also on other rhythmically adventurous composers such as Elliott Carter.[21] In the 1950s, Karlheinz Stockhausen explored similar ideas in the article *... How Time Passes ...*, writing, 'Our sense perception divides acoustically-perceptible phases into two groups; we speak of *durations* and *pitches*.'[22] During this period, early encounters with electronic instruments were prompting composers to reevaluate the theoretical basis of

[20]Cowell, *New Musical Resources*, p. 50-51.
[21]David Schiff. *The Music of Elliott Carter*. Faber and Faber, 1998, p. 9.
[22]Karlheinz Stockhausen. '... How Time Passes ...' In: *Die Reihe* 3 (1959), p. 10.

their music. In Stockhausen's case, he sought to integrate duration within the conceptual framework of serialism. Like Cowell, he created scales of duration, but these were based on logarithmic relationships, rather than pure ratios, to mirror the even distribution of equal temperament. These ideas are particularly evident in the compositions *Zeitmasse* and *Gruppen*.

In my own work, tempi are conceived as ratios of a static base tempo. This base tempo is analogous to a tonal centre and similarly exerts a gravitational pull that may be strong or weak depending on the relationships between the tempi. It can be altered to change the overall speed of a piece, just as tonal centres can be shifted through the process of transposition. Like Cowell and Stockhausen, I often use pitch notation as a visual aid to represent tempo relationships. Unlike them, however, I do not seek an equivalence with the twelve notes of the chromatic scale. Instead, my tempi occupy the infinite harmonic space of extended just intonation.

1.7 STRUCTURE OF THE COMMENTARY

This commentary is broadly split into two sections, *The Music* and *The Technology*. The first comprises a detailed discussion of the included works. It is interspersed with a series of interludes, which touch on broader philosophical and aesthetic themes that are relevant to my music. I hope they also serve to prevent the illusion of a linear progression of ideas from one piece to the next, which would misrepresent the more muddled reality of creative work. The second section provides a detailed overview of the technological outputs of the research and their implementations. This is followed by a conclusion.

Each of the works discussed is accompanied by a recording and a reference score. These are detailed in the Media Contents. A video demonstrating the score viewer is also included, as are interactive versions of the graph figures. The software outputs of the research and accompanying source code are included in full, though the intention is that their functionality can be grasped from the text and video.

2 THE MUSIC

2.1 ELUVIUM

2.1.1 INTRODUCTION

Eluvium is a piece for clarinet and resonating tam-tam and was written for Heather Roche.[23] A contact microphone is attached to the body of the tam-tam and a speaker is placed behind. Both the clarinet and tam-tam are recorded in real-time and then replayed through the speaker. This process is repeated throughout the piece, leading to an accumulation of resonant frequencies. The score is presented using the score viewer, which allows the electronics to be precisely synchronised and the changing tempi to be accurately conveyed to the performer.

2.1.2 THE CLARINET PART

The clarinet part is derived from a single 4-bar melodic fragment. This appears in prime, retrograde, inversion and retrograde inversion forms, both at original pitch and transposed by a minor third, to create a 32-bar loop. The order of occurrences is shown in Figure 5, revealing the symmetrical structure. Each iteration of the loop contains two alternating tempi that move further apart as the piece progresses. Despite this continual variation, the relationships between the tempi ensure that the total duration of each 32-bar section remains constant. This enables the subsequent layering to take

[23]https://heatherroche.net/ (visited on 18/02/2022)

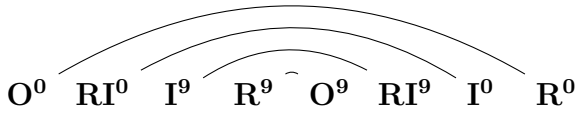

Figure 5: *Eluvium* melodic transformations

place. By the fifth iteration, the second tempo has slowed to such a degree that it occupies all of the available space, thereby erasing the first part and breaking the pattern of repetition. This sense of erasure is a defining feature of the piece.

2.1.3 THE TAM-TAM PART

The first sixteen bars of clarinet in each 32-bar section is recorded. This is played back through the speaker at half-speed, after a delay of eight bars, and the change in playback rate results in the pitches sounding an octave lower. While the clarinet is played back, the tam-tam is recorded. This process is repeated throughout the piece and with each subsequent iteration the previous recording of the tam-tam is also played back. The resulting tempi are shown in Figure 6. It is this feedback process that leads to a gradual accumulation of resonant frequencies and the erosion of the source material. After the clarinet has ceased to play, the tam-tam remains, its character now cloaking the remaining semblance of the melodic line. The recording/playback is implemented in *SuperCollider*[24] and the output level is automatically regulated in accordance with the input level. This ensures that the playback volume does not become overbearing.

[24]https://supercollider.github.io/ (visited on 18/02/2022)

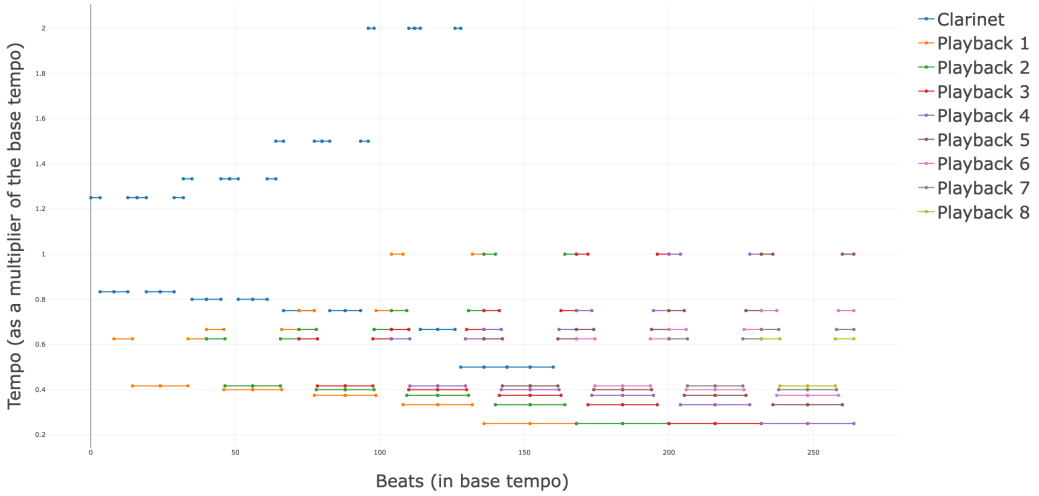

Figure 6: *Eluvium* tempi (interactive version in *commentary-graphs.html*)

2.1.4 INFLUENCES

This piece reveals the influence of two key composers: Aldo Clementi and Alvin Lucier. The use of a single diatonic fragment, layered and extended by means of specular transformation, owes much to Clementi's later works. Meanwhile, the feedback process, in which the source material gradually becomes engulfed by the latent characteristics of an inanimate object, is reminiscent of Lucier's seminal work, *I Am Sitting In A Room*. It is significant that the piece starts with solo clarinet and ends with solo tam-tam. What intervenes is a conceptual morphing between these two aesthetics.

As in Clementi's music, the use of mirror-like forms enables the melodic line, which is decidedly linear, to acquire a sense of stasis. Writing of the influence of Escher on Clementi, Paolo Emilio Carapezza observes, 'In both cases the reiteration of figures (themes or images) produces a spatio-temporal

dimension that has the effect of a *static motion* (or *mobile stasis*).'[25] Jennie Gottschalk echoes these thoughts in *Experimental Music Since 1970*: 'In Clementi's auditory context, and through the very methods he borrows from Escher, repetition suspends time.'[26] As in many of Clementi's works, the choice of transformations ensures saturation of the chromatic field. In *Eluvium*, however, this serves a dual purpose, both masking the melodic line and exciting the tam-tam at a broad range of pitches. Whereas a densely layered aural surface is typically evident from the outset in a Clementi piece, here it emerges gradually. As the piece unfolds, the form itself becomes transparent, allowing the focus to shift to the sonic characteristics. Alvin Lucier's recollection of hearing *KOAN for String Quartet* by James Tenney is insightful in this regard:

> I could hear the small things that were happening in the music. Once you accepted that it wasn't going to change, and there was no story, no climax, you began to hear the acoustical phenomenon.[27]

Referencing *I Am Sitting In A Room*, Lucier remarks, 'I wanted the acoustic exploration to be paramount, the room acoustics and its gradual transformation to be the point of the piece.'[28] In *Eluvium*, I wanted the 'point of the piece' to change over the course of its duration. It starts by being

[25]Paolo Emilio Carapezza. 'Aldo Clementi musicus mathematicus'. In: *Interdisciplinary Studies in Musicology* 12 (2012), p. 60.
[26]Jennie Gottschalk. *Experimental Music Since 1970*. Bloomsbury Academic, 2016, p. 138.
[27]Alvin Lucier. *Music 109*. Wesleyan University Press, 2012, p. 194.
[28]Lucier, *Music 109*, p. 90.

about the clarinet, conversing with itself, and gradually becomes about the acoustic exploration of the tam-tam. I feel that the relatively flat surface of the clarinet part, devoid of dialectical contrast, is essential in allowing these other details to emerge as the objects of attention.

In *Aldo Clementi's System*, Michele Zaccagnini writes:

> In particular, one can find the germ of such a connection in Clementi's musical ideas of proliferation of a single element, and of self-erasure, both being pervasive in his aesthetic and musical thought.[29]

These two ideas—proliferation of a single element and self-erasure—have become recurring features of my work. It is, perhaps, in this piece that they are made most explicit.

2.1.5 SCORE VIEWER

Eluvium was the first piece to be composed with the score viewer in mind and there are several reasons that the score technology is essential to its performance: the clarinettist must move between different tempi with a high degree of accuracy; cues in the live electronics part for recording and playback must be triggered correctly; and the clarinet and electronics must remain synchronised throughout. While an alternative approach may have been to provide the performer with a static score and a separate click track, a dynamic score presents a number of significant advantages. The embedded

[29]Michele Zaccagnini. 'Aldo Clementi's System'. PhD thesis. Brandeis University, 2014, p. 55.

visual metronome enables the performer to accurately determine the tempi without an auditory aid, thereby allowing them to remain fully present in the performance space. The visual representation of the pulse gives a sense of the current position within the beat, which helps the performer to quickly adjust to changes in tempo (the current position in the score is also highlighted). Additionally, the interactive nature of the score puts the clarinettist in control of the performance and removes the need for an additional electronic performer. Starting the score, either by tapping the screen or engaging a foot-pedal, also starts the electronics part and this then operates autonomously. A synchronisation algorithm ensures that the two parts do not drift during the performance.

This first incarnation of the score viewer was created specifically for *Eluvium* and, as such, there were some key limitations that would be addressed in future versions. The visual metronome marked out the 4/4 time signature and the position in the score was indicated by highlighting the current bar. As I built up a repertoire of pieces requiring this technology, additional features and greater flexibility were required. This gradually led to the development of a more generic and full-featured application.

2.2 INTERLUDE: SPACE AND TIME

> Let's begin with a simple fact: time passes faster in the mountains than it does at sea level.[30]

This is the opening statement in Carlo Rovelli's book, *The Order of Time*. The chapter is titled 'Loss of Unity', a phrase that has equal relevance to the temporal structures of my recent music. Albert Einstein was the first to comprehend this slowing down of time and it is now easily verified with precision clocks. His theories proved both that space does not exist independently from time, and that spacetime and the gravitational field describe the same phenomenon. Just as masses exert a gravitational force, they also modify the structure of time around them. This is why time passes faster in the mountains than at sea level; the sea is closer to the mass of the earth. Once this is accepted, it is clear that there is no single 'true' time. Instead, there are a vast multitude of times: one for every point in space. As Rovelli writes:

> The single quantity 'time' melts into a spiderweb of times. We do not describe how the world evolves in time: we describe how things evolve in local time, and how local times evolve *relative to each other*.[31]

This idea, which is at the heart of general relativity, has had a profound effect on my musical thinking. Just as performers can occupy different phys-

[30]Carlo Rovelli. *The Order of Time*. Penguin Books, 2019, p. 9.
[31]Rovelli, *The Order of Time*, p. 15.

ical spaces, they can also inhabit different times: none truer than the other but all nonetheless related. In musical terms, these times are represented by tempi. They may be unique or shared; static or changing. In my own works, the tempo relationships are often arranged to create a sense of slowing down over the course of a piece. I feel that this evokes the natural sensation of falling, of things gravitating towards where time moves more slowly.

Before general relativity, Einstein's earlier theory of special relativity had already fundamentally challenged our intuitive understanding of time. It revealed that, just as there is no single 'true' time that permeates the universe, there is also no universal moment that can meaningfully be called the present: 'In technical terms, we say that Einstein has understood that 'absolute simultaneity' does not exist: there is no collection of events in the universe which exist 'now'.'[32] Our notion of the present must be modified and supplanted by a new concept: the *extended present*. This is the set of events that are neither past nor future. It is not an instantaneous moment but rather an intermediate zone, the duration of which depends on the distance of an event from the observer. On Earth these distances are very small, meaning that the duration of the present is generally too short to observe and the idea of 'now' has a practical use. However, as Rovelli writes, 'The idea that a well-defined *now* exists throughout the universe is an illusion, an illegitimate extrapolation of our own experience.'[33] In music, I feel that canon can serve as a metaphor for the extended present. Delayed occurrences of the same

[32]Carlo Rovelli. *Reality Is Not What It Seems*. Penguin Books, 2017, p. 56.
[33]Rovelli, *The Order of Time*, p. 40.

material occupy the intermediate zone between past and future and the duration of this zone (or present) is determined by the echo distance between voices. This duration is itself flexible and can be expanded and contracted through the use of divergent tempi, which vary this echo distance over time.

In my music, I seek to draw on these two principles: the multiplicity of times and the impossibility of 'now'. It is not my intention that they are immediately evident to the listener. Instead, I see them as physical characteristics of the world in which I compose; intrinsic properties of the virtual space that my music inhabits.

2.3 STUDIES 1, 2 AND 3 FOR STRING QUARTET

2.3.1 INTRODUCTION

Studies 1, 2 and 3 were written for Apartment House.[34] They were the first ensemble pieces to use the score viewer and feedback from the performers was important in further developing the application. They were also an opportunity to explore the possibilities of tempo canon in greater depth and develop new compositional tools. I consider the pieces to be studies because of the way in which they enabled me to learn from these various interactions with technology, which now spanned both composition and performance.

2.3.2 COMPOSITION ENVIRONMENT

While composing these pieces, it quickly became evident that the computer could play a valuable role as a compositional aid. Just as tempo canon clearly poses significant challenges to performers, it also pushes the limits of manual paper-based methods of composition. Notes need to be spaced with high precision to correctly indicate the rhythmic relationships and the complex intertwining rhythms are often impossible to realise accurately at the piano. In addition, the methods by which I was transforming material—expanding, contracting and shifting it in time as well as transposing and inverting its pitch content—are operations ideally suited to computer-based manipulation. These factors led to the development of my own composition environment, comprising a JavaScript library and an extension for the *Visual*

[34] http://www.apartmenthouse.co.uk/ (visited on 18/02/2022)

Studio Code[35] editor. It enables fragments of material to be defined, transformed and combined into larger structures. Scores generated in this way can be viewed and played back as well as exported in a variety of formats, including MusicXML[36] and MEI,[37] facilitating interchange with other notation software. Additionally, it generates and exports the timing data for the score viewer, a process that is otherwise manual, laborious and error-prone.

2.3.3 STUDY 1

The four instrumental voices in *Study 1* are derived from a two-part canon. The upper part is played by the violins while the lower part is played by the viola and cello. Within these pairings the tempi diverge, resulting in four independent voices. For the first section of the piece, violin 1 and viola maintain a static tempo while violin 2 and cello perform a controlled decelerando. The roles then reverse, proceeding until all parts coincide at the final chord. These tempo relationships are shown in Figure 7. The unidirectional nature of the tempo changes means that the echo distance between the two instrumental pairs continues to grow throughout. The expansion of two-part counterpoint to four independent voices is reminiscent of the excerpt from Ockeghem's *Missa Prolationum* discussed in Section 1.4.

