Playing the Ear: Non-Linearities of the Inner Ear and their Creative Potential

Maynooth University
National University of Ireland Maynooth

Brian Connolly; BMus, MA

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Department of Music

Faculty of Arts, Celtic Studies & Philosophy

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Head of Department: Professor Christopher Morris

Supervisor: Dr Gordon Delap

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Glossary of Terms

As many of the terms used in this thesis are not commonly used within discussions concerning electroacoustic composition, a glossary of terms is provided below. Should the reader wish to obtain a greater understanding of any or all of the various phenomena in question, the author advises referring to the relevant section within Chapter 2 of this text. Furthermore, this material is also provided as a means of enhancing the level of accessibility for the composer. That is a key consideration in this thesis.

Auditory Beating

> Collective term used in this thesis referring to either binaural or monaural beating, or both.

Binaural Beating

> Slow amplitude modulations called binaural beats are perceived when tones set approximately 15 Hz apart are presented separately to each ear.[1]

Critical Bandwidth

> Each component of an input sound will give rise to a displacement of the basilar membrane at a particular place [...] The displacement due to each individual component is spread to some extent on either side of the peak [...] As the frequency difference is increased further there is a point where the fused tone gives way to two separate tones but still with the sensation of roughness, and a further increase in frequency difference is needed for the rough sensation to become smooth [...] The frequency difference between the pure tones at the point where a listener's perception changes from rough and separate to smooth and separate is known as the "critical bandwidth."[2]

Distortion Products

> Distortion products are those components at the output of the system that were not present at the input.[3]

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[1] Gerald Oster, 'Auditory Beats in the Brain', *Scientific American*, 229 (1973), 94-102 (p.94)

[2] David M. Howard and Jamie Angus, *Acoustics and Psychoacoustics,* 4th edn. (Oxford: Focal Press, 2001), p.83-4

[3] Stanley A. Gelfand, *Hearing*, 5th edn. (Essex: Informa Healthcare, 2010), p.220

Harmonic Series/Overtones

> In practice [...], no vibrating body produces a pure tone. All musical instruments produce composite tones called harmonics. They are produced simultaneously and belong to the harmonic series. The harmonic of the lowest frequency is called the fundamental and it is generally more intense than the other frequencies and determines the pitch of the composite tone. The frequencies of the other harmonics are multiples of the frequency of the fundamental so that if x is the frequency of the fundamental the other harmonics in the series have frequencies 2x, 3x, 4x,...[4] Furthermore, the harmonics above the fundamental are often referred to as overtones.

Intracranial Motion

> With binaural beat perception, there is often a sense of the perceived beat feeling as though it is moving through the listener's head. This movement is known as intracranial motion.

Localisation

> The law or rule by which the location of an auditory event (e.g., its direction of distance) is related to a specific attribute or attributes of a sound event or of another event that is in some way correlated with the auditory event.[5]

Monaural Beating

> Monaural beats occur when two frequencies are alternately in phase and out of phase and, thus, alternately cancel and reinforce each other; the intensity fluctuates at a rate equal to the frequency difference between the two tones.[6] In this thesis, a single ear is also discussed as being capable of producing monaural beats as two simultaneous inputs into one ear from two independent sources results in the same beating effect.

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[4] Erwin Hiebert, *The Helmholtz Legacy in Physiological Acoustics* (Switzerland: Springer, 2014) p.7

[5] Jens Blauert, *Spatial Hearing: The Psychophysics of Human Sound Localization,* rev. edn. (Massachusetts: MIT Press, 1997), p.37

[6] Brian C.J. Moore, *An Introduction to the Psychology of Hearing*, 6th edn (Bingley: Emerald, 2012), p.252

Otoacoustic Emissions

Otoacoustic emissions (OAEs) are sounds given off by the inner ear when the cochlea is stimulated by a sound.[7]

Four types of OAEs are discussed in this thesis:

Quadratic difference tones (QDT) can be provoked as follows f2-f1 (when f2 > f1). Two stimulus tones entering the ear at 1000 Hz (f1) and 1,200 Hz (f2) will produce a QDT at 200 Hz.

Cubic difference tones (CDT) relate to the two stimulus tones with the following formula: 2f1-f2.

Sum tones (STs) are generally quite weak in intensity and consequently, are not always audible.[8] STs will exhibit frequency content as a result of two pure tones acting as a stimulus with the following formula: f1 + f2 = ST

Transient-evoked otoacoustic emissions (TEOAEs) can be generated through stimuli of very short duration. These transient sounds, which can be short bursts of broadband noise, clicks or tones impulses, activate an extensive area of the basilar membrane.[9]

Psychoacoustics

The science of the hearing system as a receiver of spectral information.[10]

Residue Pitch

If the lower harmonics are removed from a complex tone, the pitch hardly changes. [...] The pitch of the (incomplete) harmonic tone without fundamental frequency usually corresponds closely to the pitch of its fundamental.[11] The common difference in frequency between a number of harmonics will result in the listener perceiving a pitch close to that frequency, without a tone at that frequency being input into the listener's ear.

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[7] 'Otoacoustic Emissions (OAEs), *American Speech-Language-Hearing Association*, *http://www.asha.org/public/hearing/Otoacoustic-Emissions/* [Accessed 26th September 2016]

[8] Stanley A. Gelfand, *Hearing*, p.220

[9] Jessica Arrue Ramos, Sinnet Greve Bjerge Kristensen and Douglas L. Beck, 'An Overview of OAEs and Normative Data for DPOAEs', p.33

[10] Hugo Fastl and Eberhard Zwicker, (2007) Psychoacoustics: Facts and Models, Springer-Verlag, Berlin, p. vii

[11] Ibid, p. 120

Spectral Masking

> When two or more pure tones are heard together an effect known as “masking” can occur, where each individual tone can become more difficult or impossible to perceive, or it is partially or completely “masked,” due to the presence of another tone. In such a case, the tone which causes the masking is known as the “masker” and the tone which is masked is known as the “maskee.”[12]

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[12] David M. Howard and Jamie Angus, *Acoustics and Psychoacoustics,* p.260

Abstract

This thesis concerns the application of psychoacoustic phenomena relating to the non-linear nature of the inner ear as an electroacoustic compositional tool. The compositions included in this portfolio explore the validity of a variety of non-linear inner ear phenomena within composition by employing them as primary compositional devices.

Psychoacoustics research into the non-linearities of the inner ear has proven that the inner ear has much more to offer the composer than has been previously considered. By reversing the role of the ear from, what Christopher Haworth describes as, 'being a submissive receiver',[13] to becoming an active participant in the creative process, an exciting level of opportunity opens up for both the composer and listener. A focus is given in this research to auditory distortion products and bandwidth phenomena with references to the author's own compositional material.

While it is relatively common for composers to have explored various elements of psychoacoustics in their work, a project of this size, which explicitly explores such material, has not been carried out until now. The work of Maryanne Amacher, Alvin Lucier, Diana Deutsch, and others has highlighted the possibilities of employing psychoacoustic principles in music. This research takes a new approach by placing a direct focus on the benefits of the utilisation of these non-linear mechanisms of the inner ear for the composer, while also positing a number of new creative methodologies with respect to the non-linearities of the inner ear.

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[13] Christopher Haworth, 'Vertical Listening: Musical Subjectivity and the Suspended Present' (unpublished doctoral thesis, Queen's University Belfast, 2012), p.184

Bregman claims that just a 'trickle of studies' in auditory research had been published by the late 1960s.[14] Such a finding coincides with the birth of digital audio, which has facilitated such research to flourish and so the employment of electroacoustic music as an investigative tool into auditory studies seems a natural inclusion into the field.

Adorno once stated that the ear is a 'dozy and inert' organ and, by reconsidering such a view, one can destabilise common assumptions about psychoacoustics and the potential of the ears within music composition.[15] With a specific focus on phenomena relating to the non-linear biomechanical mechanisms of the inner ear, this research seeks to highlight the added physical dimension that can be experienced by the listener whose ears are being performed.

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[14] Albert Bregman, *Auditory Scene Analysis: The Perceptual Organization of Sound*, (USA: MIT Press, 1999), p.xi

[15] As referenced in; Christopher Haworth, 'Vertical Listening: Musical Subjectivity and the Suspended Present' (unpublished doctoral thesis, Queen's University Belfast, 2012), p.107

Declaration

Some of the ideas discussed in this thesis have already appeared in the following publications:

Brian Connolly, 'The Inner Ear as a Musical Instrument', *Proceedings of Meetings on Acoustics,* 25 (2015) <http://scitation.aip.org/docserver/fulltext/asa/journal/poma/25/1/2.0000202.pdf?expires=1477573392&id=id&accname=guest&checksum=CE556977A9CB2305E095C1B537117C21>

Brian Connolly, ‘Compositional Applications for Binaural Beating in Timbre Modulation’, *eContact!* 18.4, (2017)

<https://econtact.ca/18_4/connolly_binaural.html>

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1 Introduction

1.1 Background to the Work

Upon embarking on this journey to investigate the potential for psychoacoustic phenomena within composition, a number of factors significantly influenced the direction in which this research was taken. In comparison to acoustics research, evidence of the application of psychoacoustic studies within music composition is significantly less. Furthermore, existing texts within this modest output only begin to explain the application of such material in a compositional setting and do not attempt to address the scope of all distortion products across a variety of contexts within electronic music. Investigations into bandwidth phenomena (which primarily includes monaural/binaural beating, consonance and dissonance studies) has resulted in a sizeable amount of research published by psychoacousticians and psychologists, yet these studies are carried out in the context of gaining a further understanding of sound perception rather than the musical application of sonic materials. While some research is evident in relation to monaural beating and consonance/dissonance within composition, there is little published material from composers that directly addresses the application of binaural beating in electroacoustic composition. Consequently, there is a lack of understanding concerning the finite behaviour (thus, the full potential) of binaural beating within composition. It is also clear that even a strong academic background in music composition and technology is frequently insufficient in researching this area as many texts relating to hearing are often quite inaccessible due to their language and contexts being heavily rooted in the fields of medicine and neuropsychology.

Once this became apparent, I was required to rethink the manner in which this material should be presented. It was clear that my primary concern for this research was to make my findings accessible for composers and so I sought to provide the necessary details of the phenomena in question, which allow a composer to begin to explore these concepts further. By constantly questioning what it was that I would have benefited from, were this material to have already existed in such form, I can confidently say that this research has been compiled with the knowledge that such an approach to this material has never before existed in such detail and form.

The material in this thesis seeks to form a theoretical foundation upon which further creative practices can be based. While possible routes of exploration for composers are offered here, they are by no means considered to be definitive modes of practice. Furthermore, my proposition of these methodologies is in no way a denial of the effectivity of pre-existing approaches to electroacoustic composition.

1.2 Overview of Existing Work in the Field

1.2.1 Introduction

As a means of obtaining a deeper understanding of the place of this research within the field of electroacoustic music and audition, it is necessary to outline some pre-existing works which utilise psychoacoustic phenomena in their construction. This study will answer a number of questions regarding the role of the phenomena (which do not necessarily relate directly to the inner ear) within the compositions, as well as highlighting how they have been an asset to various composers within their work. By choosing a wider variety of psychoacoustic phenomena, a greater scope is provided concerning the broader potential of considering auditory perception within composition, thus assisting in the contextualising of this research.

1.2.2 Bandwidth Phenomena

The first notable application of bandwidth phenomena in composition is James Tenney's *Critical Band (*1988). This work is written for sixteen or more sustaining instruments with electronics providing a delay line. *Critical Band* demonstrates the nature of frequency distance within a critical bandwidth and the timbral implications from the interactions between the various frequency components. This work begins with a group of instruments performing a sustained A4 (440 Hz) and the various instruments shift with microtonal movement in both directions away from the starting frequency which creates a 'band of frequencies.'[16] As the frequencies move away from the sustaining 440 Hz tone, auditory beating is heard before a rough timbre becomes apparent.[17]

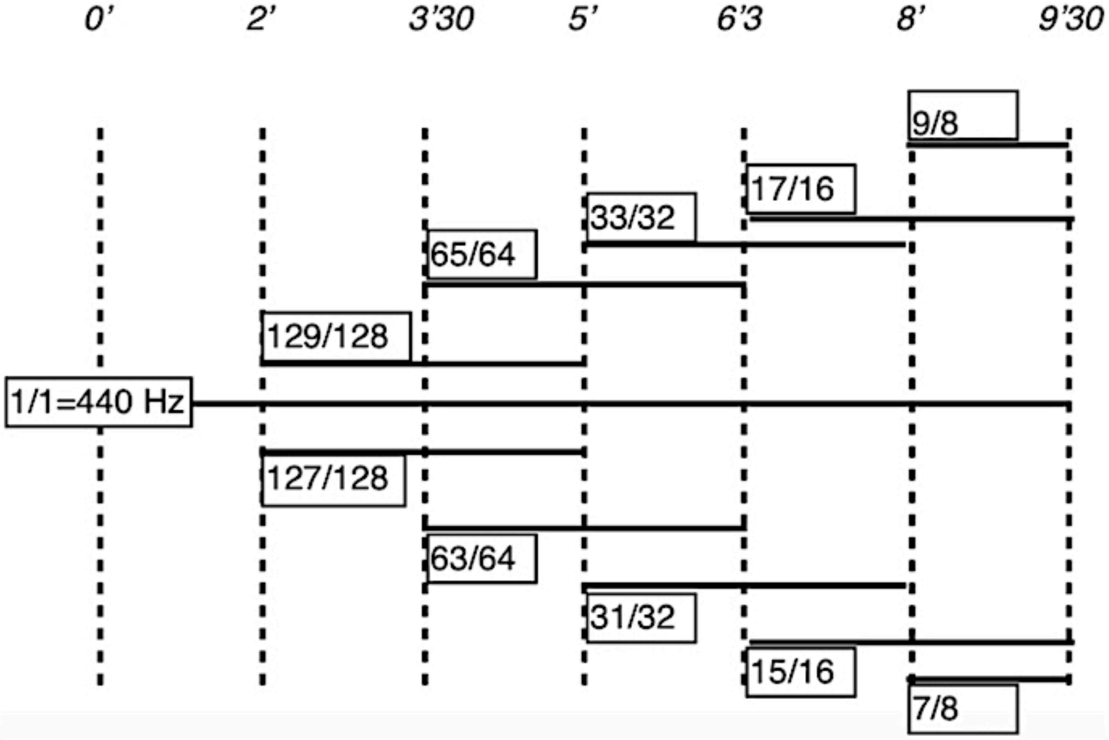

Figure 1: Frequency ratio reduction demonstrating the gradual expansion from unison in the first half of Tenney's *Critical Band*[18]

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[16] Rob Haskins, *John Cage,* (London: Reaktion Books, 2012), p.142

[17] Juan Sebastian Lach Lau, 'Harmonic Duality: from interval ratios and pitch distance to spectra and sensory dissonance' (unpublished doctoral thesis, Leiden University, 2012), p.115

Brian Bridges, 'Towards a Perceptually–grounded Theory of Microtonality: issues in sonority, scale construction and

Tenney's exploration of inner harmonic functionality has been described by Franklin as being 'essentially, an experiment in tuning as a means of achieving a pure dominant harmony.'[19] The composer's employment of critical bandwidth here highlights the significance of the interactive nature of frequencies presented within the same critical bandwidth. Sonic material which falls within a single critical bandwidth can and should not be treated in the same manner as entirely independent frequency components. In Tenney's own words

> only after the expansion process has exceeded the critical bandwidth do the pitch relations begin to be heard as *harmonic.*[20]

Furthermore, what has been described as a 'radiant [...] otoacoustic harmony' providing a 'stunningly beautiful' effect is an aspect of psychoacoustical consideration which is part of the closing section of this piece.[21] Tenney's ground-breaking creative investigation of harmony is further highlighted by Cage's now well-known response to the work in which he said 'if that's harmony, I take back everything I ever said. I'm all for it.'[22] Such a response is important to note in the context of this thesis as it directly highlights a ground-breaking step forward in music composition at which a direct employment of psychoacoustical phenomena is at the centre.

The drone work of Phill Niblock has pushed the boundaries of the application of binaural beating within music (see section 2.2.3). Niblock's work entitled *3 to 7 – 196 (*1974) provokes binaural beating through the hard-panning of closely related tones to the left and right channels. While such

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auditory perception and cognition' (unpublished doctoral thesis, National University of Ireland, Maynooth, 2012), p.264

[19] Joseph Franklin, *Settling Scores: A Life in the Margins of American Music, (*Santa Fe: Sunstone Press, 2006), p. 247

[20] James Tenney, 'program note by James Tenney', Critical Band for variable ensemble and tape delay system *https://www.musiccentre.ca/node/7757* [Accessed 18th October 2016]

[21] Janet Danielson, 'Beautiful Harmony: Kuyper, Dooyeweerd, and the American Musical Avante-Garde', in *The Kuyper Centre Review, Vol 3: Calvinism and Culture*, ed. by G. Graham, (Michigan, Cambridge: Eerdmans, 2013), p.115

[22] John Cage, 'John Cage: An Autobiographical Statement', Autobiographical Statement, *http://johncage.org/autobiographical_statement.html* [Accessed 5th October 2016]

panning techniques are necessary in order to avoid monaural beating occurring within the loudspeakers, they also provide a greater sense of depth to this work which uses the listener's auditory system to create 'slow beating patterns [...] between the two channels, in space.'[23] Niblock employs subtle microtonal techniques which cause various levels of beating. Depending on reflection sensitivities of the performance space, elements of monaural beating may also be evident in this work (see section 2.2.2). This process results in modulations in timbre throughout the work. *3 to 7 - 196* ends with a total of 28 elements of sonic material comprised of distortion products and binaural beating patterns between 3 Hz and 32 Hz which allows the listener to experience the lowest octave between C0 and C1.[24]

Alvin Lucier's interrogation of acoustic phenomena in his compositions is a significant influence on the methodological approaches of this research. In *Music on a Long Thin Wire* (1977) an audio oscillator is connected to a wire upon which a magnet is placed and the wire is extended across a room. Contact microphones are used to detect the sound generated from the wire which consequently produces both harmonic and inharmonic structures. The environmental settings of the room determine the behaviour of the wire and its frequency modulations. Parameters such as room temperature and the proximity of individuals to the wire are among the conditions that influence the listener's perception of both monaural and binaural beats.

Lucier has expressed that his fascination with auditory beats, relating to the psychoacoustic phenomenon of critical bandwidth (see section 2.2.1), is a particular area of focus in his compositions. These auditory beats (see section 2.2.2/3) provide the textural foundations of *Music on a Long Thin Wire*, as the slow fluctuations in frequencies, combined with the drone-like nature

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[23] Volker Straebel, 'Technological Implications of Phill Niblock's Drone Music', *Organised Sound*, 13 (2008), 225-235 (p.227)

[24] Ibid, p.227

of the waves, results in gradual timbral modulations throughout. The repetitive beating acts in complete contrast to the static drones of the pure waves playing simultaneously.

Lucier further explores bandwidth phenomena in *Crossings* (1984) which is written for a pure tone and orchestra. In this work, the frequencies produced by the orchestral instruments interact with a pure tone which continuously sweeps the entire spectral range of the orchestra (32.70–4,186.01 Hz) resulting in constant textural fluctuations due to this phenomenon. Lucier has stated that the intention of *Crossings* was to

> explore interference phenomena between sound waves. When two or more closely tuned tones are sounded, their oscillations periodically coincide to produce audible beats of sound. [...] under certain acoustic conditions, the beats may be heard to spin around the room.[25]

Lucier's intent to incorporate these phenomena is evident as the continuously ascending sine sweep constantly intersects the frequency regions in which the sustained acoustic instruments are situated in the spectrum. Due to the phenomenon of auditory beating, it is in the moments wherein the frequency content of both the sustained notes and pure tone sweep become close together where the essence of this work is to be found.

1.2.3 Localisation phenomena

There are a number of phenomena relating to the human auditory system's processing of directional cues which reveal the assumption-based nature of much of the listening process. Enda Bates and Christopher Haworth have applied two such biomechanisms relating to localisation perception

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[25] Alvin Lucier, 'Alvin Lucier: Crossings', *Dram Online, http://www.dramonline.org/albums/alvin-lucier-crossings/notes* [Accessed 18 August 2014]

within their work as a means of investigating the potential of localisation phenomena in composition more deeply.

The 'Franssen effect' is a psychoacoustic illusion that demonstrates 'the inability of a listener to accurately localise a steady-state sine tone in a reverberant space'.[26] This effect also reveals the place of spatial perception in the hearing process. Gary Kendall has outlined that the Franssen effect

> demonstrates that listeners must be mentally constructing and updating some form of spatial representation in which events have spatial persistence.[27]

Bates has explored various techniques relating to spatialisation in music. As well as investigating the application of spatialisation techniques as a clarification and separation tool in the presentation of sonic material, Bates has explored the advantages of employing localisation phenomena, such as the Franssen effect, as a compositional device. In his octophonic work *Auto Harp (*2009), Bates uses sustained layered sine waves in the opening and closing sections which are in contrast to the intersecting material constructed of plucked harp notes that the composer considers 'highly localisable' due to the transient qualities resulting from their attack method.[28]

On discussing the benefits of employing the Franssen effect as a compositional tool, Bates has stated that

> the use of the Franssen effect in the opening section of this work has proven to be highly effective [...] due to the inherent difficulty in localising sine tones in a reverberant environment, the speed at which the sine tones move from right to left in this section is quite unpredictable, which introduces a nice element of variability

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[26] Enda Bates, 'The Composition and Performance of Spatial Music' (unpublished doctoral thesis, University College Dublin, 2006), p.184

[27] Gary S. Kendall, 'Spatial Perception and Cognition in Multichannel Audio for Electroacoustic Music', *Organised Sound*, 15 (2010), 228-238 (p.231)

[28] Enda Bates, 'The Composition and Performance of Spatial Music', p.188

> into this fixed media piece.[29]

The 'Haas Effect' (also known as the 'precedence effect' and 'the law of the first wavefront') concerns the

> brain's assumption [...] that a sound that arrives in the first fraction of a millisecond indicates the direction of a sound source.[30]

This effect can be simply described by stating that if two identical monophonic tracks are simultaneously presented dichotically to a listener, the listener will perceive the location of the sound as though it is centred. Should one of those monophonic tracks be delayed by 5–30 ms, the listener will perceive the sound as though it is arriving from the direction of the track that is not delayed.[31] The listener will neither experience the sound as though it is hard-panned in one direction or will the perceived signal (a combination of both the original line and the delayed line) appear distorted, providing they are positioned within close temporal space. Haworth's piece *The Law of the First Wavefront (*2008) experimented with the application of this auditory illusion as the primary tool in the spatial positioning of acoustic signals. Haworth writes that this work 'uses only the precedence effect to spatialise sound. There is no panning in the piece.'[32] Through the delicate use of time delays and pitch shifting of the various signals and their assignment to the loudspeakers, the listener will perceive the materials as though they are panned from a computer system or sound desk rather than as a result of a perceptual confusion. Haworth has expressed a dissatisfaction with this work as

> only expert listeners seem to be able to tell they are hearing a ‘non-standard’ form

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[29] Ibid, p.188

[30] Mike Goldsmith, *Sound: A Very Short Introduction*, (New York: Oxford University Press, 2015), p.60

[31] Alec Nisbett, Sound Studio: Audio Techniques for Radio, Television, Film and Recording, 7th edn, (New York and London: Focal Press, 2013), p.26

[32] Christopher Haworth, 'Composing with Absent Sound', *ICMC 2011 Proceedings*, 342-345 (p.342)

> of spatialisation.[33]

It would seem that Haworth's dissatisfaction with this approach relates to the audience's awareness of the method being employed. Thus, it could be argued that the method itself proved quite effective in relation to the role in which it was given in the spatialisation of the sound materials.

1.2.4 Shepard-Risset Glissando

Research into psychoacoustics has brought about the exploration of auditory illusions. Jean-Claude Risset's notable work in this area includes the Shepard-Risset glissando and the Risset rhythm illusion, as well as his monumental studies into timbre. In his work *Computer Suite from Little Boy* (1968), which depicts the dropping of the first atomic bomb, Risset employs the 'never-ending glissando' to evoke the bomb's descent. Shepard's role in the initial discovery of a scalic version of this psychoacoustic illusion is acknowledged by Risset's use of some of Shepard's original tones in this piece.[34]

The Shepard-Risset glissando exploits the listener's pitch tracking mechanism at the heart of this work. Carson's outline of the construction of the illusion is as follows:

> [the Shepard-Risset glissando illusion demonstrates] the paradoxical potential of artificial pitch height ambiguity by repeatedly traversing the circle of pitch classes, steadily adding new octave partials while subtracting them from the other end and leaving the position of the spectral envelope immobile. The result is an impression of infinite ascent or descent.[35]

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[33] Ibid, p.342

[34] James S. Walker and Gary Don, *Mathematics and Music: Composition, perception and performance* (Florida: CRC Press, 2007), pp. 157-8

[35] Ben Carson, 'Musical Illusions and Paradoxes by Diana Deutsch; Phantom Words and Other Curiosities by Diana Deutsch' (Review), *The American Journal of Psychology,* 120 (2007), 123-140 (p. 132)

The effect of this illusion in *Computer Suite from Little Boy* is heightened, to some extent, by the composer's treatment of multiple descending figures in the higher frequencies, which serve to distract the listener on some level from the illusion itself. This allows the glissando figure to exist in the background and thus ensures that the listener fully absorbs the material in the context of the entire work.[36]

1.2.5 Otoacoustic Emissions

Otoacoustic emissions (OAEs) (see section 2.3.3) are intrinsically paradoxical as they are low-intensity sounds that are produced by the listener's inner ear and travel backwards towards the outer ear.[37] These inner ear vibrations are responses to external acoustic stimuli, which range from short broadband bursts of sound to two pure tones.

Maryanne Amacher (d.2009) and Jacob Kirkegaard are two prominent composers exploring distortion product otoacoustic emissions (DPOAEs) (see section 2.3.3.1). Amacher has expressed that she 'wanted to create a kind of music that [the listeners'] ears are making'.[38] In 1999 Amacher released her album *Sound Characters (Making the Third Ear),* which presents many compositions, often displaying fast repetitive material composed of sine waves played in short bursts. Amacher's work entitled *Chorale 1* from *Sound Characters* presents an arpeggiated tonality through DPOAEs that are created by alternating fifths in the left ear and closely tuned alternating thirds in the right ear, which cause textural shifts.[39] The resulting inner ear counterpoint creates what Amacher describes as a 'perceivable tonality', which are a consequence of the DPAOEs.[40] Amacher delicately

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[36] James S. Walker and Gary Don, *Mathematics and Music: Composition, perception and performance,* p.158

[37] Jonathan Kirk, 'Otoacoustic Emissions as a Compositional Tool', *ICMC 2010 Proceedings*, 316-318 (p.316)

[38] Frank J. Oteri, 'Maryanne Amacher in Conversation with Frank J. Oteri', *New Music Box* *http://www.newmusicbox.org/assets/61/interview_amacher.pdf* [Accessed 23 August 2014]

[39] Jonathan Kirk, 'Otoacoustic Emissions as a Compositional Tool', p.318

[40] Frank J. Oteri, 'Maryanne Amacher in Conversation with Frank J. Oteri', *New Music Box* *http://www.newmusicbox.org/assets/61/interview_amacher.pdf* [Accessed 23 August 2014]

introduces the listener to the distortion products, which are masked at the beginning of the work and then gradually become more prominent throughout the duration of the composition.[41]

While listening to such music, the audience should experience both the sonic material produced by their ear as well as the material presented from the loudspeaker output. The added physical dimension in Amacher's music, involving a feeling of one's ears working as 'neurophonic instruments' has been described by Frank J. Oteri as follows:[42]

> As I listened I actually felt something. I felt my ear vibrating. It was startling. I felt it listening to the disc before, but I never felt it as strongly as I did this afternoon. It was a very intense physical experience. I think the only other time I'd ever felt it was when music had been too loud and it was painful. It's something we're actually taught to avoid. But this wasn't painful. This was something else. It was actually rather the opposite of painful. It felt like my ears were being tickled. It is a very, very interesting phenomenon.[43]

Kirkegaard's *Labyrinthitis (*2007) relies on 'the non-linearities of both his own ears and that of the audience'.[44] The title of the piece relates to the outer casing of the inner ear known as the 'osseous labyrinth'. This work requires sixteen loudspeakers positioned in a spiral formation, reflecting the coiling shape of the inner ear's cochlea (see section 2.1.2.2). Kirk describes *Labyrinthitis* as

> an experiment in counterpoint between the stimulating frequencies and the resultant distortion products

In this work Kirkegaard recorded DPOAEs produced in his own ear before using them as stimuli in

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[41] Jonathan Kirk, 'Otoacoustic Emissions as a Compositional Tool', p.318

[42] Sleeve notes on; Maryanne Amacher, *Sound Characters (Making the Third Ear)*, (Tzadik, 1999)

[43] Frank J. Oteri, 'Maryanne Amacher in Conversation with Frank J. Oteri', *New Music Box* *http://www.newmusicbox.org/assets/61/interview_amacher.pdf* [Accessed 23 August 2014]

[44] Jonathan Kirk, 'Otoacoustic Emissions as a Compositional Tool', p.318

the provocation of a similar response in the ears of the audience. Once the DPOAEs are established in the ears of the listeners, then the initial material is faded out and replaced with tones that match those now being emitted within the inner ears of the audience as a means of creating further emissions, and so forth.

While a variety of possibilities exist in the possible presentation of stimulus material when composing with distortion products, the drone-like nature of the music of Niblock could be said to be the ideal platform for such material to be presented. Such music of Niblock's has been described as follows:

> In many cases [music which is rapidly changing and developing] auditory distortion may simply go unrecognized. Niblock’s approach therefore magnifies the conditions for the discrimination of auditory distortion from acoustic sound.[45]

A unique approach to considering distortion products in composition has been taken by Alex Chechile who, in his collection of 24-channel works *On the Sensations of Tone I-II... (*2010–present), employed a custom scale system that

> derived from particularly resonant ear tones selected by [Chechile] from sweeping the frequency spectrum with a constant CDT value.[46]

Chechile's scale produces the values of two stimulus tones and their resulting distortion products, which allows for a complex presentation of DPOAEs in this work.[47] Furthermore, the composer also encourages the audience to move within the listening space (where possible) while also asking them to turn their heads during sustained material as it is in these moments where the audience can

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[45] Gary Kendall, Christopher Haworth and Rodrigo Cádiz, 'Sound Synthesis with Auditory Distortion Products', *Computer Music Journal*, 38 (2014), 5-23 (p.9)

[46] Alex Chechile, 'Creating Spatial Depth Using Distortion Product Otoacoustic Emissions in Music Composition', *ICAD 2015 Proceedings*, 50-53 (p.51)

[47] Ibid, p.51

truly explore their own ears performing along with the work.[48] This fine collection of work also explores the process of microscopic and macroscopic listening through the shifting of the listener's attention between the primary tones and the ear tones.[49]

One of the more influential works on the direction that my own research has taken has been Michael Gordon's *Industry (*1992), for solo cello and electronics, which contains difference tones. This composition is constructed upon a repetitive cello figure which climaxes gradually throughout. The cello signal is directed through a distortion unit that Gordon delicately introduces. The composer indicates on the score that the distortion 'should increase very gradually, beginning imperceptibly'.[50] In this piece, Gordon constantly shifts between sustained major and minor thirds in the violin part in the middle register (generally between D4–293.66 Hz and A4–440 Hz) and, as a result, the difference tones produced are in the register below D3 (146.83 Hz). For example, in bar 26 the violin plays a double-stopped F4 (349.23 Hz) and A4 (440 Hz) and the difference tone of 90.77 Hz can be faintly heard to protrude from beneath these notes. As both the perception and creation of distortion products varies due to the strengths and sensitivities of each individual's own inner ear, this phenomenon is listener-specific. In bar 25, which precedes this example, the composer directs the performer to produce 'more and more intense' sound. The increase in intensity adds to this effect, in combination with the increased gain from the distortion pedal, which becomes more effective throughout the work.[51]

While this work is of particular interest to me from an aesthetic perspective, I am fascinated with an

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[48] Ibid, p.52

[49] Alex Chechile, 'On the Sensations of Tone', *Projects, http://alexchechile.com/projects.html* [Accessed 25 September 2016]

[50] Michael Gordon, 'Score preview: Industry', *Music*, *http://michaelgordonmusic.com/music/industry* [Accessed 28 August 2014]

[51] Ibid

aspect of the creation of this piece which only came to my attention following correspondence between myself and the composer. *Industry* is somewhat unique in the context of this discussion as Gordon states that, while this psychoacoustical element might be an attractive aspect of the work to some listeners, it was not intentional in his initial compositional plan as. He writes:

> The difference tones in Industry are a product of the double stops but they are a bonus add-on to the piece I meant to write - I didn't set out to explore difference tones, they just happened to be there and I liked them.[52]

Consequently, due to Gordon's satisfaction with the presence of these phantom tones within his work (albeit entirely accidental), it could be suggested that, were the composer to investigate the application of the distortion products within composition, an increased level of research output in the area would prove beneficial for further work.