In contrast to the distinct tempo changes in *Eluvium*, the tempi in *Study 1* vary gradually over time. To achieve this effect, each beat corresponds with a different tempo. An accelerando/decelerando is defined by its start

[35]https://code.visualstudio.com/ (visited on 18/02/2022)
[36]https://www.musicxml.com/ (visited on 18/02/2022)
[37]https://music-encoding.org/ (visited on 18/02/2022)

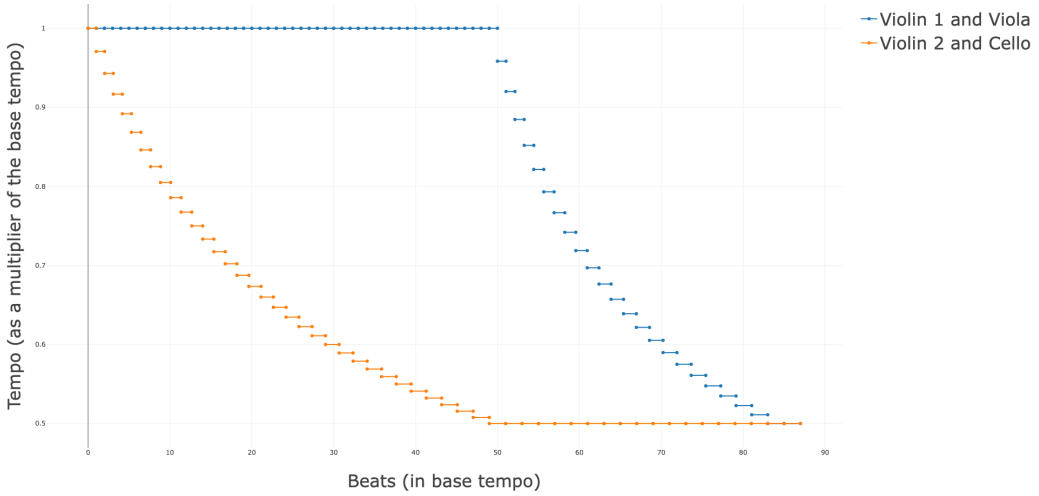

Figure 7: *Study 1* tempi (interactive version in *commentary-graphs.html*)

tempo, end tempo and total number of beats. These properties can then be used to calculate the intervening tempi. The method is as follows: first the start and end tempi are converted to durations; next, an arithmetic sequence is created between these two values, containing the desired number of beats; finally, the resulting durations are converted to tempi. An example, based on the first decelerando in *Study 1*, is shown in Figure 8. As in all of my polytemporal works, tempi are conceived as fractions of a static base tempo. Due to the reciprocal relationship between tempo and duration, converting between the two is simply a matter of inverting these fractions.

Although gradual tempo changes are common in many musics, Conlon Nancarrow was the first to approach them as a structural device that could be controlled with mathematical precision. In *The Music of Conlon Nancarrow*, Kyle Gann writes, 'Although there are precedents for ostinato, isorhythm, and even tempo canon, there is no history of acceleration prior to Nancar-

Beat tempo: $1 \rightarrow 1/2$
Beat duration: $1 \rightarrow 2$
Number of beats: 33

Beat durations: $(\frac{33}{33}, \frac{34}{33}, \frac{35}{33}, \frac{36}{33}, ..., \frac{65}{33})$

Beat tempi: $(\frac{33}{33}, \frac{33}{34}, \frac{33}{35}, \frac{33}{36}, ..., \frac{33}{65})$

Figure 8: Beat tempi and durations for the first decelerando in *Study 1*

row to delve into for precedents.'[38] Nancarrow uses two types of acceleration/deceleration in his works: arithmetical and geometric. The arithmetical method is the approach that I use in *Study 1* and involves altering each successive beat by the same duration unit. Geometric acceleration, by contrast, is achieved by altering each beat by the same proportion. Distributing the rate of increase evenly in this way requires finding the nth root of the total change and the resulting tempi are therefore almost always irrational. The geometric method is analogous to the way that pitches are calculated within the octave in equal temperament. In fact, moving up stepwise in twelve-tone equal temperament is conceptually equivalent to a geometric acceleration from 1/1 to 2/1 over twelve beats (the intervening tempi in this case would equal those of Stockhausen's *scale of durations*).[39] Arithmetical acceleration, on the other hand, is more akin to the uneven distribution of the harmonic series, though in this case inverted. I have so far used the arithmetical method in all of my works involving gradual tempo changes, partly because rational values are more straightforward to represent notationally, but also

[38]Gann, *The Music of Conlon Nancarrow*, p. 146.
[39]Stockhausen, '... How Time Passes ...', p. 21.

because of the particular character it lends. In decelerandi the change becomes more gradual over time, meaning that slower tempi are accompanied by a slower rate of change. This effect can be made more subtle by spreading this change over a greater number of beats. Beyond the two methods given, there are many other possible ways to distribute a gradual change in tempo, each exhibiting their own character and worthy of further investigation. The concurrent use of changing and static tempi in *Study 1* led to the development of methods to calculate the points at which they converge. The relevant equations are included in Appendix A. While the temporal underpinnings of *Study 1* are informed by Nancarrow's works, the piece itself bears no stylistic resemblance. To an extent, the slow and sparse texture serves to mask the changes in tempo, which I consider to be an essential part of the fabric of the work rather than a clearly discernible dramatic device.

It was while composing *Study 1* that the need for new compositional tools became apparent. As the piece progressed it became impossible to keep track of the relationship between the two instrumental pairs. In a different composition I may have embraced this uncertainty and allowed the diverging parts to simply coexist. Here, however, with closely knit voices and a homogeneous texture, I was trying to achieve a crystalline transparency that demanded detailed moment to moment control of the resulting pitch relationships. In developing the composition environment, I was able to successfully integrate the computer as a compositional aid. The software allowed me to define the canonic and temporal relationships between the parts and then input the material as a single melodic line.

My interest in canon stems partly from the way in which it introduces

feedback into the compositional process. By being able to instantly see and hear the consequence of each decision, this sense of feedback was heightened and became an integral part of my experience of writing the piece. I still chose, however, to balance this with periods of writing at the piano. These enabled me to zoom out and capture the overall shape and feel of a melodic idea before I examined and reworked it. Moving between these two environments would often refresh my perspective and is a strategy that I continue to find useful. I am reminded of the advice that Morton Feldman received from John Cage: 'On the second day I knew him, he suggested that I copy out my score nicely, and as I'm doing it I'll get ideas for what's going to happen.'[40]

2.3.4 STUDY 2

In *Study 2*, the four voices share the same melodic line. The entries are staggered and each part adheres to its own temporal scheme, with marked rather than gradual changes in tempo. Due to the way in which the parts overlap and intertwine, the transparency of the opening soon transforms into a web of convergence periods and echo distances.

As is true for much of my music, *Study 2* uses very little material. In this case it is derived from a single melodic fragment that is transposed, stretched, layered and repeated. It was through working on this piece that I began to gain a deeper understanding of the kinds of material that could withstand these transformations effectively. Above all, I am searching for a quality that

[40]Morton Feldman. 'H.C.E. (Here Comes Everybody): Morton Feldman in converstion with Peter Gena, January 1982'. In: *Morton Feldman Says: Selected Interviews and Lectures 1964-1987*. Hyphen Press, 1982, p. 127.

I describe as *malleability*. This is difficult to define and, as with so many aspects of composition, the properties necessary to achieve it are elusive and to some degree intangible. It is clear that some features may be indicative of a greater or lesser degree of malleability. A line containing sharp contrasts in pitch or rhythm, for example, is likely to be constrained to a more limited range of transformations. Digging deeper, however, I believe that at its heart there lies an important paradox: the need for material to be both arresting and neutral.[41] In the case of *Study 2*, the falling fifths are very distinctive and their character permeates throughout. In contrast, the repeating movement downwards by a tone has a neutralising effect; it is easy to lose oneself in the symmetry created by the resulting whole-tone scales. I feel that these features highlight something about the balance that I am trying to achieve. While I use canonic techniques to build connections between the different layers, to some extent compensating for the loss of unity in the temporal sphere, I do not wish for these connections to be made too explicit. I enjoy a degree of ambiguity and generally prefer the relationships between parts to be non-hierarchical. A melodic line with too many distinctive features has the potential to upset this balance. In some ways these concerns are not so far removed from those of Renaissance counterpoint. In *Counterpoint: The Polyphonic Vocal Style of the Sixteenth Century*, Knud Jeppesen writes:

> All details must unite in entirely undisturbed harmony, must fuse into a higher unity in spite of individual independence. An abso-

[41] The phrase 'arresting and neutral' was arrived at in a conversation with Howard Skempton.

> lute, completely free balance between the elements was required; no one element could be emphasized at the expense of another; everything must work together smoothly and harmoniously.[42]

Malleability lies at the heart of the composition environment that I continued to develop while writing this piece. In many ways, the software became a medium for experimenting with these ideas. The fundamental unit that users work with is the fragment. This is a musical fragment of any length and comprising any number of layers. It may contain musical expressions, defined using a subset of the *LilyPond*[43] notation syntax, as well as other fragments. In computer science, to *compose* means to combine simple data types into more complex ones. At a fundamental level, musical composition is based on the same principle. As Thor Magnusson writes, 'it is about putting (-ponere/-positus), stuff together (com-), or placing things next to each other.'[44] It is this ability to compose fragments which unlocks a great deal of freedom and flexibility. In the composition environment, fragments can also be transformed. The software provides several methods to alter the pitch, rhythm and tempo as well as a generic *pipe* method that can be used to apply arbitrary transformations. The number of concepts introduced is deliberately kept to a minimum and I have instead chosen to expose a small number of simple primitives that can be combined in powerful ways.

In contrast to some of my other works, the form of *Study 2* was not pre-

[42]Knud Jeppesen. *Counterpoint: The Polyphonic Vocal Style of the Sixteenth Century.* Dover, 1992, p. 83.
[43]http://lilypond.org/ (visited on 18/02/2022)
[44]Magnusson, *Sonic Writing*, p. 80.

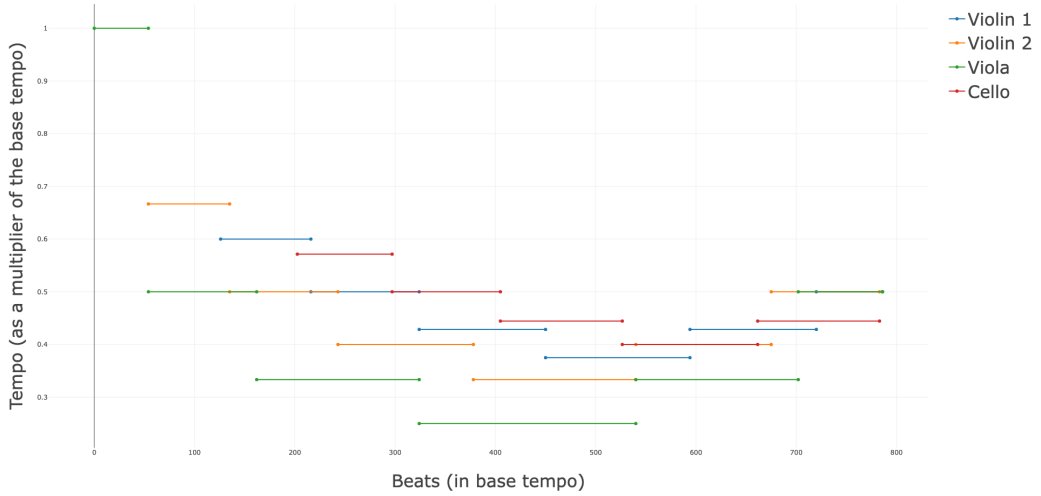

Figure 9: *Study 2* tempi (interactive version in *commentary-graphs.html*)

conceived and instead emerged gradually during composition. The staggered entries allowed me to carefully judge the tempo of each new voice against those already present and with each new entry the parts naturally became more intertwined. A unique temporal arc began to emerge for each part, which I then further developed with the aid of the software. As in *Study 1*, feedback was deeply embedded in the compositional process and each decision had consequences elsewhere in the piece. The tempo relationships are shown in Figure 9.

2.3.5 STUDY 3

Like *Eluvium* before it, *Study 3* owes much to the influence of Aldo Clementi. The four members of the quartet play melodic material derived from the same diatonic fragment and constituting the four specular transformations. The piece partly came about through a desire to gain a deeper understanding of

Clementi's working methods and use of algorithms. While Clementi's procedures were entirely paper-based, I felt that they could inform my work with the computer and provide valuable context for interrogating this relationship.

In *Aldo Clementi's System*, Michele Zaccagnini provides a detailed analysis of Clementi's use of the magic square. Clementi used the square to visualise the intervallic content of a melodic fragment. These visualisations then informed the choices he made when layering different transpositions and transformations. His aim was to saturate the intervallic space and he achieved this by avoiding repetition of the same interval at the same pitch. By doing so, he established a contrapuntal principle that would enable him to achieve clarity and distinctness within an otherwise opaque texture. In contrast to many other post-serial approaches to pitch organisation, the focus was on intervals rather than individual pitches.

Clementi's methods share much in common with ideas that I was already exploring. His interaction with the magic square was an important source of feedback in the compositional process; the addition of each subsequent layer determined and further restricted the remaining options. Furthermore, the purpose of his procedures was to promote features of each individual line that would ensure a particular outcome when they were combined. These were not moment to moment decisions but were rather choices made outside the time frame of a piece to determine properties of the aggregate, irrespective of rhythmic placement. In other words, Clementi had created a method to ensure the malleability of his material. This has clear relevance to my own work, in which I was also searching for melodic fragments that could withstand processes of layering and transformation.

Though Clementi did not use a computer while composing, the manner in which he used the magic square was nevertheless algorithmic. As Zaccagnini writes, 'His complex procedures only take place on paper; nonetheless, they inevitably achieve an absolute level of exactitude characteristic of computer aided algorithmic composition.'[45] While working on *Study 3*, I created a software version of Clementi's algorithm. I then used this to experiment with material and determine the transpositions of the four voices. Composing in this way expanded the means by which I was using the computer as a compositional aid. Significantly, the algorithm does not generate musical material. Instead, the user provides a melodic fragment and the software then analyses its intervallic content in different transpositions and transformations. Each selection that is made eliminates any remaining conflicting instances. It quickly became evident that this rapid feedback loop encourages playful experimentation and that over time this could lead to an intuitive feel for the kinds of material that maximise the number of possible voices. This is similar to the way that my own composition environment was allowing me to quickly transform material and experiment with different temporal schemes. In both cases, the creative impetus resides with the composer but technology facilitates the rapid iteration of ideas.

As in *Study 2*, each of the four voices moves between tempi independently. In *Study 3*, however, the role of canon is expanded and the order of tempi is itself canonic. These tempi are displayed as pitches in Figure 10 and in graph form in Figure 11. Each occurs first in violin 1, before reoccurring in

[45]Zaccagnini, 'Aldo Clementi's System', p. 55.

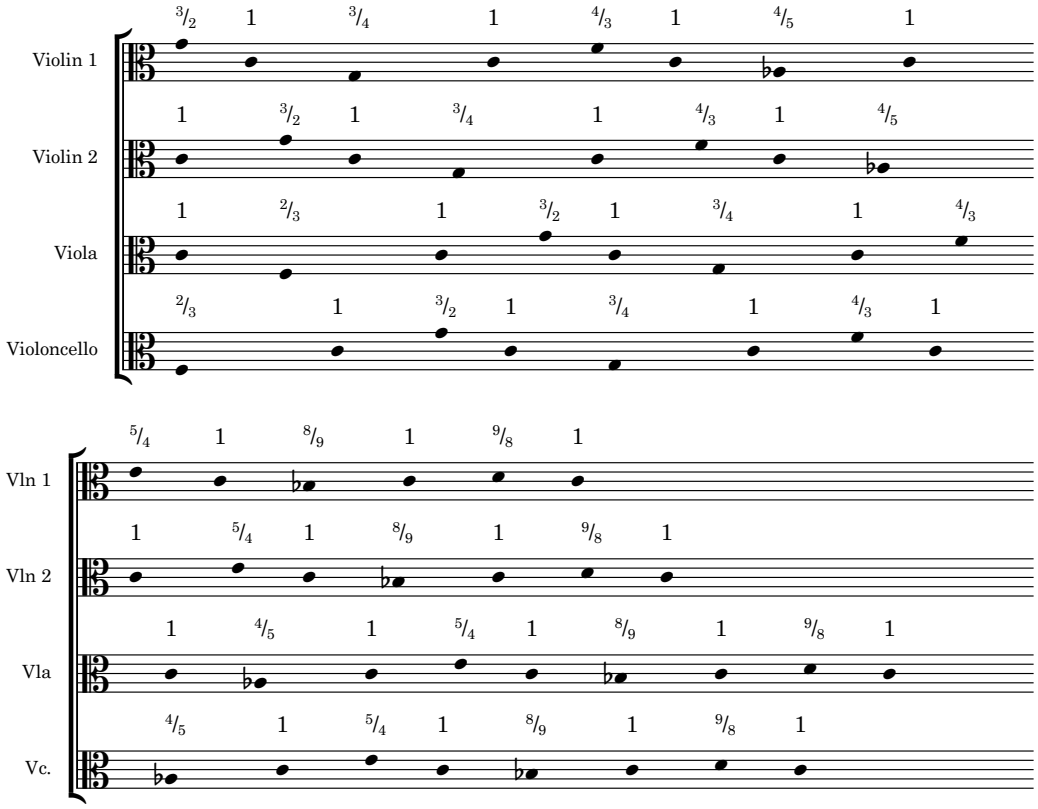

Figure 10: *Study 3* tempi as pitches

violin 2, cello and viola. This approach to tempo is where I diverge most clearly from Clementi. As in all the studies, it places unique demands on the performers, which I sought to address with the score viewer.

2.3.6 SCORE VIEWER

The string quartet studies presented an opportunity to further develop the score viewer and gain important feedback from performers. Working with a broader range of pieces revealed some of the limitations of the initial prototype and helped to clarify the core requirements. These included features specific to practice and rehearsal, which I began to consider in more detail.