1.2.6 Conclusion

Through a brief outline of multiple works that consider an array of psychoacoustic phenomena, the number of advantages and opportunities that are available to the composer employing such concepts in their work is apparent. It is clear that in works wherein either a direct exploration, general employment or unintentional application of psychoacoustic phenomena is evident, such considerations are capable of playing both primary and passive roles within electronic music as well as offering a broad wealth of possibilities to the composer.

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[52] Michael Gordon, Private email correspondence [3 September 2014], (permission for use granted)

1.3 Electroacoustic Music: The Ideal Platform?

Psychoacoustics research has changed how composers and audiences are engaging with music. A rapid growth in digital technologies has allowed investigation into the perception of sound to flourish within musical creativity. A field with minimal studies prior to the digital age (which allowed for greater accuracy in auditory experimentation) has evolved into an exciting arena of exploration for composers striving for their audience to experience music on a much more physical level than ever before as they can now consider their listeners ears directly within their work. It is through considering the impact of such technological advances on existing methodologies in auditory research where the wealth of potential of the audience's ears in contemporary electronic music is revealed.

A relative lack of research being conducted within audition resulted in the field being somewhat left behind within perception studies. Bregman has explained that 'audition had not attracted the attention that vision had' and so it would seem that the wait for technological advances came at a cost to the field.[53] Coinciding with developments in digital technology since the mid-1900s, new discoveries in audition were commonly credited to researchers within an array of sectors including physicists, computer programmers and musicians. Evidence of this interdisciplinary nature is seen contemporaneously with the earliest inventions in audio software. In 1957, under the directorship of John Pierce at Bell Labs in New Jersey, electrical engineer Max Mathews developed the first widely used sound synthesis software MUSIC. Mathews subsequently wrote the ground-breaking *Science* magazine article *The Digital Computer as a Musical Instrument* and he later became known as 'the father of computer music.'[54] A colleague of Mathews at Bell Labs was the physicist and composer Jean-Claude Risset. While discussing the interdisciplinary nature of psychoacoustics research and

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[53] Albert Bregman, *Auditory Scene Analysis: The Perceptual Organization of Sound*, p.xi

[54] Max Mathews, 'The Digital Computer as a Musical Instrument', *Science*, 142 (1963), 553-557 (553)

music Risset stated that

> Sound research involves physics, data processing, signal processing, psychoacoustics and music. [...] It is a question of specialists from different fields working on the same project. But the level of dialogue remains low if each one doesn't venture into the world of the other at some level.[55]

As composers of electronic music uncovered the link between digital technology and psychoacoustic exploration, an interest grew among a small community of composers in relation to the employment of psychoacoustic concepts as creative devices within one's music. This has been a key factor in the dissemination of research into auditory perception becoming embedded in the world of music. Haworth postulates that

> perhaps more so than in any other discipline, it is the artist who creates electronic music that must grapple with the science of perception in order to realise his work.[56]

This statement highlights a deeper connection between electronic music within psychoacoustics research as it references the advantages for the composer in having an understanding of perception-based studies in their work.

The role of the digital age within psychoacoustics research combined with its uncontested hold on electronic music, suggests that merging psychoacoustics and electronic composition has never before seemed as relevant. A wealth of accessible repositories presenting scientific discovery in areas including masking, otoacoustic emissions, auditory beating, and pitch perception theories, combined with enthused practitioners and audiences, sees the modern day as ideal for such

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[55] RTD info, 'Portrait: Jean-Claude Risset – The Paradoxes of Perception', *https://ec.europa.eu/research/rtdinfo/special_as/print_article_820_en.html* [accessed 7 August 2011]

[56] Christopher Haworth, 'Composing with Absent Sound', p.342

consideration.

The listening system is theoretically simple in terms of its structural behaviour. The ear's physical construction results in it behaving as a three-stage energy converter, primarily acting in a 'cause and effect' manner. As the behaviour of the ear is somewhat predictable in terms of reaction to acoustic stimuli, the level of control over sonic material that is evident in electronic music, due to its relationship with the computer, makes it a well-suited platform upon which the listener's ears can be employed as a musical instrument. Chowning once stated that

> computers require us to manage detail to accomplish even the most basic steps. It is in the detail that we find control of the sonic, theoretical and creative forms[57]

This statement makes a very relevant point in relation to the discussion in question. Through the incorporation of theoretical data within templates of various creative methodologies, it is clear that electroacoustic music can offer the practitioner greater potential for having a heightened control over their artistic material, particularly when exploring detailed theoretical components. The level of precision on offer to the composer working with digital tools is second to none. While acoustic musical instruments controlled by human performers are capable of providing the source material for a number of psychoacoustic effects in music, composers using digital tools now have access to levels of manipulation of their audience's ears that are scientifically sound and are therefore both more accessible and effective.

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[57] John Chowning, 'Fifty Years of Computer Music: Ideas from the Past Speak to the Future', in *Computer Music Modeling and Retrieval*, ed. by R. Kromland-Martinet, Sølvi Ystad and Kristoffer Jensen, (Berlin Heidelberg: Springer, 2008), p.1

2 Non-Linear Inner Ear Phenomena

2.1 Non-Linear Hearing Phenomena

2.1.1 Introduction

One of the most influential factors on this research has been the manner in which composers and authors have referred, in both creative practice and text, to various aspects of the listening process which perhaps question, or provide an intriguing insight into, the human auditory system. In Howard and Angus' book *Acoustics and Psychoacoustics* the following phrase was employed while introducing research into hearing; 'the effect the normal hearing system has on sounds entering the ear.'[58] The use of such a phrase is particularly relevant to this research as it places direct focus on the ear having an active role in the interpretation of sonic energy, thus acknowledging that there is a level of potential for the organ to impose itself on an incoming sound signal.

The ear itself can be broken down into the outer, middle and inner ear; however, this section will only explain the processes of the inner ear in more extensive detail as such is the focus of this research. However, a brief outline of the outer and middle ear structure and mechanisms is provided to highlight that non-linear listening mechanisms are not peculiar to the inner ear.

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[58] David M. Howard and Jamie Angus, *Acoustics and Psychoacoustics,* p.74

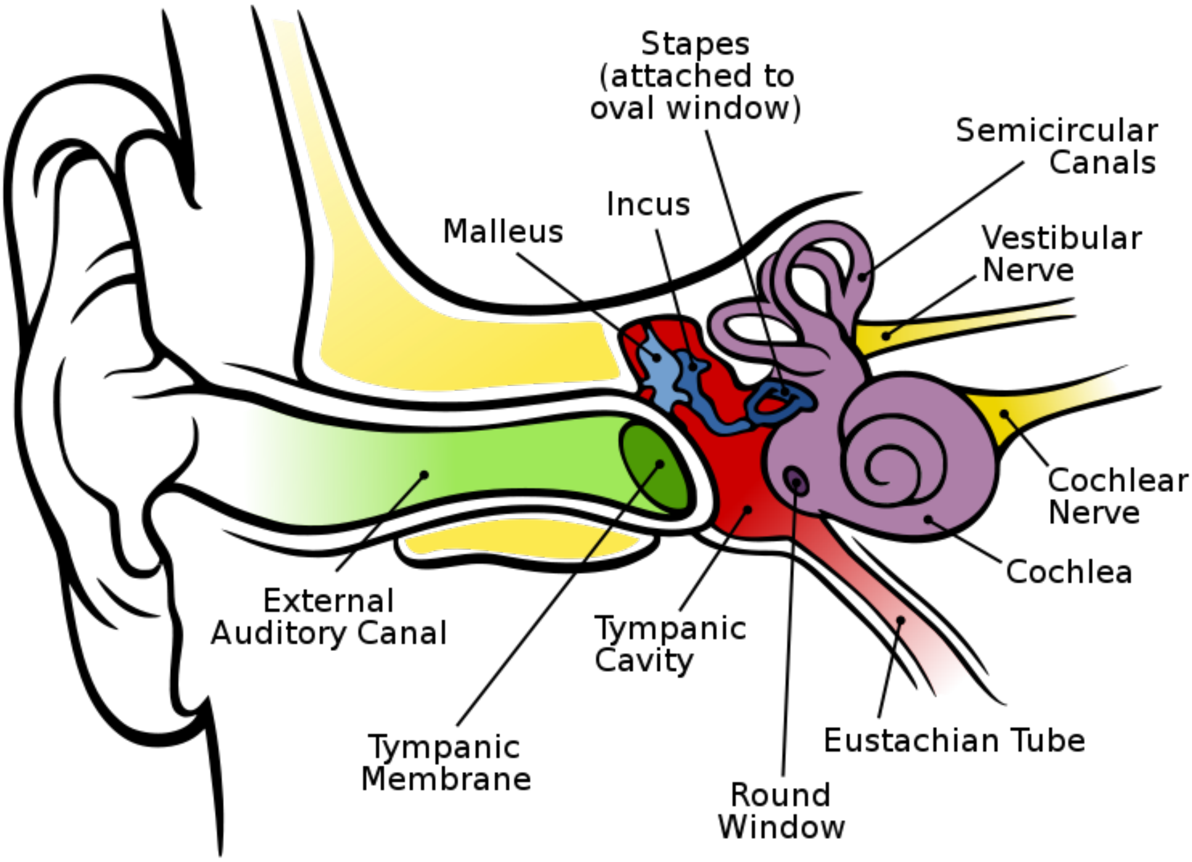

Figure 2: Image of the outer, middle and inner ear [59]

Reichenbach and Hudspeth have expressed that the non-linear nature of the listening system is responsible for 'the remarkable properties of hearing.'[60] The first physical obstacle that acoustic energy will meet after the beginning of its propagation, due a disturbance at the source, is most frequently the auditory canal of the outer ear [Figure 3] (also known as the 'external auditory meatus'). This is a tube-like structure with a length of 2.5–3 cm with a changeable width (due to jaw movement) that funnels the energy through the outer ear towards the tympanic membrane (forming

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[59] Sound, soundphysics.ius.edu/wp-content/uploads/2014/01/800px-Anatomy_of_the_Human_Ear.svg_.png [Accessed 26 October 2016]

[60] Tobias Reichenbach and A. J. Hudspeth, 'The physics of hearing: fluid mechanics and the active process of the inner ear', *Reports on Progress in Physics*, *http://iopscience.iop.org/article/10.1088/0034-4885/77/7/076601/pdf* [Accessed 23 February 2016]

the 'eardrum') where it is then transferred to mechanical energy.[61] The external auditory meatus contains two bends at significant angles: the concho-meatal angle (CM) and the cartilaginous-bony angle (CB).

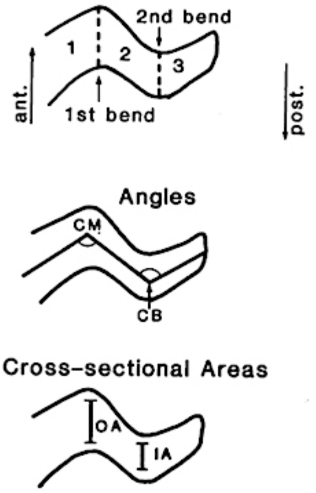

Figure 3: Axial view of bends within the external auditory meatus[62]

As with any physical structure, the auditory canal has its own properties which will result in certain areas of particular resonance such as canal width, factors that impact on efficient energy transfer (bends, etc), and skin thickness. One of the earliest and most ground-breaking studies in the area of frequency perception was conducted by Fletcher and Munson in 1933, in which they found that the 'sizes and shapes of the ear canals' cause listeners to have peaks in sensitivity to input signals at approximately 3,500–4,000 Hz and 13,500 Hz.'[63]

As sound energy enters the middle ear via tympanic membrane vibrations, a transduction process takes place and the acoustic energy becomes mechanical energy. This energy then passes through a lever system comprising of the malleus, incus and stapes ossicles. An increased waveform pressure

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[61] Lynn S. Alvord and Brenda L. Farmer, Anatomy and Orientation of the Human External Ear, *Journal of the American Academy of Audiology*, 8 (1997), 383-390 (p.386)

[62] Ibid, p.387

[63] Harvey Fletcher and Wilden A.Munson, 'Loudness, Its Definition, Measurement and Calculation', *Journal of the Acoustical Society of America,* 5 (1933), 82-108 (p. 89)

of approximately 30.6 dB is evident as a result of the middle ear's level system. This is due to the contrasting lengths of these bones, combined with the differing surface areas of both the tympanic membrane and stapes footplate, which is connected to the inner ear.[64] The middle ear is also responsible for the acoustic reflex mechanism which, through the stiffening of the ossicular chain, protects the inner ear from sudden bursts of loud sounds (above approximately 75 dB SPL) and, providing it has 60−120 ms to adjust to the sudden influx of energy, can attenuate the SPL of the sound energy which passes into the inner ear by 12−14 dB.[65]

2.1.2 The Inner Ear

2.1.2.1 Introduction

At this point, it is important to note the level of scientific detail relating to the biological and chemical mechanisms of the inner ear that will be exhibited in this section. The following material has been compiled to provide accessible data for composers rather than for those with backgrounds relating to the medical sciences which is often required to fully understand the majority of research output in relation to the inner ear.

2.1.2.2 Physiology and Functionality

Mechanical energy enters the oval window at the cochlea of the inner ear via the stapes footplate. The primary role of the cochlea is to convert resonances that are caused along specific regions of the basilar membrane, into electrical signals that the brain can process as sound.

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64 David M. Howard and Jamie Angus, *Acoustics and Psychoacoustics*, p.70

65 Ibid, p.79

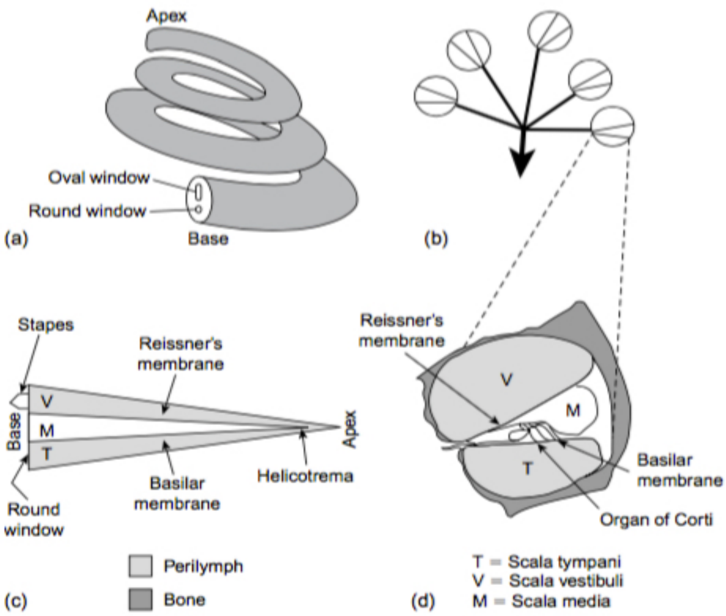

Figure 4: (a) The spiral nature of the cochlea. (b) The cochlea "unrolled." (c) Vertical cross-section through the cochlea. (d) Detailed view of the cochlear tube.[66]

The cochlea is connected to the middle ear by its base and terminates at its thick apex. Howard and Angus define the function of the cochlea as being responsible for the conversion of 'mechanical vibrations into nerve firings to be processed eventually by the brain.'[67] It is often said to resemble the same shape as a snail shell as it is coiled over approximately 2.5 turns (the word '*Cochlea*' is also Latin for 'snail.'). If the cochlea were to be straightened out, it would have a length of approximately 3.2cm.[68]

The cochlea is constructed of three primary inner channels. The two outer channels are the scala vestibuli and the scala tympani. They are separated by the scala media. The scala media contains the Organ of Corti, which is responsible for the translating of mechanical energy into the neural impulses that are processed by the brain as sound. The basilar membrane is a strip that runs through the length of the cochlea within the Organ of Corti and it can be understood as the spectral analyzer

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[66] Ibid, p.80
[67] Ibid, p.79
[68] Hugo Fastl and Eberhard Zwicker, *Psychoacoustics: Facts and Models*, (Berlin: Springer-Verlag, 2007), p. 26

of the inner ear. As mechanical energy travels through the basilar membrane, various points will resonate in response to certain frequencies, which will stimulate the afferent inner hair cells (positioned between the basilar and tectorial membranes where efferent outer hair cells are also positioned) to fire neurons containing electrical information. This electrical information then travels to the brain via the auditory cortex.

The theoretical frequency range of human hearing is 20 Hz–20K Hz; however, this particularly diminishes over time with a noticeable reduced sensitivity to higher frequencies increasing with age as a result of presbycusis.[69] Figure 5 exhibits the areas of resonance which trigger neuron firings along the basilar membrane and how they run in a very linear manner; the highest frequencies cause resonance near the base and the frequencies caused by resonance decreases as the position moves closer to the apex.

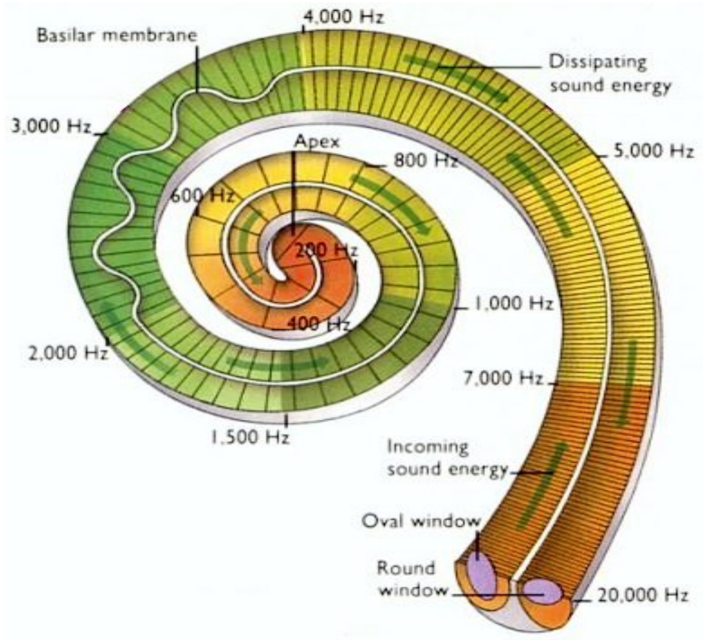

Figure 5: Slightly uncoiled cochlea[70]

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[69] Sharon G. Kujawa and M. Charles Liberman, 'Acceleration of Age-Related Hearing Loss by Early Noise Exposure: Evidence of a Misspent Youth', *The Journal of Neuroscience*, 26 (2006), 2115-2123, (p.2121)

[70] Neuromorphics Laboratory*, http://nl.bu.edu/wp-content/uploads/2011/10/i10-85-cochlea22.jpg* [accessed 20th May

2.2 Bandwidth Phenomena

2.2.1 Critical Bandwidth and Spectral Masking

Within the cochlea lies approximately 3,500 outer/11,000 inner hair cells.[71] The complexity of the basilar membrane as a frequency analyser becomes significantly more complex when considering critical bandwidth phenomena. Each component of an input sound will give rise to a displacement along a specific place of resonance along the basilar membrane. The nature of this displacement affects any other possible displacements which may take place within close distance of the original frequency. The manner in which such displacements can interfere with the efficiency of another taking place concerns spectral masking. This is a 'process in which one sound renders one or more other sounds to be inaudible.'[72] The most commonly noticed form of masking is simultaneous masking, whereby the 'masker' and the 'maskee' are presented together with the masker having a higher intensity value. Fastl and Zwicker describe simultaneous masking in everyday life with the following explanation:

> For a conversation on the pavements of a quiet street, for example, little speaker power is necessary for the speakers to understand each other. However, if a loud truck passes by, our conversation is severely disturbed: by keeping the speech power constant, our partner can no longer hear us. There are two ways of overcoming this phenomenon of masking. We can either wait until the truck passes and then continue our conversation, or we can raise our voice to produce more speech power and greater loudness[73]

The *Oxford Handbook of Auditory Science: Hearing* explains that the excitation along the basilar membrane is responsible for masking, which is dependent on the intensity levels of the input

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[71] Jonathan Ashmore, 'Cochlear Outer Hair Cell Motility', *Physiological Reviews*, 88 (2008), 173-210, (p.175)

[72] Andrew J. Oxenham and Magdalena Wojtczak, 'Frequency selectivity and masking', in *Oxford Handbook of Auditory Science: Hearing*, ed. by Christopher Plack, (Oxford: Oxford University Press, 2010), p.9

[73] Hugo Fastl and Eberhard Zwicker, *Psychoacoustics: Facts and Models*, p. 61

signals.[74] This view is also shared by Howard and Angus in *Acoustics and Psychoacoustics*.[75] **[Audio Demonstration 1]**

Two other types of masking, 'forward' and 'backward', also exist. The former is the most accessible and effective of the two within music composition and so it is only necessary to discuss this phenomenon here. Forward masking can take place for a period of up to approximately 30 ms between the end of the masker and the start of the maskee. This occurs when the excitation along the basilar membrane (at a certain point) is of such an extent that, once the stimulus is no longer acting, the basilar membrane has yet to return to its normal resting state at the time in which another stimulus attempts to disturb the basilar membrane. This can result in the second stimulus proving entirely ineffective. Such effects can prove quite useful when the composer is working with sustained lower intensity material (maskee), which they wish to interject with short bursts of broadband noise/tones at a higher intensity level (masker). The combination of these components will result in an effect similar to an amplitude modulation of the sustained material (maskee). **[Audio Demonstration 2]**

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[74] Andrew J. Oxenham and Magdalena Wojtczak, 'Frequency selectivity and masking', p.11
[75] David M. Howard and Jamie Angus, p.261

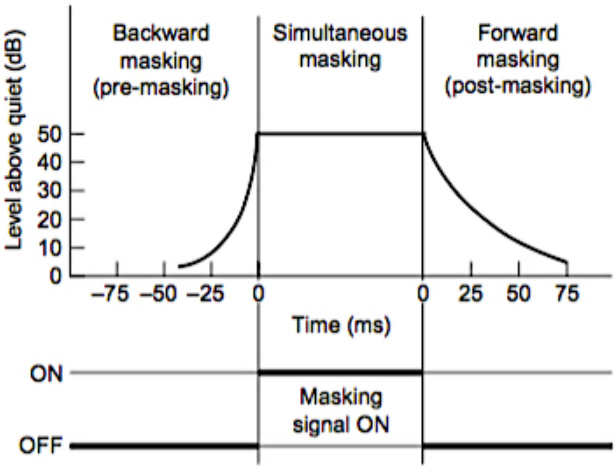

Figure 6: Howard and Angus' 'idealised illustration of simultaneous and non-simultaneous masking'[76]

It should also be noted that lower frequencies, which excite thicker areas closer to the apex, cause wider disturbances than higher frequencies which cause resonance along thinner sections of the basilar membrane as it moves towards the base [Figure 7].

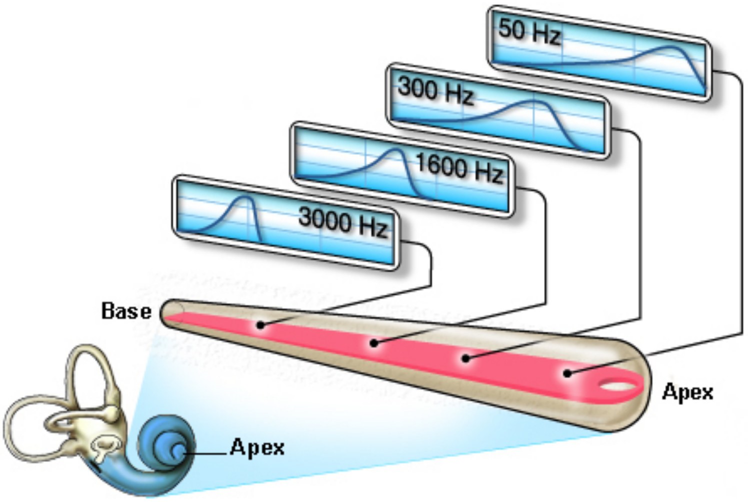

Figure 7: Basilar membrane displacement along its length as a function of frequency [77]

The term 'critical bandwidth' was first used by Fletcher in 1940 and it refers to these places along

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[76] Ibid, p.263

[77] NeurOreille, 'Travelling Waves', *Cochlea*, *http://www.neuroreille.com/promenade/english/cochlea/cocphys/cocphys.htm* [Accessed 23rd May 2016]

the basilar membrane which are generally a constant physical measurement of 1.25mm.[78] While these strips of distances remain constant, the perceived frequencies, which are transmitted by excitation within these short strips, can vary significantly and are dependent on their distance from the base. Numerous studies have been conducted in the area of calculating the exact critical bandwidth for centre frequencies at different points and the complexity of this enquiry can be somewhat summarised by stating that the context in which the centre frequency is being analysed is crucial, and the results are not universal between subjects. Experiments that have been conducted in relation to critical bandwidths have seen a multitude of contexts within which the data was collected including; complex sounds, masking, phase and loudness of complex sounds.[79]

In the context of my own research I have found the work carried out by Moore and Glasberg in relation to Equivalent Rectangular Bandwidth (ERB) to be an ideal summation of human auditory filters. Due to the individual-specific nature of the listening process, combined with various other factors relating to the source signal (s) such as intensity, frequency, complex/simplicity of source signal (s), subject's loudness/frequency sensitivity and levels of hearing damage/presbycusis, Fastl and Zwicker state that only 'a reasonable estimation of the width of the critical band' can been determined.[80] Figure 8 provides an outline of Moore and Glasberg's linear model in relation to frequencies at moderate sound levels between 100–10,000 Hz which applied the following formula:

$ERB = 24.7 (4.37f + 1)$
f = centre frequency in K Hz

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[78] Donald D. Greenwood, 'Critical Bandwidth in Man and Some Other Species in Relation to the Traveling Wave Envelope', in *Sensation and Measurement,* ed. by Howard R. Moskowitz, Bertram Scharf and Joseph C. Stevens (Netherlands: Springer, 1974), pp. 231-239 (p.231)

[79] As summarised in; Robert Mannell, 'The perceptual and auditory implications of parametric scaling in synthetic speech', *Chapter 2: Auditory Processing and Speech Perception*, *http://clas.mq.edu.au/speech/perception/psychoacoustics/chapter2.html* [Accessed 25 May 2016]

[80] Hugo Fastl and Eberhard Zwicker, *Psychoacoustics: Facts and Models*, p. 158

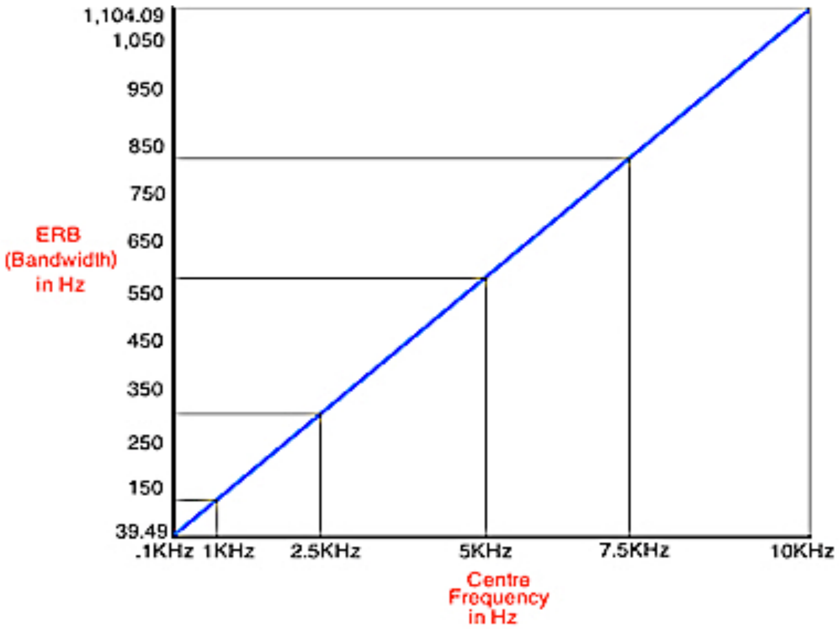

Figure 8: Moore and Glasberg's Linear Model

Simultaneous masking effects can be applied in simple terms by raising the intensity of a single frequency/peak frequency and anything that appears simultaneously within the same critical bandwidth will be affected either by being entirely covered by the masker or by reducing the subject's sensitivity to the masked frequency.

2.2.2 Monaural Beating

Monaural beating is a physical phenomenon concerning the combination of two static signals to form a single beating frequency. Moore states that the frequency of the resulting beat is the mean frequency of the two input tones.[81] The rate of the beat will be equivalent to the mathematical difference in Hertz between the two input tones and the fluctuation in amplitude will change from maximum to minimum intensity for the tones. **[Audio Demonstration 3]**

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[81] Brian C.J. Moore, *An Introduction to the Psychology of Hearing*, p.12

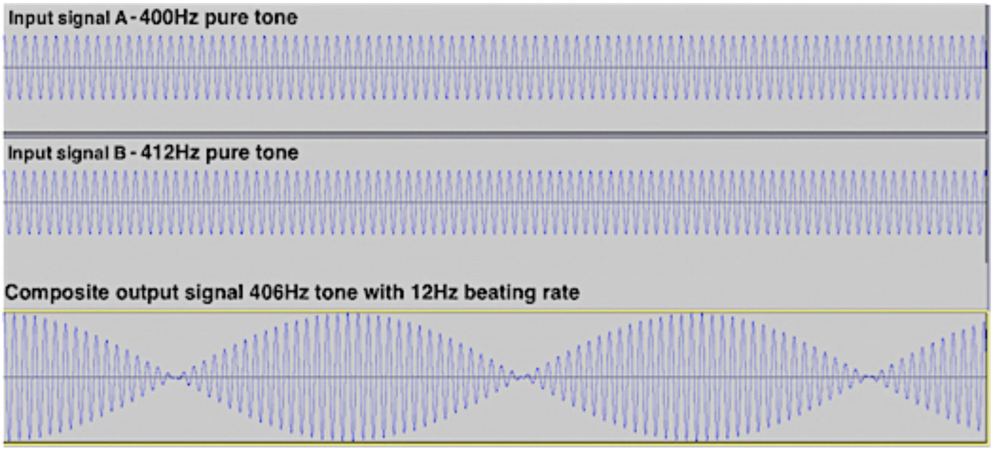

Figure 9: Creation of composite output which displays monaural beating

It is important to note that for pure monaural beats, the amplitude of the two input signals must be presented in an identical manner, otherwise the resulting amplitude of the instantaneous algebraic sum will always be a positive number, thus the amplitude modulation of the composite tone will never reach a pressure level of zero.[82] An understanding of monaural beating is vital for composers wishing to employ binaural beating techniques (see section 2.2.3) within their work as it can often offer solutions to factors relating to practicalities in performance. While monaural beating is not a psychoacoustic phenomenon, at least some level of monaural beating should be expected when working with binaural beats, unless headphone listening with hard-panning is employed. To avoid monaural beating occurring at the output stage of loudspeaker/headphone performance, it must be understood that if frequency components are within approximately 30 Hz (this can vary significantly due to factors relating to frequency and amplitude), and are not entirely separated in the loudspeaker arrangement (not hard-panned), then monaural beating is very likely to be an element of the resulting output content. Should a composer wish to avoid such effects then a knowledge of all primary frequency components (including overtones for periodic content) is necessary in ensuring that problematic frequencies are never distributed along the same channels simultaneously at any given time.

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[82] Gerald Oster, 'Auditory Beats in the Brain', p.96

2.2.3 Binaural Beating

Binaural beating is a direct consequence of a non-linear processing mechanism between the auditory nerve and the brain. While it is a very complex neurological phenomenon, Oster has simplified it by stating that

> the simplest explanation is that the number of nerve impulses from each ear and the route they travel to the brain are determined by the frequency of the incident sound, and that the two nerve signals interact somewhere in the brain.[83]

As designated zones along the basilar membrane resonate in response to particular frequencies, the subsequent disturbance of hair cells, cause the firing of neurons along the auditory cortex towards the brain.

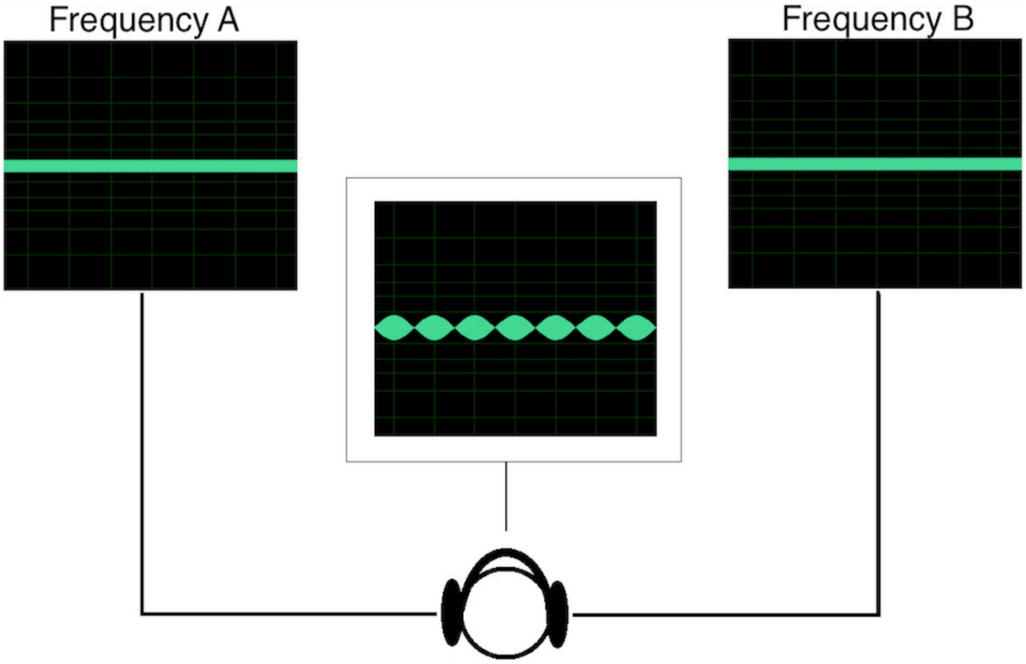

Figure 10: Binaural beating - representation of signal flow order with frequencies A and B < c. 15 Hz apart

In its most simple terms, binaural beating can be explained as follows: when two frequencies are below (approximately) 15 Hz apart, and are presented dichotically through headphones, the listener

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[83] Ibid, p.98

will perceive a composite tone that beats at a rate of the mathematical difference between the two frequencies per second.[84] **[Audio Demonstration 4]** Binaural beating is most effective when both frequencies are lower than 1,000 Hz and are particularly prominent at approximately 440 Hz.[85] As the two frequencies move further away from each other the beating will become less noticeable and roughness is perceived. This rough sensation is a result of faster levels of beating, the speed of which does not allow for prominent amplitude modulations. It should also intensity binaural beat may be experienced when the beat stimuli are set 'almost' an octave apart (for example, 200 Hz in the left ear and 398 Hz in the right ear will provoke a 2 Hz beat). **[Audio Demonstration 5]**

The primary perceptual difference between monaural and binaural beating concerns the fluctuation in amplitude which Oster explains as follows:

> Monaural beats [...] pulse from loudness to silence, as their waveform would suggest. Binaural beats, on the other hand, are only a slight modulation of a loud background. I have tried to estimate the depth of the modulation, and it seems to be about three decibels.[86]

Monaural beats will naturally be caused as a secondary product due to reflections within the listening space. For example, a frequency of 100 Hz being emitted from a loudspeaker positioned to the left of the listener and a simultaneous 105 Hz frequency coming from a loudspeaker to the right of the listener will cause a 5 Hz binaural beat. However, reflections of both signals will most likely be a factor in a typical performance environment, which will result in the listener's ears receiving both the direct signal from one loudspeaker and the reflected signal of another in the same ear

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[84] Ibid, p.94
[85] Ibid, p.95
[86] Ibid, p.97

simultaneously, which can result in monaural beating.

In relation to applications of binaural beating within music composition, to date there is very little published material directly proposing methods for its employment. The discussion in relation to uncovering finite data regarding the perceived amplitude modulation and exact active range of binaural beating (which differs for each individual) remains ongoing. While studies are commonly conducted into various binaural phenomena, those which investigate binaural beating are much less common; consequently, a significant lack of output exists within research concerning compositional methodology. In the 1970s a relatively sizeable amount of research was conducted on binaural beats; however, other than discussions regarding the fundamental theoretical components of the phenomenon which were outlined by Oster, very little progress has since been made in the area that could be beneficial to composers. Such findings have been described by Grose, Buss and Hall, as 'scattered observations' while also stating that 'findings [c. 1970] were sparse and oddly disjointed.'[87] Creative methods concerning the interplay of the beating composite tone and primary tone parameters, estimated perceptual responses to differing amplitude levels between primary tones, and binaural beats triggered from complex inharmonic sound sources remain almost untouched and could prove to be a major benefit to the application of the phenomenon within music composition.

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[87] John H. Grose, Emily Buss, William W. Hall III, 'Binaural Beat Salience', *Hearing Research*, 285 (2012), p.40-45 (p.40)

As well as Oster's material, research output in the 1970s also included Jerry Tobias' *Curious Binaural Phenomena,* which considered varying perceptual sensitivities between men and women. Perrott and Musicant's paper *Rotating Tones and Binaural Beats* claimed that the upper limit of binaural beat perception could stretch up as high as 1,170–1,255 Hz.[88] McFadden and Pasanen's *Binaural Beats at High Frequencies* argued that binaural beats could be produced with acoustic primary tones (APTs) of 3,100/3,101 Hz.[89] The problem with this theory was that the authors also stated that, while the aforementioned frequencies were to be presented dichotically to the listener, a tone of 3,000 Hz must also be presented to both ears.[90] Eric Heller's book *Why You Hear What You Hear* disproves any beating that the listener perceives through this method by explaining the nature of monaural waveform beats.[91] More recent research from Grose et al., in the paper *Binaural Beat Salience* made some progress in relation to AM behaviour within binaural beats. This method sought to match listener's responses to sinusoidal amplitude modulated tones to their perception of AM within binaural beats.[92] The resulting data found that perception of AM shifts in binaural beating is quite weak (in the range of 400–500 Hz where beating is at its strongest) and, while the finer details of these findings are presented in this research, they would not prove beneficial to composers.[93] As a result of these factors relating to a staggered output and lack of clarification within this area of research, many composers are aware of binaural beats but have few repositories to consider when investigating the area and so their application and validity is predominantly overlooked in composition.

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[88] David R. Perrott and Alan D. Musicant, 'Rotating Tones and Binaural Beats', *Journal of the Acoustical Society of America*, 61 (1977), 1288-92 (p.1288)

[89] Dennis McFadden and Edward Pasanen, 'Binaural Beats at High Frequencies', *Science*, 190 (1975), 394-396 (p.394)

[90] Ibid, p.394

[91] Eric J. Heller, *Why You Hear What You Hear*, (Princeton and Oxford: Princeton University Press, 2013), p.484-8

[92] John H. Grose, et al., *Hearing Research*, p.40

[93] Ibid, p.45

Headphones could be seen as the ideal listening environment for such application procedures as they remove the possibility of an intrusion of monaural beats as a result of reflections, while also allowing the stimulus to directly enter the necessary ear of the listener at a sufficient intensity level. Multichannel loudspeaker arrangements are also quite effective in demonstrating this phenomenon within a compositional paradigm, however, a greater level of reflections and possibility of less-effective intensity levels do exist in a free field concert hall environment. The nature of intracranial motion is somewhat peculiar to binaural beat perception. Intracranial motion relates to the perceived movement of a binaural beat within one's own head and its theory is quite simple. The listener will often perceive a movement of the binaural beat as though it is traveling through their head at a rate of the binaural beat frequency. This phenomenon offers the composer a heightened sense of movement, which is listener-specific and the movement need not be generated explicitly by the composer in the loudspeaker setup through panning, etc. Akeroyd's brief document entitled *A Binaural Beat Constructed from a Noise* in 2010 addressed noise-based stimuli for binaural beating by considering bands of noise presented dichotically to the listener with the phase and amplitudes of the components all modulated by a set frequency in one ear.[94] Akeroyd found that, while such a method resulted in a stronger 'percept of motion' the data collected from the test subjects varied in relation to the behaviour of this movement.[95] This would suggest that, while intracranial motion can prove effective, a less specific treatment of this perception of movement should be considered within music composition.

Binaural beats can also be seen as a device that can add a greater sense of physical place within, in particular, a multichannel loudspeaker arrangement. Certain tones are perceived as being created

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[94] Michael A. Akeroyd, 'A Binaural Beat Constructed from a Noise', *Journal of the Acoustical Society of America,* 128 (2010), 3301-3304 (p.3301)

[95] Ibid, pp.3301-3304

within the listener's own head, while the sounds being emitted from the loudspeakers are perhaps perceptually travelling in many directions within the listening space. When considering a sense of space within a work, it is important to note how a perception of physical space can be created within such a context. A sizeable perceptual space does not need a large level of stimuli to be created. When positioned accordingly, two basic sonic elements are sufficient in creating a significant sense of space, both in relation to pitch height as well as dimensional depth. The generation of binaural beating can be achieved with just two pure tones, which are closely positioned in terms of frequency and set in opposition to each other in a loudspeaker/headphone environment. This simple gesture will automatically generate a third sonic event within the listener's own head while the listener will also be perceiving the tones that are being performed by the loudspeakers, as well as intracranial motion. Were the two tones in question not close in frequency, and therefore not to provoke binaural beating, the listener would experience a reduced sense of space in relation to how they perceive their own proximity to these loudspeaker tones. Chechile applies similar thinking in his work with DPOAEs in composition. Chechile writes:

> In addition to loudspeaker-based sound diffusion, a second layer of spatial depth is created by provoking the ears to emit frequencies of their own.[96]

Much like its monaural equivalent, binaural beating techniques can also be an efficient tool for timbre modulation as research into sensory dissonance directly relates to levels of beating and roughness. Stefan Koelsch has explained that

> when the beats have higher frequencies (above ~20 Hz), these beats are perceived as *roughness* and are a sensory basis for the so-called *sensory dissonance.*[97]

One of the primary elements of the perception of harmonic and inharmonic material is the nature of

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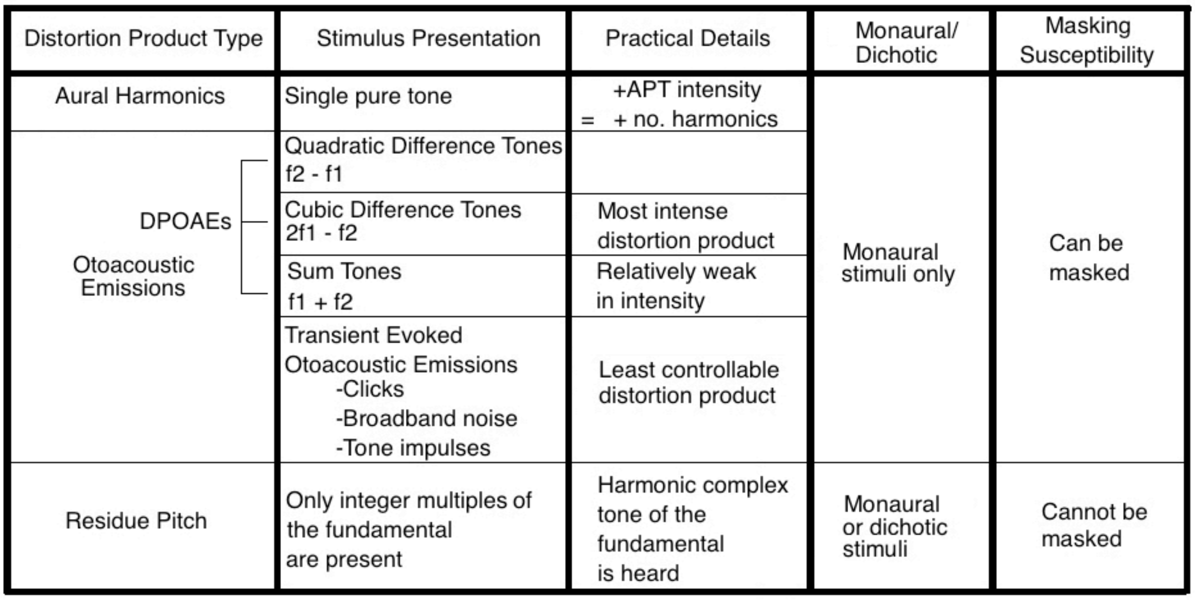
[96] Alex Chechile, 'Creating Spatial Depth Using Distortion Product Otoacoustic Emissions in Music Composition', p.50

[97] Stefan Koelsch, *Brain and Music*, (Oxford: Wiley Blackwell, 2013), p.10

various bandwidth phenomena, which also plays a key role in the perception and creation of binaural beating. By considering these factors it appears that a direct link can be made between timbre modulation and binaural beating. In relation to periodic material presented by acoustic instruments, the addition of electronics to a work can allow for manipulation of overtones. This can generate an effective shift in timbre, intracranial motion as well as a widening of the perceptual listening space. For example, if a cello is playing a sustained A3 (220 Hz) its first two harmonics will be presented at 440 Hz and 660 Hz. Digital signal processing can control the hard panning of the raw input recorded signal to one stereophonic position. By frequency-shifting the 440 Hz and 660 Hz up/down by 5 Hz and directing them to the opposite stereo position, a 5 Hz binaural beat will be generated within the harmonic series of the A3 note. If such an effect were to be presented balanced (and monaural beating was evident) the behaviour of the beating and character of the dissonance would be entirely different as it would not appear to be moving. It would also display a smaller perceptual space which would not be the case if this method was conducted through binaural treatment. This method can also be applied to complex inharmonic structures, providing the use of notch filters (or similar) are applied to create stimulus tones. Inharmonic applications of binaural beats can prove very effective when considering spatial positioning and perceived movement within the listening space, particularly when considering thick complex sonic materials.

While certain elements of binaural beats remain unknown, their application within a variety of compositions in this research has proven that qualitative research methods are not only required, but are beneficial for their potential applications within composition to be established.

2.3 Auditory Distortion Products



Distortion Product Type	Stimulus Presentation	Practical Details	Monaural/ Dichotic	Masking Susceptibility
Aural Harmonics	Single pure tone	+APT intensity = + no. harmonics	Monaural stimuli only	Can be masked
Otoacoustic Emissions DPOAEs	Quadratic Difference Tones f2 - f1			
	Cubic Difference Tones 2f1 - f2	Most intense distortion product		
	Sum Tones f1 + f2	Relatively weak in intensity		
	Transient Evoked Otoacoustic Emissions -Clicks -Broadband noise -Tone impulses	Least controllable distortion product		
Residue Pitch	Only integer multiples of the fundamental are present	Harmonic complex tone of the fundamental is heard	Monaural or dichotic stimuli	Cannot be masked

Figure 11: Chart outlining the primary details of Aural Harmonics, OAEs and residue pitch

2.3.1 Introduction

In this section a number of provocation methods will be outlined in which input acoustic energy into the ear of the listener can illicit an acoustic response from their inner ears. For many years it was thought that non-linearities in the listening system were due to mechanical factors relating to the middle ear; however, White and White state that

> any nonlinearity lies within the neural system of the cochlea itself [...] (and) is related in a complicated way to the frequency distribution of vibrational energy in or around the hair-like cilia or neurons.

Furthermore, White and White's research has outlined the following thresholds at which, when intensity/frequency levels are greater, the ear begins to behave non-linearly:

30 dB	350 Hz
50 dB	1,000 Hz
55 dB	5,000 Hz

Figure 12: White and White's outline of intensity/frequency level at which hearing moves from linear to nonlinear[98]

Auditory distortion products result in lower amplitude acoustic energy (relative to the stimulus signal), which the listener can also perceive, being emitted from the back out towards the outer ear at frequencies which are not present in the stimulus signal. These phenomena allow for composers to directly use the ears of the listeners as sources of frequency content, which is independent from the external free-field acoustic environment.

2.3.2 Aural Harmonics

The most simple auditory distortion products are aural harmonics, which can be provoked using a single pure tone in one ear at a 'high enough' frequency level.[99] This phenomenon concerns frequency content relating to integer multiples of a stimulus tone being emitted out from the ear at decreasing intensity levels with increasing frequency value.[100] **[Audio Demonstration 5]** These aural harmonics are susceptible to masking and a correlation is seen between an increase in primary tone intensity level and the number/intensity level of aural harmonics that are produced.[101] A substantial number of studies have been conducted into determining the exact measurements of both

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[98] Harvey E. White and Donald E. White, *Physics and Music: The Science of Musical Sound* (New York: Dover Publications Inc, 2014), p.188

[99] Stanley A. Gelfand, *Hearing*, p.220

[100] Ibid, p.220

[101] Ibid, p.188

the intensities of the produced harmonics and their correlation to both the frequency and intensity of the stimulus tone; however, various debates have remained prolific in this research area in relation to the construction of an effective model for aural harmonics.[102]

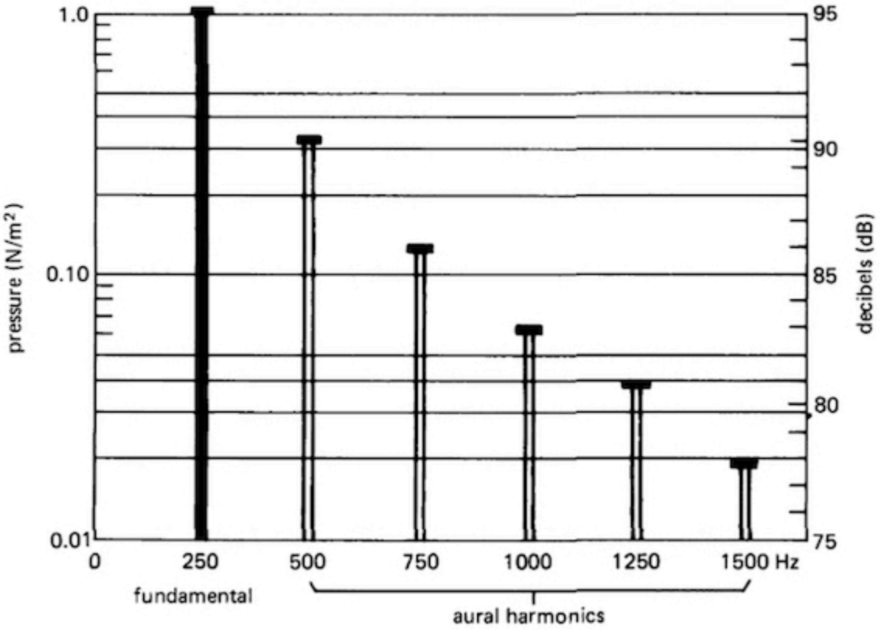

Figure 13: Example of aural harmonics generated with a 250 Hz pure tone at 95 dB[103]

Furthermore, their lack of intensity, combined with susceptibility to masking renders them relatively ineffective and unreliable as an auditory distortion product within complex sonic environments. Campbell and Greated have gone as far as stating that aural harmonics

> are at such a low level in comparison with the original sound that they are of no musical significance.[104]

While such a statement is highly subjective, it highlights the reduced effectivity of such a distortion product within composition in comparison to others. Furthermore, the required 95 dB as referenced in Figure 13 may not be considered practical for sine tone demonstration in a musical context as it

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[102] Ref 1; Earl D. Schubert, 'History of Research on Hearing', in *Hearing: Handbook of Perception v.4*, ed. by Edward Carterette and Morton P. Friedman, (New York, San Francisco, London: Academic Press, 1978), p.55
Ref 2; William M. Hartmann, *Signals, Sound, and Sensation* (New York: Springer-Verlag, 2005), p.513-4

[103] Harvey E. White and Donald E. White, *Physics and Music: The Science of Musical Sound,* p.188

[104] Murray Campbell and Clive Greated, *The Musician's Guide to Acoustics*, (London: J.M. Dent & Sons Ltd, 1987), p.64

may cause discomfort in some listeners. Prolonged exposure to such intensity can result in irreparable hearing damage and so use of very loud/impulsive material should be considered carefully.

2.3.3 Otoacoustic Emissions

Otoacoustic emissions (OAEs) are sounds of cochlear origin caused due to fluctuations of the outer hair cells, which travel backwards towards the auditory canal where the acoustic energy can be detected by an in-ear microphone.[105] The fluctuation of these hair cells, as a result of electrical energy, causes them to change their shape.[106] This transduction from electrical to mechanical energy is known as the 'electromotile response', which is responsible for OAE production.[107] Ramos, Kristensen and Beck state that

> OAEs may therefore be considered acoustic sounds that originate secondary to movement of the cochlea's hair cells.[108]

OAEs can be categorised into two main types: distortion product otoacoustic emissions and transient-evoked otoacoustic emissions. Furthermore, as the fundamental details of the method would suggest, the stimulus tones for OAEs must be presented monophonically.

2.3.3.1 Distortion Product Otoacoustic Emissions

Two of the most accessible distortion product otoacoustic emissions (DPOAEs) for composers are quadratic difference tones (QDTs) and cubic difference tones (CDTs). DPOAEs are also commonly known as 'combination tones' due to their dependence on the existence of a combination of acoustic

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[105] David T. Kemp, 'Otoacoustic emissions, their origin in cochlear function, and use', *British Medical Bulletin*, 63 (2002), 223-241 (223)

[106] Jessica Arrue Ramos, Sinnet Greve Bjerge Kristensen and Douglas L. Beck, 'An Overview of OAEs and Normative Data for DPOAEs', *Hearing Review*, 20 (2013), 30-33, (p.33)

[107] Ibid, p.33

[108] Ibid, p.33

primary tones (APTs).[109] The most basic DPOAE is the QDT, which can be provoked as follows f2-f1 (when f2 > f1). Two stimulus tones entering the ear at 1,000 Hz (f1) and 1,200 Hz (f2) will produce a QDT at 200 Hz, which will have similar sonic properties to that of a square wave or a low intensity buzzing. **[Audio Demonstration 6a]** The simultaneous presentation of 1,000 Hz and 1,200 Hz stimulus tones can also generate a sum tone (ST) of 2,200 Hz (f1 + f2). Sum tones are generally quite weak in intensity (particularly lower in intensity in relative terms to other DPOAEs) and consequently, are not always audible.[110] These stimulus tones force the natural behaviour of the cochlear amplifier ('without which the auditory system is effectively deaf') to be 'rendered audible to the listener.'[111]

Kemp has expressed that 'more powerful excitation is practical with continuous tones'.[112] From this point alone, a clear connection between prolonged sine waves in electroacoustic music are the ideal (and most reliable) source of stimulation for such a phenomenon in music. Furthermore, the most powerful DPOAEs are generated when the two stimulus tones are within half an octave of each other and when f1 has a greater intensity of 10–15 dB.[113] The approximate range of 84–95 dB sound pressure level (SPL) will provide the most audible distortion products in the ears of the listener in the context of a free-field loudspeaker environment.[114]

The cochlear amplifier is capable of producing OAEs from -10 dB to +30 dB SPL in the ears of healthy hearing individuals.[115] In relation to the lowest effective SPL of acoustic primary tones, an

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[109] Murray Campbell and Clive Greated, *The Musician's Guide to Acoustics*, p.64
[110] Stanley A. Gelfand, *Hearing*, p.220
[111] Ref 1; Jonathan Ashmore, 'Cochlear Outer Hair Cell Motility', *Physiological Reviews*, 88 (2008), 173-210 (p.174). Ref 2; Christopher Haworth, 'Ear as Instrument', p.61
[112] David T Kemp, 'Otoacoustic emissions, their origin in cochlear function, and use', p.226
[113] James Wilbur Hall, *Handbook of Otoacoustic Emissions*, (San Diego: Cengage Learning, 2000), p.22
[114] Alex Chechile, 'The Ear Tone Toolbox for Auditory Distortion Product Synthesis', https://ccrma.stanford.edu/~chechile/eartonetoolbox/Chechile_ICMC16.pdf [Accessed 27th September 2016]
[115] Jessica Arrue Ramos, Sinnet Greve Bjerge Kristensen and Douglas L. Beck, 'An Overview of OAEs and Normative

SPL of at least 60 dB must be provided.[116] A steady state distortion product can also be created when the stimulus tones are modulating in frequency providing the mathematical difference between the two tones remains consistent. Distortion products with modulating frequencies can also be generated easily through these methods, as the frequency distance between the APTs over time requires simple consideration. The formulaic nature of provoking QDTs and CDTs (2 (f1) - f2) allows for simple inclusion of distortion products within composition as only basic calculations are required. Providing the distance in frequency is constant, modulating APTs can produce a static DPOAE. **[Audio Demonstration 6b]** Furthermore, if the frequency distance is shifting between APTs, a modulating DPOAE can be produced. [Audio Demonstration 6c] Multichannel loudspeaker arrangements are particularly well-suited for the demonstration of complex distortion product arrays which can, if applicable, allow the listener to experience a multiplicity of timbral colours within an immersive sphere of, what Chechile describes as, microscopic and macroscopic elements.[117] Furthermore, an inverse relationship is evident between QDTs and CDTs regarding the intervallic distances of their APTs.
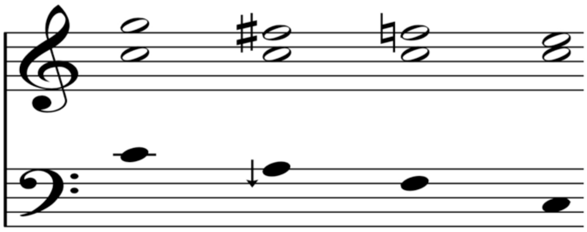
Figure 14: Decrease in APT interval causes QDT value to fall (above) and CDT value to rise (below)[118]

While DPOAEs are often created in test procedures through pure tones, due to their simplicity and accuracy, that is not to say that all stimuli used in the provocation of DPOAEs must be pure tones.

Data for DPOAEs', p.33

[116] As referenced in; Stanley A. Gelfand, *Hearing*, p.225 (Secondary Source)

[117] Alex Chechile, 'Creating Spatial Depth Using Distortion Product Otoacoustic Emissions in Music Composition', *ICAD 2015 Proceedings*, 50-53 (p.53)

[118] Murray Campbell and Clive Greated, *The Musician's Guide to Acoustics*, p.65

Quadratic difference tones were known as 'Tartini tones' in the mid-1700s after the violinist Giuseppe Tartini discovered that two finely tuned intervals on the violin could provoke a third tone. With regards to complex non-periodic sound sources, stimulus tones can also be created through simple equalisation procedures concerning the amplification of a clear peak centre frequency within a bandwidth of up to approximately 20–30 Hz. This method is effective as the peak frequency will not be subject to masking and it can behave as an independent stimulus tone providing the second stimulus tone is not present within close proximity (below 30–40 Hz) in the same critical bandwidth.

2.3.3.2 Transient Evoked Otoacoustic Emissions

Transient-evoked otoacoustic emissions (TEOAEs) are often referred to as click-evoked otoacoustic emissions (CEOAEs) and delayed otoacoustic emissions (DEOAEs), and they can be generated through stimuli of very short duration. These transient sounds, which can be short bursts of broadband noise, clicks or tone impulses, activate an extensive area of the basilar membrane[119]. Kemp has described the nature of TEAOEs as being a cochlear 'echo.'[120] **[Audio Demonstration 7]** Due to the effectivity of TEOAEs in inducing a response from the listener's ears they are used in the medical profession in hearing testing procedures at 80–85 dB SPL with click-based stimuli proving most common.[121] A typical delay time of 5−15 ms is most evident; however, latency is inversely correlated to frequency.[122]

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[119] Jessica Arrue Ramos, Sinnet Greve Bjerge Kristensen and Douglas L. Beck, 'An Overview of OAEs and Normative Data for DPOAEs', p.33

[120] David Kemp, 'What are Otoacoustic Emissions?' Paper presented at the *International Symposium on Otoacoustic Emissions*, 1991

[121] Kathleen C.M. Campbell, 'Otoacoustic Emissions', *Medscape*, *http://emedicine.medscape.com/article/835943-overview#a2* [accessed 25 March 2016]

[122] Ref 1; Jessica Arrue Ramos, Sinnet Greve Bjerge Kristensen and Douglas L. Beck, 'An Overview of OAEs and Normative Data for DPOAEs', p.33.
Ref 2; Hugo Fastl and Eberhard Zwicker, *Psychoacoustics: Facts and Models*, p. 44.

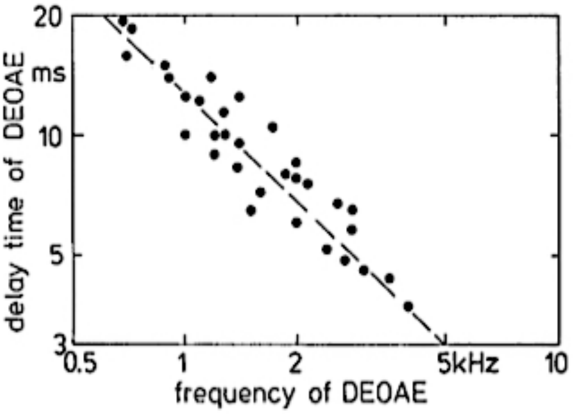

Figure 15: Graph outlining latency versus frequency content in TEOAEs (here referred to as DEOAEs)[123]

While research findings remain somewhat inconclusive into the exact frequency components that can be evoked through click-like stimuli, TEOAE amplitude levels can reach up to just 5–10 dB below the stimulus level.[124] Research from Ramos, Kristensen and Beck stated that TEOAE frequencies are generally between 1–4K Hz while also highlighting that TEOAE amplitudes are larger in infants than in adults.[125] These differences in TEOAE behaviour across varying ages has also been addressed by Yates who found that responses of up to 6–7K Hz can be experienced in young ears.[126] These limitations were found to be incorrect as, TEOAEs (and DPOAEs) have been recorded as high as 16K Hz through improved testing procedures, addressed limitations in pre-existing measurement procedures.[127] Nonetheless, the aforementioned findings in relation to diminished TEOAE sensitivity with age remain unchanged.

In relation to the evoking of TEAOEs, research conducted on TEOAEs in the range of 1–5 Hz has

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[123] Ibid, p.44

[124] Hugo Fastl and Eberhard Zwicker, *Psychoacoustics: Facts and Models*, p. 42

[125] Jessica Arrue Ramos, Sinnet Greve Bjerge Kristensen and Douglas L. Beck, 'An Overview of OAEs and Normative Data for DPOAEs', p.33

[126] As referenced in; David T Kemp, 'Otoacoustic emissions, their origin in cochlear function, and use', p.225

[127] Shawn S. Goodman, Denis F. Fitzpatrick, John C. Ellison, Walt Jesteadt and Douglas H. Keefe, 'High-frequency Click-Evoked Otoacoustic Emissions and Behavioral Thresholds in Humans', *Journal of the Acoustical Society of America*, 125 (2009), 1014-1032, (p.1014)

found that, as the stimulus duration exceeds 300 microseconds, the signal-to-noise ratio reduces.[128] Consequently, it could be suggested that more prominent TEOAEs can be produced with longer duration stimuli. TEOAEs are in stark contrast to DPOAEs in that their frequency content in relation to multiple simultaneous listeners, is almost entirely indeterminable; however, bursts of thick high frequency spectral content in between clicks/noise bursts, etc, is very much predictable. Sutton's broad description of the spectral characteristics of TEOAEs describes them as presenting several dominant frequency bands that are separated by weaker and narrower bands of frequency content.[129] This uncertain nature is only emphasised by the fact that, while TEOAE amplitude and frequency values will differ between listeners, they will also vary from ear to ear of the listener.[130]

TEOAEs are quite a peculiar auditory distortion product as, while QDTs and CDTs present OAEs that are predominantly present while the stimulus is active (some backward masking methods are somewhat effective), TEOAEs do not require the simultaneous presentation of the stimulus and thus can be heard unaccompanied. Furthermore, the listener is also very likely to physically feel their ears beating/pulsating in response to these transient stimuli.