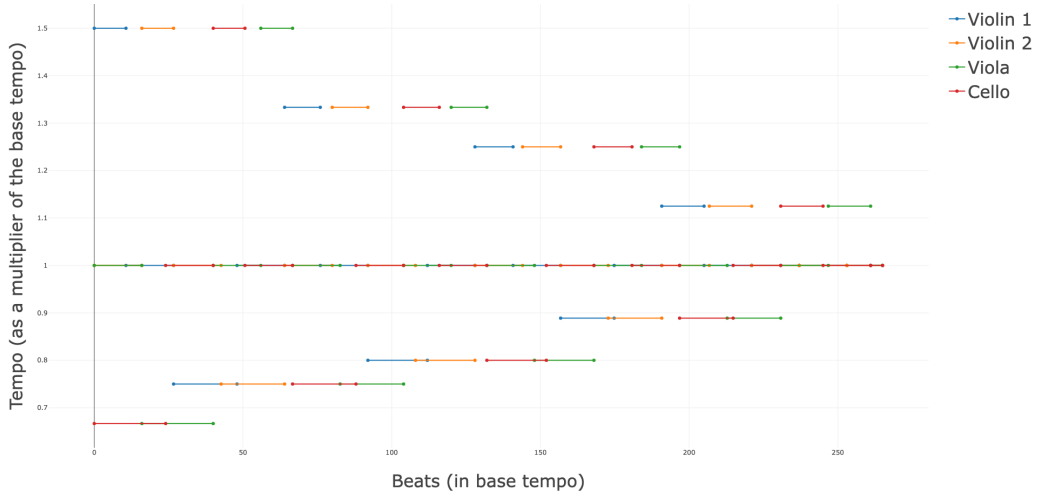

Figure 11: *Study 3* tempi (interactive version in *commentary-graphs.html*)

A key area of research was the design of the visual metronome. This is crucial to the performance of the pieces as it provides a reference for the current pulse and this pulse is often unique to each part. The design of the metronome went through several versions of varying degrees of complexity. These explored different kinds of motion, with some more closely simulating the movements of a real conductor. In the end, however, I reverted to one of the simplest designs: a dark grey circle that fades linearly to white over the duration of a beat. I settled on this after presenting a range of possibilities to the members of Apartment House and establishing some important criteria in response to their feedback. These were: that it must be clear and simple enough to be used as a reference in peripheral vision; that the start of each beat must be completely unambiguous; and that the speed of the beat must be clearly and quickly discerned. Whereas in *Eluvium* the position in the score was conveyed by highlighting the current bar, I now highlighted the

current event. This provided a more focused point of reference, which was equally applicable to scores with or without barlines. It became evident through working with the musicians that the visual metronome worked in combination with the event highlighting to convey a clear sense of pulse.

There are several respects in which the practical aspects of a rehearsal are taken into account in the design of the application: each player can navigate the score independently in order to look through their part; they can use the *snap* feature to move everyone to the same location; and the *start* and *stop* controls are available to all players, giving each member of the ensemble equal control. Additionally, the base tempo can be altered to change the overall speed. Other design features ease both rehearsal and performance. For example, two systems of the score are visible at any given time. The performer reads from the top system and this is then replaced by the bottom system as the music proceeds. Performers find this to be very natural and appreciate being able to look ahead. Additionally, the slider displaying the overall position in the score proved to be useful in *Study 3*, where the performers gradually move from *ordinario* to *sul ponticello* over the duration of the piece. Changes were also made to the content of the scores in response to performer feedback. One such request was the addition of bracketed tempo markings in advance of tempo changes. These enabled the performers to quickly discern the relationship between the outgoing and incoming tempi.

The score viewer proved to be a practical and effective aid in the performance of the string quartet studies. Working with an ensemble over a longer period enabled me to develop the application while carefully factoring

the performance experience into the design. Additionally, rehearsal and performance scenarios were now considered on an equal footing. At this point, the process of exporting scores for use in the score viewer was the main drawback as it still involved a lot of manual editing of graphical data. This was an issue that was to be resolved in the next stage of development.

2.4 INTERLUDE: THE EXTENDED MIND

> [T]he actual local operations that realize certain forms of human cognizing include inextricable tangles of feedback, feed-forward, and feed-around loops: loops that promiscuously criss-cross the boundaries of the brain, body and world.[46]

2.4.1 ACTIVE EXTERNALISM

The concept of the extended mind was introduced in an essay by Andy Clark and David Chalmers in 1998. They begin with the question, 'Where does the mind stop and the rest of the world begin?', and respond by proposing the idea of *active externalism*, which is 'based on the active role of the environment in driving cognitive processes.'[47] When first encountered, this idea may seem to simply support the widely accepted view that features of the environment influence the cognitive processing that takes place in the brain. The view advocated, however, is much more radical; it is that the active features of the environment actually constitute a part of the cognitive processing. In other words, cognition can meaningfully be considered to extend beyond the boundaries of the body. In clarifying this distinction, Richard Menary writes:

> The coupled system constitutes a cognitive system. It is not simply that external features, to which the organism is interact-

[46] Andy Clark. *Supersizing the Mind: Embodiment, Action and Cognitive Extension*. Oxford University Press, 2011, p. xxviii.

[47] Andy Clark and David J. Chalmers. 'The Extended Mind'. In: *The Extended Mind*. MIT Press, 2010, p. 27.

> ively linked, have a causal influence on the cognitive processing of the organism; rather, the interactive link *is* the cognitive processing.[48]

This insight is highly relevant to my research, in which I seek to reimagine the interrelationships between composer, performer and technology. I will therefore expand upon the core principles of the extended mind thesis before evaluating my own work in this context. Two further concepts are introduced: *causal coupling* and *the parity principle*. Both are necessary to confirm the presence of active externalism, and by extension the extended mind.

2.4.2 CAUSAL COUPLING

To establish what is meant by causal coupling, Clark and Chalmers state, 'In these cases, the human organism is linked with an external entity in a two-way interaction, creating a *coupled system* that can be seen as a cognitive system in its own right.'[49] In addition, constituent components should all play an active causal role, thereby jointly governing behaviour, and the removal of an external component would be deemed to have a detrimental effect on the system's behavioural competence. Menary, in his interpretation of the theory, further requires that the influence is symmetric and, therefore, that 'the inner and outer features have a mutually constraining causal influence

[48]Richard Menary. 'Introduction: The Extended Mind in Focus'. In: *The Extended Mind*. MIT Press, 2010, p. 2.
[49]Clark and Chalmers, 'The Extended Mind', p. 29.

on one another that unfolds over time.'[50] He names this property *cognitive integration*.

2.4.3 THE PARITY PRINCIPLE

To define the parity principle, Clark and Chalmers state, 'If, as we confront some task, a part of the world functions as a process which, *were it done in the head*, we would have no hesitation in recognizing as part of the cognitive process, then that part of the world *is* (so we claim) part of the cognitive process.'[51] In other words, the location of a process should not determine whether or not it is considered a constitutive part of a cognitive system. This is further emphasised by Clark in *Supersizing the Mind*: 'Such considerations of parity, once we put our bioprejudices aside, reveal the outward loop as a functional part of an extended cognitive machine.'[52] It is significant that at no point is it claimed that each constituent part is itself cognitive. This is a common misunderstanding of the theory, which assumes that parts of a system must have the same properties as the whole.

2.4.4 COMPOSER AND TECHNOLOGY

To evaluate whether the way I use technology as a composer can be viewed as embodying features of the extended mind, it is first important to consider traditional paper-based methods of composition. The use of notation in composition is largely analogous to use of the written word in other fields,

[50]Menary, 'Introduction: The Extended Mind in Focus', p. 4.
[51]Clark and Chalmers, 'The Extended Mind', p. 29.
[52]Clark, *Supersizing the Mind: Embodiment, Action and Cognitive Extension*, p. xxvi.

of which Clark writes, 'The loop through pen and paper is part of the physical machinery responsible for the shape of the flow of thoughts and ideas'.[53] The composer and manuscript form a coupled system in which each plays a causal role and the resulting behaviour is ultimately determined by the interaction between the two. Whether this causal role can be deemed active or the behavioural competence would drop in the absence of the manuscript largely depends on the techniques involved. I certainly believe that this is true in the case of contrapuntal techniques such as canon and fugue, which to a large extent depend upon this externalised visual representation. In this light, it seems no coincidence that these techniques emerged soon after the advent of new forms of notation. Externalised thinking, in these cases, significantly reduces memory load and fundamentally transforms the nature of the problem at hand. These examples also satisfy the parity principle as there is no doubt that they would be considered cognitive processes if they were completed entirely in the head. In fact, were someone to attempt these tasks in this way, they would likely do so by visualising the representation on the page. This is similar to how many musicians visualise a piano keyboard when thinking about pitch and reveals the attempt to internalise fundamentally externalised ways of thinking.

The composition environment that I have developed as part of my research builds on the coupling already present in interactions with the page and further expands the role of active externalism. The software plays an active causal role by applying temporal and canonic rules, as well as other

[53]Clark, *Supersizing the Mind: Embodiment, Action and Cognitive Extension*, p. xxv.

transformations, and the rapid visual and auditory feedback creates a tightly coupled loop between human and machine. While these processes could theoretically be carried out in the head, they would pose potentially insurmountable challenges. This would undoubtedly have a detrimental effect on the system's behavioural competence. In support of the parity principle, however, there would in this case be no hesitation in considering them part of a cognitive process. When using the composition environment, the influence in the human-machine interaction is symmetric and mutually constraining, thereby satisfying the conditions of cognitive integration. This influence unfolds over time, seamlessly shaping the flow of thoughts and ideas.

2.4.5 PERFORMER AND TECHNOLOGY

The score viewer can also, in some respects, be considered part of the extended mind, this time in relation to the performer. In contrast to traditional static scores, the presentation is dynamic and provides real-time cues in the form of a visual metronome, event highlighting and automated system changes. These elements each play an active causal role that unfolds over time. The performer and score jointly govern behaviour and the application aids the performer in overcoming considerable rhythmic challenges. In conventional ensemble playing, the feeling of pulse is already partly externalised as it emerges cooperatively through the mutual influence of the players. Here, however, this externalisation is made more explicit through a direct coupling of performer and machine. Conversely, the influence cannot properly be considered symmetric as the player is unable to influence the score during performance. This is reflective of the current scope of the score

viewer, which I have deliberately limited in order to thoroughly investigate the application's use and effectiveness. In the future, further avenues could be explored that encourage bidirectional or even multidirectional communication and result in a mutually constraining causal influence. These might range from simple interactions, such as allowing performers to cue the start of sections, to deeply integrated real-time decision making.

2.5 BRACKEN

2.5.1 INTRODUCTION

Bracken is a composition for string quartet and electronics and was also written for Apartment House. In some senses it is a departure from the other included works as it does not make use of polytempo and is rooted in a very different approach to pitch and rhythm. This approach is reminiscent of *Shimmer*,[54] an earlier piece of mine for double bass and electronics, and is characterised by sustained pitches in extended just intonation. As with the other works, technology played an important role, both during composition and in performance. In this piece, however, I further tilted the creative balance towards the machine by developing an algorithm that was responsible for the placement and orchestration of events.

2.5.2 MATERIAL

In determining the pitch material for the piece I began by examining partials of adjacent members of the harmonic series. While studying the resulting intervals, I was drawn to the repeating pattern of a unison enclosed by two superparticular ratios, as shown in Figure 12. This seemed to suggest certain pathways between the pitches. Significantly, the largest of these ratios is 16:15, which is an example of a just semitone. The remaining intervals therefore explore finer microtonal gradations of pitch. I was keen for all the

[54]James Opstad. 'Portfolio of Compositions'. MA thesis. University of Birmingham, 2017, p. 10.

partials to be played as natural harmonics and therefore investigated different tunings that would spread the base pitches amongst the members of the quartet. I settled on a tuning that shared the initial array of pitches between the viola and cello and then repeated the same structure an octave higher in the violins, as shown in Figure 13. The resulting pitches, shown in Figure 14, can be considered members of a single harmonic series with an imagined low G fundamental (24.5 Hz). The highest partial that is played on a given string is equal to the lowest partial on the string above. These pitches are used as pivots when crossing strings and serve to orient the player to the new nodal location. When on the same string, players always move between adjacent harmonics. The scordatura are kept within a practical range and the restriction to the first nine partials ensures that the harmonics can be played accurately.

At this stage, the pitch material for the piece had been abstractly defined without yet being placed in time. While the means by which I selected this material involved a degree of subjectivity, it was equally determined by studying intrinsic qualities of the instruments I was working with and physical properties of the sounds they produce. There was, in a sense, a certain distance between myself and the material, which I wished to maintain. This attitude, sometimes viewed as characteristic of experimental music, is described by Jennie Gottschalk:

> One of the points that initially seems most contradictory is that in order for a listener to have a rich, subjective, differentiated experience, a composer of experimental music often feels a necessity to

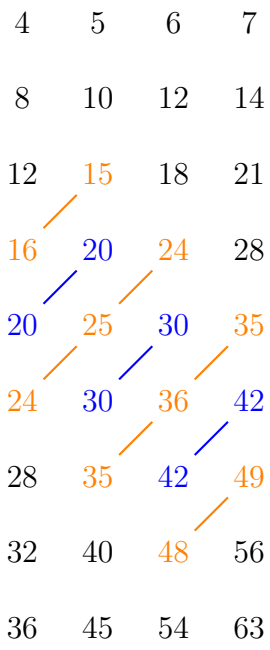

Figure 12: Partials of adjacent members of the harmonic series (unisons in blue and superparticular dyads in orange)

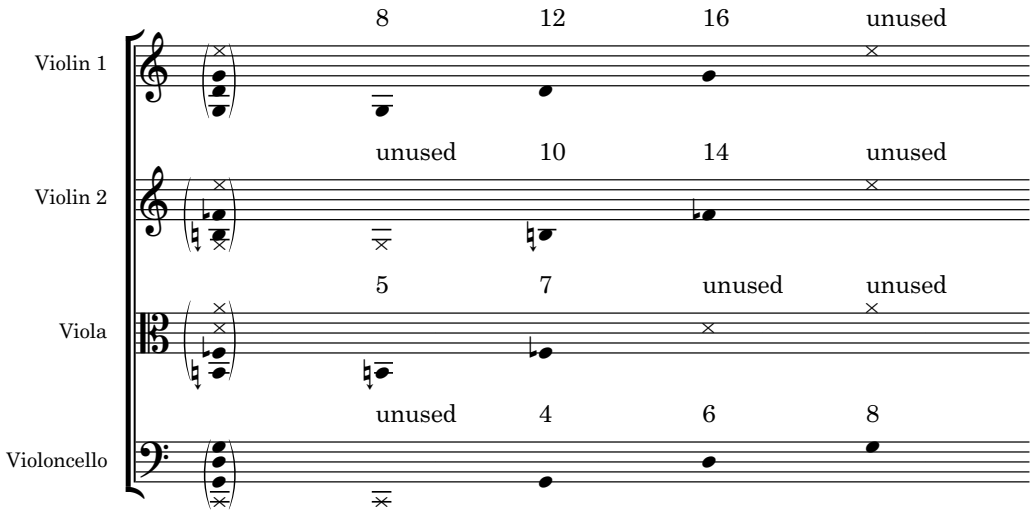

Figure 13: *Bracken* tuning (numbers indicate the position in the harmonic series)

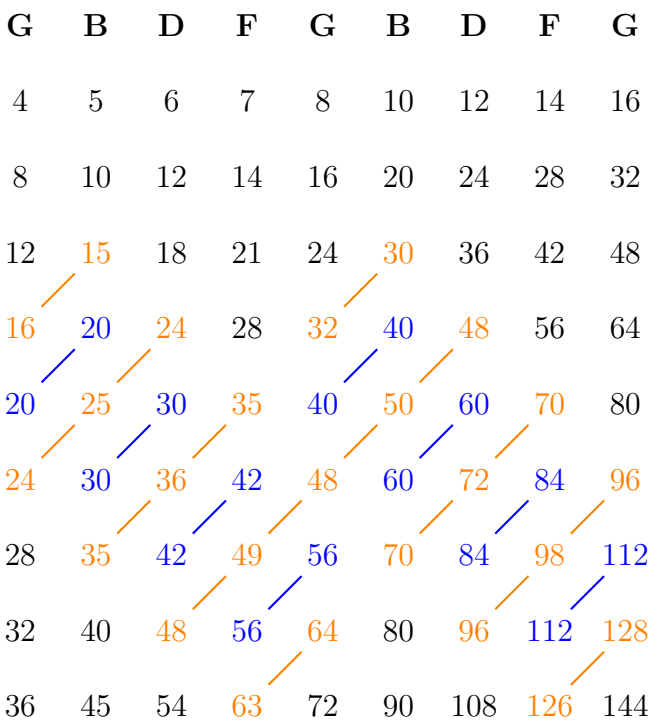

Figure 14: *Bracken* pitches (potential unisons in blue and potential superparticular dyads in orange)

> remove her own subjectivity—tastes, associations, discernment, emotions—as much as possible from the process of making the work.[55]

An interesting parallel can be drawn between this notion of nonsubjectivity and a nonlinear (or vertical) conception of time. In *The Time of Music*, Jonathan Kramer defines nonlinearity as 'the determination of some characteristic of music in accordance with implications that arise from principles or tendencies governing an entire piece or section.'[56] This is in contrast to linearity, where characteristics arise from implications of earlier events. Echoing Gottschalk's description above, Kramer writes, 'The context of vertical music allows a listener to make contact with his or her own subjective temporality.'[57] While it can be argued that all music reveals aspects of both subjectivity and nonsubjectivity, linearity and nonlinearity, in this piece it was these nonsubjective and nonlinear qualities that I was hoping to promote. I envisioned my compositional role as being part instigator, part observer and sought to achieve this goal by introducing an algorithm with a degree of autonomy.