2.3.4 Residue pitch

Residue pitch (also known as the 'missing fundamental phenomenon' or 'virtual pitch') concerns the scenario in which the listener is presented with a complex harmonic signal and the fundamental tone is removed; however, the listener hears a harmonic fundamental tone (or very close to it) despite only being presented with a number of its overtones. **[Audio Demonstration 8]** This can be

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[128] Jayashree S. Kaushlendrakumar, Pearl Edna D'costa Bhat and Christina Jean Vivarthini, 'Effect of Different Click Durations on Transient Evoked Otoacoustic Emission', *International Journal of Computational Intelligence and Healthcare Informatics,* 4 (2011), 31-33 (p.33)

[129] As referenced in; Raymond M. Hurley and Frank E. Musiek, 'Effectiveness of Transient-Evoked Otoacoustic Emissions (TEOAEs) in Predicting Hearing Level', *Journal of the American Academy of Audiology*, 5, (1994), p.195-203 (p.196)

[130] Ibid, p.196

simplified by stating that the listener can perceive a tone which is the equivalent to the common frequency distance between a presented stack of partials. Sharine and Letowski have described residue pitch as being

> an indication that our listening system responds to the overall periodicity of the incoming sound wave.[131]

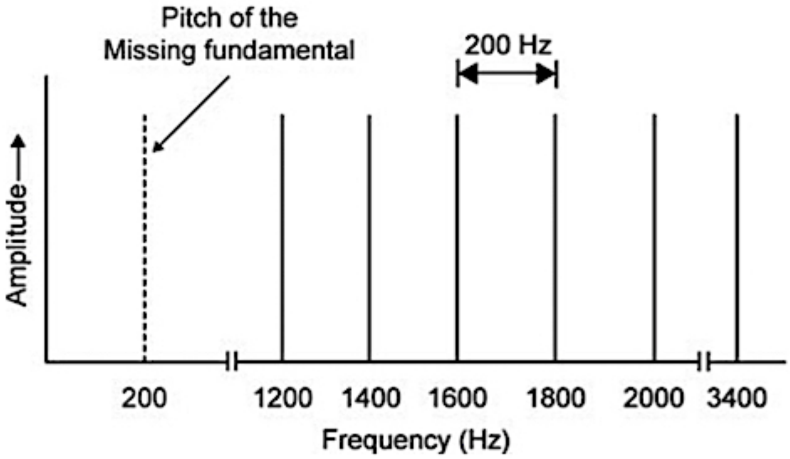

Figure 16: Spectrum illustrating the missing fundamental phenomenon[132]

Gelfand explains that, in Schouten's model,

> the auditory system is responding to the period of the complex periodic tone (5 ms or 0.005 s), which corresponds to the period of 200 Hz (1/0.005s = 200 Hz). [Figure 21]

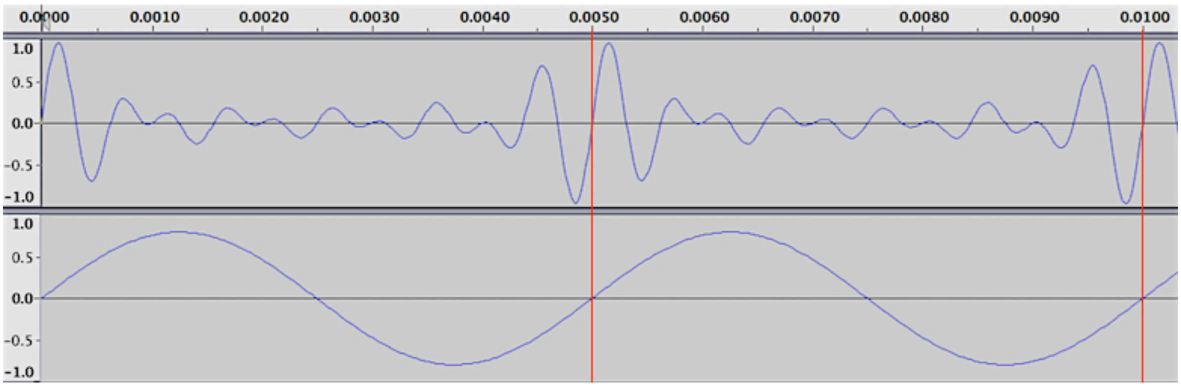

Figure 17: Timeline displaying a complex periodic tone containing partials at 1,200 Hz, 1,400 Hz, 1,600 Hz, 1,800 Hz and 2,000 Hz (above) which exhibits the same period as a 200 Hz sine wave (below).

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[131] Angelique Sharine and Tomasz R. Letowski, ‘Auditory Conflicts and Illusions’, in *Helmet-mounted displays: Sensation, perception and cognition issues*, ed. by C.E. Rash, M.B. Russo, T.R. Letowski and E.T. Schmeisser (Alabama: U.S. Army Aeromedical Research Laboratory, 2009), pp.579-598 (p.583)

[132] Stanley A. Gelfand, *Hearing*, p.225

Residue pitch is quite a durable source of frequency content that can be heard with the SPLs of stimulus tones as low as 20 dB.[133] The upper limit for its detection among listeners has been posited by Plomp and Moore as being approximately 1,400 Hz.[134] A clear benefit of this mechanism relates to issues concerning the speed of energy transfer and the positioning of the base and apex in relation to the flow of energy through the inner ear. Patterson has expressed that residue pitch

> enables the listener to extract the low pitch associated with the fundamental of a sound much faster than it would be possible if the information had to be extracted from the fundamental alone.[135]

Furthermore, residue pitch can be created despite multiple lower overtones not being present and, unlike combination tones, it cannot be masked by an incoming acoustic signal, thus making it a more robust compositional device in certain contexts.[136] This aspect of the phenomenon also results in residue pitches being unable to behave as primary tones in monaural beating techniques and so it could be argued that compositional methods employing this phenomenon have an accessible level of control over its frequency content which methods utilising OAEs cannot offer.[137] The primary tones for this mechanism may also be presented dichotically and remain effective which Roederer believes indicates that residue pitch is a result of a higher level neural processing.[138] In relation to a practical application of this phenomenon, the greater the number of partials present, the greater the intensity of the produced residue pitch. The perception of residue pitch could be easily confused as being a DPOAE due to its illusory nature as the perceived tone is not present in the acoustic signal. The perceived tone relates to the common mathematical difference between the partials that are present, thus particularly relating it to DPOAE perception.

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[133] Ibid, p.225

[134] As referenced in; Stanley A. Gelfand, *Hearing*, p.225

[135] Roy D. Patterson, Robert W. Peters and Rober Milroy, 'Threshold Duration for Melodic Pitch', in *Hearing: Physiological Bases and Psychophysics,* ed. by Rainer Klinke and Rainer Hartmann, (Berlin, Heidelberg, New York, Tokyo: Springer-Verlag, 1983), p.321

[136] Gary Kendall, Christopher Haworth and Rodrigo Cádiz, 'Sound Synthesis with Auditory Distortion Products', p.7

[137] Stanley A. Gelfand, *Hearing*, p.225

[138] Juan Roederer, *The Physics and Psychophysics of Music: An Introduction*, 4th edn (New York: Springer, 2008), p.51

Gelfand has also outlined that, while various theories which attempt to explain the exact biomechanical processes that take place in the perception of residue pitch, none can provide a 'comprehensive account' of this perceptual behaviour.[139] As can be seen in the existence of a number of place theories, as well as temporal theories and a combined theory of pitch perception, such inconclusive data is both common and to be expected in this area of research. Furthermore, Gelfand has addressed pitch ambiguity relating to the pitch-extracting mechanism comparing a peak of one cycle in a complex waveform with an inequivalent peak in the next cycle as one such example of uncertainty that is evident.[140] Nevertheless, the primary aspects of residue pitch are much clearer in relation to the essential details of the relationship between the input stimuli and the biomechanical 'output'; therefore, its reliability as a compositional tool remains strong.

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139 Stanley A. Gelfand, *Hearing*, p.227
140 Ibid, p.226

3 The Inner Ear as a Musical Instrument

3.1 Introduction

Directly considering the inner ear as a musical instrument places the audience in a new position within the listening process. While the listeners are not given any explicit tasks to conduct consciously, their ears are given active roles within the musical performance. By viewing the listener corporeally in this context, a connection is made between the acoustic energy and the listener's inner ear. Such an approach bridges the gap, to some extent, between the composer of such music and their audience, as the physicality of the listener now has an integral part to play in the realisation of the music itself; the facilitation of the performance of the work. The audience's ears become a stage on which much of the work is performed.

3.2 Universal Limitations on Compositions

In relation to OAEs, Haworth's central thesis is that the listener is 'drawn inward' by the phenomenon which causes them to become 'both an agent and recipient of the sound.'[141] This added level of interaction between the listener and the musical material does not place any more responsibility on the listener or make any assumptions about the individual's own ability. Such compositional praxis makes no more demands of the listener than any other creative method in music which must assume that its audience will have varying hearing sensitivities and thus each audience member will, in certain respects, experience their own version of the material.

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[141] Christopher Haworth, 'Ear as Instrument', p.61

While a composition that considers the ear directly as a primary compositional device places more focus on the ear of the listener than perhaps other styles, it would be irrational for such methodology to place any expectancy on the individuals or to make assumptions regarding the health of their ears. An immeasurable level of variables already exists within the perception of sound and music. Helmholtz found that individuals are subject to one of two modes of listening: analytical and synthetic, thus highlighting that listeners will vary in how they fundamentally listen, which neither the composer nor listener can determine.[142] Analytical listeners rely on analysing the entire spectrum of a sound, with each component heard separately, while synthetic listeners generally focus on the entirety of complex sounds as a whole.[143] Oliveros' studies into attention patterns has proven that each individual will also experience sound differently depending on their own attention levels which affects their perception of the musical product.[144] Oliveros has described the multidimensional process of perceiving music by stating that

> the ear hears, the brain listens and the body senses vibrations [...] we confuse hearing with listening [...] listening, or the interpretation of sound waves [...] is subject to time delays. Sometimes what is heard is interpreted anywhere from milliseconds to many years later or never[145]

Wallaert, Moore and Lorenzi's investigations into the effects of age on amplitude and frequency modulation (AM and FM) detection, have shown that with increasing age (the older test group was aged 44–66 years), a reduction in sensitivity for both AM and FM is clearly evident. This study

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[142] Hermann von Helmholtz, *On the Sensations of Tone,* 3rd edn (London and New York: Longmans, Green, and co, 1895) p.62

[143] Olga Tsoumani and Marie Posta-Nilsenová, 'Perceiving sounds: analytic and synthetic listening, global-local processing and possible links with empathy and self-construal', *CogSci 2013 Proceedings,* 3587-3592 (p.3587)

[144] Alan Baker, 'An Interview with Pauline Oliveros', American Mavericks, http://musicmavericks.publicradio.org/features/interview_oliveros.html [accessed 28 September 2016]

[145] Pauline Oliveros, *The difference between hearing and listening | Pauline Oliveros | TEDxIndianapolis*, online video recording, YouTube, 12 November 2015, <https://www.youtube.com/watch?v=_QHfOuRrJB8>, [accessed 20 June 2016]

highlighted the reduced efficiency with age in processing excitation patterns and cues relating to AM and FM detection. With these findings of Helmholtz, Oliveros and Wallaert et al., a level of uncertainty regarding the audience's perception is evidently already a factor within the presentation of one's work. Furthermore, it is clear that a composer can, at best, only make informed assumptions with regards to the sensitivities of their audience's ears.

There are a number of possible factors which may result in OAEs having little or no effect on the listener. In some cases the listener's ears may be producing these distortion products effectively yet the individual may be unable to identify them. However, these issues are by no means peculiar to works employing the inner ear as an instrument.

Another impact of aging on the ears is presbyacusis, which results in a reduction of frequency sensitivity over time. Consequently, composers who focus on, for example, timbral subtleties within higher frequency sounds are always at risk of elements of their work proving less effective on more senior audience members or on those with reduced sensitivity due to hearing damage. Furthermore, the physical positioning of each audience member within the listening space will result in alternating levels of reflections which will cause various binaural/monaural effects as well as proximity to the individual loudspeakers resulting in a somewhat listener-specific nature of the performance of works, in particular, those which involve multichannel diffusion. As employing the inner ear as an instrument directly relies on the abilities of the listener's ears in order for a true realisation of the work to take place, it does not mean that, as an artistic product, it is any less susceptible to a risk of certain aspects of its performance not fully translating to the entirety of its audience.

One of the more challenging aspects of employing such material in one's compositions is in relation to a somewhat reduced effectivity at times which can be a consequence of audience scepticism, a function of hearing damage, dissatisfying intensity levels or perhaps a simple inability to identify the material having never practiced listening in such a way before. Chechile writes that

> The intimacy of allowing a layer of the music to be generated within one's own ears is, however, not for everyone. Audience members suffering from tinnitus or hearing loss occasionally report the experience as disagreeable, or in the latter case, not perceivable. [146]

Those who can both produce and identify OAEs will experience a sensation that is unique to the strengths and/or weaknesses of their own listening system. Heller has explained that the 'perceived strength is dependent on the listener, context, and training' and also that

> there may be no fixed set of answers to the question of what phantom tones are heard under a given set of circumstances

and this provides an insight into the subjective nature of the material at hand.[147]

It must be noted that listeners with hearing damage may find a reduced sensitivity to identifying OAEs as well as a reduced ability for their ears to produce them. In their article *Transient evoked otoacoustic emissions and cochlear dysfunction,* Uribe-Escamilla, Poblano and Alfaro-Rodríguez stated that 'only healthy cochlear systems are able to produce emissions.'[148]

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[146] Alex Chechile, 'The Ear Tone Toolbox for Auditory Distortion Product Synthesis', https://ccrma.stanford.edu/~chechile/eartonetoolbox/Chechile_ICMC16.pdf [Accessed 27th September 2016]

[147] Eric J. Heller, *Why You Hear What You Hear*, p.495-6

[148] Rebecca Uribe-Escamillia, Adrián Poblano and Alfonso Alfaro-Rodríguez, 'Transient evoked otoacoustic emissions and cochlear dysfunction', *Egyptian Journal of Ear, Nose, Throat and Allied Sciences*, 14 (2013), 195–200 (p.196)

3.3 Exclusivity of the Methodology

Utilising the audience's inner ears within the performance potentially adds an entirely new dimension to the listening experience. Sounds created by OAEs, residue pitch and binaural beating are entirely positioned within the listener's own head and thus are independent of the loudspeaker/headphone output. This creation of a uterine environment through inner ear manipulation also allows the listeners to physically explore a listening space such as turning one's head within a multichannel environment to modulate the timbre or by experiencing varying levels of masking if moving through the listening space is possible. This approach to composition also offers a greater opportunity for the listeners to obtain a heightened awareness of their own ears and their potential within musical performance. In many cases relating to OAEs, the listeners can physically feel their ears responding to the acoustic energy entering the inner ear thus providing the audience with a relatively rare sensory experience within the music.

The question of being able to replicate the sonic product that is created by the inner ear through external means often arises from a fundamental misinterpretation or misunderstanding of the ear as an instrument concept. OAEs and residue pitch allow the listener to perceive tones which can be below both the common threshold of the loudspeaker output and inner ear input sensitivities. OAEs also allow the listener to move within a listening space and feel external sounds moving while the distortion products literally travel with them within their own ears, while binaural beats allow for sounds to perceptually travel within one's own head. Aside from facilitating the production of sounds which may be otherwise impossible, it is the case that non-linear inner ear phenomena may also be responsible for the creation of material which could be seen to be somewhat replicated synthetically. In certain circumstances the fundamental sonic presentation of binaural beats can be easily synthesised through specific AM procedures carried out on sine waves; however, replicating the intracranial motion, without disturbing the APT presentation, is not so accessible. Likewise, the buzz-like nature of DPOAEs could be generated through low intensity square waves (or similar), although none of these methods have the ability of replicating the intrinsic behaviour of these phenomena relating to their varying responses to critical bandwidth. Furthermore, sounds being presented through loudspeakers/headphones can never be experienced by the listener as though they are occurring solely within their ears as in OAEs. The level of intimacy, as is evident in OAE perception, cannot be replicated by external sound sources as the sounds will never sound as though they are coming from within the listener's own ears. Distortion products will frequently be experienced as though they are occurring inside the listener's ears.

While these phenomena are subject to many limitations relating to their potential for application, they contain similar restrictions that are evident with the use of many musical instruments. As these various phenomena offer exciting possibilities for perceptual exploration within music, it could be argued that any of their limitations can be traded-off against the potential for opening up a new platform for creative employment when their behaviour is carefully and directly considered.

3.4 Performance Considerations

A number of factors relating to varying performance spaces should be explicitly acknowledged and addressed when presenting work with a psychoacoustical focus. The most effective venues for the performance of material which has a heavy use of transient or sinusoidal materials are those in which minimal reflections are present in the acoustic design of the space as well as a sound desk being well positioned in the path of all loudspeaker outputs. Reflections of transient sounds that are employed in the provocation of TEOAEs can cause much of the distortion products to be masked. Works that include a significant use of sine tones as provocative agents in the employment of OAEs and binaural beats will prove less effective in acoustic environments in which a prominent level of reflections result in the Franssen effect becoming apparent in the space. Depending on the level of intrusion in a work, the Franssen effect can result in the composer's spatial positioning of the pure tones often being quite unidentifiable, or even rendered useless, at times. This acoustic phenomenon can impact upon works in which binaural beats are a primary compositional tool as they can enhance monaural effects and will reduce the listener's awareness of the positioning of the primary tones. Reflective environments will also increase the likeliness of spill into microphones which may be positioned on instruments, such as a grand piano, outside of the loudspeaker arrangement. Should the microphone input contain any material that is present in the loudspeaker outputs, there is a sizeable risk of monaural beating becoming a factor in the loudspeakers which are outputting the microphone signal. For example, loudspeakers A and B are each presenting a single primary tone set 5 Hz apart (to provoke binaural beating) while also both containing the microphone signal of a live acoustic instrument. If the microphone is positioned in close proximity to loudspeaker A then it is likely that its signal will also be sent to loudspeaker B through the microphone channel, and so forth.

While fixed electronic components within a work provide a reliable delivery of a large proportion of the sonic material to the listener's ears, live instrumental performers are not without a level of uncertainty which can be used to the composer's advantage within works considering bandwidth phenomena. Slight intonational flaws (for keyless/fretless/etc. instruments) can enhance auditory beating effects particularly in the lower frequency regions when performing notes below approximately C4 (261.626 Hz). As the frequency distance between any two adjacent notes (a semitone apart) below C4 is less than 15 Hz, a slight mistuning can result in very effective beating effects if accounted for within the compositional process. Should the composer be willing to allow for such slight inaccuracies to become a part of the performance of a work, the use of a timer from which a performer follows cues within a score can also cause such effects to take place particularly when there are multiple live performers performing with fixed electronic elements. Each performer will have varying response times to the timer's display and, should the score directions offer an element of creative license to the performer (such as the movement between two notes/dynamics over a prolonged period of time), the effect can potentially be heightened further.

Due to the level of unreliability and occasional misrepresentation of one's work in various performance spaces, the justification for certain works (whereby the delicate manipulation of the inner ear is required) to be readily performed in many venues must occasionally be questioned. For stereo fixed medium composition it could be argued that, in many respects, headphones are the ideal platform from which material performing the inner ear can be presented. Any issues relating to room acoustics are no longer an issue and, providing the positioning/movement of the listener within the listening space, or physical spatial positioning are not factors in the work, composing for headphone performance seems ideal. If binaural beating and/or OAEs are included in the work, headphone listening will ensure the optimum presentation of the acoustic primary tones, thus maximising the desired effects within the performance. Certain practicalities will naturally become an issue with headphone performances such as programming considerations for concerts which will often prove inaccessible for such works due to the greater level of technology and setup required for simultaneous headphone performance to a large audience. Furthermore, headphone compositions are very accessible to event programming when proposed as a listening station installation.

3.5 Compositional Challenges

An increased dissemination of both text-based and practical research within this field is also required as a further disadvantage afforded to the composer is evident when considering the creative application of certain psychoacoustic phenomena in electroacoustic music. The use of the ear as an instrument is intrinsically removed from the use of visualisation software in the analysis of works which apply such methods. Many psychoacoustic phenomena are not represented within common computational analytical tools. Waveform and spectral analysis systems are predominantly reliant on the output waveform, which will be emitted from the loudspeakers/headphones, or through analysis of the recorded acoustic input as it is received by a microphone. Factors such as binaural beating, residue pitch and DPOAEs are not readily considered in these visualisation platforms, thus composers working with such material must manage these factors externally. Consequently, when composing for the inner ear, an in-depth knowledge of the relevant biomechanical behaviour combined with their sonic potential is imperative, as musical analysis of these phenomena being employed is much less accessible.

In 2016, Chechile released the *Ear Tone Toolbox,* which he states as being

> a collection of open-source unit generators for the production of auditory distortion product synthesis.[149]

The *Ear Tone Toolbox* completes the essential mathematical elements required for the employment of QDTs and CDTs. This software also provides a visual display to the user upon which a combination of both acoustic primary tones and expected distortion products can be viewed simultaneously [Figure 18].

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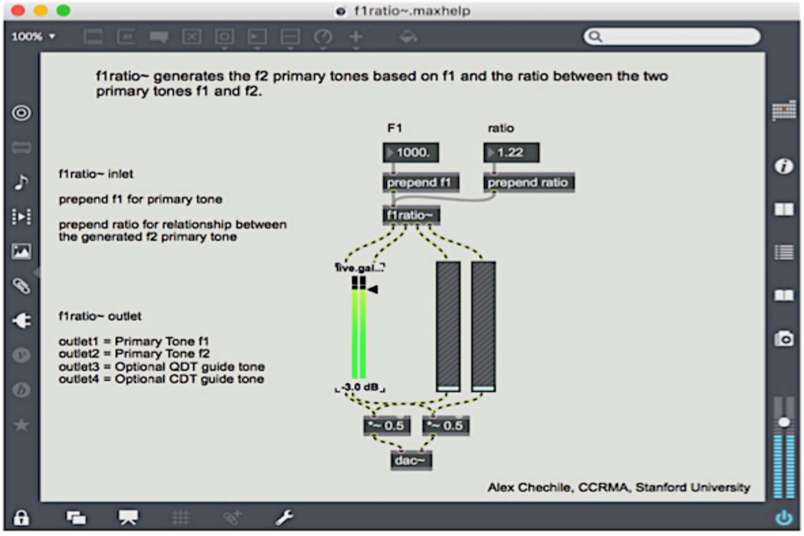
[149] Alex Chechile, 'The Ear Tone Toolbox for Auditory Distortion Product Synthesis', *https://ccrma.stanford.edu/~chechile/eartonetoolbox/Chechile_ICMC16.pdf* [Accessed 27 September 2016]



f1ratio~ generates the f2 primary tones based on f1 and the ratio between the two primary tones f1 and f2.

f1ratio~ inlet

prepend f1 for primary tone

prepend ratio for relationship between the generated f2 primary tone

f1ratio~ outlet

outlet1 = Primary Tone f1
outlet2 = Primary Tone f2
outlet3 = Optional QDT guide tone
outlet4 = Optional CDT guide tone

Alex Chechile, CCRMA, Stanford University

Figure 18: Screenshot of the Ear Tone Toolbox software in use[150]

While this software is a fine and accessible addition to the devices available to the creative individual who is seeking to consider the creative application of auditory distortion products, there is one significant omission in the absence of TEOAE applications. This is unsurprising given the complexity and level of indeterminacy within the application of this distortion product type, which is significantly removed from the formulaic nature of QDTs and CDTs.

Composers using the inner ear as a musical instrument find themselves in an interesting position; should they want to push the boundaries and engage with these psychoacoustic phenomena on any greater level, the relatively minimal research findings available result in the composer having to choose to accept a limit in their creative potential in this context, or conduct the research themselves. In many cases, composers must seek the assistance of individuals with a sufficient competence in areas such as programming and psychoacoustics. This collaborative nature is often

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150 Alex Chechile, 'The Ear Tone Toolbox for Auditory Distortion Product Synthesis', *https://ccrma.stanford.edu/~chechile/eartonetoolbox/Chechile_ICMC16.pdf* [Accessed 27 September 2016]

required in order for the research projects to be completed successfully. For example, Chechile employed the assistance of CCRMA programmers in the building of the *Ear Tone Toolbox,* while the ground-breaking paper for employment of auditory distortion products in composition *Sound Synthesis with Auditory Distortion Products* was a collaborative project by electroacoustic composer and analyst Gary Kendall, artist Christopher Haworth and electrical engineer Rodrigo F. Cádiz. [151]

It is clear that the current state of affairs regarding existing relevant theoretical material within the field suggests that, for these proposed creative applications to become embedded in mainstream compositional culture, affected composers must actively work towards expanding these concepts. This may be achieved through practice, research output and consideration in pedagogical curricula. An adequate level of dissemination required for continued explorations to take place must be maintained, while promoting emergent intelligence within accessible concert and/or repositorial settings. Furthermore, composers must continue to work sympathetically with any boundaries that are encountered as a result of inaccessible/unknown theoretical data.

3.6 Using the Ear to Play the Ear

Existing work in the field would suggest that the acoustic stimuli used in the provocation of these phenomena must generally come from loudspeaker/headphone sources whereas the inner ear can be used also to produce the required primary tones. In the right conditions (wherein masking, spectral saturation and insufficient intensity is not a factor), the sonic product of these non-linear inner ear phenomena (created from loudspeaker/headphone primary tones) can be used as stimuli to provoke

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151 Ref 1; Alex Chechile, 'The Ear Tone Toolbox for Auditory Distortion Product Synthesis', *https://ccrma.stanford.edu/~chechile/eartonetoolbox/Chechile_ICMC16.pdf* [Accessed 27th September 2016]. Ref 2; Gary Kendall, Christopher Haworth and Rodrigo Cádiz, 'Sound Synthesis with Auditory Distortion Products', *Computer Music Journal*, 38 (2014), 5-23.

other psychoacoustic phenomena. Gelfand has described the characteristics of the 'stimulus-like nature' of certain DPOAEs by stating that they

> themselves interact with primary (stimulus) tones as well as with other combination tones to generate beats and higher-order (secondary) combination tones, such as 3 (f1) – 2 (f2) and 4 (f1) – 3 (f2).[152]

The employment of such an approach in composition could be seen as using the ear to play itself. For example, DPOAEs and residue pitches can be used as primary tones for binaural beating. Figure 22 shows the creation of two QDTs separated dichotically. The listener will hear a binaural beat of 5 Hz which directly relates to the mathematical difference between f1 and f2.

[Audio Demonstration 9]

	LEFT	**RIGHT**
PRIMARY TONE	1,450 Hz	2,455 Hz
PRIMARY TONE	1,000 Hz	2,000 Hz
QDT	450 Hz	455 Hz

BINAURAL BEAT	**CENTRED**
	455 – 450 = 5 Hz

Figure 19: Outline of provocation method for QDTs to become the primary tones of binaural beats

Figure 20 requires a higher number of stimulus tones to create residue pitch; however, it still employs the same methodology as Figure 19, as the resulting residue pitches (f1 and f2) are presented dichotically and the same 5 Hz binaural beat is evident. **[Audio Demonstration 10]**

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[152] Stanley A. Gelfand, *Hearing*, p.221

	LEFT	**RIGHT**
PRIMARY TONE	3,000 Hz	5,020 Hz
PRIMARY TONE	2,500 Hz	4,515 Hz
PRIMARY TONE	2,000 Hz	4,010 Hz
PRIMARY TONE	1,500 Hz	3,505 Hz
PRIMARY TONE	1,000 Hz	3,000 Hz
RESIDUE PITCH	500 Hz	505 Hz

BINAURAL BEAT	**CENTRED**
	505 – 500 = 5 Hz

Figure 20: Outline of provocation method for residue pitches to become the primary tones of binaural beats

DPOAEs can also be used to create residue pitch [Figure 21]. The resulting residue pitch will often have a fuzz-like presence and is substantially less 'tonal' in character. **[Audio Demonstration 11]**

BALANCED

RESIDUE PITCH PRIMARY TONE TYPE	FREQ
DPOAE	1,800 Hz
DPOAE	1,600 Hz
DPOAE	1,400 Hz
DPOAE	1,200 Hz
DPOAE	1,000 Hz

RESIDUE PITCH (Hz)	200 Hz

Figure 21: Outline of provocation method for QDTs to become the primary tones for residue pitch

Due to the high number of primary tones required in this method, it is recommended that a random number generator is used in conjunction with an impulse oscillator which outputs two sinusoidal components at any given time as demonstrated in the SuperCollider code in Figure 22. The individual outputs can then be mixed together. By having control over the set differences in frequency between the two random output tones, the user has control over QDT output. Increasing the frequency value of the impulse oscillator's output ensures movement in height across the frequency spectrum which allows for the acoustic primary tones to become somewhat sonically removed from the sustained QDTs. This method assists in reducing the number of sustained tones that are required within the process.

```
[...]
var baseFreq =
TRand.ar
 (2000, /*lowest output frequency value*/
4000, /*highest output frequency value*/
Impulse.ar (20)).lag (0.01); /*frequency of impulses per-second*/
out  =  SinOsc.ar  ([baseFreq,  baseFreq  +  250],0,[1,0.7]).mean!2  /*oscillator
output with frequency  and amplitude arrays*/
[...]
```

Figure 22: SuperCollider impulse oscillator instrument used to generate acoustic primary tones for QDTs. In this example two random sine waves are output simultaneously with a consistent frequency distance of 250 Hz. The frequency range for the sine waves is between 2,000–4,000 Hz. F1 and F2 will have an amplitude ratio of 1:07

Residue pitch cannot offer viable primary tones for DPOAEs. A perceptual conflict will occur as a result of both phenomena requiring monophonic stimulation with a substantial number of APTs in each ear. When combined, a complex spectrum with varying distances between partials is presented thus causing multiple DPOAEs and residue pitches, which will significantly reduce both the likelihood and efficiency of such methods concerning the use of residue pitches as primary tones for the stimulation of DPOAEs.

DPOAEs, however, can be used to create residue pitch which, in turn, will provoke binaural beating [Figure 23].

RESIDUE PITCH PRIMARY TONE TYPE	**LEFT**	**RIGHT**
DPOAE	1,900 Hz	3,208 Hz
DPOAE	1,600 Hz	2,906 Hz
DPOAE	1,300 Hz	2,604 Hz
DPOAE	1,000 Hz	2,302 Hz
DPOAE	700 Hz	2,000 Hz

RESIDUE PITCH	300 Hz	302 Hz

BINAURAL BEAT	**BALANCED**
	2 Hz

Figure 23: Outline of provocation method for QDTs to become the primary tones for residue pitch which become the primary tones for binaural beats

When employing such methods as in Figure 23, the effects of the desired phenomenon will often become diluted and its theoretical attraction may be greater than its practical potential. Therefore employment of this method should be considered carefully within composition.

4 Commentaries on Portfolio of Work

4.1 Critical Bands

Fixed medium

(stereo headphones)

c. 6mins

This composition explores the use of monaural and binaural beating, and their potential as timbre modulation tools. The term 'timbre modulation' is simply used here in reference to changing timbres. The time-scaling of material containing monaural beats is employed to create pulsating material, which are used to create a number of effects such as impulsive, almost 'rhythmic', elements.

Monaural beats are a key compositional device in *Critical Bands.* In this work, various processing techniques (including filtering and time-stretching) are carried out on samples of recorded acoustic instrumental sound sources (piano, electric cello and electric guitar) and the manipulated samples are then layered on top of each other. One of the samples is then placed through a slight frequency shifting control, thus provoking the monaural beats to occur. These beats cause the instrumental sounds to exhibit a somewhat tremolo-like effect, due to the fluctuations in amplitude that are caused as a result of the monaural beating. It should be noted that the time-stretched periodic material will, over time, have a reduced intensity if the instrument was non-sustaining (such as the electric guitar and piano samples) in the original recording. Consequently, their employment as APTs for binaural beat generation must take that into consideration. With regards to samples of bowed instruments, towards the end of the recorded sample, if the player was to reduce their force, this will result in quite drastic changes in clarity towards the end of the sample when it has been time-stretched.

The following superimpositional procedure is frequently applied in *Critical Bands* in the creation of binaural beating using a single sample [Figure 24].

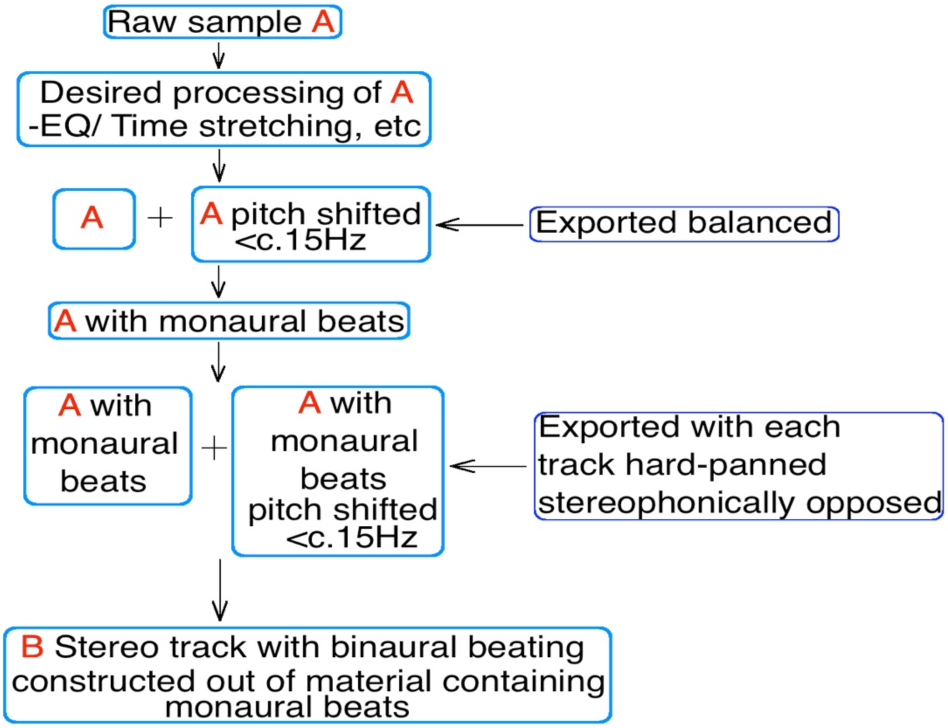

Figure 24: Method for creating binaural beating output from material containing monaural beats

The complete list of source material for this work is as follows: distorted electric guitar, white noise passing through resonant filters, crash cymbal, metal, computer hum, glockenspiel, electric double bass, flute and piano.

The reason for choosing more traditional musical instruments for the source material is due to the overtone structures of their periodic waveforms. The frequency-shifting technique was also applied to certain overtones of these harmonic sounds and the resulting material was then layered over the original sample. During this process, various overtones were cut from the spectrum, frequency-shifted, then placed into the spectrum from which the material was cut. The application of this technique allowed for an internal dissonance to be created within some of these periodic sounds. This method was also applied to a number of inharmonic sound sources, such as the cymbal and the metallic cage, which were both struck for the recording of the samples. It was found that by delicately frequency-shifting these samples and layering them over their original versions, a very thick and saturated timbre could be created which, after various equalisation procedures, could add a sense of movement to these sounds without noticeably altering them. From 2'00"–2'41", an inverted notch filter (available in Adobe Audition) is used to enhance 200 Hz and 205 Hz on a sample of processed computer noise. It is recommended that for such an approach a high Q factor is used as it allows for a narrower bandwidth to which a gain is applied. Both versions of the filtered sample are then hard-panned to the left and right sides causing a 5 Hz binaural beat, which results in intracranial motion. The original sample exhibited a slight rumble and this treatment using binaural beats and notch filtering, enhances the intensity of that rumble while also creating a perceived movement between the stereophonic positions during this climactic section.

Critical Bands opens with an exploration of the use of auditory beating to create pulsating material during what seems to be a battle between the low and middle frequencies. A high drone is presented throughout this section in order to provide a sense of spectral depth and to add a smoothness to an otherwise unsettled section.

The middle of this work investigates the application of the aforementioned various layering techniques on inharmonic sound material while also applying auditory beating to periodic sounds, as a means of creating a tremolo-like effect.

The closing material in this piece is a combination of the ideas explored in the opening sections. The final note is the first time any of the periodic or inharmonic material is presented in the work without being layered by a slightly altered version of itself. Here, a sample of a flute closes the piece on a relatively-unprocessed sample (time-stretching is applied), which highlights the strengths of the techniques that have been presented throughout this work as binaural beating is not present, despite its presentation being very similar to that of other material in the work.

4.2 Invisibilia

Fixed medium

(enhanced stereo – two pairs of four loudspeakers)

c. 8 mins

This work explores the use of distortion product otoacoustic emissions (DPOAEs) as compositional material, utilising quadratic (QDTs) and cubic (CDTs) difference tones, as well as sum tones (STs). *Invisibilia* presents stimulus signals within both simple and complex harmonic and inharmonic structures. The source material in this work include sine/sawtooth waves, glass, bells and violin/cello tones. Within the inharmonic material (such as the glass and bell sounds), equalisation techniques are used to generate formant regions, which create stimulus tones at the peak frequencies, provided that frequency is present. In relation to the application of periodic source material (such as the violin and cello), by removing a substantial number of its harmonics and leaving a narrow bandwidth around the fundamental frequency, an auditory product which, in colour, is more similar to that of a pure tone, but with some slight increased timbral detail can be created. Such a method is also applied in this piece in the creation of stimulus tones. These equalisation methods facilitate similar effects to that of the use of pure tones, while offering a significantly increased degree of variety in relation to timbre.

Invisibilia is significantly influenced by the notion of the 'real' versus 'unreal' in relation to both sound synthesis and auditory distortion products. This idea is explored using the unreal nature of distortion products, as they are heard without ever entering the ear. Simple harmonic sounds create a link to the distortion products that are employed in this work. They are seen as a gateway between the real and unreal sounds that are present in the piece. Furthermore, complex harmonic sounds are used here to somewhat bridge the gap between the simple harmonic and the complex inharmonic material. Finally, the complex inharmonic sounds are used, at times, as a form of veil, which covers over vast amounts of the spectrum when present and often temporarily masks any distortion products that are present in the listener's ears at the time. During these sections (most noticeable at 3'55"–4'31" and 5'37"–6'00"), when the complex inharmonic material begins to attenuate, the distortion products become more prominent. It is as if these unreal sounds are emerging from behind the real material.

A common technique used in this piece is the delicate fading out of a frequency before subtly replacing it with a distortion product in the listener's ears. An example of this method is evident at 1'37"–2'23", wherein a 100 Hz sine wave is faded in at 2'05" which replaces (masks) the 100 Hz QDT that was present due to the 200 Hz and 300 Hz acoustic primary tones (APTs) from 1'50"–2'05". It is also important to note that there is a strong likelihood of the presence of aural harmonics during sections with minimal loudspeaker output other than, for example, a single pure tone. This method of replacing DPOAEs with loudspeaker tones, is also frequently used from 3'45" until the end of the piece concerning a 101.88 Hz tone, which directly relates to the mathematical difference in frequency between a G4 (392 Hz) and B4 (493.88 Hz). The interval of a major third (equal temperament) was chosen for *Invisibilia* as a slight homage to Michael Gordon's *Industry,* which significantly influenced the exploration of quadratic difference tones (QDTs) in my own work. The opening section of *Industry* plays around with double stopped major and minor thirds in the cello line (equal temperament tuning) which produces QDTs in certain circumstances.[153] 101.88

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[153] Michael Gordon, 'Score preview: Industry', *Music*, *http://michaelgordonmusic.com/music/industry* [Accessed 28 August 2014]

Hz is provoked multiple times in *Invisibilia* through numerous methods. At 5'10", a 600 Hz sawtooth wave is presented above a time-stretched bell sound, which has EQ settings to contain a prominent formant region at 498.12 Hz and, when combined, a 101.88 Hz QDT is produced. Later in the piece, at 5'45" a time-stretched recording of a sustained violin note is frequency-shifted to produce fundamental frequencies (and their corresponding harmonic series) at 1,001.88 Hz and 900 Hz. This occurs simultaneously to the combination of the 498.12 Hz and 101.88 Hz stimulus tones, which enhances the overall perception of the 101.88 Hz QDT. Furthermore, modulating stimulus tones are employed in the creation of the QDT at 7'25" when the 1,001.88 Hz and 900 Hz tones glissando down to 981.88 Hz and 880 Hz respectively. While the stimulus tones are modulating, as the frequency difference between the two stimulus tones remains consistent, a correlation is evident in the QDT value which also remains static.

The presentation of the 101.88 Hz frequency is presented in a variety of ways, including through time-stretched instrumental sounds (struck and bowed), as pure tones, DPOAEs and as the centre frequency of various formant regions. Such an approach proves effective when attempting to highlight the contrasting colours of the stimulus tones and the distortion products to the listener. Any low intensity buzz-like material experienced during the performance of this piece is almost-certainly being generated within the listener's ears.

One of the most intriguing aspects of the application of DPOAEs as a compositional device in *Invisibilia* is that it contains 36 acoustic primary tone (APT) events that are played through the octophonic loudspeaker arrangement. As a result of the application of DPOAEs in this composition, if one was to analyse the spectrogram of *Invisibilia,* the level of varying sonic materials that are experienced by the listener would not be accurately reflected. A calculation of the primary distortion products that are provoked in this piece add at least an additional 16 other significant auditory products, which are key to the sound world that is created in this work [Figure 25].

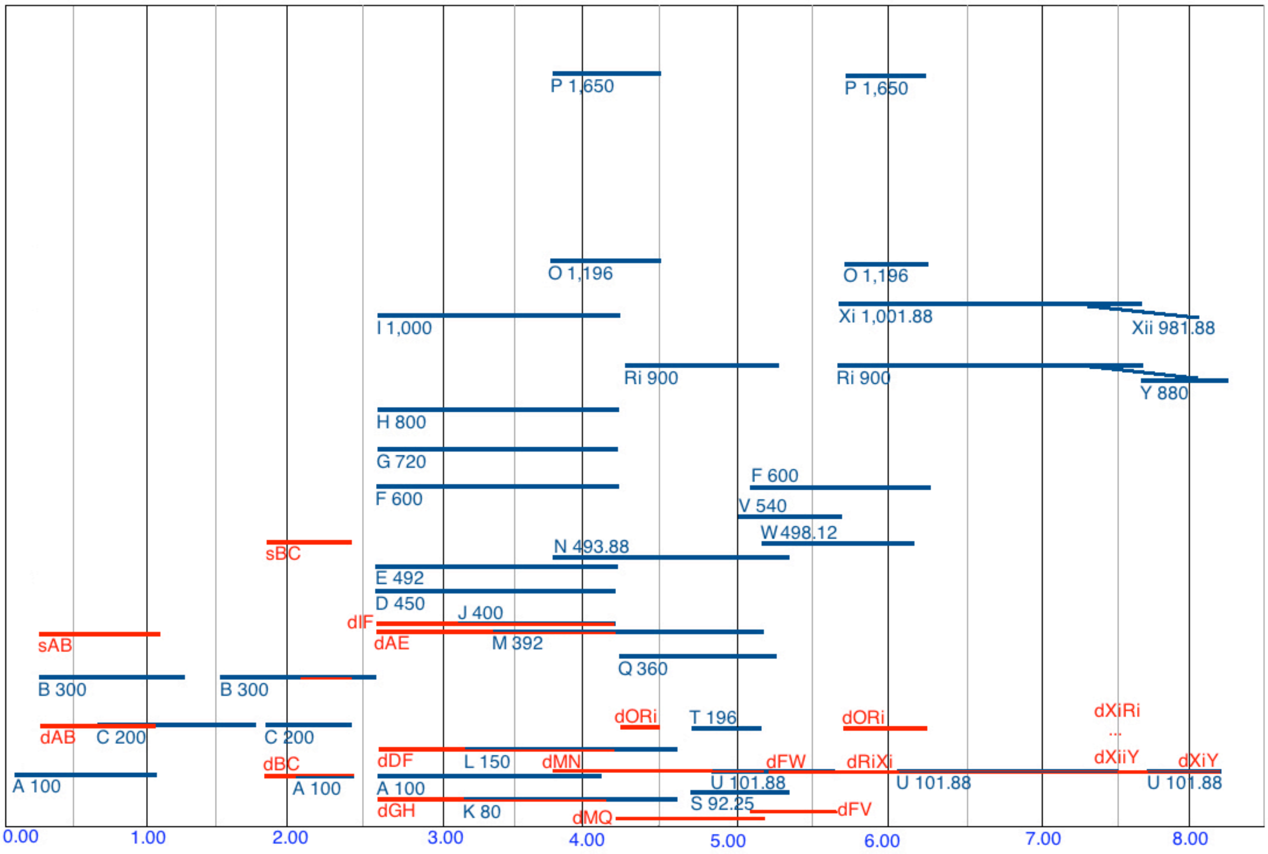

Figure 25: Reduction of the leading frequencies/ formant regions in *Invisibilia*

S – Sum tone

D – Difference tone (CDT or QDT)

Example: 'DAB' – Difference tone generated as a result of tone A and tone B being presented simultaneously. The tones emitted from the loudspeakers are marked blue and the DPOAEs are presented in red.

The octophonic loudspeaker arrangement is utilised in the building of a complex DPOAE stack from 2'40"–4'18". The loudspeaker arrangement is divided into quarters, comprising of four sets of two loudspeakers with each APT pair occupying a single loudspeaker within each quarter. Consequently, 4 DPOAEs are presented through APTs which are spread across 8 loudspeakers as in Figure 26.

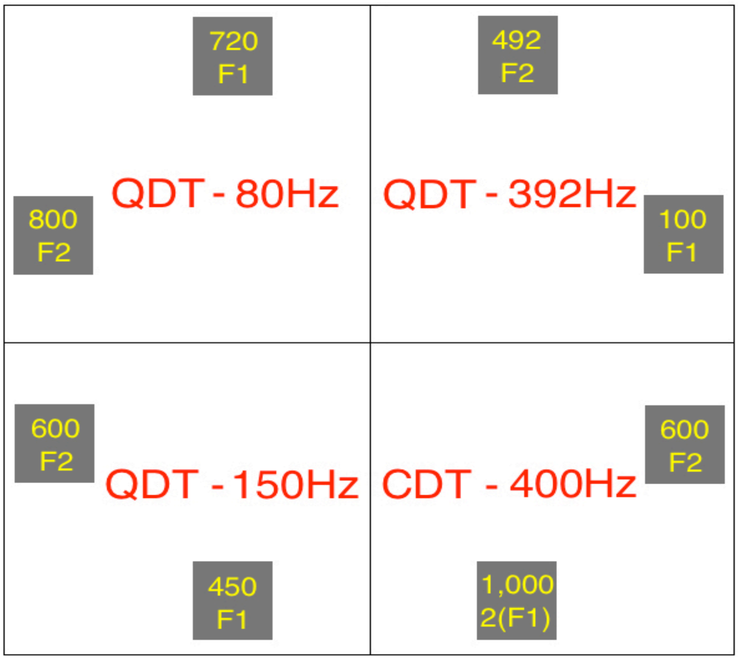

Figure 26: Loudspeaker/APT arrangement for complex DPOAE stack in *Invisibilia*.

As a means of further blurring the lines between distortion products and loudspeaker emissions, from 3'10"–4'30", pure tones with the equivalent frequency values to those of the DPOAEs in this section are presented from loudspeakers in an opposing position. For example, a 150 Hz pure tone, which matches the DPOAE frequency in the bottom left quarter, is played through the loudspeakers in the upper right quarter, and so forth.

Invisibilia interrogates the intensity differences between the stimulus tones and the distortion products by presenting the stimulus tones at a variety of ratios. QDTs are primarily explored in this work, as the frequency of the distortion product is generally presented at a much lower value than its stimulus frequencies. These low frequency distortion products are also well-suited to the aesthetic consideration which separates real from unreal, and so a clear division in frequency height, at times, is desirable here. QDTs are an accessible distortion product for composers using minimal material. As the sonic space becomes more saturated in the latter parts of this work, the aforementioned method regarding the utilisation of notch filters is required for such distortion products to remain effective. Furthermore, the most significant factor that influences the intensity of these distortion products relates to the ratio difference between the stimulus frequencies, as opposed to their independent intensities. *Invisibilia* explores a variety of frequency ratios in its provocation of QDTs and it generally begins with the widest ratios before gradually decreasing over time. For instance, this work exhibits stimulus tones in 3:1 and 2:3 combinations in the opening section, while 5:4.9 is evident in the middle and also in the final stages of the piece. Here, a static tone merges to unison with a sine wave, which glissandos in a descending movement. Furthermore, as the angle of the listener to the stimulus tones shifts (due to listener movement or panning), the individual will often notice stark fluctuations in colour and intensity levels of both the stimulus tones and distortion products.

Each audience member will hear their own version of *Invisibilia* in many respects as these 'phantom' tones will differ in type and intensity from listener to listener. These DPOAEs will sound something similar to a soft buzzing or ringing when present. Thus, the listener's own inner ears will determine the final dimension of the realisation of this piece.

4.3 Occultum Tabulatum

Electric cello and fixed medium

Eoin Kenny (electric cello)

(octophonic)

c. 9mins

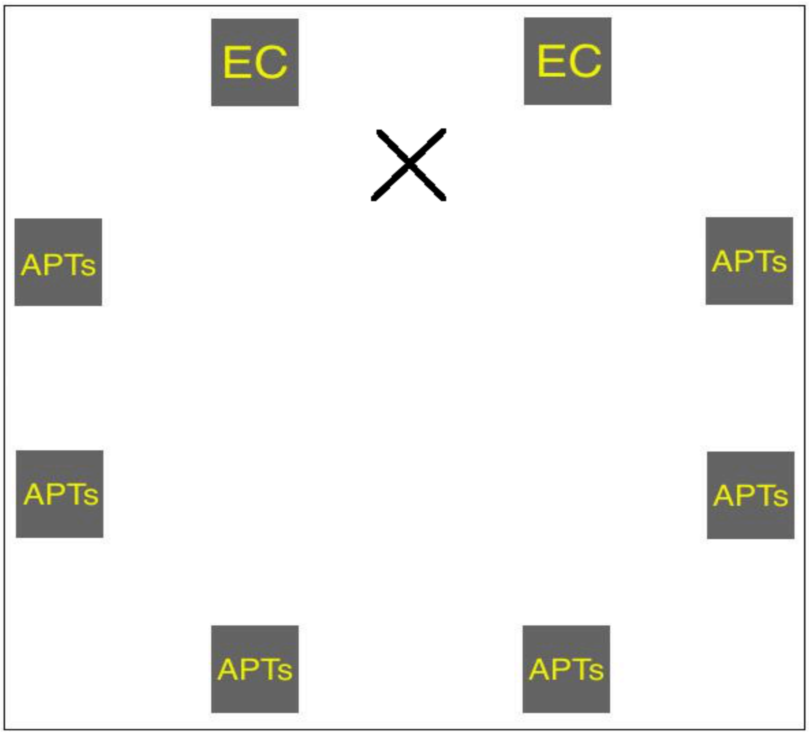

Figure 27: Loudspeaker arrangement in *Occultum Tabulatum.*

EC – Electric cello

APTs – Acoustic primary tones for the residue pitch (sine wave stack is balanced across all loudspeakers in question)

X – Cellist position

This work explores the creative potential of residue pitch and auditory beating. Here, the listener's ears perform the primary drone material over the duration of the piece. In *Occultum Tabulatum (*which translates from Latin as 'missing floor') the audience is presented initially with a stack of 16 sine waves, each an integer multiple of C1 (32.205 Hz) beginning on the first overtone (65.41 Hz) and ascending [Figure 28]. Throughout the course of this piece, the overtones are delicately attenuated one at a time, from the bottom and rising. A change in the perceived 32.205 Hz residue pitch is not evident until just one sine wave remains, at which point only the existing frequency of 548.485 Hz can be heard. As the number of acoustic primary tones (APTs) reduces, the intensity of the residue pitch will also reduce however, a residue pitch close to 32.205 Hz can be heard when there are just two APTs remaining.

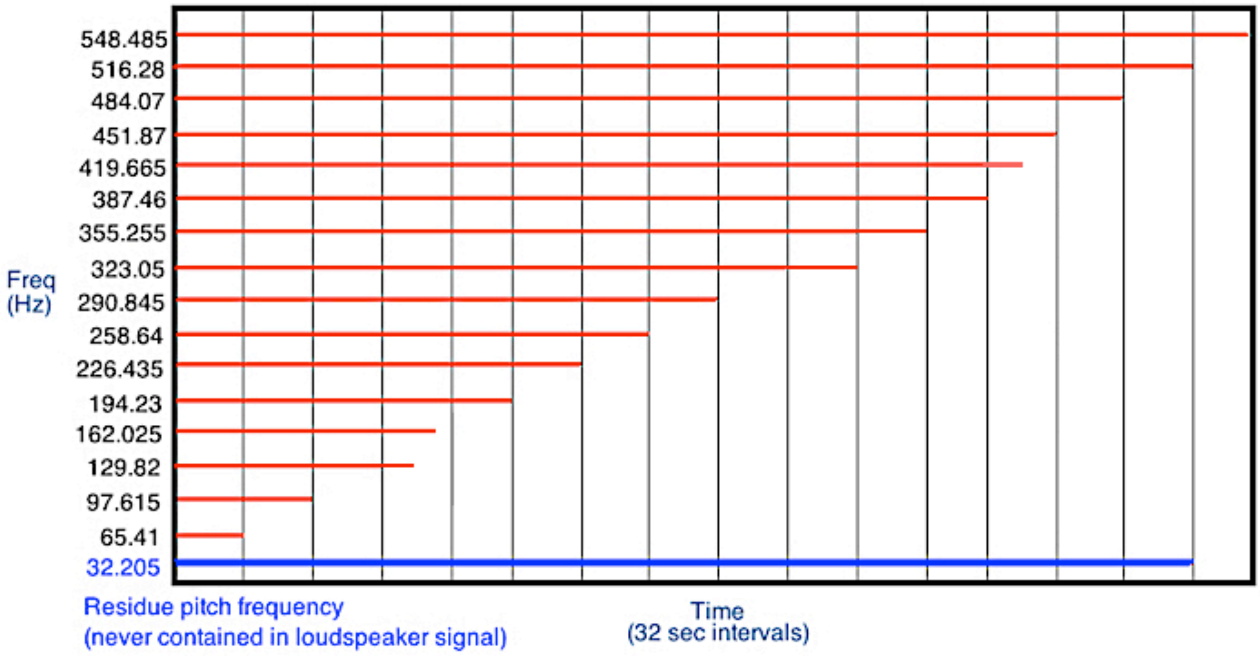

Figure 28: Graphic representation of the sine wave stack and its 16 divisions over time in *Occultum Tabulatum*

As the number of overtones reduces, the audience should continue to perceive a residue pitch of 32.205 Hz, without it ever being present in the acoustic signal during the entire duration of the work. Many concert loudspeakers, which are regularly used in the performance of octophonic electroacoustic music such as the Genelec 8040A, are unable to reproduce this frequency without distortion, thus further proving that the perceived 32.205 Hz tone is in fact solely occurring in the listener's ears as a result of effective stimulation.[154]

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[154] Genelec, '8040A Studio Monitor', *Studio Monitors*, *http://www.genelec.com/studio-monitors/8000-series-studio-monitors/8040b-studio-monitor* [accessed 12 April 2016]

As the sine waves are slowly being removed from the electronics, an electric cello performs the more melodic aspects of the work. The number of notes-per-bar generally increases over time in this piece. This creates a contrast between the busier cello line and the ever-decreasing electronics parts. The fundamental frequencies of the notes performed by the electric cello are restricted in this work to predominantly just playing two notes over any section which correspond to the lowest two sine waves that are present at the time; the frequency being attenuated and the next frequency to be attenuated.

Due to standard notation practices, the majority of partials in the electronics do not correlate to a note as it would be normally indicated on either the bass or treble staff. Consequently, microtonal markings are placed on the score which indicate to the performer the nearest equal tempered note, combined with the level of cents either above or below that note which are required to match the frequencies of the electronic parts. The performer is strongly encouraged to perform notes somewhat out of tune and to use the cent markings as a guide by which they can determine their 'mistunings'. These microtonal markings allow the performer to see what degree of tuning would accurately correspond to the lowest sine wave being output at any given point. Anything close to that marking would result in an increase of beating/roughness. The performer is in no way expected to perform with these tunings. They are only to be used as a guide for the performer in order for them to experiment with the levels beating/roughness that are produced in the performance. For example, if an indication of -26 cents appears on the score, the performer is expected to use that as a starting point and to perform in the proximity of that tuning in order for prominent beating/roughness to occur. Furthermore, while an indication of 50 cents appears on the score and could simply be identified as a quarter tone, all tunings are present as cent markings to remain consistent with the presentation. Depending on the performance space, each performer will have their own interpretation of what level of dissonance is required to maintain a significant layer of auditory beats. This approach to the performance of *Occultum Tabulatum* allows the performer to enhance certain dissonances created by both monaural and binaural beating. Furthermore, this heightens the delicate nature of the inner harmony of the harmonic C1 note being explored. As these potential aspects of the performance are considered an asset to the live presentation of the work, the score contains a direction which states that the performer is encouraged to employ vibrato at their own discretion as a means of increasing the level of frequency modulation.

Figure 29 shows a section of the score in which the distance between the bowed notes is now significantly restricted to almost a semitone (circled). One note that is exempt from the note restrictions over each section is the lowest string on the cello (C2). This note is regularly played pizzicato in this work to provide a contrasting low cello note, which allows a brief moment of 'breath' to be taken as the intervallic space constantly diminishes between arco notes. The creative decision to allow this note to be frequently played was also to highlight the depth of the C1 residue pitch which neither the electric cello or loudspeaker can produce. The electric cello is required to explore the internal harmony of a C1 note without ever being able to perform the note in question.

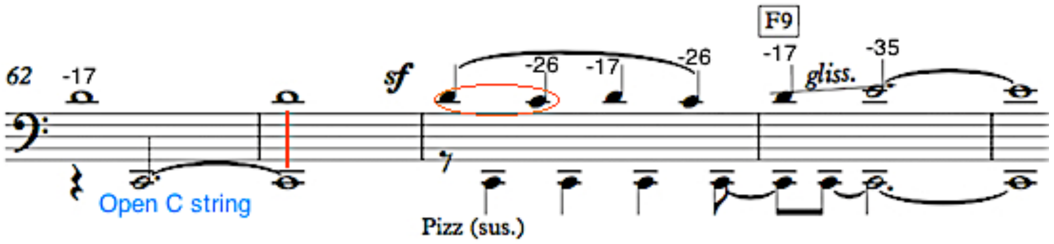

Figure 29: Sample of *Occultum Tabulatum* score showing contrasting intervallic space between the arco notes and open C string as well as between adjacent arco notes

The reduction in tones in the stack of sine waves creates a change in timbre of the perceived residue pitch, which gradually falls in intensity as the number of sine waves reduces, with the lowest partial constantly attenuating over each section.

The electric cello was chosen for this work for two reasons. It has a greater ability to sustain the open C2 string than an acoustic cello and its dry/somewhat dampened sound compliments the dominating colour of the sine stack in this piece. Essentially, the aesthetics of this composition depict an emerging force from beneath a restrictive suppression. A sense of frustration grows over the course of the piece as the notes become more restricted in relation to the intervallic distance between them. The auditory beating enhances this shift in energy, while also adding to the sense of turbulence at times.

4.4 Oscima

Fixed medium

(enhanced stereo – four pairs of two loudspeakers)

c. 13mins

Oscima is a binaural exploration of the methodology presented by Lucier in *Crossings.* This work takes Lucier's concept of static harmonic tones, with a frequently intersecting sine sweep, to a new domain by placing a bank of noise-based resonant filters over a sine wave, while their bandwidths shift around fixed centre frequencies.

Over the course of this piece, a sine wave ascends from 50 Hz to 2,160 Hz before descending once more to 50 Hz. The sine wave passes through six resonant filters (each with an input of noise). These filters contain modulating bandwidths (50–100 Hz) with centre frequencies of 200 Hz, 500 Hz, 750 Hz, 1000 Hz, 1200 Hz and 1600 Hz.

As the sine wave enters within approximately 15 Hz in distance from the centre frequency of each filter, binaural beats will become apparent, thus causing fluctuations between smooth and rougher textures. When the sine wave is within approximately 15–30 Hz of the filters' centre frequencies, a rough texture is evident.[155] This shift between smooth, roughness and beating is a key factor in creating the timbre for this piece. While harmonicity and tonality are not considered directly in the construction of the work, the constant shifting between smoothness, roughness and beating is directly linked to variations between perceived consonance and dissonance. Consequently, the timbre is continuously changing in this work as the spectrum frequently alternates between periods

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[155] David M. Howard and Jamie Angus, *Acoustics and Psychoacoustics,* 4th edn (Oxford: Focal Press, 2009), p.84

of stability and instability. On ascent, as the sine wave approaches the proximity of an inactive filter's maximum bandwidth the filter is activated, and remains so until the sine wave crosses through it once more on its descent [Figure 30].

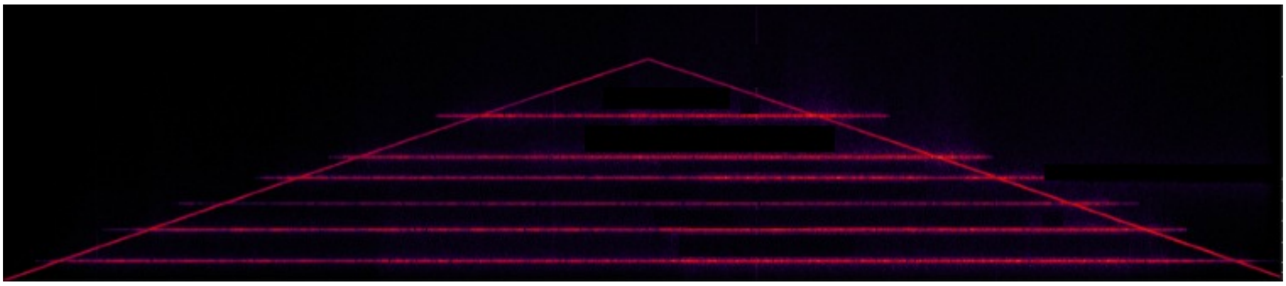

Figure 30: Monophonic reduction of the spectrogram in *Oscima*

As there are just six basic sonic elements in this piece, (sine wave with modulating frequency and six filtered noise instruments) it was important for this work to have colour produced by the filters themselves. Consequently, a resonant filter was chosen for this work.

The bandwidth of each filter is altered throughout this piece. While the bandwidths may appear somewhat consistent across all six filters, the nature of bandwidth phenomena dictates that the relative corresponding intervallic distances will decrease significantly with increasing frequency value. A filter with a 200 Hz centre frequency and a 100 Hz bandwidth will represent a relative intervalic size the approximate equivalent of an augmented fifth, whereas the same bandwidth for a filter with a centre frequency at 1,000 Hz will represent the equivalent interval of close to a major second.