2.5.3 ALGORITHM

The methods I used to compose *Bracken* are most clearly defined by a division between macro and micro decision making. The macro decisions are those that I made to determine the overall shape and form of the piece; they are

[55]Gottschalk, *Experimental Music Since 1970*, p. 3.
[56]Kramer, *The Time of Music*, p. 20.
[57]Kramer, *The Time of Music*, p. 57.

fixed. The micro decisions, by contrast, were delegated to the algorithm and determine the moment to moment placement and orchestration of events; they are indeterminate. The algorithm therefore operates with a degree of freedom but within clearly defined bounds. No two renderings of the piece would be the same, but they would nevertheless be recognised as having much in common.

The various parameters governing the piece can be seen as exerting layers of influence. It is the shadows of these influences that are manifest in the individual events. The first of these layers is the pitches. At the beginning I wanted the parts to overlap in the centre of the grid (Figure 14). The violins therefore start with their lowest pitches and work upwards whereas the viola and cello start in the high register and work down. Upon reaching the outer edges, the parts then begin to creep back towards the centre. Time brackets, unique to each part, are defined in which each of these pitches can occur. These are shown in Figure 15. The next layer is the range of possible durations. These are determined by a minimum and maximum duration, both of which gradually increase at regular intervals throughout the piece. Other layers of influence include the maximum number of simultaneous voices and the number of entries before the same voice can reenter. Given all these user-defined variables, the algorithm then traverses the piece to create and allocate events. Voices are randomly selected from those that are currently flagged as available and the duration and placement of events is randomly determined within the currently defined bounds. The nature of this traversal ensures that there is always some overlap between the parts.

As Laurie Spiegel writes, 'Algorithms are essentially shorthand notations

for large numbers of specifics.'[58] In *Bracken*, the use of algorithms meant that I could work in broad brushstrokes while entrusting the finer details to chance. As a consequence, the full canvas of the work was always in view. In fact, while composing, I would often render graphs to gain a visual impression of the piece as a whole. I feel that this perspective enabled me to approach a more vertical conception of time. While it may seem contradictory that some formal aspects of the piece, such as the movement between pitches, are overtly linear, my feeling is that this ensures an inevitability that shifts focus elsewhere. To quote Kramer again, 'Vertical music can be, paradoxically, totally nonlinear or else so totally linear that (as in process music) predictability reigns.'[59] The use of chance was important in counterbalancing the systematised construction of the piece and restoring a sense of aimlessness to a structure that may otherwise have felt too goal-oriented.

2.5.4 ELECTRONICS

The electronic parts mirror the acoustic quartet and were generated using the same algorithm. Different time brackets were used, however, with the electronics proceeding through the material at a slower rate. The relationship between the acoustic and electronic parts can therefore be viewed as another example of tempo canon. In this case, however, the interpretation is much looser than in the other pieces and it is the process, rather than the exact placement of events, that is canonic. Samples were recorded of the four

[58]Laurie Spiegel. 'Thoughts on Composing with Algorithms'. In: *The Oxford Handbook of Algorithmic Music*. Oxford University Press, 2018, p. 105.
[59]Kramer, *The Time of Music*, p. 62.

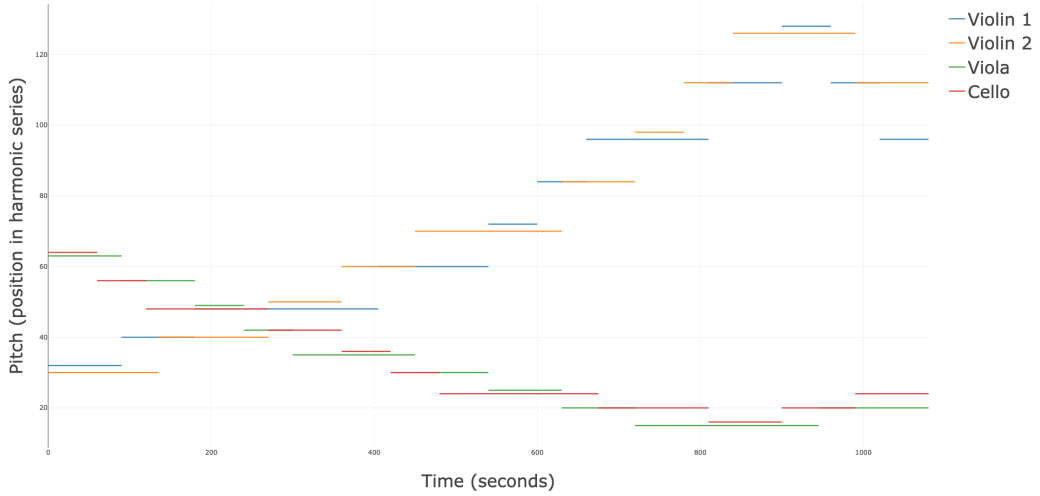

Figure 15: *Bracken* time brackets (interactive version in *commentary-graphs.html*)

members of the quartet playing the harmonics and these are played back and filtered to emphasise the first eight overtones. This has the effect of creating a purer tone quality that is more sinusoidal in nature. The sound sits somewhere between being identifiably acoustic or electronic, with the instability of the source reflected in the subtly fluctuating overtones. In contrast, the acoustic instruments feel richer with the more present sound of the bow hair contributing to a greater complexity. Together, the acoustic and electronic parts blend effectively, becoming more discrete as they diverge.

2.5.5 SCORE VIEWER

Bracken is distinct from the other included works in the requirements it makes of the score viewer. There are no tempi and the passing of time is not measured in beats; instead, durations are expressed directly in seconds (to two decimal places). I therefore chose to replace the visual metronome

with a progress indicator. This is a circle with an outer ring that fills during the course of an event. As events include both notes and rests, they are always contiguous. Each event is treated as an isolated unit and presented in its own system, a notation that is similar to that used by John Cage in his *Number Pieces*. As is true of the other scores, the current and next systems are always visible.

A significant advantage of presenting the score using the application is that the players are not required to perform the role of timekeepers. While performances of Cage's *Number Pieces* and similar works typically require the use of stopwatches, here both the current event and the position within it are conveyed visually. I feel that this allows the players to immerse themselves more fully in the performance and that this is especially important given the subtle adjustments required to produce the harmonics. Aesthetically, I also prefer that time, in this context, is represented as circular and continuous rather than broken into discrete values. As in *Eluvium*, the use of the score viewer greatly eases synchronisation with the electronics and again removes the need for an additional electronic performer.

2.6 INTERLUDE: FREEDOM AND CONTROL

> The question continually on my mind all these years is: to what degree does one give up control, and still keep that last vestige where one can call the work one's own?[60]

Questions of freedom and control, process and intuition have been ever-present in my recent work. These concerns have been foregrounded by my use of technology and the task of mediating its participation in the acts of composition and performance. As a result, my attitude towards these issues has changed a great deal and will no doubt continue to do so. Whereas in the past I might have more readily subscribed to an experimental aesthetic predicated on what Christopher Fox describes as a 'distancing of creative will from created sound',[61] I now prefer to acknowledge that a more distanced approach in some areas can facilitate greater focus in others. This thinking has been key to the way that I have so far integrated the computer into my compositional work. I have come to believe that a work of art should capture something intangible about the creative process, some quality that evades rational analysis. In *The Hidden Order of Art*, Anton Ehrenzweig writes:

> While the artist struggles with the medium, unknown to himself he wrestles with his unconscious personality revealed by the work

[60]Morton Feldman. 'The Anxiety of Art'. In: *Give My Regards to Eighth Street*. Exact Change, 1965, p. 30.

[61]Christopher Fox. 'Why Experimental? Why Me?' In: *The Ashgate Research Companion to Experimental Music*. Ashgate, 2009, p. 8.

> of art. Taking back from the work on a conscious level what has been projected into it on an unconscious level is perhaps the most fruitful and painful result of creativity.[62]

This idea of the work revealing in itself something about the creative act is echoed by Morton Feldman: 'There is nothing but the integrity of the creative act. Any detail of the work is sufficient to establish this.'[63] It is significant in this regard that the algorithmic techniques of other composers that I have chosen to study and learn from are not those that generate material, but rather those that reveal its latent properties. This is true of both Aldo Clementi's use of the magic square and Iannis Xenakis's sieve theory, which was developed to study internal symmetries in pitch and rhythm structures.[64] Xenakis is an important figure in this discussion as many of his ideas were based on mathematical concepts. He believed, in fact, that his primary contribution to the development of music was using 'ideas in composing that are completely alien to music'.[65] He would later reflect that, 'All those years served as a kind of training. I can now work with the theories intuitively—they've become an innate part of my thinking.'[66] I hope, in some ways, to follow a similar path and would like to believe that my work with new compositional techniques serves also to train the unconscious mind. Xenakis was

[62]Anton Ehrenzweig. *The Hidden Order of Art*. University of California Press, 1967, p. 57.

[63]Morton Feldman. 'Give My Regards to Eighth Street'. In: *Give My Regards to Eighth Street*. Exact Change, 1971, p. 101.

[64]Dimitrios Exarchos. 'Iannis Xenakis and Sieve Theory: An Analysis of the Late Music (1984-1993)'. PhD thesis. Goldsmiths College, University of London, 2007.

[65]Bálint András Varga. *Conversations with Iannis Xenakis*. Faber and Faber, 1996, p. 79.

[66]Varga, *Conversations with Iannis Xenakis*, p. 200.

quick to acknowledge, however, the risk of creative stagnation that this can pose; the assimilation of old techniques must be balanced by a continuing curiosity for the new. My changing outlook can be viewed as a reaction to working with technology but also as a recognition of the characteristics of my personality that this interaction has revealed. My mind can be very analytical, a positive attribute in some regards but also one that leads me to be easily seduced by geometric forms and patterns, structures to which computers lend themselves too readily. In contrast, my background as an improvising performer reveals a more intuitive and spontaneous side. Balancing these conflicting traits is a significant challenge and is further complicated by a nagging and persistent sense of doubt. This self-doubt is something that I suspect many composers face but few speak openly about; it is the pain that Ehrenzweig refers to. When confronted with feelings of doubt it is common to exert greater conscious control and to revise those aspects of a work that cannot be rationally justified. Gradually, with time, I am learning to resist this impulse. Ehrenzweig writes:

> Any work of art functions like another person, having independent life of its own. An excessive wish to control it prevents the development of a passive watchfulness towards the work in progress that is needed for scanning half consciously its still scattered and fragmented structure.[67]

This in turn reminds me of a comment made by the pianist John Tilbury regarding Christian Wolff's music: 'With this music you learn the prime

[67]Ehrenzweig, *The Hidden Order of Art*, p. 102.

qualities needed in performing: discipline, devotion and disinterestedness.'[68] I feel that these qualities may be equally relevant to composition. Perhaps this 'passive watchfulness', this 'disinterestedness' is the distance that is needed in creative work; the ability to trust oneself and make judgements that are fluid rather than overbearing; the ability to know instinctively when a work is finished, to stand back and to let it be free.

[68]Michael Nyman. *Experimental Music: Cage and Beyond.* Cambridge University Press, 1974, p. 69.

2.7 PIANO AND PERCUSSION PIECES

2.7.1 INTRODUCTION

Nymphaea and *Drift* were written for the GBSR Duo,[69] comprising percussionist George Barton and pianist Siwan Rhys. The opportunity to write for piano and percussion presented a welcome contrast to my recent work with strings and encouraged me to explore new compositional directions. During this collaboration I was also able to redevelop the score viewer, resulting in its most mature and flexible incarnation.

2.7.2 NYMPHAEA

Nymphaea is a piece for piano and vibraphone and builds on the concepts introduced in *Study 1*. Gradual tempo changes and static tempi again occur concurrently, though here both accelerandi and decelerandi are used. In a similar manner to *Bracken*, the pitch material and form were determined prior to placing the events in time. In *Nymphaea*, however, I chose not to use algorithmic procedures and instead worked intuitively within the predefined structure. The order of tempi repeat a pattern of slowing by the ratio 2/3, maintaining the new tempo, accelerating by the ratio 4/3 and maintaining the new tempo again. When conceived as pitches, as shown in Figure 16, these tempi form a succession of unisons, descending fifths and ascending fourths. The tempo relationships (shown in graph form in Figure 17) are themselves canonic, with the piano always one change behind the vibraphone. Each

[69] https://www.gbsr.co.uk/ (visited on 18/02/2022)

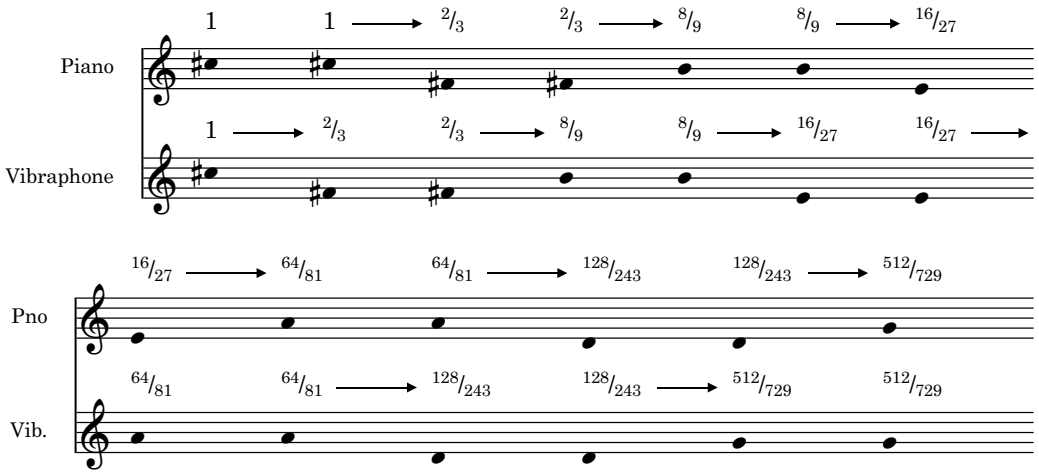

Figure 16: *Nymphaea* tempi as pitches

new section begins at a convergence point and these occur after forty one beats of the changing tempo. The number of static beats depends on the position in the cycle and this variability results in the echo distance between the parts expanding and contracting over the course of the piece. This echo distance and the properties by which it is determined are shown in Figure 18. The overall impression is of the parts drifting further apart and the tempo gradually slowing. More locally, however, the piece is defined by a continual ebb and flow. The piano and vibraphone share the same material but the chords in the vibraphone are reduced to dyads.

Working within a predefined structure had a significant impact on the feel of writing this piece. With the help of the composition environment, I was able to devote my attention fully to the pacing and interaction of the parts. The software once again enabled me to enter a single layer and have each event appear at its respective position in both voices. I found that the continual presence of the form was something that I not only worked within

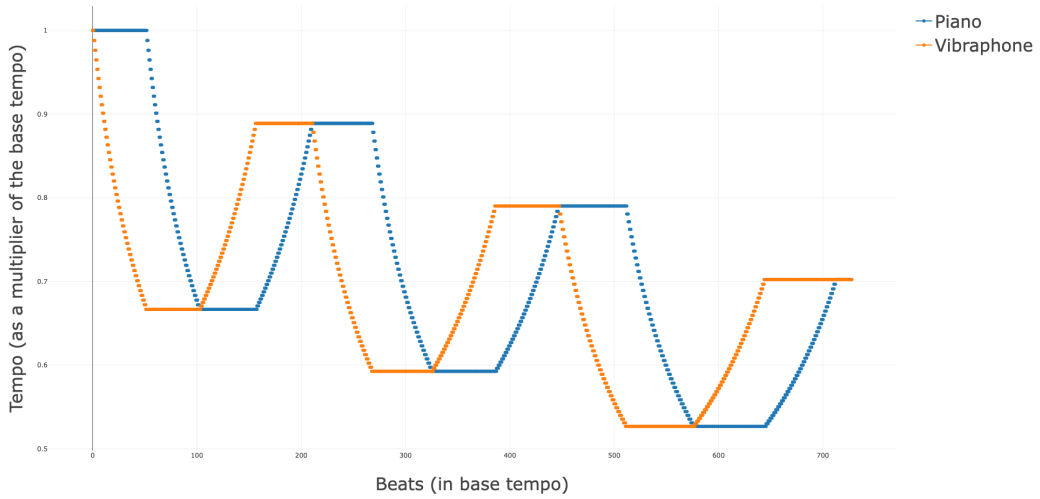

Figure 17: *Nymphaea* tempi (interactive version in *commentary-graphs.html*)

Piano		**Vibraphone**		**Echo Distance**
Tempo	Beats	Tempo	Beats	
1	51	$1 \to 2/3$	41	10
$1 \to 2/3$	41	$2/3$	34	17
$2/3$	36	$2/3 \to 8/9$	41	12
$2/3 \to 8/9$	41	$8/9$	48	5
$8/9$	51	$8/9 \to 16/27$	41	15
$8/9 \to 16/27$	41	$16/27$	34	22
$16/27$	36	$16/27 \to 64/81$	41	17
$16/27 \to 64/81$	41	$64/81$	48	10
$64/81$	51	$64/81 \to 128/243$	41	20
$64/81 \to 128/243$	41	$128/243$	34	27
$128/243$	36	$128/243 \to 512/729$	41	22
$128/243 \to 512/729$	41	$512/729$	48	15

Figure 18: *Nymphaea* echo distances

but also pushed against, an experience that I liken to that of improvising on familiar jazz forms. Experienced improvisors will often anticipate or delay resolutions to create a sense of openness and evade a feeling of boxy regularity. Similarly, I often found myself delaying the arrival of a change in harmony beyond the convergence point. In this piece, I feel that the role of the form was to define the physical laws governing the temporal fabric of the music. By using canon, I was simultaneously composing present and future events, and this inherent feedback was essential to gaining an intuitive feel for these laws.