The passing of the sine wave through the filter outputs results in binaural beating at just six of the crossover points (through the lowest three filters on ascent and descent) due to the frequency limitations of the phenomenon. Monaural beating will be evident at all other crossover points.

Subtle levels of binaural beating will be heard throughout the duration of this work as, when the lower three filters continue to produce an output, minor fluctuations in their frequencies (as the noise input to the filter is not steady), combined with room reflection times and the output of the other lower three filters, result in multiple possibilities for timbral changes throughout a performance of *Oscima.* The output of a loudspeaker to the listener's right-hand side may become an acoustic primary tone (APT) for binaural beating with a loudspeaker to the listener's left as a result of the phenomenon of beating in which the two APTs are almost mathematically related. Furthermore, reflections of a loudspeaker output from the right of the listener may be picked up by their left ear and cause binaural/monaural beating. The results of this process are dependent on the time delay from the source as well as its exact frequency output at the time of the reflection's arrival at the opposite ear, and so forth.

A sense of perceived physical pitch height is offered in *Oscima* as a result of the lower three filters susceptibility to binaural beating, combined with the ever ascending/descending sine wave. As the sine wave passes through the centre frequency of these filters, the intracranial motion, which results in the listener experiencing the beat as though it is passing through their head, offers a sense of intimacy with the sonic material. Consequently, the listener should feel a greater sense of closeness with the various sound sources during the lower three crossover points as binaural beating offers the listener a heightened level of interaction with the sound than monaural beating.

As a means of heightening the effects of one's ear as an instrument, at no point are the filtered noise and sine wave being emitted from the same position in the performance space when their frequency regions cross. Therefore the colouration changes are almost entirely being generated within the listener's ears in this immersive and physical work.

4.5 Transcape

Stereo headphones

c.10mins

This work generates transient evoked otoacoustic emissions (TEOAEs) in the listener's ears which become the cornerstones of the work itself. After extensive research in the area, it seems that *Transcape* is the first electroacoustic music composition which directly employs TEOAEs as sonic material. These TEOAEs are provoked in the listener's inner ears through the use of noise bursts and tone impulses which, at times, sound as though they are reflecting back from the ears of the listener. As the stimulus material is most frequently abrupt and indelicate in nature, and TEOAEs are generally presented with a soft and shimmering quality, *Transcape* seeks to combine these two significantly contrasting textures as a means of addressing the potential for utilising TEOAEs in composition as the primary objective of the work. These TEOAEs allow the listener to hear their own ears assisting in the performance of the piece at moments where there is a flatline in the waveform activity of the stimulus. TEOAEs can be experienced by the listener from the beginning of this piece. Many listeners will also physically feel their ears rhythmically pulsating in response to these repetitive stimuli.

This work is constructed over three sections. The opening section evokes TEOAEs which are heard in between the short and repetitive white noise bursts. These white noise bursts exhibit various attack rates and durations, and is expected to cause the listener to feel somewhat unsettled due to the invasive nature of the thick bursts. Furthermore, as the rate of these bursts increases and decreases, the listener will most likely feel less comfortable, as they are unable to settle into any particular consistent pacing. As the rate of repetition decreases, a certain degree of relative calmness would be expected, however, as the rate decreases, the duration of these thick noise bursts is elongated, thus prolonging the listener's exposure to these harsh sounds.

The material in *Transcape* is predominantly created by two instruments, which were built in the SuperCollider software, and are controlled by a graphical user interface [Figure 31]. These instruments are both constructed around pulse/impulse oscillators.

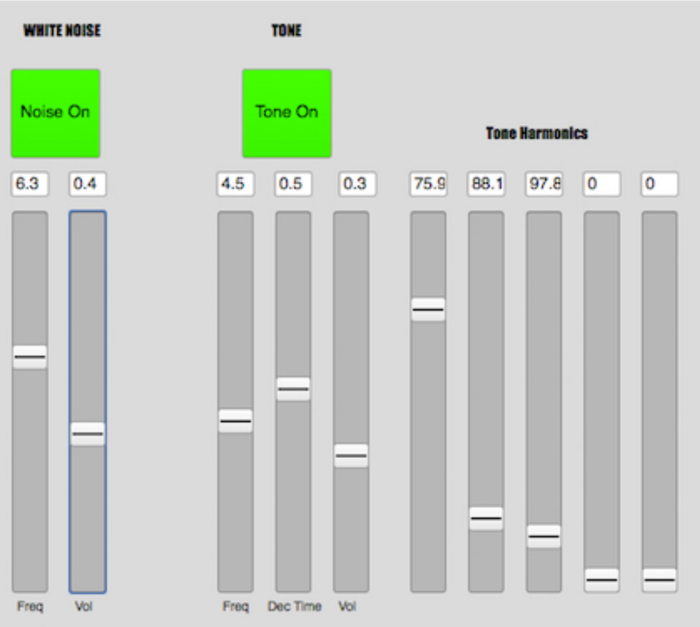

Figure 31: SuperCollider instrument constructed around a pulse generator

This white noise instrument (code outlined in Figure 32) uses the LFPulse pulse oscillator to control attack rates and durations. This simple instrument is set to provide a gap between attacks which is 9 times greater than the duration of the sound generated. Here, the minimum frequency value (of pulses) is 1 Hz which, when active, will also see the maximum durational value of 0.5 seconds. The pulse width value is equal to the durational value (in seconds) when the frequency value is at 1 Hz. Therefore, the frequency and duration values are inversely proportional, thus a fivefold increase in frequency will see a decrease in duration to 1/5 of its previous value, and so forth.

```
[...]

WhiteNoise.ar*LFPulse.ar
 (freq,    /*frequency value - controlled
by a slider*/
0,          /*no phase offset ('in
phase')*/
0.1,       /*pulse width*/
mul)    /*multiply - controlled by a
slider*/

[...]
```

Figure 32: Code for pulse oscillator controlling white noise bursts in *Transcape*

The decision to have a correlation between the duration of the transients and the temporal distances between them was made so that when the attack rate became faster, the duration of the transient would simultaneously reduce [Figure 33].

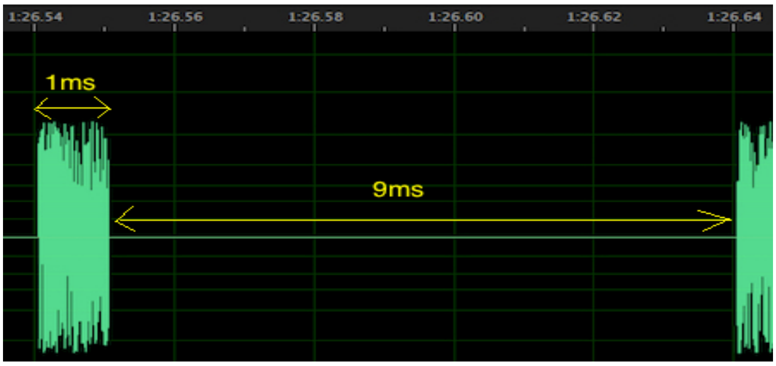

Figure 33: Waveform timeline sample of transient duration versus temporal distance between attacks.

The clicks/tone bursts are created using the Impulse UGen, which outputs non-band-limited single sample impulses.[156] Due to the non-band-limited nature of this impulse oscillator, when no tonal content is being fed into the instrument, clicks can be heard due to the single sample impulses. Furthermore, as the primary reason for the presence of thick-band bursts in this piece is to act as a TEOAE stimulus, any aliasing that may be present as a result of this non-band-limited noise is not considered to be problematic as it does not hinder the effectivity of the bursts acting as a stimulus.

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[156] SuperCollider CLASSES, 'Impulse', *UGens*, *http://doc.sccode.org/Classes/Impulse.html* [accessed 2 October 2016]

When frequency content is added to the filter, the click will still be produced. A plausible explanation for this would be that these clicks are caused by aliasing, as the effect is significantly different when a band limited impulse oscillator is used, such as the BLP UGen. While such distortion may often be deemed to be both problematic and unintentional, they are directly employed here as they are considered to be beneficial to this work, as this instrument allows for the combination of two common and effective TEOAE stimuli: clicks and tone bursts. The primary code for this instrument is shown in Figure 34.

```
[...]

Ringz.ar       /*skirt gain filter*/
 (Impulse.ar  /*input signal to the filter*/
 (freq,           /*impulse frequency - controlled by a slider*/
0,                 /*no phase offset ('in phase')*/
0.3)             /*multiply*/
,
[freq1,freq2,  freq3,  freq4,  freq5]   /*frequency  array  for  filter  -  each
controlled by a slider*/
,
decaytime,  /*60 dB decay time for the filter - controlled by a slider*/
 mul)          /*multiply - controlled by a slider*/

[...]
```

Figure 34: Primary code for click/tone stack instrument

As TEOAEs are a phenomenon in which auditory distortion products can be heard for prolonged periods after the stimulus has been presented, (rather than simultaneously) an opportunity is opened up for the composer here to present the listener with a clear demonstration of their ears performing. *Transcape* applies this nature of TEOAEs in a very direct manner as it considers that the duration of exposure of the listener to impulsive stimuli correlates to the duration of the TEOAEs. The middle section of this piece contains a 32 second section which has no headphone activity [Figure 35]. This is as a result of a temporary threshold shift in the listener's hearing sensitivities as a result of the prolonged exposure to the transient material (6 minutes and 15 seconds).[157] This form of auditory

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[157] 'Noise Induced Hearing Loss', http://american-hearing.org/disorders/noise-induced-hearing-loss/ [Accessed 10th

fatigue is responsible for any temporary ringing in the listener's ears at this point. During this section, the listener is invited to pay particular attention to any frequencies that they can hear coming from within their ears. Here, the listeners are presented with a direct demonstration of the capability of their ears as musical instruments where they will quite literally hear their ears continue to respond to the acoustic stimuli, as opposed to hearing virtually nothing which the output waveform would suggest. It could be described as the listeners being able to hear their own ears 'singing' during this section.

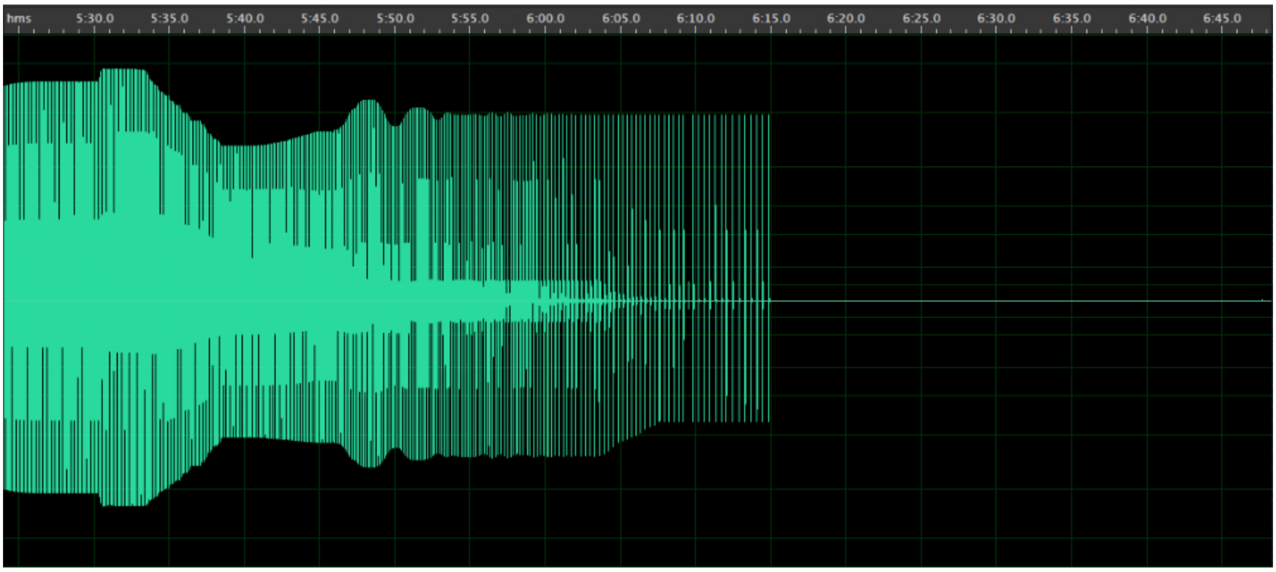

Figure 35: Prolonged section with no headphone signal in *Transcape* where the listeners will experience prolonged TEOAE activity.

This middle section begins with a thick sustained veil of noise slowly fading out beneath click-based material, which gradually evolves as layers of tone impulses are added. The clicks are introduced (2'20") with both a thicker bandwidth and intensity than the sustained noise, resulting in forward masking [Figure 36]. Depending on the nature of the TEOAEs within the listener's ears, forward masking may also be evident at both the sections which immediately precede (c. 6'00")/succeed (6'48") the prolonged section with no output signal, as the clicks may act as a masker over any TEAOEs that are present at those times. At this point in the piece, the nature of one's TEOAEs is more likely to exhibit long and sustained high frequency distortion products, which are easily subjected to temporal masking.

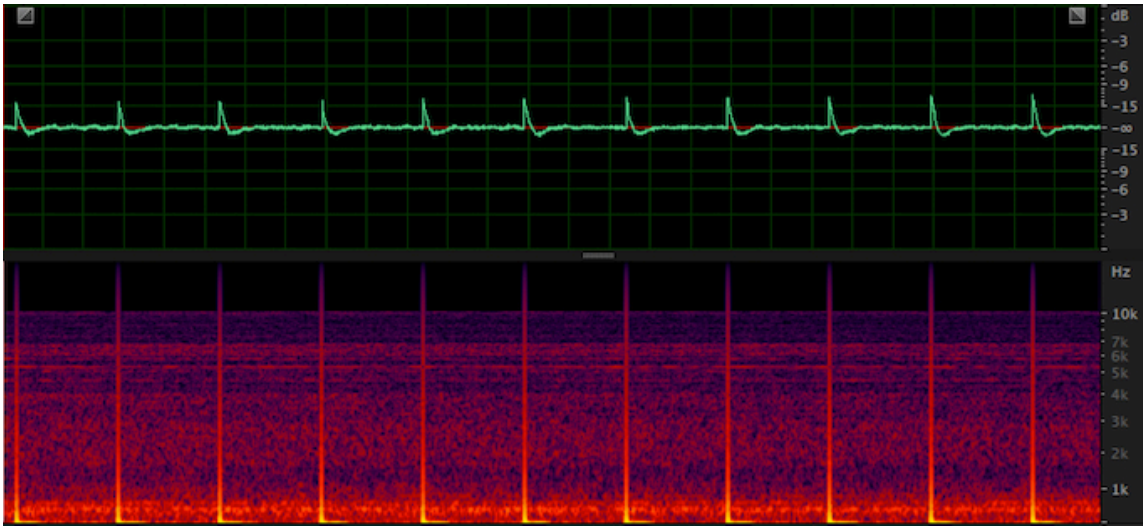

Figure 36: Clicks with higher intensity and thicker bandwidth than the background noise which causes it to become subject to temporal masking

This masking adds to a sensation of a gentle amplitude modulation immediately after the presentation of the clicks. As the duration of these clicks increases, they become more tonal (as more frequency content is added) and the rate of these impulses begins to speed up rapidly before suddenly stopping for the aforementioned 32 second period without any headphone signal. As lower frequencies (beneath 100 Hz) are added to the tone stacks, the duration of these transient sounds is somewhat elongated at those frequencies due to the decay time settings for the instrument [Figure 37]. This acts as a balance as it smoothens out the harsh nature of the clicks, while also creating a low floor above which the TEOAEs will be presented.

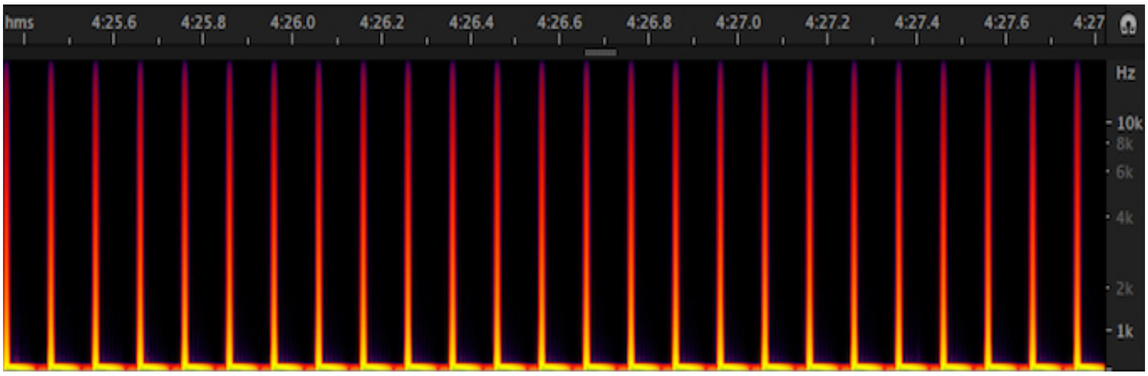

Figure 37: Impulse-based material with slower decaying low frequency content

A rough sensation is created within these tones as they are layered to each be no further than 20 Hz apart from their nearest tonal frequency component. The final section of this work is a combination of tone impulses and noise bursts, which causes a rhythmic dialogue between the two parts as they each have their own modulating pulse rates and attack durations, therefore causing their phasing to alternate. *Transcape* concludes with a sense of symmetry as it ends on bursts of white noise in a similar manner to the opening of the work.

Throughout the course of *Transcape,* just two forms of stimuli and one psychoacoustic phenomenon are consistently employed. In experimental works such as this, the validity of using such a minimal level of material may come in to question as there is little/less room for musicality. In terms of the spectral content that is output from the headphones, this work is primarily comprised of thick broadband content and there is little diversity in that regard. The listener will experience an exciting level of variation in relation to the rate at which this transient stimulus material is presented here, while also hearing their ears respond, with a greater degree of variation, to said stimuli.

Furthermore, the repetitive and somewhat monotonous nature of the stimuli allow the listener to shift their focus towards the changing distortion products in their inner ears as well as becoming aware of the feeling of their ears pulsating during the slower moments in the piece. The listener's ears are the true instruments in *Transcape* and it is entirely their response to the acoustic stimuli where most variation occurs in this piece.

Transcape was originally written for octophonic performance; however, there were a number of issues concerning reverberation and room materials resonating within the performance space as a result of the intensity of the transients. Even in listening spaces that are specifically built for loudspeaker performances, it is evident that works which are reliant upon such transient material, combined with a minimal reverberation time in order for the listener to hear the TEOAEs, are not very well-suited to the most common loudspeaker performance environments. Consequently, it would appear that electroacoustic works that require the effective presentation of TEOAEs in their performances are best-suited for either headphone listening or anechoic environments.

There are two significant applications of TEAOEs in this work which aid the piece as a compositional product. During times when the rates of attack for the stimuli are slow the listener will hear the TEOAEs during the longer gaps between headphone signals. When the rates of attack are more rapid the listener will not necessarily be able to identify the TEAOEs as being between these bursts/impulses and so they will perceive the TEAOEs as though they are occurring somewhat simultaneously to the stimuli. This seemingly simultaneous presentation of the bright/high pitched distortion product and the thick bursts of noise/lower tone impulses can be seen as a suitable combination as the TEAOEs add a bright shimmering which, in the context of balance, somewhat softens the presence of an otherwise harsh auditory signal.

4.6 Maeple

Fixed medium

(octophonic)

c. 6mins

Maeple employs a variety of psychoacoustic phenomena including residue pitch, spectral masking and binaural beating as vital compositional devices in its realisation. As spectrally minimal source material, such as sine waves, saw tooth waves and clicks, are used, the results are less spectrally complex than a composition such as *Critical Bands*, yet are more blatant due to their clear and simple presentation. The primary focus for writing this work was to address the potential that non-linear inner ear phenomena had in enhancing the complex nature of minimal sonic material.

This piece begins with a variety of pure tones and tone impulses with clicks being presented to the listener in different loudspeaker positions, before being presented simultaneously to provoke auditory beating effects. Spectral masking is used in the opening section to generate beating effects. Through the application of tone impulses intersecting a static pure tone (0'50"–1'18"), forward masking occurs. In this section, a 73 Hz sine wave is presented in the centre before two pulsating tones at 70 Hz and 140 Hz appear to the listener's right. Two further pulsating tones at 75 Hz and 150 Hz soon enter to the left of the listener. Consequently, binaural dissonances will be perceived between the perception of the pulsating tones (70 Hz/75 Hz and 140 Hz/150 Hz), while the listener will also experience an amplitude modulation (AM) effect on the static 73 Hz centred pure tone as a result of forward masking. Figure 38 provides an example of two beating effects as they are experienced in *Maeple.* While they are similar, they are by no means identical and they are provoked by two different psychoacoustical mechanisms. From 0–9 seconds of this example, the listener is presented with the static sine wave at 73 Hz while the broadband impulsive click with peak centre frequencies at 75 Hz and 150 Hz intersects it at a rate of 4 Hz with both signals centered. During this section, the listener will experience AM immediately after each click as a result of forward masking. This will be perceived as a slight beating of the static sine wave. 0'09"–0'17.5" in this example sees a hard-panning of both signals, which results in no forward masking taking place as the two signals are no longer conflicting in relation to basilar membrane activity. The listener will still experience AM in the static pure tone in their right ear; however, it will be during the moments of attack for the click in the left ear. This is due to binaural conflict, however, the impulses are not long enough in duration for binaural beats to successfully complete cycles. Furthermore, particularly prominent binaural beating is evident from 1'26"–1'36" in *Maeple*.

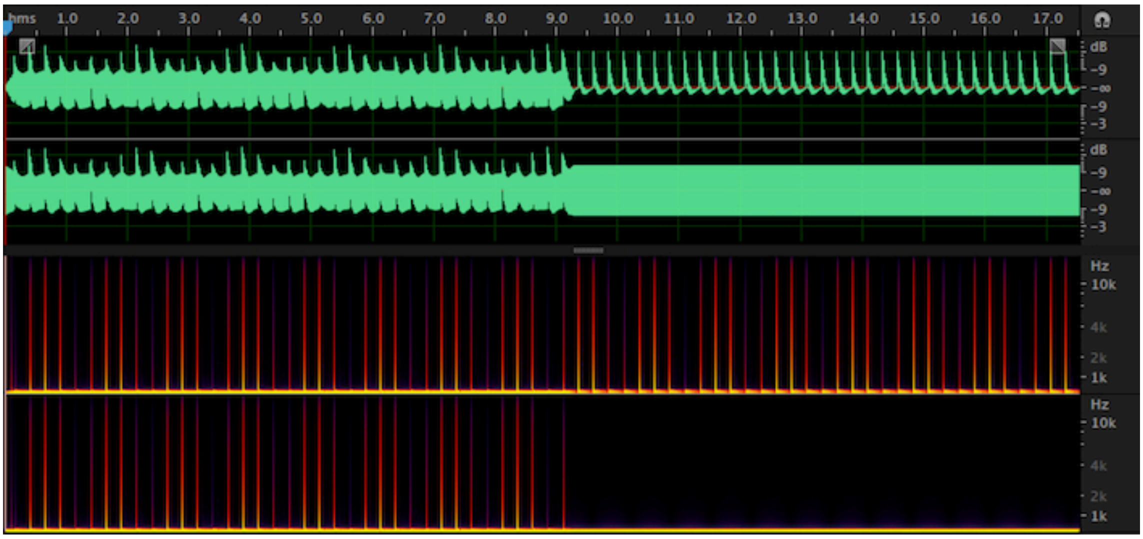

Figure 38: Two adjacent examples presented: beating due to forward masking (0'00"–0'9") and beating due to binaural dissonance (0'9"–0'17.5"). Forward masking occurs here as the wide-band transient material temporarily masks the sustained tone that is present underneath. Beating due to binaural dissonance is evident as both the static pure tone and the pulsating tones/clicks are hard-panned to opposite stereophonic positions.

Residue pitch is also employed as a primary compositional device in the closing section of *Maeple* whereby stacked sawtooth waves at 2,000 Hz, 2,500 Hz, 3,000 Hz, 3,500 Hz, 4,000 Hz, 4,500 Hz and 5,000 Hz generate an intense residue pitch at 500 Hz. As with any combination of APTs, other residue pitches may occur at times, however, in this section, only the residue pitch of 500 Hz is considered. Initially a sawtooth wave is presented to the listener before the aforementioned partials are delicately introduced over it [Figure 39]. The 500 Hz sawtooth wave is then removed from the loudspeaker output, yet the listener continues to clearly hear the frequency, which increases in intensity as additional stimulus tones are layered. During this section, the listener will most likely be unaware of the fact that their own ears are generating the most prominent frequency that they are listening to. The level of variation in the impulse rates results in a greater sense of movement and turbulence in this section. Consequently, the listener is expected to be drawn inward by the various impulses while the strength of the 500 Hz residue pitch intensifies. By the time the 500 Hz tone is removed from the loudspeaker output, the listener will be entirely unaware of the fact that the 500 Hz tone that they are hearing is no longer coming from the loudspeakers.

Frequency	Time	Impulse Rate
500 Hz	3:35 – 4:51	2 Hz
500 Hz	5:43 – 6:16	N/A (sawtooth wave)
2,000 Hz	4:01 – 6:07	2 Hz
2,500 Hz	4:14 – 5:41	6 Hz
3,000 Hz	4:30 – 6:42	10 Hz
3,500 Hz	4:43 – 5:48	14 Hz
4,000 Hz	5:03 – 5:56	18 Hz
4,500 Hz	5:18 – 6:21	10 Hz
5,000 Hz	5:43 – 6:16	11 Hz

Figure 39: Outline of all frequency content during the closing section of *Maeple*

As is evident in Figure 39, there is no 500 Hz signal being emitted from the loudspeakers between 4'51" and 5'43", yet a very prominent residue pitch of 500 Hz should be perceived by the listener during this time. Furthermore, the stimulus tones are presented with ever-increasing rates of impulses (consequently, the tones often appearing to be darting through the listening space) and, combined with rapid panning procedures, this results in a highly immersive and physical listening experience for the audience.

4.7 Ear Walk

Single headphone and 8 loudspeakers

c. 10mins (looped)

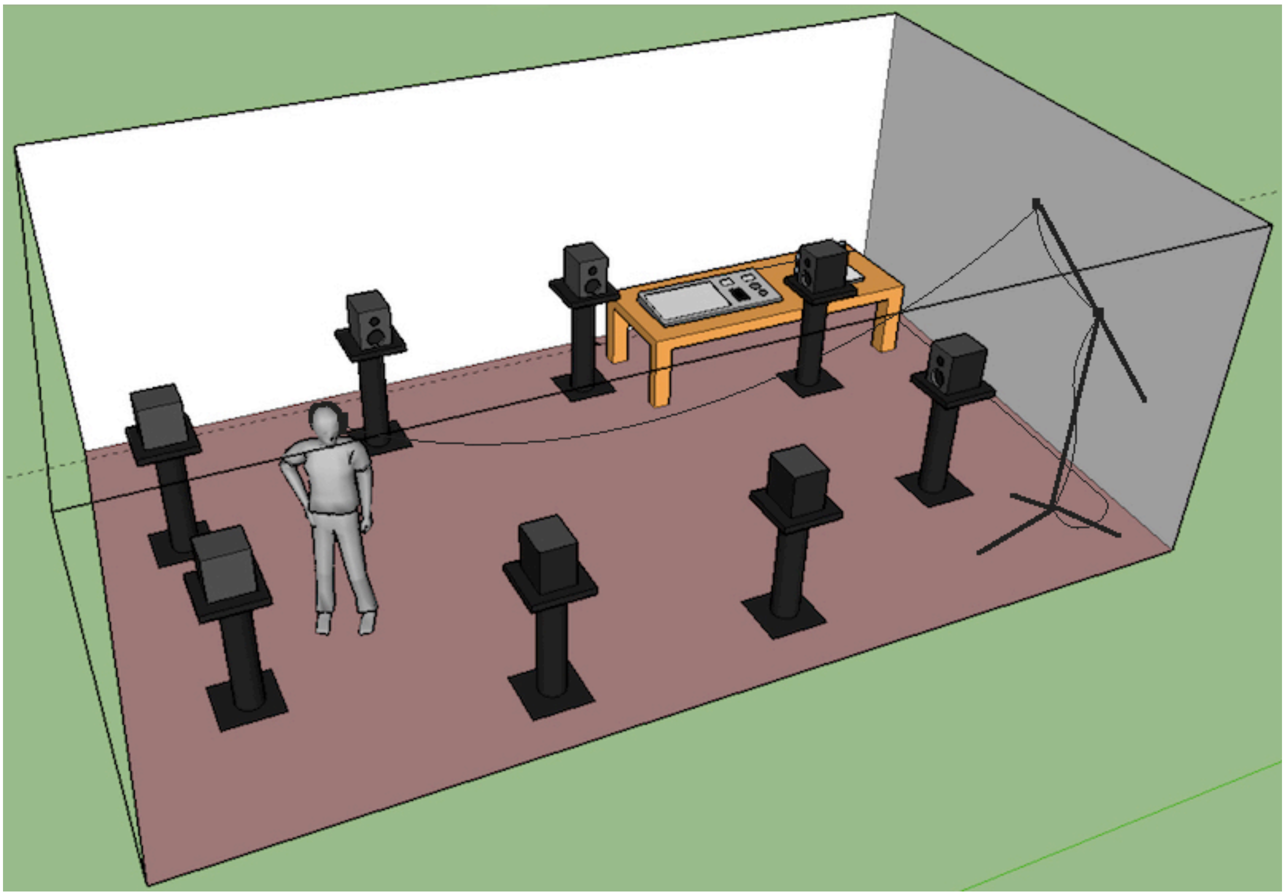

Figure 40: The *Ear Walk* listening space

This installation utilises spatial auditory beating and residue pitch as creative devices in a sound art exploration of timbre modulation in relation to listener-loudspeaker proximity. There are two sound worlds being presented to the listener which, when combined, will provoke a third to be perceptually positioned within the head of the listener. These two sound worlds are created by the output of both the single headphone and the combination of the 8 loudspeakers. *Ear Walk* is an ideal demonstration of the potential of the listener's ears within sound art performance.

The headphone simply outputs a single sliding pure tone which modulates between 420–380 Hz over a 45 second period and descends and ascends in a looped pattern. This headphone is placed on the listener's left ear which, when combined with the loudspeaker signals that the individual receives in their right ear, will provoke binaural beating.

If the listener were to be in a position to listen to the headphone independent of the loudspeaker signal, they would hear a single static sine wave without any constant frequency modulation due to its slow and gradual modulation which falls below the just-noticeable difference for frequency modulation detection at c. 400 Hz.[158]

Each loudspeaker will output a single fixed pure tone, which is set with its own amplitude envelope. These envelopes are used to allow for changes in colour for the 100 Hz residue pitch, without the perceived 100 Hz ever being altered, while also allowing varying levels of intensities to exist for the binaural beat APTs. The loudspeakers will each present a different frequency, each of which will be a multiple of 100 Hz, with the lowest being 100 Hz and the highest set at 800 Hz.