Nymphaea reveals some important aspects of my approach to pitch. As was already evident in *Study 1*, I often have a preference for pure intervals and clear voice leading. Whether or not I consider an interval to be pure does not necessarily correlate with traditional ideas of consonance and dissonance. Instead, it has its basis in tuning; the defining property is that a ratio is superparticular (either directly or by octave equivalence). As such, I often have an implicit tonal centre in mind at any given moment. Although I was working with equal tempered instruments in this piece, this approach still affected the way that the pitches were conceived and their enharmonic spelling. In Figure 19, the first three chords are broken down into their constituent intervals and corresponding ratios. Figure 20 shows the voice leading between these chords, once again revealing the superparticular relationships. To further demonstrate the origins of these concepts, Figure 21 again shows the pitches from the first three chords but this time positioned in the five-limit lattice from which the ratios derive. By adding the unused pitches, shown in brackets, the collection becomes the nine note mode that Olivier

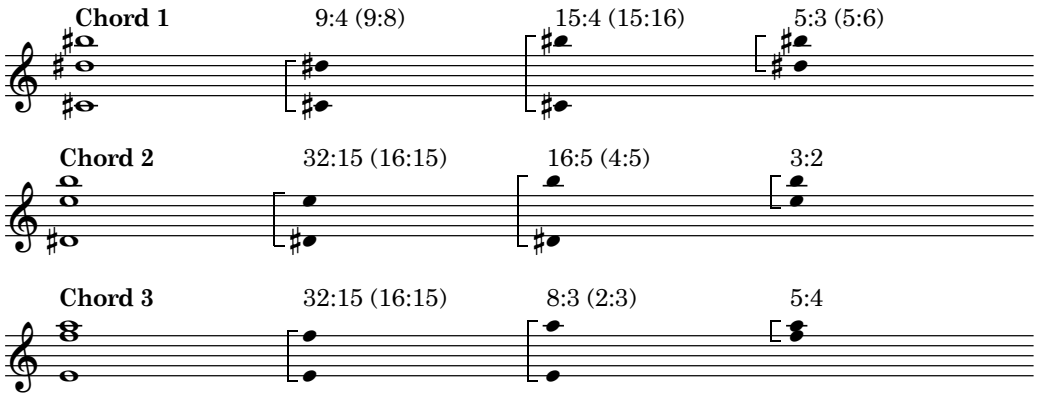

Figure 19: Intervals in the first three chords of *Nymphaea* (octave reductions in brackets)

Messiaen identifies as the *Third Mode of Limited Transpositions*.[70] This is a mode that I have often drawn upon in my music. It can be both neutral and characterful, with a somewhat paradoxical nature that is capable of bridging the worlds of symmetry and asymmetry. While composing I arrived at these harmonies by exploring sonorities directly at the piano. The principles that I have described have been part of my thinking for some time, gradually informing my sensibilities and seeping into my work.

Besides the pitches themselves, the choice of register is also significant to the mood of the piece. All the pitches are notated in the treble clef and occupy the middle and upper ranges of the piano. In a pragmatic sense, this brings them into the more limited range of the vibraphone. I am also, however, attracted to the sonority of this register and feel that the avoidance of low pitches leads to a feeling of weightlessness, as if the harmonies are suspended in space. Interestingly, although I am a double bass player, I often

[70]Olivier Messiaen. *The Technique of my Musical Language*. Alphonse Leduc, 1944, p. 90.

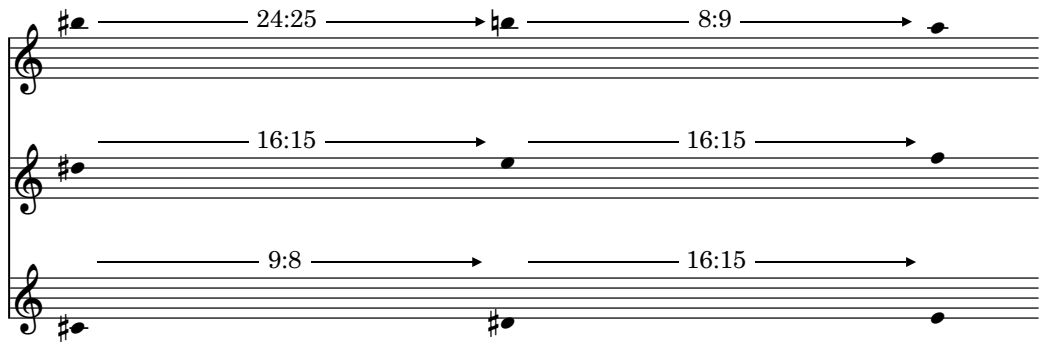

Figure 20: Voice leading in the first three chords of *Nymphaea*

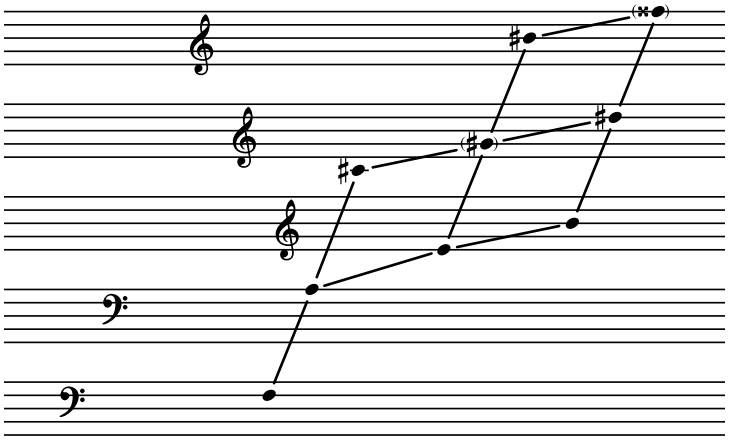

Figure 21: Five-limit lattice for the first three chords of *Nymphaea* (pitches in brackets not used)

find myself omitting the low register when composing. This may partly be because I have become conditioned to hear the bass notes as contextualising the other pitches and resolving the very ambiguities that I would like to persist.

Another feature that I am drawn to is the decay of the sound and many of the timbres in *Nymphaea* arise from the interaction of interlocking sustains. This focus on decay was a key feature of Morton Feldman's music. He writes, 'Decay, however, this departing landscape, *this* expresses where the sound exists in our hearing—leaving us rather than coming toward us.'[71] I feel that this sense of departure goes some way to explaining my own affinity with decay. This impression of 'leaving us rather than coming toward us' bears relevance not only to my treatment of sonic events but also to my approach to tempi, which often slow and dissipate over the course of a piece. Feldman's influence can also be sensed in the way that the piano and vibraphone start together with the same material and then gradually drift apart. In two pieces written in 1957, *Piece for Four Pianos* and *Two Pianos*, Feldman introduced a new notational procedure whereby the performers would read from the same score but each proceed at their own pace. He described the result as, 'like a series of reverberations from an identical sound source.'[72] Despite the contrast between the inherent temporal indeterminacy in Feldman's approach and my precisely determined rhythmic placement, the resulting effect is undoubtedly similar. Feldman would later share an anecdote that highlights this relevance

[71]Feldman, 'The Anxiety of Art', p. 25.

[72]Morton Feldman. 'Liner Notes'. In: *Give My Regards to Eighth Street*. Exact Change, 1962, p. 7.

to my work:

> Many years ago, I met a very young pianist, Frederic Rzewski, and he said, 'You known that canon for two pianos?' Canon, me, write a canon!? Oh yes, that free-durational piece. It's a canon![73]

In his eagerness to break free of past conventions, Feldman would never have entertained the idea of deliberately writing a canon. Nevertheless, these works can be considered not only canons but indeterminate tempo canons.

2.7.3 DRIFT

Drift is written for piano and temple blocks and is the longest of the included works. Each player has a single controlled decelerando that lasts the entire duration of the piece, during which the relationship between the tempi gradually shifts from 5:7 to 9:11. These tempi are shown in Figure 22. The work does not use canon and is instead built upon repetition, incremental change and the recontextualisation of material.

In composing this piece I began to use the composition environment in a markedly different way. Rather than inputting fully formed fragments of material, using the familiar *LilyPond* syntax, I utilised the underlying JavaScript language to declare individual variables that were then used to construct fragments incrementally. For the piano part, I began with the pitch class array shown in Figure 23 and programmatically created the four

[73]Morton Feldman. 'Darmstadt Lecture, July 1984'. In: *Morton Feldman Says: Selected Interviews and Lectures 1964-1987*. Hyphen Press, 1984, p. 192.

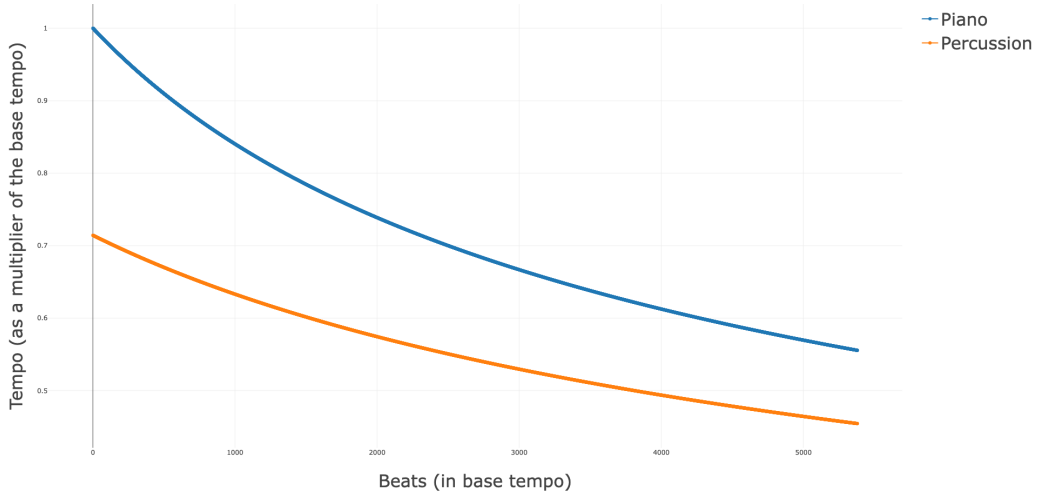

Figure 22: *Drift* tempi (interactive version in *commentary-graphs.html*)

specular transformations. I then created additional arrays for octave displacements and durations, which were mapped to the pitch classes. The resulting events were used as the basis for a series of more complex transformations in which the material was composed into larger structures, finally resulting in the complete piano part. The percussion part was created with a similar, though more restricted, set of procedures.

By defining the constitutive properties of musical events as independent variables and progressively building larger fragments of material, I was able to engage with the technology as a fluid medium for the structuring and rearrangement of ideas. Within this process the computer clearly functioned as an integrated and indispensable part of my thinking. The philosophical implications of technological interactions of this kind are discussed by Thor

(0, 1, -2, 2, -3, 4, -4, 5, -6)

Figure 23: *Drift* pitch class array

Magnusson:

> If our objects serve as instruments of thinking, as epistemic tools, the millennia-old distinction so clearly articulated by Plato between *episteme* (knowledge) and *techne* (skill) breaks down, and we need to investigate how our tools of grammatisation, of externalising our thoughts into systems of discrete elements, play a crucial role in our musical practice.[74]

This description of *grammatisation* as, 'externalising our thoughts into systems of discrete elements', demonstrates the relevance to the way in which I was working. The concept of grammatisation was introduced by the philosopher Bernard Stiegler and builds upon Jacques Derrida's notion of *grammatology*. It forms an interesting parallel to the extended mind thesis, discussed in Section 2.4, as it similarly addresses ideas of externalised thinking. Stiegler writes:

> By grammatization, I mean the process whereby the currents and continuities shaping our lives become discrete elements. The history of human memory is the history of this process. Writing, as the breaking into discrete elements of the flux of speech (let us invent the word *discretization* for this possibility), is an example of a stage in the process of grammatization.[75]

[74]Magnusson, *Sonic Writing*, p. 9.

[75]Bernard Stiegler. 'Memory'. In: *Critical Terms for Media Studies*. The University of Chicago Press, 2010, p. 70.

While *discretization* is already inherent to musical notation, in writing this piece I was explicitly using code to create discrete elements at varying degrees of abstraction, as if zooming in and out. Crucial to the theory of grammatisation is memory, of which Stiegler states, 'A tool is, before anything else, memory: if this were not the case, it could never function as a reference of significance.'[76] In computers, the primacy of memory is made explicit by its existence as one of the core components, without which the device would fail to function. In our interactions with computers we can utilise this externalised memory as an extension of our own. For Stiegler, these interior and exterior memories are inseparable. While composing *Drift*, the externalisation of memory was essential to the flow and exchange of ideas. The computer code was more than a notational substitute, as the compositional procedures were themselves inscribed and it was possible to retrospectively intervene in any part of the process. This meant that my focus could seamlessly shift between micro and macro perspectives. As in *Bracken*, I feel that this change in viewpoint influenced the sense of time that the piece evokes and encouraged the coexistence of linear and nonlinear approaches. While I do not wish to assume aspects of the listened experience, it seems possible that it could be permeated by the very dislocation of memory that is present in the work's conception.

Repetition is central to the treatment of material in *Drift* and operates at multiple levels. The percussion part, for example, comprises one long

[76]Bernard Stiegler. *Technics and Time, 1: The Fault of Epimetheus*. Stanford University Press, 1998, p. 254.

repeated cycle, but also contains shorter rhythmic cells that reappear more locally. This layered approach has a disorientating effect that makes it difficult to discern where the cycle begins and ends. The piano part further extends this principle by transposing and reordering existing material. The long sections, demarcated by rehearsal marks, are repetitions that are progressively lowered by a semitone. Within these, shorter fragments of material are transposed and joined in various configurations, with shared pitches used as pivots. The intention is once again a feeling of disorientation, of hazy familiarity rather than predictability. While there is much that repeats, the exact nature of these repetitions and the context within which they occur is always changing. Dora A. Hanninen characterises this reframing of material as *recontextualization*, which she describes as, 'a strange kind of repetition—better, an *estranged* repetition, in which repetition doesn't sound (primarily) like repetition.'[77] Its essence is, 'the *phenomenal transformation* of repetition prompted by a change in context.'[78] In *Drift*, though the tempi of the parts is globally coordinated, the relationship between them is constantly shifting. Repetitions are therefore always cast in a new light, always recontextualised. If we, as listeners, sense that repetition is occurring, it is by abstracting ideas from this ever-changing context. As Hanninen writes, 'Recontextualization, by any means, concerns a misfit between a listener's concept of a thing and a particular manifestation (repetition, instance) of that thing in a particular

[77]Dora A. Hanninen. 'A Theory of Recontextualization in Music: Analyzing Phenomenal Transformations of Repetition'. In: *Music Theory Spectrum* 25.1 (2003), p. 61.

[78]Hanninen, 'A Theory of Recontextualization in Music: Analyzing Phenomenal Transformations of Repetition', p. 64.

context.'[79]

As in *Nymphaea*, the register used is significant and the middle and upper ranges of the piano once again dominate. Both pieces feature progressive downward transpositions, echoing the slowing of the tempo and leading to a gradual thickening of the timbre. I feel that this pairing of register and speed enhances the sensation of falling and evokes the inevitable pull of gravity. The use of just two temple blocks rather than a broader range of timbres or pitches is also important. This limitation leads to the pitches themselves not being treated as such, as Samuel Z. Solomon describes: 'When a single sound is repeated, the ear can tire of its pitch and instead listen to it only in terms of its rhythmic function.'[80] Though two sounds rather than one are used in this case, their continual presence throughout achieves a similar effect. Introducing a further voice at any point would be considered a major event and interrupt the suspended vertical conception of time to which the piece aspires. As Jonathan Kramer writes, 'A vertically conceived piece defines its bounded sound-world early in its performance and stays within the limits it chooses.'[81]

2.7.4 SCORE VIEWER

While the requirements of the score viewer made by the piano and percussion pieces were similar to those made by the string quartet studies, the inter-

[79]Hanninen, 'A Theory of Recontextualization in Music: Analyzing Phenomenal Transformations of Repetition', p. 72.

[80]Samuel Z. Solomon. *How to Write for Percussion: A Comprehensive Guide to Percussion Composition*. Oxford University Press, 2016, p. 16.

[81]Kramer, *The Time of Music*, p. 55.

vening time provided an opportunity to reconsider the implementation and build a more resilient and full-featured application. I had recently worked on a placement with the team at Steinberg responsible for the *Dorico*[82] notation software and this gave me access to new methods for exporting graphical metadata. As a result, I was now able to eliminate the need for manual editing of graphical exports, which significantly streamlined the export process. For both technical and musical reasons, I decided to move away from highlighting individual events and instead chose to highlight the area of the score corresponding to the current beat. For pieces such as *Drift*, that include a high density of events, this reduces what would otherwise be a very rapid succession of visual changes. The revised approach matches and reinforces the pulse of the visual metronome and additionally provides the option of fading the highlight colour over the course of the beat's duration. This and other options are located in a new settings drawer and can be individually set by each performer. An optional audible click is also now included, which has proved particularly useful in rehearsal situations. Finally, once a performer has selected a piece and part, they can now switch seamlessly between score and part layouts. This lets players quickly see how their part corresponds to other members of the ensemble and leaves to personal preference the choice of which layout to perform from. The version of the score viewer described is the culmination of my research in this area and is discussed in greater detail in Section 3.1.

[82]https://www.steinberg.net/dorico/ (visited on 18/02/2022)

2.8 INTERLUDE: THE SUBLIME IN MINIATURE

> TO AND FRO in shadow from inner to outershadow
> from impenetrable self to impenetrable unself
> by way of neither[83]

When considering the music that I connect with most deeply, whether it be by composers such as Morton Feldman and Iannis Xenakis, or improvisors such as John Coltrane and Keith Jarrett, there is a common thread that unites my listening experience: the music exists on the threshold of my comprehension. For the most part, music that I can comprehend in its entirety does not resonate with me as fully and can quickly becomes dull. Likewise, music that is too far beyond my comprehension fails to engage. These categories are not fixed as the threshold itself shifts with time and increased familiarity. While this may seem to imply an insatiable hunger for the new, it is the music that continues to hover in this liminal region after many repeated listens that is, to me, the most special.

In philosophical terms, the experience that I seek closely resembles that of the sublime. Immanuel Kant's early formulations of the sublime divide it into two categories, both of which overwhelm the human subject in some way. These are the mathematical, which does so with great magnitude, and the dynamical, which does so with great force. It is the mathematical sublime that I am most drawn to. Philip Shaw writes:

[83]Samuel Beckett. 'neither'. In: *The Complete Short Prose, 1929-1989*. Grove Press, 1976, p. 258.

> In the mathematical sublime, the imagination is overwhelmed by a spatial or temporal magnitude that is great beyond all comparison; the experience is too great for the imagination to 'take it all in' at once.[84]

For Kant, the beautiful is bounded whereas the sublime is boundless. The feeling of the sublime, however, arises from our ability to comprehend this boundlessness. This feeling, as Mark A. Cheetham writes, 'relies upon the perfect harmony of "apprehension" and "comprehension", which in turn depends upon the correct physical placement of the human observer.'[85] It is this placement (or threshold), this framing alluded to by Kant, that was to form the basis of Jacques Derrida's reading of the sublime. The frame, or *parergon* in Derrida's terminology, can contain the beautiful but cannot contain the sublime. The sublime is neither inside nor outside the frame, but instead exists in its interaction with it, an interaction unique to each observer. Cheetham writes:

> The experience and pleasure of the sublime do not stem from the promise of something noumenal outside a given frame but rather from the perpetual, yet always provisional, activity of framing itself, from the parergon.[86]

In this postmodern interpretation, the sublime is revealed to be paradoxical, as elucidated in Derrida's statement, 'The inadequation of presentation

[84]Philip Shaw. *The Sublime*. Routledge, 2017, p. 103.
[85]Mark A. Cheetham. *Kant, Art, and Art History*. Cambridge University Press, 2001, p. 116.
[86]Cheetham, *Kant, Art, and Art History*, p. 107.

is presented.'[87] I understand this to mean that in moments of sublime experience we can comprehend our very inability to comprehend. In this light, it seems possible to free the sublime of some of its historical baggage, particularly its links to Romanticism and a distinctly masculine mode of thinking. To me, it also seems possible to free it of the grandeur with which it has previously been associated, and to do so by responding to a question posed by Derrida: 'why is the sublime large and not small?'[88]

I believe that the sublime can be small and that notions of scale are always relative. Just as science has demonstrated the vastness of the known universe, it has also revealed the microscopic world of quantum mechanics. Between these extremes, any given point may determine a conceptual frame. In music, restricting the range of a parameter, such as pitch or dynamic, alters this frame of reference. My work with rhythm and tempo has highlighted that the path to infinity can be travelled in both directions. Small durational units may be added together or larger units may be divided. Though these methods may seem analogous, the cumulative division arising from combined fractional tempi often leads to an extremely fine-grained rhythmic grid. In these cases the common additive unit becomes imperceptibly small. These combined tempi may serve to challenge the listener's comprehension, overwhelming their ability to 'take it all in', and it is significant in this regard that I often mask convergence points and end pieces in advance of moments of arrival. The only perceptual frame that I can be sure of, however, is my

[87] Jacques Derrida. *The Truth in Painting*. Trans. by Geoff Bennington and Ian McLeod. University of Chicago Press, 1987, p. 131.

[88] Derrida, *The Truth in Painting*, p. 136.

own. The sublime that I am seeking is therefore a subjective and deeply personal one; a low-key and understated sublime; the sublime in miniature.

3 THE TECHNOLOGY

3.1 SCORE VIEWER

3.1.1 INTRODUCTION

The score viewer is a web application that runs on a local network. A macOS, Windows or Linux computer acts as the host and any device on the same network can then access the app by entering the correct URL. For performance purposes, a dedicated WiFi network should be used. Once scores are loaded, network traffic is kept to a minimum and the only data transferred are transport commands (start, stop and snap) and a periodic synchronisation algorithm. This contrasts with the approach used by existing software such as *INScore*[89] and *Drawsocket*,[90] where each event is sent in real-time over the network, and avoids potential issues with network latency and outages. As a result, the system is very robust in performance and the players can continue uninterrupted even if connectivity is lost. Visual and auditory cues are scheduled locally on each device and it is therefore possible to achieve accurate timing and a consistent frame rate. These architectural decisions were dictated by the primary purpose of the application: aiding the performance of fixed polytemporal scores. There are therefore different trade-offs in comparison with existing score-reading applications, which typically priorit-

[89]Fober et al., 'Distributing Music Scores to Mobile Platforms and to the Internet using INScore'.

[90]Gottfried and Hajdu, 'Drawsocket: A Browser Based System for Networked Score Display'.

ise real-time generation of material (*INScore* and *Drawsocket*) or graphical forms of musical notation (*Decibel ScorePlayer*).[91] The score viewer is equally well suited to rehearsal and performance and puts the performers firmly in charge; each member of the ensemble has equal control and can personalise their settings. Much effort has been made to ensure that the application is easy to use, with a clear and intuitive user interface.

3.1.2 LAYOUT AND FUNCTIONALITY

A video demonstrating the score viewer accompanies this section.

The application layout adapts to different screen sizes but is optimised for tablets in landscape orientation. The home screen is shown in Figure 24 and lists the available scores. Selecting a score takes the user to the part selection screen shown in Figure 25. As well as displaying the available parts, this adds a home button and the name of the selected score to the header. Selecting a part takes the user to the main score screen shown in Figure 26. The name of the selected part as well as a number of additional items are now added to the header. The *start/stop* button starts and stops the performance while the *snap* button can be used when navigating the score to move everyone to the same position. A dropdown menu is used to switch between the available layouts, which typically include a full score and a part. To the right, the synchronisation and connection status are displayed. If the green circle changes to red then it indicates that the connection to the server has been lost. It can then be tapped to reconnect. Finally, there is a cog icon

[91] Hope et al., 'The DECIBEL Scoreplayer - A Digital Tool for Reading Graphic Notation'.

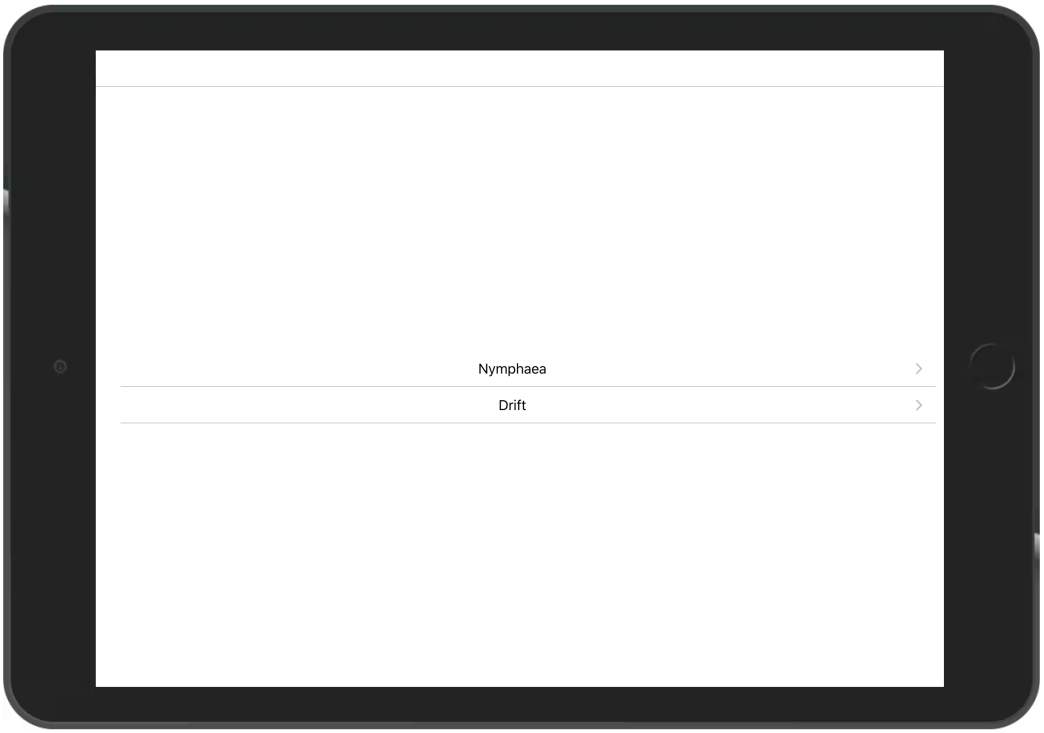

Figure 24: Score viewer home screen

that opens the settings drawer.

The main area of the screen is occupied by two systems of score. The player always reads from the top system and the bottom system is used to look ahead. The current beat is highlighted by a transparent yellow box and there is a gap above the score where the visual metronome appears. During performance, beat and system changes are automated, but otherwise the user can interact with the score using touch. Swipe gestures can be used to navigate, while tapping a beat moves to the selected position. The footer contains a slider, which also displays and sets the current position.

Figure 27 shows the settings drawer. The base tempo can be adjusted using a slider and affects all players for the given piece. This is very useful for

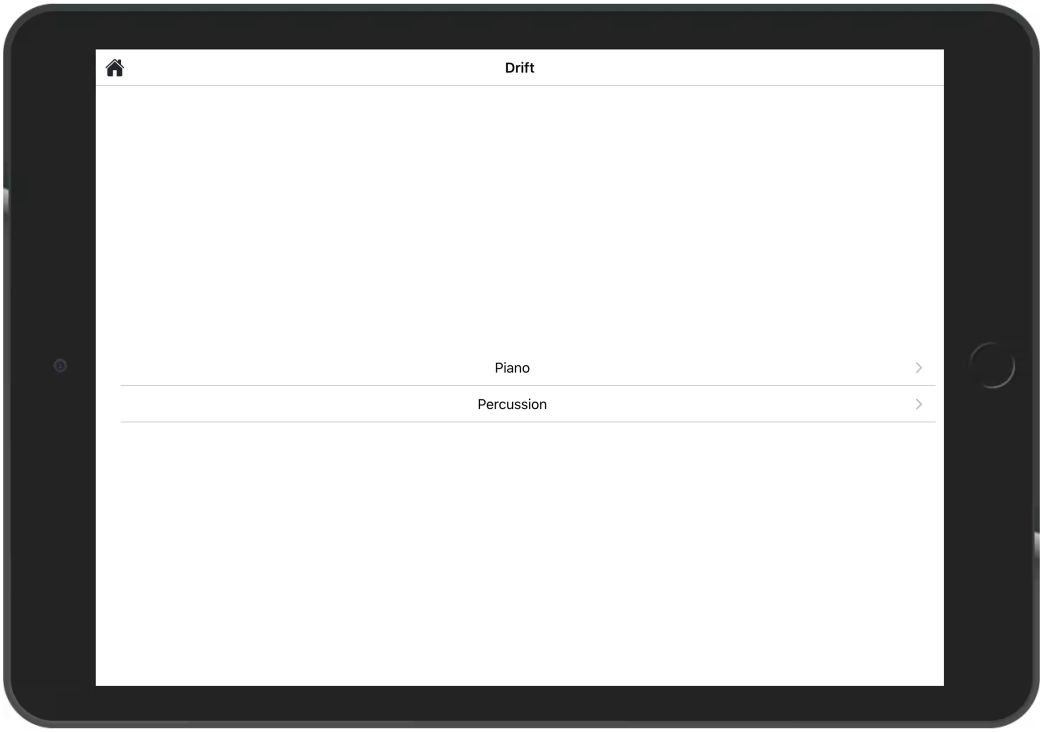

Figure 25: Score viewer part selection screen

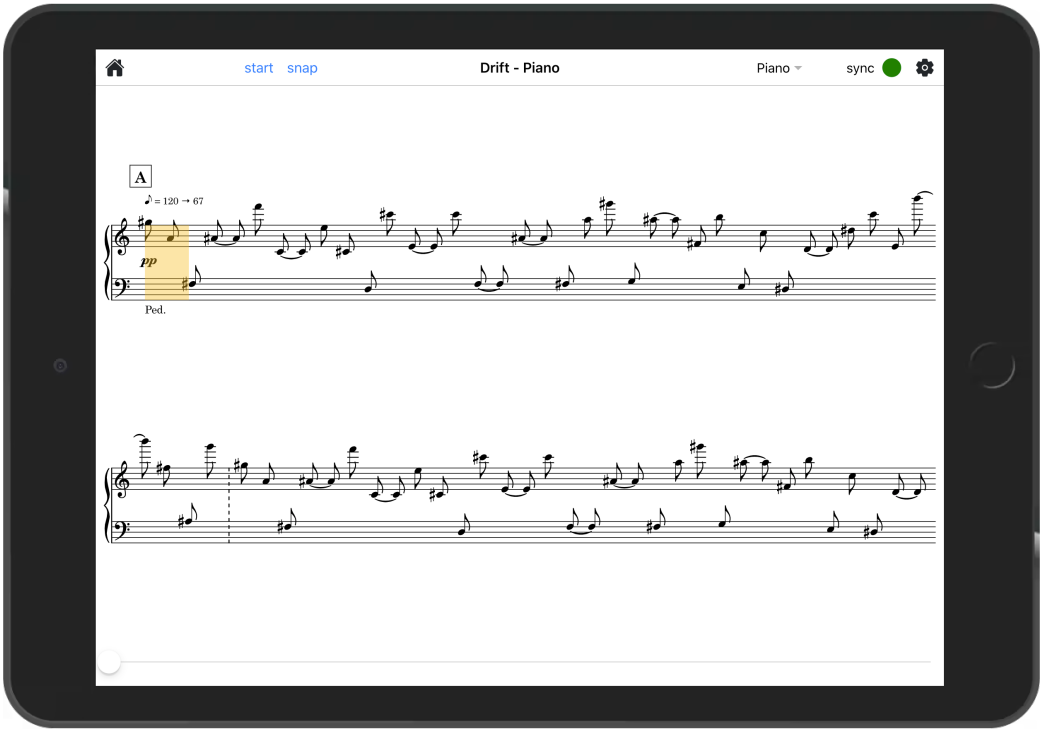

Figure 26: Score viewer score screen

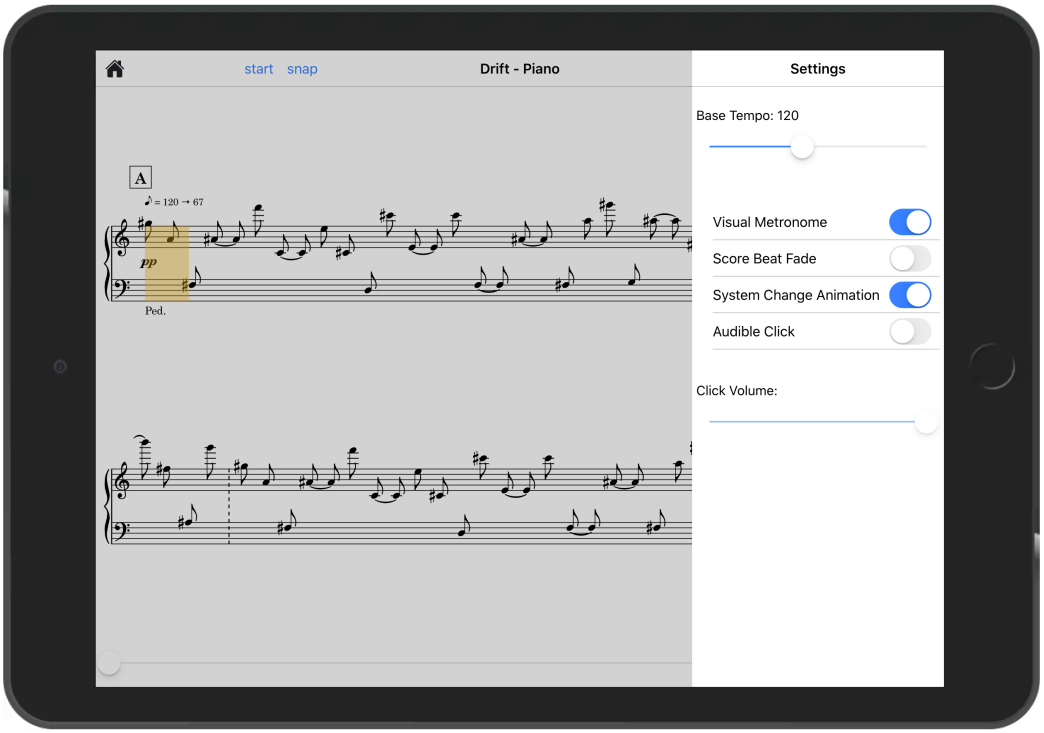

Figure 27: Score viewer settings drawer

adapting the overall speed during rehearsals. The other controls apply only to the current player and enable the functionality to be altered in line with their preferences. These determine if the visual metronome is enabled; if the transparent box fades over the duration of each beat; if the system changes are animated; and if there is an audible click. All of these options have proved useful and have been developed in response to performer feedback.