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[158] Hugo Fastl and Eberhard Zwicker, *Psychoacoustics: Facts and Models*, p.185

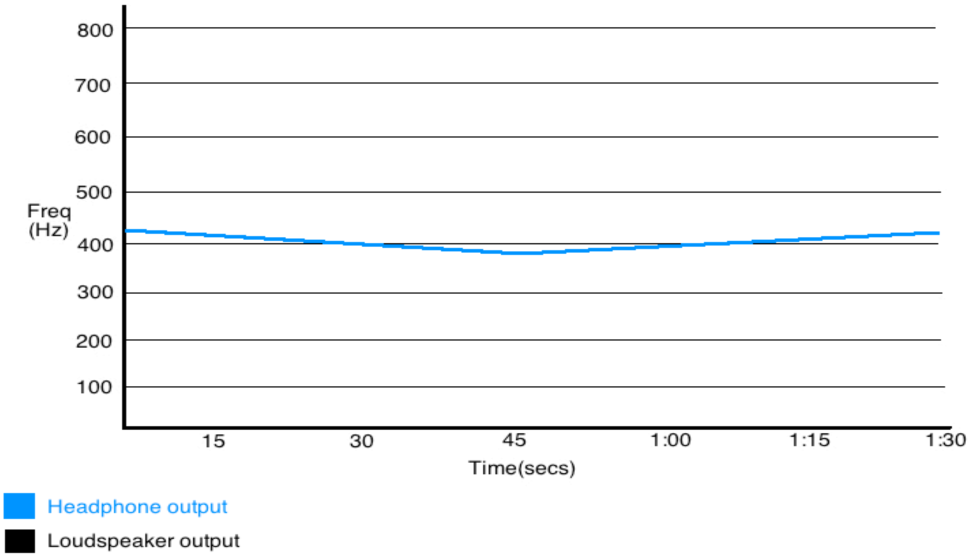
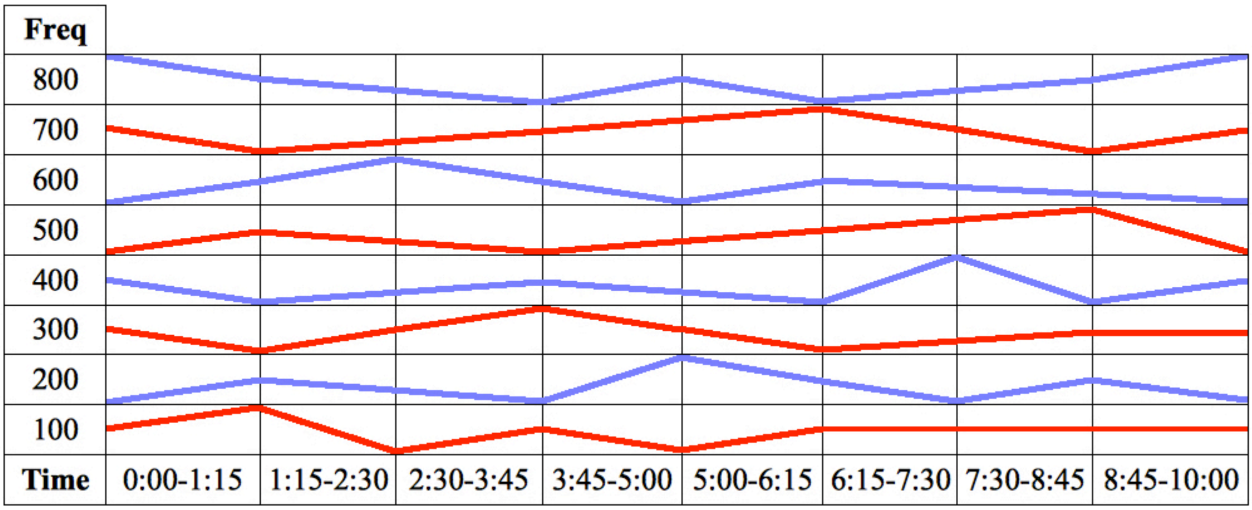


Figure 41: Loudspeaker and headphone frequency content. It should also be noted that binaural beats will not just occur in relation to the headphone signal crossing over with the 400 Hz loudspeaker output. The phenomenon of binaural beats caused by APTs that are almost mathematically related is employed here.

During the course of the audio loop, the colour of the perceived 100 Hz tone will shift based on the fixed levels of amplitude modulation that are outlined in Figure 42.



	Most intense frequency
	Second intensity level (-c.8dB)
	Lowest intensity level (-c.20dB)

Figure 42: Outline of the amplitude modulation settings in *Ear Walk*

As there are 8 loudspeakers, each of which present a single frequency value, the amplitude modulations are set to highlight each frequency on one occasion during the loop. The loop can be divided into 8 different sections of equal length. Each section begins with one loudspeaker producing a relatively prominent intensity, 4 loudspeakers set approximately 8 dBs below that and the remaining 3 loudspeakers set approximately 20 dB below the highest. Over the course of each section the intensity levels will slowly modulate until they arrive at the appropriate level for the start of the next section. The intensity levels were chosen through ensuring that a balance was struck between the higher and lower level loudspeakers so that, at no point, the intensity levels would be appearing to lean towards one particular area. Such an approach allows for a constant shift in timbre, while the most prominent frequencies move across the octophonic setup. This level of movement in intensities around the loudspeaker environment, combined with the listener's own free exploration of the space, greatly increases the intended effects of both residue pitch and binaural beating causing the listener's sense of localisation to be significantly blurred within the installation. Furthermore, the decision was made to have loudspeakers presenting a difference in frequency no more than 200 Hz apart from that of either of its neighbouring loudspeakers [Figure 43]. This encourages a loose sense of uncertainty in the listener in relation to the exact output of the nearby loudspeakers as such closeness in mathematically related frequencies can be more difficult to clearly separate in such a full sonic environment.

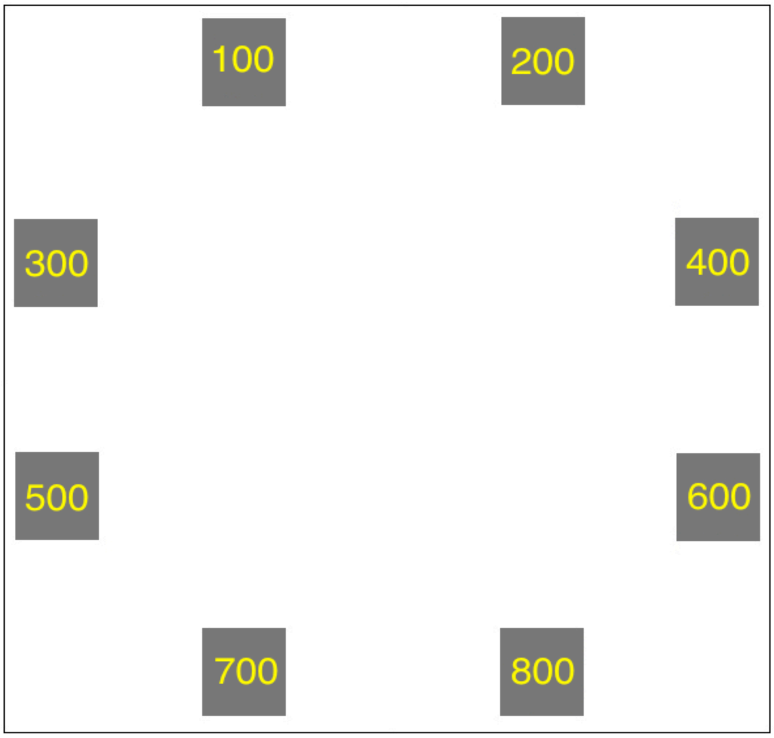


Figure 43: Octophonic loudspeaker layout for *Ear Walk*

This combination of pure tones allows for the provocation of residue pitch within the listener's ears. A secondary effect of this presentation concerns audibility of low intensity sum tones (STs), and a lesser likelihood of aural harmonics, as a result of this thick layer of sine waves. The frequency and intensity values of the STs is dependent on both the amplitude of the stimulus tones and the proximity/angle of the individual to their respective loudspeakers. Upon entering the listening space, one may be surprised to hear so many higher frequencies above 800 Hz, which are very common. These ST frequencies can be heard up to a maximum of 1,500 Hz (if the pairing of primary tones is 700 Hz and 800 Hz). Providing sufficient amplitude is being provided by the amplitude modulators, the listener will experience the most prominent STs when they are positioned in a way which creates a triangular shape between the ear and the two loudspeakers within the listening space. The parameters of this positioning will differ between each listening space. Quadratic difference tones (QDTs) are not so prevalent in this work due to each possible QDT value that could be obtained from acoustic primary tones between 100 Hz and 800 Hz resulting in values below 800 Hz. Therefore, these QDTs are significantly more vulnerable to masking. The listener will experience a harmonic tone with a fundamental frequency of 100 Hz at all times. The amplitude modulations of the individual frequency components will result in a fluctuating timbre, which will alter the spectral density over time. On occasions, the loudspeaker outputting the 100 Hz tone may not be emitting any significantly audible signal; however, the reliance of the inner ear on processing the overall periodicity of an input signal will cause the listener to continue to hear a harmonic 100 Hz tone, despite its lack of prominence.

If the listener chose to explore this installation space with either the headphone or the loudspeakers independently the sonic events would remain uninteresting and relatively unchanging. However, when experiencing this work as intended, the listener does not simply perceive a combination of the two signals as would be expected. The listener hears an auditory product which is often substantially removed from either of the two original signals as a result of non-linearities in human listening procedures. These mechanisms cause stark colouration changes and a third perceived sound world is created due to prominent beating and roughness (which are neither evident in the headphone or loudspeaker signals), the frequency modulation of the headphone output, continuous amplitude modulations and the listener's proximity to the various loudspeakers.

During *Ear Walk,* the listener is asked to explore the space within the octophonic arrangement and to approach various loudspeakers as they wish. The listener is encouraged to stand still at various points to enhance the effects of both the binaural beating, intracranial motion and residue pitch, as constant movement will result in more notable changes in the perceived sonic environment. The listener will be hearing their own ears interpreting the signals which will often differ entirely from the next individual due to ear sensitivity being individual-specific. Intracranial motion, generated within the listener's head will often add a significant sense of movement to the listener, who may be standing still (or perhaps walking in the opposite direction to that of the intracranial motion) at the time.

4.8 Waves

Violin, cello and fixed medium (stereo)

Niamh Fallon (violin)

Eoin Kenny (cello)

c. 12 mins

Waves explores the creative potential of combining the application of psychoacoustic phenomena with more traditional compositional methods. Through the employment of binaural beating (panning controlled live from the sound desk) and spectral masking, the electronics strive to both augment and alter the tonality presented by the strings. The roughness, created by the binaural beating, is a key feature of this composition, which places many of the sonic events physically within the listener's own head, while also successfully achieving sensory dissonances at key moments through techniques relating to binaural/monaural beating. Binaural beating is used in this work to create a sense of movement as the material performed on the violin and cello is particularly static and drone-like. Intracranial motion is used to open up a new perceptual space in this work that exists only within the listener's head. Consequently, when any minor changes are made within the static-sounding material, they can have more significant effects on a perceptual level. A decision was made to use only minimal movement in the violin and cello in order to heighten the listener's perceptual experience, as the acoustic material was not a distraction. Spectral masking is employed in *Waves* to reduce the harmonic clarity of the sustained violin and cello parts, while also using the intensity of thick bands of noise.

The total effects of the binaural beating, spectral masking and residue pitches are dependent on the listener's location within the listening space. Spectral masking techniques exploit the frequency processing mechanism of the basilar membrane which causes many of the primary periodic waveforms to become enveloped in ever-thickening bands of filtered noise. As the strings find any sense of harmonicity, the combination of sinusoidal/sawtooth waves and noise filters seek to destabilise any harmonic foundations that these instruments may possess by imposing themselves on the non-linear mechanisms of the listener's inner ear. Due to the addition of the loudspeaker material, the provocation of these various psychoacoustic phenomena results in this harmonic material from the string instruments being subject to various perceptual processes, resulting in a diminished sense of harmonicity for the listener.

Waves is comprised of four short sections, each lasting approximately 2–3 minutes in duration. The opening section sees the cello and violin begin in counter-intuitive registral positions with the cello beginning on a C#5 and the violin below it at A4. Hard panning is used in this section to create binaural beating. The beating is most prominent at 0'38", 1'02"–1'16" and 1'40". Over the course of this first section, the string instruments simply glissando in opposing directions until they cross over with each other before ending the section just below/above where the other instrument began (violin – G#4/cello - D5). In contrast to the sliding nature of the strings, the electronics part performs only two static sine waves at any given time. The frequency of these sine waves is relative to the starting point of the string instruments at the point at which the sine waves begin. Once the strings have each completed a glissando over the distance of a semitone (approximately 30 seconds) the sine waves will switch to new frequencies matching the fundamental frequencies of the strings at that point, and so on. In aesthetic terms, this technique of combining static pure tones with glissando-based material creates a sense of tension and release due to the push and pull nature of the overall timbre, which is created by the natural auditory beating followed by roughness and then smoothness before the process repeats itself as the sine waves switch to new frequencies. The bowing patterns of the two performers (at their own discretion) also enhances the sense of tension and release here.

The constant fluctuation between harmonicity, dissonance and prominent beating is presented with varying rates of amplitude modulation, which are causing this regular shift in timbral colour. While the rate of these beats will naturally vary in beats-per-second as the sliding violin and cello lines enter the proximity of the static sine waves, the overall intensity of this timbral effect will vary between registral ranges: the higher the frequencies – the less the overall intensity of this effect, and so forth.

The second section begins (2'43") with a significantly more stable psychoacoustical structure. The strings begin with a frequency ratio of 4:5 while the electronics display a stack of pure tones at integer multiples of 110 Hz. These tones present a theoretical harmonic A2 tone and sum tones above 880 Hz may become apparent to the listener depending on their proximity to the loudspeakers; however, sum tones are not being employed explicitly in this piece. A slight instability and timbral change is introduced in this section as, for the first time in the work, the strings employ double stopping (3'33"). The violin holds its C#5 note and introduces a D4 note below it, while the cello holds its A4 and introduces a C3 below it. Meanwhile, the electronics seek to augment the shift in tonality in the string parts by moving to a reduced harmonic structure which presents a combination of D3 (146.83 Hz), D4 (293.66 Hz), A4 (440), D5 (587.33 Hz) and A5 (880). The roughness caused between the violin's C#5 and D4, combined with the cello's C3, destabilizes the existing tonality. The cello follows this process by sustaining the C3 and adding a D4 (3'47"), thus emphasising the inharmonic material. The harmonic stability of the opening of this section between all instruments returns (4'02"); however, it is quickly destabilised once more with broadband noise being gradually introduced in the electronics (4'33") through three filters with modulating bandwidths which cover the entire output of all pre-existing sonic material in a blanket of noise through the employment of spectral masking techniques. These three filters start simultaneously with centre frequencies placed at 220 Hz, 440 Hz and 770 Hz before expanding out until the entire existing spectrum becomes saturated by the noise. This process results in the listener perceiving the violin/cello as continuously becoming less and less bright, as their higher frequency overtone content will be the first to be subject to auditory masking. While just a single filter is used elsewhere in this piece, multiple filters were used simultaneously here in order to build a thick spectrum of noise quickly without awarding dominance to any particular centre frequency. The section ends with a significantly reduced level of activity as the string instruments end on A notes (three octaves apart) while the electronics now present less smooth sawtooth waves (5'12") with the lowest note being 110 Hz (A2) and the highest A5 (880 Hz), as before, however there are no frequencies in the space between them.

The third section can be divided up into two clear subsections. The first displays binaural beating with a variety of stimuli, which applies a very simple structure in its demonstration. Initially one instrument will present an unaccompanied tone and its microphone signal is hard-panned to one stereophonic position. After a brief rest the second instrument will present a similar idea (very close in frequency) at the opposing stereophonic position. Following another brief rest, the two instruments then present their ideas simultaneously but, due to the binaural beating, the perceived sonic event will be quite different to the initial individual presentation of said material with an added centralised sine-like beating. This binaural beating offers a great shift in both movement and energy within the listening space that is not evident in either of the stimulus parts when presented independently. Here a variety of combinations between the violin, cello and electronics are performed. The second subsection (7'31") balances out the close and restricted nature of sensory dissonance. As a result, the violin and cello now play E notes spaced 4 octaves apart (E2 and E6 respectively) while, in contrast, auditory beating is caused by two sawtooth waves which are presented by the electronics, just 5 Hz apart. Following on from this (8'01"), the filtered noise enters once more with a prominent centre frequency placed at the heart of the registral span of the spectrum at 700 Hz. Once this filter finishes expanding, it is switched off (8'21"), yet is immediately replaced by another expanding filter with a clear centre frequency of 249.58 Hz. This centre frequency is equidistant (in Hz) to the corresponding frequencies of A3 (220 Hz) and C#4 (279.17 Hz), which are then presented by the violin and cello respectively. This gradually fills the expansive empty space, while also masking much of the spectral components of the pre-existing material. The masking causes the violin and cello to be submerged and to somewhat lose their spectral independence.

The beginning of the final section of this work (8'55") is somewhat in opposition to the construction of its opening section. The electronics return to performing pure tones (hard-panned to create binaural beating) which mimic the glissando material presented by the strings in the first section, while the violin and cello now play static B4 (493.88) notes in unison. The B4 notes were chosen as a means of presenting an unstable structure between the sliding pure tones of the electronic part which both move between 554–440 Hz. Intonational differences here will also cause beating sensations. As the tones cross-over with one another, binaural beats will be generated. Once these pure tones intersect, the B4 notes as presented by the strings (these instruments are also hard-panned during live performance), monaural beating will be emitted from the respective loudspeakers. This work ends with a much more harmonically stable relationship between the strings and electronic parts with all notes reflecting frequency ratios of 1:2, 3:5 and 4:5 (9'57"). The listener's sensitivity to these consonant components is reduced one final time by the masking of the noise filter (10'26"), which contains a centre frequency of 196 Hz. This final filter centre frequency is chosen as it is the equivalent of the fundamental frequency of the G3 note upon which a strong major chord is built in the violin and cello parts at this time. This choice of material allows the work to close on a consonant statement with the filter being seemingly unable to expand and thus disrupt the perceived harmonic structure through masking. The filter is left to simply flutter away without intrusion while supporting the harmonicity of the closing statement.

4.9 Chase

Piano and fixed medium

Maegan Wallace - Piano

(octophonic)

c. 4mins

Chase is a short work which is loosely influenced by early minimalist piano repertoire in its exhibition of subtle, yet consistent, changes taking place within limited material, as a means of gradually expanding/altering the original themes. Only the electronic material is output through the loudspeakers, while all piano material is performed live and is not connected to any loudspeakers.

This piece begins with a minimal range of notes, which constantly expand until the end of the work. Dissonance is created from the outset, as the piano begins on an F4 (349.63 Hz) along with a static sawtooth wave at 179.81 Hz (equidistant in frequency between F3 and F#3), which sustains for the duration of the piece and is output through all loudspeakers for the full duration of the work. The two modulating sine waves begin 180 degrees out of sync with each other, they travel in an anti-clockwise motion and, over time, they move closer together. This effect offers an internal feeling of chasing within the electronics part and, just as the two sine waves are about to be presented from the same loudspeaker, they fade away having never joined. Soon after, two continuously modulating sine waves begin at 369.99 Hz (F#4), and they immediately split with one sliding towards 32.70 Hz and the other modulating to 4,186.01 Hz over the course of the work. As these two sine waves begin to move in opposite directions, binaural beating will occur when they are close to an octave in frequency distance apart from each other.

The extremities of the piano part begin to be vigorously chased by the sine waves out from the middle of the instrument (F4 349.63 Hz) towards C1 (32.70 Hz) and C8 (4,186.01). It should be noted here that, while the fundamental (most intense) frequencies of the piano notes will interact most effectively when crossing over with the electronically generated frequencies, binaural and monaural beating will continuously be evident throughout *Chase* as the frequencies generated in the electronics parts crossover with the overtones of the piano notes. Any beating that occurs during interaction between frequencies above approximately 900 Hz will be monaural. This level of beating will be subtle, but effective, as it will enhance the blurred, rippling and unstable feel to this colourful work. The most prominent beating that will be evident in this piece will be when the fundamental frequencies of the bass notes on the piano are in close proximity to the descending sine wave. Consequently, relative to the notes on the treble clef (forte), the pianist is asked to perform any bass notes with extra intensity (fortissimo) in order for this beating to be more pronounced and prolonged.

The pianist is allowed to randomly play the notes in this piece with one restriction, which is not to surpass the highest (right hand) or lowest (left hand) notes allowed at any given time. The pianist uses a timer display positioned on the piano for the duration of the performance. Sonically, the piano material is quite thick and its range constantly expands (from the middle-out) over the course of the work. The piano note ranges are determined by the frequency of the corresponding sine waves at any given time. In order to preserve a sense of turbulence and increased sensory dissonance, the performer is asked to hold the sustain pedal down throughout the entire duration of the piece and, combined with steady glissandos and clusters being played, the piano part can now generate thick bands of sonic material which strive to engulf and mask the electronics as they perceptually run out from the middle of the piano's range.

This work poses a number of questions regarding what Marc Sabat has described as the 'irrational proportions' upon which modern tempered tuning is based, while also considering the potential for a number of psychoacoustic phenomena within a compositional paradigm.[159] The speed of the sine wave modulations is constant (in Hz per-second) for the duration of the piece whereas the piano part is constructed around both the calculations of the position of these sine waves at any given time and their nearest corresponding key on the piano at that point. This causes the piano range to be restricted by the rate of the sine waves which are moving up and down at a rate of 18.17 Hz and 1.61 Hz respectively [Figure 44]. As the pianist is not expected to maintain absolute accuracy with regards to the expansion of the notes over time, various dissonant effects concerning auditory beating and spectral masking will be evident throughout the work. These factors result in constant minor fluctuations in timbral colour throughout as the speed and choice of notes played by the pianist, combined with the modulating and static tones, consistently cause subtle layers of dissonance.

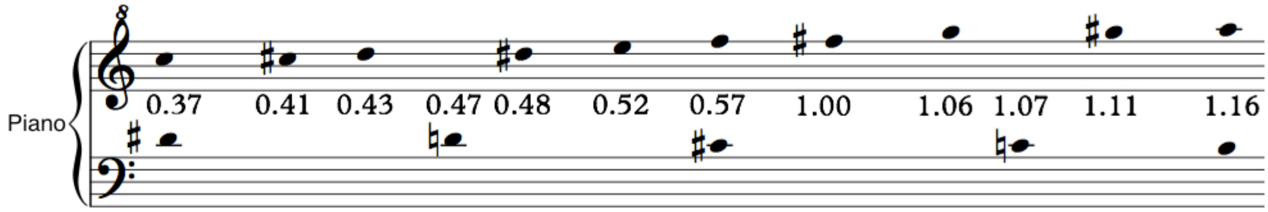


Figure 44: Sample of the piano score from *Chase.* Range expansion for the piano is governed by the set modulation rates of the two sine waves.

With each performance of *Chase,* different results will be evident. Each pianist will have their own interpretation of the score and, furthermore, each pianist will almost certainly never replicate the same performance.

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[159] Marc Sabat, 'On Ben Johnston's Notation and the Performance Practice of Extended Just Intonation', *Marc Sabat : Music & Writings*, http://www.marcsabat.com/pdfs/EJItext.pdf [Accessed 15 April 2016]

4.10 Swarm

Fixed medium

(Octophonic)

c. 12mins

This work considers a combination of both free-field and distortion product primary tones in the creation of binaural beats and residue pitches. In this piece, which comprises of 4 sections, source material simply contains samples of an oud as well as square, sawtooth and sine waves. Various combinations of these materials, and the interactions of their resultant distortion products, cause a complex sonic environment to be constructed. While no thematic material links the individual sections, the 4 sections are drawn together through the use of similar source materials. Intracranial motion and the interplay of the material being generated by the listener's own ears play a vital role in the sense of movement and space within this piece. *Swarm* also makes use of the buzz-like nature of distortion product otoacoustic emissions (DPOAEs), which often sound similar to a sawtooth wave, while binaural beats often create a sinusoidal-like product that is independent from any loudspeaker output. Consequently, a balance can be struck between the colour of the DPOAE/binaural beat and their acoustic primary tones (APTs) when using the aforementioned stimulus types.

The harmonic structure of the A3 (220 Hz) note, as presented by the oud in this piece, is at the centre of *Swarm's* frequency content. The chosen sample of the note contains the typical overtone content of an A3 note with one exception; there is a higher level of intensity at the first harmonic (440 Hz) than at the fundamental, this was carried out as an equalisation process. [Figure 45].

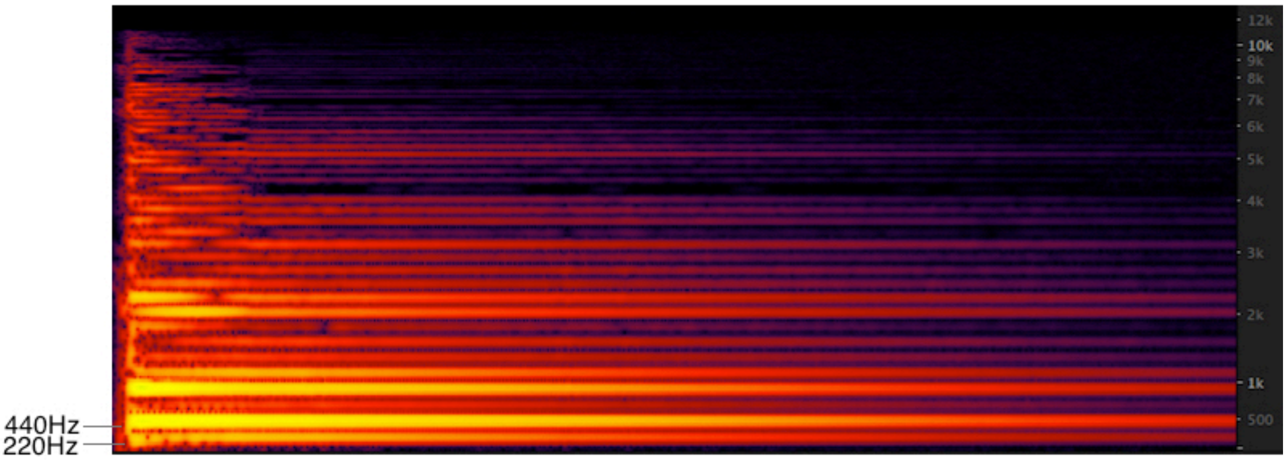

Figure 45: Spectrogram of oud with more energy at 440 Hz (first harmonic) than 220 Hz (fundamental)

The first section (0'00"–c. 3'38") opens with a 440 Hz square wave encircling the listener as it swiftly rotates around the octophonic setup. This wave pulsates in and out of the loudspeakers as it passes through them before finally becoming static to the left of the listener (0'57"). At this point, a square wave enters to the right of the listener. This square wave modulates rapidly in frequency between 408.63–481.37 Hz, at which the centre frequency is 445 Hz. The boundaries for the modulation for this wave were calculated from Moore and Glasberg's equivalent rectangular bandwidth (ERB) model, which states that the ERB value for a 445 Hz centre frequency is 72.73 Hz. This wave eventually stops modulating in frequency as it settles on its 445 Hz centre frequency. The combination of the 440 Hz and 445 Hz waves positioned to the left and right of the listener respectively, produce a 5 Hz binaural beat with a very clear sinusoidal-like 442.5 Hz pulsation. These two primary tones (both occupying 4 loudspeakers) begin to rotate around the listener, while remaining in stereophonically opposite positions. The intracranial motion and positional shifting of the APTs between speakers provides an interesting sense of movement for the listener.

The second section (c. 3'38"–c. 5'40") is constructed around manipulated oud samples which combine to create a complex layer of binaural beat frequencies, all of which beat at a close, but different rate. The oud samples that are used in this piece are time-stretched. As the intensity reduces consistently over time, a correlation is evident in the spectral complexity of the original sample. This reduction in complexity results in the effectivity of these samples, which are providing APT material, also becoming less effective over time. Each APT pair consists of the same sample with one pitch-shifted up by a set frequency value. As the primary tones gradually enter in different loudspeaker positions around the listener, with the APTs never entering either in pairs nor in succession, the buildup of this thick layer of beats is somewhat delicate [Figure 46] In contrast to the delicate nature of the APT introductions, the turbulent sound world that is created through such a procedure will have various layers of sinusoidal-like pulsations perceptually moving through the listener.

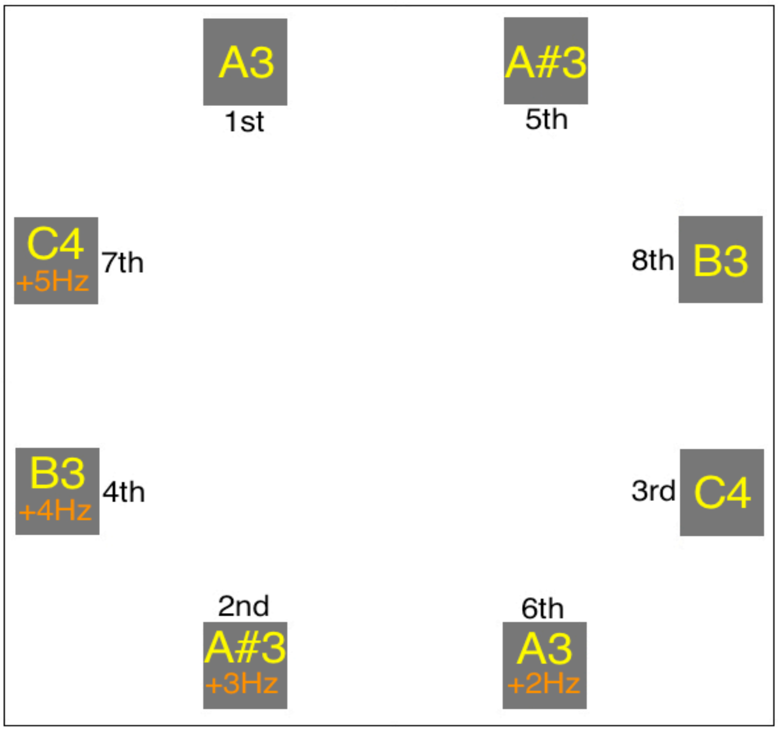

Figure 46: Image showing loudspeaker positions and orders of entries for APTs in *Swarm* section 2. APT pairs are positioned as follows: front left/bottom right, front right/bottom left, front mid-right/rear mid-left and front mid-left/rear mid-right

The third section (c. 5'40"–c. 8.'10") of *Swarm* sees DPOAEs used as the stimulus tones to create binaural beats. Residue pitch is also applied here in the building of stacks of sawtooth waves, which become APTs for the generation of the DPOAEs. DPOAEs at 440 Hz and 442 Hz are created to the left and right of the listener through APTs at 880 Hz/1,320 Hz and 1,760 Hz/2202 Hz respectively. Consequently, a 2 Hz binaural beat will be heard as each DPOAE will only be produced by one of the listener's ears due to the hard-panning of the APTs, which produced the DPOAEs (e.g. 6'08"). This section draws to a close with the DPOAEs remaining static, while their APTs simultaneously modulate in frequency from 1,320 Hz/880 Hz to 880 Hz/440 Hz on the left and from 2,202 Hz/1,760 Hz to 1,760 Hz/1318 Hz to the right of the listener (7'34").

The closing section of *Swarm (*c. 8'10"–c. 11'30") opens in a similar manner to that of the first section with a 5 Hz binaural beat being generated by 440 Hz and 445 Hz APTs. At this point, binaural beating may not be experienced if the listener turns their head in different directions. After a short and raw demonstration of binaural beating, a complex stack of sine waves is presented at both sides of the listener (8'28"). These stacks of sine waves are presented in pairs through the loudspeakers with each one producing a different binaural beat rate when considering the opposite loudspeaker position [Figure 36]. Following on from this, the oud enters once more at 440 Hz (begins subtly at 9'30"), to mask the existing DPOAEs due to the intensity of the first harmonic at 440 Hz.

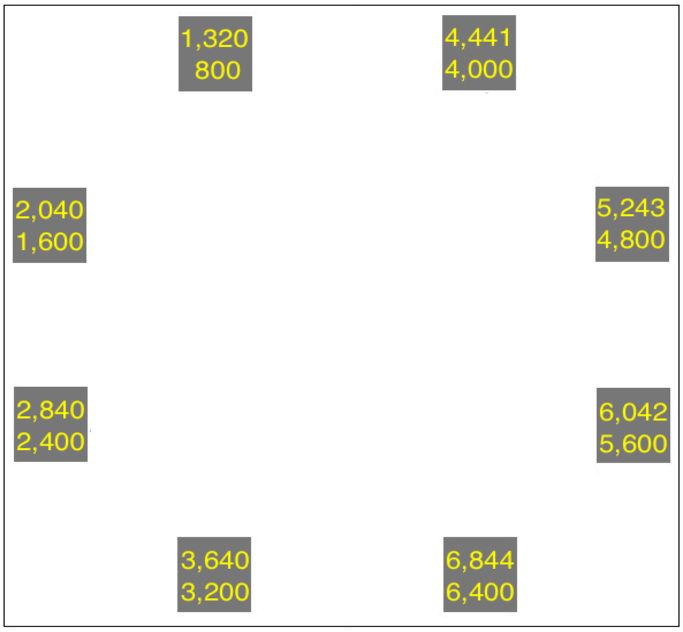

Figure 47: Loudspeaker positioning of APTs in the closing section of *Swarm*

From beneath these turbulent sounds, a random impulse generator instrument is used to present DPOAEs between 426.69 Hz and 453.31 Hz, at which 440 Hz is the centre frequency (9'45"). As before, this frequency region represents the ERB of the centre frequency in question. Below the rapid swarm of random tones, which are set to be no lower/higher than 2,000 Hz/3,000 Hz, a swiftly modulating DPOAE can be heard to buzz around the listener (e.g. 10'17"). After some time, this instrument's output pans to the right of the listener, while a similar instrument creates a 440 Hz DPOAE to the listener's left ear (10'38"). Together they will cause binaural beating with the modulating DPOAE in their right ear before it too eventually settles on 440 Hz. At this point of the closing section, the listener may experience an auditory event similar to a fly buzzing within their ears.