3.1.3 CLIENT ARCHITECTURE

A number of factors led to me choosing to build a web application rather than a native iOS or Android app. Primarily, I wished to be able to distribute new versions instantly, without waiting for app store approval, and for users to

be able to access the app without installing anything on their devices. Web technologies have reached a high level of performance and sophistication in recent years and a robust system of backwards compatibility guarantees a high degree of longevity that is otherwise often absent in independent software projects. On tablet devices, the user can choose to add the application to their home screen and it will then appear alongside native apps and open in a fullscreen window.

The user interface is built using *React*,[92] an open-source JavaScript library that was originally developed by Facebook. *React* makes it possible to build an application by combining small, encapsulated components and declaring how they respond to changes in state. It is well suited to musical scores where the state is changing over time and in response to events. The core application logic is implemented using *XState*,[93] an open-source JavaScript library for state machines and statecharts. While earlier versions used *Redux*,[94] I have found that using statecharts to model the behaviour and explicitly define all the possible states has resulted in a more reliable and predictable application. Decoupling the core timing logic from the user interface layer also allows it to be reused in different environments. In *Eluvium*, for example, this meant that I could use the same code as the foundation for an electronic score, running in *Node.js*,[95] that sent commands to *SuperCollider*.[96] All of my code is written in TypeScript, a superset of JavaScript

[92]https://reactjs.org/ (visited on 18/02/2022)
[93]https://xstate.js.org/ (visited on 18/02/2022)
[94]https://redux.js.org/ (visited on 18/02/2022)
[95]https://nodejs.org/ (visited on 18/02/2022)
[96]https://supercollider.github.io/ (visited on 18/02/2022)

that adds static type checking.

3.1.4 SERVER ARCHITECTURE

The score viewer is hosted by a web server that is launched on the host computer. This runs in *Node.js* and is packaged as a single executable file. It displays a URL that can be entered in any web browser on the same WiFi network to access the app. The score images and data are served using HTTP while the bidirectional communication uses WebSockets. The WebSocket server is responsible for relaying transport commands to all connected clients and synchronising each client to a master clock. This clock synchronisation is done using the open-source *@ircam/sync*[97] JavaScript library, which periodically compares the client clock to the server clock and compensates for any drift.[98] In practice, this means that all connected clients can share a common clock to synchronise events. When a performer presses *play*, this command is relayed to all clients along with a start time in the future, ensuring that all the devices start together.

3.1.5 SCORE DATA

The process of creating the required data for the score viewer is where much of the complexity resides. The score is exported from *Dorico*[99] as a number of image files (one for each layout) that are accompanied by JSON files

[97]https://github.com/ircam-ismm/sync/ (visited on 18/02/2022)

[98]Jean-Philippe Lambert, Sébastien Robaszkiewicz and Norbert Schnell. 'Synchronisation for Distributed Audio Rendering over Heterogeneous Devices, in HTML5'. In: *2nd Web Audio Conference*. 2016.

[99]https://www.steinberg.net/dorico/ (visited on 18/02/2022)

containing graphical metadata. This metadata describes the positioning of the systems as well as the horizontal positioning and timing of the musical events. As *Dorico* does not natively support polytempo, this data does not convey the relationship between the timing of events and tempi. However, as the musical content of the scores is created using the composition environment, the additional timing data can be exported directly. I have developed a JSON format for encoding this score timing data and the schema is included in Appendix B. This format makes it straightforward to change the beat groupings at any point in the score, in line with performer preference. As an example, a performer may prefer a crotchet pulse to be reduced to minims above a certain tempo. A script takes the images, graphical metadata and score timing data as input and, for each piece, outputs SVG image files, a JSON timing data file unique to each player, and a JSON layout data file unique to each player and layout. These are the files that are loaded by the score viewer when the user navigates to a score. The separation of timing and layout data avoids duplication and ensures that layouts can be switched seamlessly.

3.1.6 FUTURE DIRECTIONS

The score viewer has proved itself to be a practical and effective aid in performing my music. Rehearsal and performance scenarios have been considered on an equal footing and the performer experience has been carefully factored into the design. At present, it is only possible to export compatible scores from *Dorico* and this relies on features of the software that are not currently publicly available. In future, these features could also potentially

be implemented in open-source notation software, such as *LilyPond*.[100] The JSON format that I have developed to encode score timing data is deliberately decoupled from the composition environment so that other tools could utilise it in the future.

There are several features that could be added to further enhance the score viewer that are beyond the scope of this research. The most useful to performers would be the ability to annotate scores. A current workaround is that the images can be annotated in a separate application and then imported. Additionally, it would be useful to be able to alter the beat groupings from within the app. At present, this can only be achieved by manually editing the score timing JSON and then regenerating the data. Developing methods to make these changes interactively would be a significant but worthwhile undertaking. Finally, it would be beneficial to develop a graphical user interface for the host application. The current format has the advantage that it can be run on a device without a screen and launched remotely, including on inexpensive computers such as the *Raspberry Pi*.[101] A GUI would, however, make the application more user friendly and could provide additional features, such as configuration for communicating with other software via MIDI and OSC.

[100] http://lilypond.org/ (visited on 18/02/2022)
[101] https://www.raspberrypi.org/ (visited on 18/02/2022)

3.2 COMPOSITION ENVIRONMENT

3.2.1 INTRODUCTION

While computer-aided composition environments, such as *OpenMusic*,[102] have existed for many years, my particular requirements demanded a fresh approach. The composition environment comprises a JavaScript library and an extension for the *Visual Studio Code*[103] editor. The library can be used standalone or in combination with the extension. It exports the primitives that the composer uses to construct a score, as well as methods for transforming material and exporting to other formats. The extension takes the generated score and renders it to musical notation in a web browser window. It also integrates the export methods into the editor. The notation window can be easily updated when changes are made and provides playback functionality, including MIDI output. The available export formats are MusicXML,[104] MEI[105] and the score timing JSON used to generate data for the score viewer.

3.2.2 FRAGMENTS

The fundamental building block for creating scores in the composition environment is the *fragment*. As they are used so frequently, fragments are created with an underscore. They use a feature of modern JavaScript, known as *tagged template literals*, which parses a template literal with a function. Tem-

[102]https://openmusic-project.github.io/ (visited on 18/02/2022)
[103]https://code.visualstudio.com/ (visited on 18/02/2022)
[104]https://www.musicxml.com/ (visited on 18/02/2022)
[105]https://music-encoding.org/ (visited on 18/02/2022)

plate literals are strings that may contain embedded expressions, meaning that fragments can be authored in a familiar text format while also containing other fragments. This becomes a very powerful pattern for composing larger fragments out of smaller ones. The text format used is a stripped down subset of the *LilyPond*[106] input format, a popular and easy to learn syntax for encoding musical data. Letters are used for notes and rests, with chords enclosed in angle brackets; numbers and dots are used for durations; and the tilde symbol is used for ties. Notes are automatically placed in the closest octave to the previous note and the octave can be lowered by appending an apostrophe or highered by appending a comma. Fragments may contain multiple layers, separated by two backslashes, and multiple staves, separated by two forward slashes. To demonstrate the format, Figure 28 includes three fragments: *voice1* encodes the first two bars of *Row, Row, Row Your Boat*; *voice2* embeds *voice1* within another fragment after a semibreve rest; *combinedVoices* takes the two previous fragments and places them on separate staves. To continue notating this two part canon, only *voice1* would need to be updated.

The *Fragment* class that is returned by the tagged template literal has a number of methods for transforming fragments. These include *tempo* and *accel* methods for applying immediate or gradual tempo changes and a generic *pipe* method that can be used to transform the fragment's contents. This *pipe* method accepts one or more callback functions that are called sequentially. Each is called for every layer within the fragment and passed the layer and its

[106]http://lilypond.org/ (visited on 18/02/2022)

```
voice1 = _`
  c4 c c8. d16 e4
  e8. d16 e8. f16 g2
`

voice2 = _`
  r1 ${voice1}
`

combinedVoices = _`
  ${voice1} // ${voice2}
`
```

Figure 28: Composition environment fragment example

index as arguments. The layer in turn exposes its own *pipe* method, which can be used to transform the individual events. These *pipe* methods offer a great deal of flexibility to users in the way that they transform material. Transformations can be encapsulated in simple functions that are then combined to create more complex behaviours. For convenience, *transpose* and *invert* methods are also included, which both use the *pipe* method internally. Fragments and layers are immutable, with their methods always returning new instances. This ensures that existing fragments within the score remain unaffected.

The ability to compose fragments by embedding them inside each other, to stretch fragments in time with immediate or gradual tempo changes, and to transform fragments by piping their contents through user defined functions all contribute to the malleability at the heart of the composition environment. This powerful primitive has been carefully designed to combine simplicity and expressiveness and to aid rather than inhibit the compositional process.

3.2.3 LAYERS

When fragments are created, the musical layers within are automatically generated from the text input. By importing the *Layer* class directly, however, it is also possible to construct layers programmatically. In this case, the layer is created from an array of objects representing musical events. This facilitates more advanced use cases, such as generating material algorithmically. The user can use the JavaScript programming language in any way they choose to construct sequences of events and these will then be converted into the correct data structures. These layers can then be included within fragments, just as other fragments can. This is the method that I used in *Drift* to gradually accumulate fragments from the constitutive properties of musical events. It provides an alternative approach for particular scenarios that do not lend themselves well to text input. As both methods can be combined within the same score, the user is not limited to one way of working.

3.2.4 PARTS AND SCORES

Part and *Score* are the remaining primitives used to construct a score. *Part* simply takes a fragment (or an array of fragments) and a part name. *Score* takes an array of parts and an object containing additional properties of the score. At present, this consists of the base tempo, which comprises a beat unit and BPM. It is the returned *Score* instance that exposes the *output* method for exporting score data. The available export formats are MusicXML, MEI, event data and score timing data. MusicXML is the standard interchange

format used by notation software such as *Dorico*,[107] *Sibelius*[108] and *Finale*,[109] and is what I use to import the score in *Dorico* for engraving and further refinement. MEI is used to load the score in *Verovio*,[110] the software that renders score graphics in the *Visual Studio Code* extension. The event data is used by the extension for playback. Finally, the score timing data is used to produce the data for the score viewer. It is the ability to export scores in these various formats that has enabled me to integrate the composition environment with new and existing applications. This means that I can still use the advanced engraving features provided by *Dorico*, while filling the gaps that exist in its functionality for my own compositional work. The MusicXML export is particularly complex because it automatically calculates and generates the hidden tuplets necessary to mimic polytempo. The values used in the tuplet ratios can be very large and would be extremely challenging to calculate by hand. The software keeps this complexity hidden from the user, enabling them to work directly with divergent concurrent tempi while composing, before continuing to work on the same score in software that does not support these features natively.

3.2.5 VISUAL STUDIO CODE EXTENSION

Visual Studio Code is a popular open-source code editor developed by Microsoft. It runs on macOS, Windows and Linux and exposes a flexible Extension API. As the composition environment uses JavaScript, *Visual Studio*

[107]https://www.steinberg.net/dorico/ (visited on 18/02/2022)
[108]https://www.avid.com/sibelius/ (visited on 18/02/2022)
[109]https://www.finalemusic.com/ (visited on 18/02/2022)
[110]https://www.verovio.org/ (visited on 18/02/2022)

Code provides many useful features by default. These include syntax highlighting and code completion. The extension is written in TypeScript, the same language that I used to write the library. It adds two commands to the editor: one to render the score in a web browser window and one to export the score to a file. Both can be invoked from the command palette or with a keyboard shortcut. The extension additionally exposes a *View* function to the edit window, which is used to access the score instance. Upon calling the render command, the extension first evaluates the code in the editor window and verifies that a score has been returned by the *View* function. If it is being called for the first time, a web server is started to host the rendered score and a WebSocket connection is established to update the score on future renders. Additionally, a browser window is opened to view the score. Next, the extension will call the MEI and event data export methods on the score instance and convert the resulting MEI data to an SVG image using *Verovio*. This SVG is then sent with the event data to the browser window, which presents the score as a single scrollable system. A slider is used to navigate and the current events are highlighted. The user can select a MIDI output device, which will then receive MIDI data during playback. Screenshots of the editor and notation windows (using the example from Figure 28) are shown in Figures 29 and 30. In my personal setup, I use the macOS *IAC Driver* to route MIDI internally to *Reaper*.[111] This enables me to use any available software instrument plugins.

[111] https://www.reaper.fm/

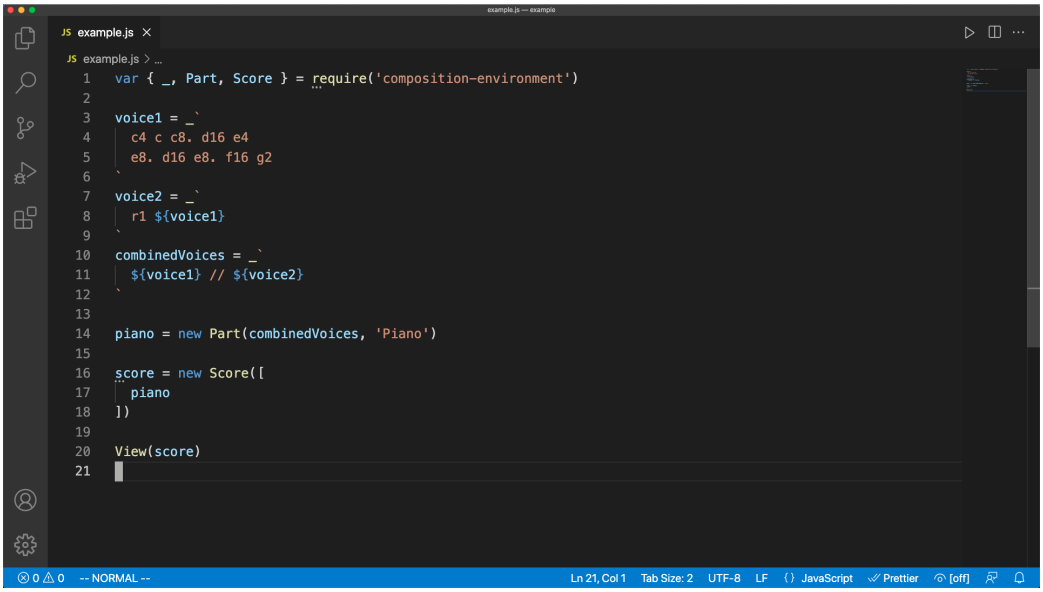

Figure 29: Composition environment editor window

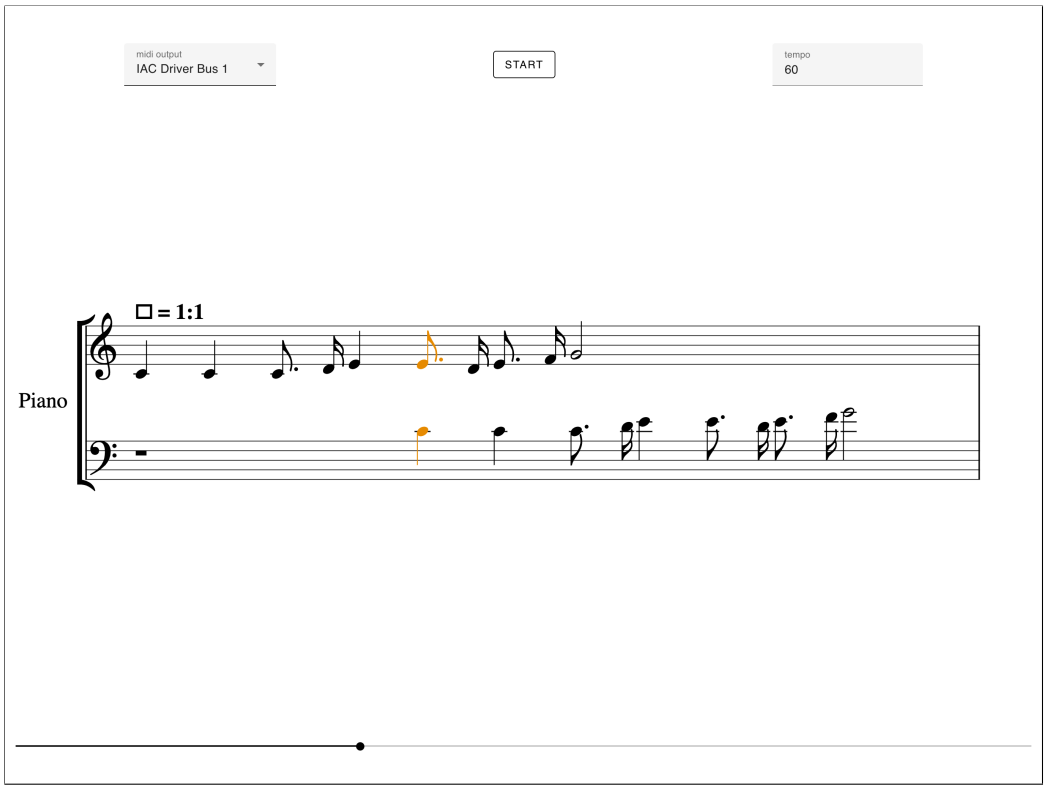

Figure 30: Composition environment notation window

3.2.6 FUTURE DIRECTIONS

The composition environment was essential to composing many of the included works. It provides a flexible environment for compositional experimentation while also bridging the gap between existing notation software and my own score viewer. So far, it has primarily been developed to meet my own needs, with a particular focus on polytempo, and there are a number of ways that I would wish to develop it further to make it more useful to others. These include adding the ability to encode barlines, dynamics and articulations, which at present can only be added after export. Careful consideration would be needed to ensure that any new features do not undermine the fundamental malleability of material that is the guiding principle of the application.

4 CONCLUSION

This research has produced a range of compositional works and two new technological outputs. These comprise a score viewer and a composition environment. The combination of compositional experimentation, technological development and interaction with performers has resulted in a rich interpenetration of ideas. While I have primarily explored the role that technology can play in the performance and composition of polytemporal music, the commentary has also touched on broader aspects of my compositional outlook and creative aesthetic.

With the development of the score viewer, I have been able to successfully realise and extend Nancarrow's vision of a technologically assisted approach to polytemporal performance. In doing so I have created an application that is straightforward to use and well suited to both rehearsal and performance. As already noted, there are a number of ways that the score viewer could be further improved. These include support for annotation and greater interoperability with existing notation software. There are also, however, further avenues for research that I would be excited to explore. One example is the possibility of spatialised performances. As the visual metronome assists with ensemble synchronisation, the musicians do not need to orient themselves towards a conductor and could instead adopt a range of configurations. One can imagine a larger ensemble situating themselves around the audience or spread across multiple areas of a performance space. I am also keen to explore means by which performers can interact with the score viewer to control and influence aspects of the performance. These interactions could take the

form of real-time cueing or decision making and have the potential to unlock a uniquely fluid approach to performance. I am particularly excited by the possibility that, through direct engagement with the score, decisions made by one performer could alter those available to others. In utilising this idea of networked indeterminacy, the interaction between composer, performer and technology would become deeply embedded in the act of performance.

The composition environment was born out of the necessity to create an application for polytemporal composition that would fill the gaps in existing notation software. In building an application of this kind, I was able to create a tool that is uniquely suited to my own compositional requirements. This provoked a thorough engagement with the principles underpinning my compositional approach, including economy and malleability of material and the use of canon and divergent tempi. Fundamentally, the composition environment became a medium for the structuring and rearrangement of ideas and enhanced the role of feedback in the compositional process. I will continue to use and engage with the software and hope to further expand its feature set. I would like for it to eventually become an open-source endeavour that is used more widely.

In addition to the technological outputs discussed, this commentary has charted my changing compositional outlook over a number of years. The intense focus and self-reflection of PhD research has naturally led to me questioning and reevaluating aspects of my work. This is perhaps most evident in the discussion of freedom and control. In particular, I have begun to place greater value on the more elusive and intangible aspects of artistic work. Throughout this research I have deliberately focused on a limited range of

compositional techniques. Going forward, I would like these to be constituent parts of a broader and more varied compositional approach. I hope to write works for larger ensembles in which a range of approaches coexist and in which technology continues to play an integral role.

REFERENCES

Beckett, Samuel. 'neither'. In: *The Complete Short Prose, 1929-1989*. Grove Press, 1976.

Carapezza, Paolo Emilio. 'Aldo Clementi musicus mathematicus'. In: *Interdisciplinary Studies in Musicology* 12 (2012).

Cheetham, Mark A. *Kant, Art, and Art History*. Cambridge University Press, 2001.

Clark, Andy. *Supersizing the Mind: Embodiment, Action and Cognitive Extension*. Oxford University Press, 2011.

Clark, Andy and David J. Chalmers. 'The Extended Mind'. In: *The Extended Mind*. MIT Press, 2010.

Cowell, Henry. *New Musical Resources*. Cambridge University Press, 1996.

Derrida, Jacques. *The Truth in Painting*. Trans. by Geoff Bennington and Ian McLeod. University of Chicago Press, 1987.

Ehrenzweig, Anton. *The Hidden Order of Art*. University of California Press, 1967.

Exarchos, Dimitrios. 'Iannis Xenakis and Sieve Theory: An Analysis of the Late Music (1984-1993)'. PhD thesis. Goldsmiths College, University of London, 2007.

Feldman, Morton. 'Darmstadt Lecture, July 1984'. In: *Morton Feldman Says: Selected Interviews and Lectures 1964-1987*. Hyphen Press, 1984.

— 'Give My Regards to Eighth Street'. In: *Give My Regards to Eighth Street*. Exact Change, 1971.

Feldman, Morton. 'H.C.E. (Here Comes Everybody): Morton Feldman in converstion with Peter Gena, January 1982'. In: *Morton Feldman Says: Selected Interviews and Lectures 1964-1987*. Hyphen Press, 1982.

— 'Liner Notes'. In: *Give My Regards to Eighth Street*. Exact Change, 1962.

— 'The Anxiety of Art'. In: *Give My Regards to Eighth Street*. Exact Change, 1965.

Fober, Dominique et al. 'Distributing Music Scores to Mobile Platforms and to the Internet using INScore'. In: *12th Sound and Music Computing Conference (SMC15)*. 2015, pp. 229–233.

Fox, Christopher. 'Why Experimental? Why Me?' In: *The Ashgate Research Companion to Experimental Music*. Ashgate, 2009.

Gann, Kyle. *The Music of Conlon Nancarrow*. Cambridge University Press, 1995.

Gottfried, Rama and Georg Hajdu. 'Drawsocket: A Browser Based System for Networked Score Display'. In: *Proceedings of the International Conference on Technologies for Music Notation and Representation – TENOR'19*. 2019, pp. 15–25.

Gottschalk, Jennie. *Experimental Music Since 1970*. Bloomsbury Academic, 2016.

Hanninen, Dora A. 'A Theory of Recontextualization in Music: Analyzing Phenomenal Transformations of Repetition'. In: *Music Theory Spectrum* 25.1 (2003).

Hope, Cat et al. 'The DECIBEL Scoreplayer - A Digital Tool for Reading Graphic Notation'. In: *Proceedings of the First International Conference*

on Technologies for Music Notation and Representation – TENOR'15. 2015, pp. 58–69.

Jeppesen, Knud. *Counterpoint: The Polyphonic Vocal Style of the Sixteenth Century*. Dover, 1992.

Kramer, Jonathan D. *The Time of Music*. Schirmer Books, 1988.

Lambert, Jean-Philippe, Sébastien Robaszkiewicz and Norbert Schnell. 'Synchronisation for Distributed Audio Rendering over Heterogeneous Devices, in HTML5'. In: *2nd Web Audio Conference*. 2016.

Lucier, Alvin. *Music 109*. Wesleyan University Press, 2012.

Magnusson, Thor. *Sonic Writing*. Bloomsbury Academic, 2019.

Menary, Richard. 'Introduction: The Extended Mind in Focus'. In: *The Extended Mind*. MIT Press, 2010.

Messiaen, Olivier. *The Technique of my Musical Language*. Alphonse Leduc, 1944.

Nyman, Michael. *Experimental Music: Cage and Beyond*. Cambridge University Press, 1974.

Opstad, James. 'Portfolio of Compositions'. MA thesis. University of Birmingham, 2017.

Perkins, Leeman L. *Ockeghem [Okeghem, Hocquegam, Okegus etc.], Jean de*. 2001. URL: https://www.oxfordmusiconline.com/grovemusic/view/10.1093/gmo/9781561592630.001.0001/omo-9781561592630-e-0000020248 (visited on 18/02/2022).

Rovelli, Carlo. *Reality Is Not What It Seems*. Penguin Books, 2017.

— *The Order of Time*. Penguin Books, 2019.

Schiff, David. *The Music of Elliott Carter*. Faber and Faber, 1998.

Shaw, Philip. *The Sublime*. Routledge, 2017.

Solomon, Samuel Z. *How to Write for Percussion: A Comprehensive Guide to Percussion Composition*. Oxford University Press, 2016.

Spiegel, Laurie. 'Thoughts on Composing with Algorithms'. In: *The Oxford Handbook of Algorithmic Music*. Oxford University Press, 2018.

Stiegler, Bernard. 'Memory'. In: *Critical Terms for Media Studies*. The University of Chicago Press, 2010.

— *Technics and Time, 1: The Fault of Epimetheus*. Stanford University Press, 1998.

Stockhausen, Karlheinz. '... How Time Passes ...' In: *Die Reihe* 3 (1959).

Varga, Bálint András. *Conversations with Iannis Xenakis*. Faber and Faber, 1996.

Zaccagnini, Michele. 'Aldo Clementi's System'. PhD thesis. Brandeis University, 2014.

Appendices

A ACCELERATION/DECELERATION CONVERGENCE EQUATIONS

A.1 USING TEMPI

x = number of acceleration/deceleration beats

y = number of static tempo beats

a = start tempo; b = end tempo; c = reference tempo

To find x:

$x = \frac{2aby+ac-bc}{ac+bc}$

To find y:

$y = \frac{acx+bcx+bc-ac}{2ab}$

A.2 USING DURATIONS

x = number of acceleration/deceleration beats

y = number of static duration beats

a = start duration; b = end duration; c = reference duration

To find x:

$x = \frac{2cy-a+b}{a+b}$

To find y:

$y = \frac{ax+bx+a-b}{2c}$

B SCORE TIMING DATA FORMAT (JSON SCHEMA)

```
{
  "$schema": "http://json-schema.org/draft-07/schema",
  "title": "Score Timing Data",
  "description": "Score timing data.",
  "type": "object",
  "properties": {
    "baseTempo": {
      "$ref": "#/definitions/baseTempo"
    },
    "endPosition": {
      "title": "End Position",
      "description": "The end position of the score. This is the
↪ duration from the start of the score and is expressed as a fraction or
↪ integer multiplier of a whole note at the base tempo.",
      "$ref": "#/definitions/integerOrFraction"
    },
    "meterParts": {
      "title": "Meter Parts",
      "description": "An array of parts containing independent meters.",
      "type": "array",
      "items": {
        "title": "Meters",
        "description": "An array of meters.",
        "type": "array",
        "items": {
```

```
          "$ref": "#/definitions/meter"
        },
        "minItems": 1
      },
      "minItems": 1
    },
    "tempoParts": {
      "title": "Tempo Parts",
      "description": "An array of parts containing independent tempi.",
      "type": "array",
      "items": {
        "title": "tempi",
        "description": "An array of tempi.",
        "type": "array",
        "items": {
          "$ref": "#/definitions/tempo"
        },
        "minItems": 1
      },
      "minItems": 1
    },
    "players": {
      "title": "Players",
      "description": "An object mapping players to meter and tempo
↪  parts.",
      "type": "object",
      "patternProperties": {
        "^.*$": {
          "$ref": "#/definitions/player"
        }
```

```
      },
      "minProperties": 1
    }
  },
  "required": [
    "baseTempo",
    "endPosition",
    "meterParts",
    "tempoParts",
    "players"
  ],
  "definitions": {
    "baseTempo": {
      "title": "Base Tempo",
      "description": "The global base tempo. All other tempi are
↪ expressed as fractions of this value.",
      "type": "object",
      "properties": {
        "beatUnit": {
          "title": "Beat Unit",
          "description": "The beat unit of the base tempo. Expressed as
↪ a fraction or integer multiplier of a whole note.",
          "$ref": "#/definitions/integerOrFraction",
          "default": "1/4"
        },
        "bpm": {
          "title": "BPM",
          "description": "The number of beats per minute at the base
↪ tempo.",
          "type": "number",
```

```
          "exclusiveMinimum": 0,
          "default": 120
        }
      },
      "required": ["beatUnit", "bpm"],
      "additionalProperties": false
    },
    "meter": {
      "title": "Meter Object",
      "description": "A meter object containing properties of the
↪ meter.",
      "type": "object",
      "properties": {
        "meter": {
          "title": "Meter",
          "description": "The meter (time signature). Expressed as a
↪ fraction, as 'open' or as 'pickup'.",
          "oneOf": [
            {
              "$ref": "#/definitions/fraction"
            },
            {
              "type": "string",
              "enum": ["open", "pickup"]
            }
          ],
          "default": "4/4"
        },
        "startPosition": {
          "title": "Start Position",
```

```
            "description": "The start position of the meter. This is the
↪  duration from the start of the score and is expressed as a fraction or
↪  integer multiplier of a whole note at the base tempo.",
            "$ref": "#/definitions/integerOrFraction"
          },
          "endPosition": {
            "title": "End Position",
            "description": "The end position of the meter. This is the
↪  duration from the start of the score and is expressed as a fraction or
↪  integer multiplier of a whole note at the base tempo.",
            "$ref": "#/definitions/integerOrFraction"
          },
          "beatPattern": {
            "title": "Beat Pattern",
            "description": "An optional array containing the beat
↪  durations. Each entry is expressed as a fraction of a whole note at
↪  the current tempo. If the total pattern duration is shorter than the
↪  section duration, the pattern is repeated until they are equal. If
↪  omitted, the beat unit of the meter is used.",
            "type": "array",
            "items": {
              "title": "Beat Duration",
              "description": "A beat duration. Expressed as a fraction or
↪  integer multiplier of a whole note at the current tempo.",
              "$ref": "#/definitions/integerOrFraction"
            }
          },
          "countIn": {
            "title": "Count-in",
            "description": "An optional count-in.",
```

```
            "type": "object",
            "properties": {
              "duration": {
                "title": "Count-in Duration",
                "description": "The duration of the count-in. Expressed as
↪  a fraction or integer multiplier of a whole note at the incoming
↪  tempo.",
                "$ref": "#/definitions/integerOrFraction"
              },
              "beatPattern": {
                "title": "Count-in Beat Pattern",
                "description": "An optional array containing the beat
↪  durations within the count-in. Each entry is expressed as a fraction
↪  of a whole note at the incoming tempo. If the total pattern duration
↪  is shorter than the count-in duration, the pattern is repeated until
↪  they are equal. If omitted, the beat pattern of the incoming meter is
↪  used.",
                "type": "array",
                "items": {
                  "title": "Beat Duration",
                  "description": "A beat duration. Expressed as a fraction
↪  or integer multiplier of a whole note at the incoming tempo.",
                  "$ref": "#/definitions/integerOrFraction"
                }
              }
            },
            "required": ["duration"],
            "additionalProperties": false
          }
        },
```

```
      "required": ["meter", "startPosition", "endPosition"],
      "additionalProperties": false
    },
    "tempo": {
      "title": "Tempo Object",
      "description": "A tempo object containing properties of the
↪ tempo.",
      "type": "object",
      "properties": {
        "tempo": {
          "title": "Tempo",
          "description": "The tempo. Expressed as a fraction or integer
↪ multiplier of the base tempo.",
          "$ref": "#/definitions/integerOrFraction",
          "default": "1/1"
        },
        "startPosition": {
          "title": "Start Position",
          "description": "The start position of the tempo. This is the
↪ duration from the start of the score and is expressed as a fraction or
↪ integer multiplier of a whole note at the base tempo.",
          "$ref": "#/definitions/integerOrFraction"
        }
      },
      "required": ["tempo", "startPosition"],
      "additionalProperties": false
    },
    "player": {
      "title": "Player",
      "description": "A solo player or section within the ensemble.",
```

```
      "type": "object",
      "properties": {
        "meterPartIndex": {
          "type": "integer",
          "title": "Meter Part Index",
          "description": "An index linking to an entry in the meter part
↪ array.",
          "minimum": 0,
          "default": 0
        },
        "tempoPartIndex": {
          "type": "integer",
          "title": "Tempo Part Index",
          "description": "An index linking to an entry in the tempo part
↪ array.",
          "minimum": 0,
          "default": 0
        }
      },
      "required": ["meterPartIndex", "tempoPartIndex"],
      "additionalProperties": false
    },
    "fraction": {
      "type": "string",
      "pattern": "^[1-9][0-9]*/[1-9][0-9]*$"
    },
    "integer": {
      "type": "string",
      "pattern": "^[0-9]*$"
    },
```

```
    "integerOrFraction": {
      "oneOf": [
        {
          "$ref": "#/definitions/fraction"
        },
        {
          "$ref": "#/definitions/integer"
        }
      ]
    }
  }
}
```