Swarm utilises an array of non-linear inner ear phenomena to create motion and turbulence, while also considering the potential for the interactivity between auditory distortion products.

5 Conclusions

5.1 Introduction

This concluding chapter will address the following areas:

- The evolution of this research.
- How reaction to this research has shaped its dissemination.

Over the course of carrying out this research, the live performance of these works was often an influential factor in relation to both the direction that my research took and to the technical applications of the acoustic material. The acoustical properties and technical setup of various performance spaces, combined with the response from audience members, often varied significantly from performance to performance. Presenting my work in a variety of contexts allowed me to conduct my own analysis within these spaces, while also engaging in conversation with audience members about my work and using their feedback to shape its dissemination.

It should be addressed here that, in the early stages of this research, I had found it very difficult to have my work (both music and papers) selected for inclusion at various events. Having made a number of changes to my submissions; such as addressing the fact that much of this material was experimental, combined with presenting myself as a composer and psychoacoustician in my applications, I noticed a significant increase in the acceptance rates for the submissions and, consequently, an interest in my work grew.

5.2 The Evolution of the Research Process

This research began with a broad working-title of 'Psychoacoustics as an Compositional Tool in Electroacoustic Music.' In the first number of months of my doctoral studies, as a means of investigating a variety of areas concerning psychoacoustics, I decided it best to compose a collection of short studies, with each directly utilising a specific area in its creative considerations. This collection of work was entitled 'Six Studies for Fixed Media' and the following areas were explored:

- Timbre
- Critical bandwidth
- Overtone perception
- Pitch height
- Composing with visualisation tools
- Localisation

The primary aim of this project was to obtain a deeper understanding of these phenomena in a compositional setting, while also discovering what aspects of this material appealed to me most both as a composer and researcher.

Towards the end of my second year, having completed *Critical Bands* and having begun working on *Invisibilia,* I noticed that I had a clear interest in bandwidth phenomena and the concept of the inner ear as a musical instrument. Furthermore, a noticeable shift was evident in the direction of focus of the content of the modules that I was teaching at Maynooth University concerning applications of psychoacoustics in composition. It was clear that, not only did I have a desire to investigate these areas further, but there was a definite interest on the part of my students in learning about this new approach to composition. As well as having an increased success rate in my submissions of work to peer review events, I felt that I had uncovered an area of research that I couldn't help but be drawn toward, in which there was also an audience interest.

5.3 Influence of the Performance Process

Having made such a definitive refinement to my research focus over the course of my second year, my rate of compositional output increased significantly in third year. With a deeper understanding of existing research output in the area (both text-based and musical), as well as a clear vision for my own research focus, my creative work was more efficient than before. I began to complete works that I had started in earlier stages of my research that I could not complete as I either did not fully understand the psychoacoustical material that I was attempting to utilise or I was not fully aware of my intentions for the work. The latter was quite a frequent issue for me in the earlier stages of my research. I found myself starting new works with a loose psychoacoustical concept that I wanted to explore, without having a full understanding of how I could apply it as a compositional device. As well as composing new material in my third year, I spent a significant amount of time applying to calls for work both locally and internationally. My work began to be accepted for performances, which were to take place towards the end of third year and over the course of my fourth year.

I will now outline some of my findings that were made during my research as a result of the performances of my work at various events. I was very pleased with the response received to the premier performance of *Invisibilia* at SMC 2015 in Maynooth University. This work was performed in Renehan Hall at the University. This room is a significantly reflective space. During the soundcheck I had noticed a prominence of the Franssen effect. Up until this point, I had never considered the potential of employing this acoustical phenomenon in my work. It was during this performance when I experienced timbre modulation upon turning my head within the work. In this performance, this reflective environment particularly reduced the effectivity of the timbre modulation as the acoustic primary tones were not only approaching the listener directly from the loudspeakers from which they are being output. At this point, *Invisibilia* was written for an enhanced stereo performance (stereo, replicated with four pairs). In the weeks that followed, I attended the Toronto International Electroacoustic Symposium (TIES) and saw a paper presentation by Ben Nigel Potts. In this paper, Potts discussed the application of quadratic differences tones in his sound sculpture works, while also demonstrating the potential for modulating difference tones when the listener's position shifts within the listening space as their ears move in and out of the path of various loudspeakers' outputs. In the months that followed, I began amending *Invisibilia* by turning it into an octophonic work, which allowed for multiple layers of difference tones as well as an enhanced level of timbre modulation that can be experienced by the listener upon rotation of their heads.

Critical Bands received its premiere performance at TIES 2015. This performance was presented in enhanced stereo. While it received a very positive response, I felt that the subtleties of the timbre modulation that were a result of the binaural beating were, at times, less effective in a large performance space. It has been noted that, unless working with particularly intense stimuli, larger spaces are not ideal for performances of work including binaural beating. This results in the audience members not receiving either a sufficient or balanced level of input in both ears, even if the space has minimal reflections. Some of the material was presented very accurately in this environment but I was not comfortable with the level of variation that would be a factor if this work continued to be performed in a loudspeaker environment. As this was written for stereo performance, it was very easy to remix the material for a headphone installation for future performances.

The premiere performance of *Oscima* at ISSTA 2015 was particularly influential on the final form of the work in question. The original version that was performed was almost half of the length of the piece that exists today. In this version, the sine wave rose up to 2,160 Hz and did not descend once more. Following the performance, a number of individuals from the audience, who were particularly intrigued by this performance, asked me various questions concerning the causes of the beating that they had heard. The general consensus was that the beating was more effective in the lower crossover points and they felt that, due to the slow, almost drone-like feel to this piece, that the work was too short. It was believed that the length (approximately 7 minutes) did not give the listener the chance to become fully immersed in the sound world that was created. Having performed a longer version for these individuals through headphones over the course of the remainder of the event, in which a descending section was included, it was unanimously believed that the longer duration was far more suitable. I was also given the feedback that the binaural beating was even more effective on the descent as its behaviour is far more 'psychoacoustical' when played after a section in which monaural beating had dominated.

This live performance of *Oscima* also highlighted the benefits of live diffusion for the modulating sine wave in some, more reflective venues. If necessary, the individual responsible for the diffusing can examine the interaction of the physical boundaries within the listening space and the sine wave in order to determine the appropriate level at which the sine wave is output. This can fluctuate depending on the resonant frequencies/reflective qualities of each performance environment. The individual will also use these factors to consider the various output intensity levels of each filter during the performance of the work. During the premiere performance, it was noted that the levels needed to be tweaked slightly during performance as the resonant properties of the venue were different once it was full of people. While the impact without live diffusion would not have been drastically negative, it should be noted that, where possible, live diffusion is ideal for this piece.

Transcape is certainly a composition in which real-world performance experience has played a significant role in shaping the format of the work's presentation. This piece was originally an enhanced stereo piece using 8 loudspeakers. Having had some spare time in Renehan Hall at SMC 2015 a few months prior to *Transcape's* performance at INTIME 2015 in Coventry, I played the work and was entirely unsatisfied with the 'performance'. The reverberation time was so long that the bursts of white noise in the opening section did not attenuate enough in the space for the listener to hear the transient-evoked otoacoustic emissions coming from their ears as masking was occurring. While I understood that such a reflective environment was not an accurate representation of the majority of performance spaces at peer-review events, I knew that this work would prove problematic as a result of its transient nature. Having contacted Tom Williams (director of INTIME 2015), I was assured that the auditorium in which *Transcape* was to be performed was far more suited to such a composition as it was a space that was acoustically treated for experimental music performance. During the soundcheck for *Transcape* at INTIME 2015, I immediately noticed that there were only minimal and un-intrusive reflections during the performance and both myself and the technicians could detect TEOAEs. I was satisfied as I had one of the technicians ask me what the high 'ping' was in between the bursts, therefore I could trust that an unbiased listener could detect the TEAOEs. Unfortunately, during the faster, more energetic sections, in which the bursts repeated at much higher frequencies, a high level of very audible shuttering, rattling, and general movement was evident in the rafters of the auditorium where speakers, lighting rigs and other equipment were situated due to the intense level of acoustic energy travelling through the space.

Having identified that a performance of *Transcape* under the conditions of the soundcheck would not prove effective, it became clear that headphone performance was the best way to present this work. Upon addressing this concern to Tom, I was grateful to be offered a space in which *Transcape* could be presented as a headphone installation for the event. This installation allowed for 6 simultaneous listeners to listen in a darkened room. The lack of light in the listening space was chosen so that the audience members could sit down, close their eyes and obtain a heightened awareness of the sounds that were coming through the headphones and the response of their ears to the transient material. I spent the majority of the day positioned outside the installation room and spoke with almost all of the listeners as they left the space. I asked each of them about their experience and they, almost unanimously, responded by stating that they had felt their ears pulsating during the performance and the majority of those agreed that it made them more aware of their ears involvement in the performance itself. There was an exceptionally positive response from the audience regarding their perception of the TEOAEs. Responses that I received included that there was a 'beautiful shimmering' during the section in which rapid clicks and noise bursts are combined, the sound of the TEOAEs was somewhat similar to the sound of a basketball bouncing off of a court (the transient bursts) and the reverberation that followed (the TEOAEs), and many felt that the physical nature of the work (the pulsating of one's ears) caused them to rethink the potential of one's ears in musical performance.

Three different performances of *Maeple* highlighted some potential issues with regards to the flexibility of musical material that relies on specific inner ear stimulation for successful performance. *Maeple* was performed at FEaST Fest at Florida International University in Miami. The loudspeaker setup for the concert venue utilised an octophonic loudspeaker arrangement in which centre front and centre back loudspeakers were positioned. As *Maeple* had been composed for an octophonic setup with four left and four right loudspeakers only, this resulted in the performance being less effective as the binaural beat stimuli were not balanced in their positions facing the left and right ears of the listeners. Consequently, more monaural beating was evident and, while the performance received a positive response, the beating was less smooth and binaural as a result of the octophonic arrangement in question.

Maeple was later performed successfully at MUSLAB 2015 in Mexico City under the appropriate loudspeaker arrangement (four left and four right). The third performance of *Maeple* took place at TIES 2016 in Toronto. During the sound check of this performance, I noticed rapid fluctuations appearing on the sound level meter on the sound desk. These were appearing at times where all individual loudspeaker outputs were smooth and static. Having spent a lot of time troubleshooting this issue, the cause of this problem was due to the fact that all 8 channels were also being directed into a subwoofer. This caused monaural beating as the left and right channels were mixed together. The perceived beating was not smooth as the amplitude modulation of the monaural beats is significantly greater than in binaural beating. Having requested that the subwoofer would not be used for the performance, it was successful and received a very positive response from the audience.

With the exception of *Occultum Tabulatum,* before composing *Waves,* I had not been writing material for acoustic musical instruments. Throughout the course of my research, the nature of conducting psychoacoustic experiments under the more controlled conditions of electronically generated stimuli, led me to writing almost entirely for electronic instruments. Furthermore, in practical terms, the level of accessibility in relation to having my fixed medium work performed internationally is quite attractive to me.

An opportunity arose for me to write a piece for violin and cello (the inclusion of fixed or live electronics was optional) in the Music Current 2016 call for works. As *Waves* was subsequently accepted for this three day event, my composition would then be discussed at two days of workshops before the final selection of works was made for Music Current's *CURRENTS* concert, which would close the event. The workshop was conducted in the Contemporary Music Centre by violinist Mira Benjamin, cellist Lucy Railton and composers Grainne Mulvey and Anne Cleare. The unanimous response from the first performance during the workshop by all four aforementioned individuals, was that there was a perceptual element to the performance. I was very pleased with this response. In terms of criticism, the only suggestion that I received was to present simplified scores for the two performers to reduce page-turning. *Waves* was then selected for performance at the *CURRENTS* concert and was therefore short-listed for the Music Current 2017 commission opportunity.

In relation to practical aspects of this performance in Dublin's Smock Alley Theatre, I learned that this work could potentially prove problematic for performances in smaller spaces or in auditoriums in which loudspeaker positioning was not flexible. The violin and cello were not connected to any microphones for this performance and the two performers were positioned in front of the audience in the centre of the stage. The left and right loudspeakers were positioned at the front left and right of the audience (approximately 8–10 meters apart) at the front of the stage and there was ample space (approximately 4–5 meters) between the speaker and the performers. This reduced the likelihood of monaural beating and, as the acoustic instruments were not connected to a microphone and were positioned behind the loudspeakers, the effects of masking were very strong in this performance. The acoustic instruments became physically lost at times in this listening space when the thick veil of noise was presented to the audience from the loudspeakers. There were no programme notes issued to the audience for this concert and so the audience were unaware of any use of their own ears being used as instruments in the performance. After the concert, composer Ailís Ní Ríain introduced herself to me and commented that she felt as though this work was heightened by its 'primal' nature. Ní Ríain stated that she was aware that her ears were involved in this performance and that it was a refreshing experience for her as an audience member. Following on from the response to this performance during the workshops, I was particularly pleased with these additional remarks as, I felt that it showed that my use of the inner ear as an instrument was successful, while also being appreciated and received positively by both composers and audience members. As a clear dissemination of my research is fundamental to my work, it is particularly satisfying to me when other composers see validity and/or appreciate my methodologies.

Chase is another work in which I explored the use of both acoustic and electronic musical instruments. At the time of writing this piece, I was particularly interested in the concept of pouring sound into the space that surrounds the listeners. The debut performance of *Chase* took place in University of Ulster, Derry's Great Hall. This large reverberant space was the ideal venue for this work to be performed as the level of reverberation enhanced the beating effects. Furthermore, the acoustic properties of this space resulted in a particular intrusion of the Franssen effect. Consequently, the sine waves, which continuously rotated around the audience, were almost entirely impossible to locate. This level of confusion enhanced the sense of spectral saturation and blurring that was to surround the listener. While it was not intended in the composition of the work, it could not be said that it hindered the performance of the piece.

The pianist, Maegan Wallace, was situated on the stage at the very top of the Great Hall. This stage is at a height of approximately 3 foot. The grand piano that was used for the performance was unable to be moved to a lower height or, more importantly, closer to the audience. As a result, I found the effects of the auditory beatings in this piece would have been more effective if the piano was closer to the audience and positioned at the same height as the octophonic loudspeaker arrangement. I was overseeing the sound desk for this performance to ensure that no frequencies were enhanced to any particular degree by the natural resonances of the room. The sound desk could not be moved and it was situated outside of the octophonic loudspeaker arrangement and in between the front left/right loudspeakers and the grand piano. Consequently, I was not placed in the most effective listening position from which careful attention was to be given to the loudspeaker outputs as I was not in the same environment as the listener. The sound of the grand piano also increasingly masked my perception of the loudspeaker outputs over the course of the performance.

While this debut performance of *Chase* was far from ideal, I learned a lot from it in relation to the accessibility of my works being performed. It is quite clear that it is not beneficial for the reception of my work, going forward, for me to not address any concerns that I may have in relation to the acoustics of the performance space as well as the technical setup. As can be seen with the aforementioned points, not addressing these issues could lead to performances of my work proving ineffective. These issues can also result in a misrepresentation of my work overall. As one of my primary concerns is to present my research to composers in a manner in which my compositional methodologies are clear and the potential results of employing them are effective, these issues in performance must be prioritised in the dissemination of my work.

The process of submitting my work to various events, both locally and internationally, as well as subsequently presenting the material, has been most beneficial to my understanding of the practicalities and logistical concerns that are associated with such performances. It is vital to the success of my work that these factors are not only addressed, but understood by the researcher and composer in order to ensure that compositions employing such material are most effective and that successful performances are experienced by one's audience.

5.4 Turning Point in the Direction of my Work's Presentation

My paper *The Inner Ear as a Musical Instrument* was selected for presentation at the Acoustical Society of America's conference in Jacksonville, Florida. At the time of writing, this paper could be seen as a summary of my work as a whole and it was a fantastic opportunity to present this material at a conference in which the primary focus was not music. Before the conference, I was informed that the content of my paper was 'identified as being potentially newsworthy.' Consequently, I was invited to write a lay-language paper for the online press room for acoustics.org, the content of which is frequently read by international news organisations. It was during the process of writing this article when the potential benefits of occasionally placing the illusory and entertaining aspects of this material to the forefront became apparent to me. In doing so, the level of accessibility to my work is immediately heightened. *The Inner Ear as a Musical Instrument* was being presented in the only session concerned with music at this conference, which had approximately 90 paper sessions with generally no less than 6 papers per session. *The Inner Ear as a Musical Instrument* was presented in a session entitled 'Musical Acoustics,' within which there were a total of six papers being presented. Furthermore, in broad terms, my paper was dealing with the least accessible subject area within this session as it referred to creative processes within a form of art music, while the other papers investigated subject matter relating to the acoustical properties of various acoustic instruments.

A total of three hours after my paper presentation, once the final paper in the session had ended, I experienced something that was entirely new to me. Approximately five or six people queued up to speak to me about my work. Three of these individuals were third level educators asking for my permission to use my research as content in their own classes. Subsequently, I had one of their students contact me to express an interest in my work. Throughout the course of writing and presenting this paper, having the work published, writing the lay-language paper and receiving feedback to all of these areas to this date, I have learned that there is a significant increase in audience interest/response to my work when the material is presented in an accessible manner. It has become apparent that, by breaking down the fundamental aspects of the biomechanical processes involved and combining them with compositional methodologies in a manner in which the audience can easily be presented with the potential results, my research can be disseminated more effectively and efficiently.

Having had such a positive experience presenting *The Inner Ear as a Musical Instrument,* I decided to use the audience's intrigue as inspiration for the creation of another work during my retreat that followed in Florida. It was quite clear that there was an interest for an audience to explore my research in a variety of contexts (paper presentations, audio demonstrations, concert hall performances, headphone performances). At that time, I had planned on creating a sound art installation that required the listener to walk through the listening space as a means of exploring the potential of their ears as musical instruments. My primary concern for this new work was that the listener would leave the space with an awareness of how their own ears can interact with external acoustic energy. Over the course of four days, *Ear Walk* was created. The process was heavily influenced by Alvin Lucier's approach of identifying a primary goal for a work, spending the necessary amount of time simplifying it down to the essential materials and then planning the technical aspects of the work itself. When designing this installation, the most challenging aspect for me was the process which ended in the decision to use a single headphone in the installation. While it may seem simple, it was not something that I had encountered before in sound art. Once the decision was made to use this single headphone along with a loudspeaker array, the foundations of the design for this piece were in place.

Ear Walk was presented in the Spiral Studio at the University of Huddersfield during the Sound and Sculpture Conference. This conference was the ideal environment for such a work to be presented as the content of the works presented were all concerned with the physicality of sound in space. The Spiral Studio was a fantastic space to present *Ear Walk* as its state of the art acoustically treated interior design results in the listener not experiencing any negative effects of monaural beats.

The response from all attendees to the installation was exceptionally positive and, once again, the enthusiastic nature of the responses that this work received was most encouraging. The most common response that I received was listeners stating that they had been aware of binaural beating for quite some time, but had either never experienced it explicitly or had never experienced them as a compositional device in a work. The listeners were also very intrigued by the potential of their own ears within the work. Many were quite fascinated by the nature of how the sound of much of what they experienced, was substantially different from either the single headphone or loudspeaker outputs when listened to independently. Additionally, a small number of those who experienced *Ear*

Walk commented on how surprised they were with how little acoustic stimuli is used in the creation of the work. This aspect of my work is something that I am always pleased to have acknowledged. In *Ear Walk,* a conscious decision was made to present the listener with less acoustic energy as it allows for more of a focus to be placed on the contribution from the listener's ears during their experience of the installation.

With an interest in my compositional methodologies growing and, based on the nature of the enquiries and comments that I was receiving from interested individuals, I believed that a means of presenting my work in an educational and explorative setting would prove beneficial to the further dissemination of my research. I had also been influenced by the interest in the three educators who approached me at the Acoustical Society of America meeting as they felt that my work would be of interest to students. I created an audio visual installation compilation of works entitled *In-Ear Performances.* This installation consisted of a single, looped, video file. The audience member would approach a wooden stand, on top of which a computer monitor and a set of headphones would be placed. The individual would hear stereo reductions (mixed for headphones) of *Transcape, Invisibilia, Oscima, Maeple* and *Critical Bands.*

On the screen, a series of still images were presented. These stills contained short text information regarding what the individual is listening to as well as images of waveform/spectrogram samples. The bottom of the screen contained a fixed row of text with succinct descriptions of DPOAEs, binaural beating, residue pitch and auditory masking. In order to remain efficient and non-repetitive with regards to the text content on the screen at any given time, this row remained throughout the duration of the looped video file as these phenomena in question regularly repeat throughout the majority of the works in question.

This installation seems an ideal platform to present my work in an unintrusive setting whereby the individual can experience as much or as little of the material as they wish. Furthermore, it gives me the opportunity to present multiple works to a single audience, while also offering explanations regarding my methodologies in an academic setting. *In-Ear Performances* offers an accessible opportunity to audience members to obtain a greater degree of understanding of these psychoacoustic phenomena while also introducing them to a small repertoire of works in which such use of biomechanics is at the heart.

The response to *In-Ear Performances* at the Northern Ireland Science Festival's 'HEArts of STEM' event was particularly positive. Having had experience transferring my work to the medium of headphones with *Transcape* just a few months previous, the response to this installation caused me to consider the use of headphones as a performance medium in the future. Initially, it was my understanding that headphone performance would be most suitable for works relying on TEOAEs, such as *Transcape.* I noticed that listeners were able to identify the DPOAEs a lot faster and, while spatial effects stemming from audience positioning or rotating one's head cannot be a part of headphone performance, it became quite clear that there are certain strengths to be found in such a medium when employing the inner ear as a musical instrument. It is the decision of the composer to decide whether headphone or loudspeaker performance best suits their individual works. One response that I noticed to be significantly different from audience members having experienced headphone performances of my work was that they felt that they could feel a heightened effect of the intracranial motion of the binaural beats at times. Almost every individual with whom I spoke at this event commented on the strange feeling of the binaural beats, whereas such a response to the intracranial motion is not so prevalent after loudspeaker performance.

Shortly after the Northern Ireland Science Festival, I presented a paper entitled *Did You Know Your Ears Can Sing?: The Muted Potential of the Ear* at BEAST FEaST at the University of Birmingham. I was quite interested in the call for papers for this event as it stated that the papers should be presented in the style of

> informal talks in the tradition of TED. Academic topics are welcome, as are intellectually demanding ones, but should be pitched for the festival audience rather than a group of scholars.[160]

Having had such a positive experience shaping my work to both non-academic and musical audiences at the Acoustical Society of America conference, I very much enjoyed presenting this paper. My presentation opened up a demonstration of residue pitch. Through a MIDI keyboard that was connected to a SuperCollider patch, I performed *Twinkle, Twinkle, Little Star* using only the residue pitch of the audience's ears as melodic material. Nothing other than random frequencies was output from the loudspeakers. At the end of my demonstration, I asked for the audience to raise their hand if they heard 'a well-known tune.' Almost the entire audience placed a hand in the air. I then asked the audience to inform me of what melody they heard, to which they responded saying that they had heard *Twinkle, Twinkle, Little Star*, *Baa Baa Black Sheep*, and 'the alphabet.' All of which have an almost identical melodic line. This was most satisfying to me as the age range of the audience members was quite broad (approximately 18–70).

Following on from this demonstration, I explained to the audience that the melodic

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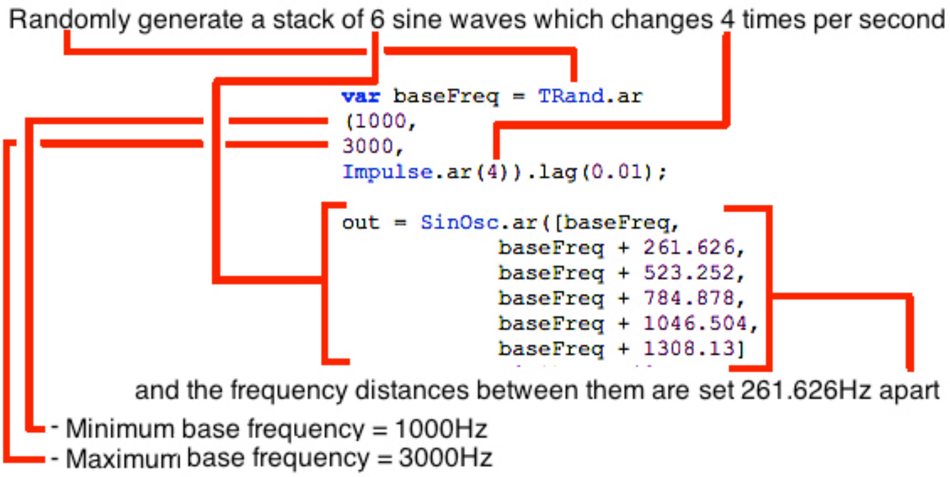
[160] BEAST FEaST 2016 Call for Works/Talks ', http://www.beast.bham.ac.uk/beast-feast-2016-call-for-workstalks/ [Accessed 2nd August 2017]

material that they heard was solely produced within their own ears. The following image was then placed on the presentation screen



Randomly generate a stack of 6 sine waves which changes 4 times per second

```
var baseFreq = TRand.ar
(1000,
3000,
Impulse.ar(4)).lag(0.01);

out = SinOsc.ar([baseFreq,
                    baseFreq + 261.626,
                    baseFreq + 523.252,
                    baseFreq + 784.878,
                    baseFreq + 1046.504,
                    baseFreq + 1308.13]
```

and the frequency distances between them are set 261.626Hz apart

- Minimum base frequency = 1000Hz
- Maximum base frequency = 3000Hz

Figure 48: Image presented at BEAST FEaST explaining the residue pitch demonstration patch from SuperCollider

Figure 48 shows the simple SuperCollider patch that was used in my MIDI keyboard demonstration. This explanation was given to the audience to prove that any melodic material that they heard was not coming from the loudspeakers. Upon giving this explanation, I then outlined the biomechanical processes relating to residue pitch, thus proving that any melodic material that the audience members had heard from the demonstration was coming from their ears. Using middle C (261.626 Hz) as an example, this image simply highlights that a stack of 6 sine waves with random frequency values assigned to each component, between 1K Hz and 3K Hz, are output. The MIDI keyboard then controls the frequency distance between the random frequency components. When middle C is pressed on the MIDI keyboard, the random frequencies will remain random, yet the frequency distance between these random frequencies is set at 261.626. This results in the listener hearing a residue pitch equal to middle C. The loudspeaker output was set between 1K Hz and 3K

Hz as the frequency range of the melodic line ranged from 261.626–440 Hz and so the demonstration of residue pitch was more effective as there was a clear distance in frequency height between the loudspeaker output and the residue pitches.

In conversation with Christopher Haworth, he explained to me about the challenges of presenting material concerning the ear as an instrument to an audience. Haworth described a scenario in which a colleague of his met significant opposition from an audience member during a demonstration. This individual was adamant that the 'distortion products' that he was hearing were being emitted through the loudspeakers. Since hearing this example, in lectures and paper presentations, I have found it significantly beneficial to also use spectrogram images, where necessary, to clarify any points being made concerning loudspeaker output. Not only has this proven to reduce opposition, it has been an advantage in explaining this material to students/audience members who may struggle to trust that they have understood the ear as instrument concept correctly.

The final composition written for my portfolio was *Swarm*. For my final year, I had been considering writing something that pushed my ideas even further, if possible. While preparing some audio demonstrations for presentation at TIES 2016 for my paper *Proposing an Application for Binaural Beating in Timbre Modulation,* the idea of using distortion products as the binaural beat stimulus occurred to me. This area of discussion was not included in my paper presentation, however, I made a note of this concept and decided to revisit it at a later date.

Upon exploring this idea by experimenting with various stimuli, I discovered that distortion products could be used as stimuli in the provocation of non-linear inner ear phenomena. I began to write a composition in which this notion would be explored further. At the time of submitting this thesis, *Swarm* has not been performed publicly, however, a stereo reduction has been included in *In-Ear Performances*, which will be installed at ISSTA 2017 at Dundalk Institute of Technology.

5.4 Conclusion

This research was undertaken with the aim of providing the field of electroacoustic music composition with a greater understanding of non-linear inner ear phenomena through practice-based research. It has always been a primary focus of my studies to place my findings on an open and accessible platform, from which further research and creative exploration could begin. I believe that the material in this thesis proves that the non-linear nature of the inner ear has significant potential within electroacoustic music composition, while also making the explored methods very accessible for composers.

Over the past four years I have found myself presenting my findings through concerts, installations and paper presentations at various conferences, festivals and symposia throughout the world. One of the most encouraging aspects of presenting this material has been witnessing such a positive and intrigued response from audience members, who often had either never before experienced nor heard of these aspects of psychoacoustics and the potential of the inner ear as a musical instrument. Having researched this material in such detail, one thing that consistently grew ever-clearer for me was that there is a significant place for this material to be disseminated within musicological repositories, combined with a clear interest among music practitioners, which I believe will see this research, and further work conducted in the area, open up exciting new avenues of exploration for composers of electroacoustic music.

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Alvin Lucier, *Three Works for Classical Instruments and Oscillators,* (Lovely Music, 1990)

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Jean-Claude Risset, *Songes • Passages • Computer Suite From Little Boy • Sud,* Audio CD (WERGO, 1988)

Maryanne Amacher, *Sound Characters (Making the Third Ear),* Audio CD, (Tzadik, 1999)

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Audio Demonstrations

These demonstrations are best suited to listening through monitor headphones.

Note: All acoustic primary tones presented through the headphone output of these demonstrations are sinusoidal.

1 Simultaneous Masking

400 Hz is presented with thin band filtered noise intersecting on two occasions. Two separate loudspeakers should be used in front of the listener for this demonstration, as monaural effects will occur, should both signals be presented through the same loudspeaker.

2 Forward Masking

400 Hz is presented with intersecting white noise bursts. Amplitude modulations of the 400 Hz tone will be caused as a result of forward masking.

3 Monaural Beating

400 Hz and 401 Hz tones are presented in succession (in that order) before being simultaneously presented.

4 Binaural Beating

a) A 400 Hz tone is hard-panned left and a 403 Hz tone is hard-panned right. After separate presentation they are played simultaneously. This will result in a 3 Hz binaural beat.

b) A 200 Hz tone is hard-panned left and a 398 Hz tone is hard-panned right. After separate presentation they are played simultaneously. This will result in a 2 Hz binaural beat.

5 Aural Harmonics

A 300 Hz sine wave is presented here. In this demonstration, the intensity will begin at zero, before peaking in the middle and returning to zero once more. It is important to direct one's attention to any additional harmonic frequency components that can be heard as the intensity increases, and the contrary as it lessens.

6 Distortion Product Otoacoustic Emissions

6a

f2 = 1,200 Hz
f1 = 1,000 Hz

Resulting in a 200 Hz DPOAE

6b

f2 = Modulating tone from 700 Hz to 1,200 Hz
f1 = Modulating tone from 500 Hz to 1,000 Hz

Resulting in a 200 Hz DPOAE

6c

f2 = Modulating tone from 1,100 Hz to 600 Hz
f1 = (Static) 500 Hz tone

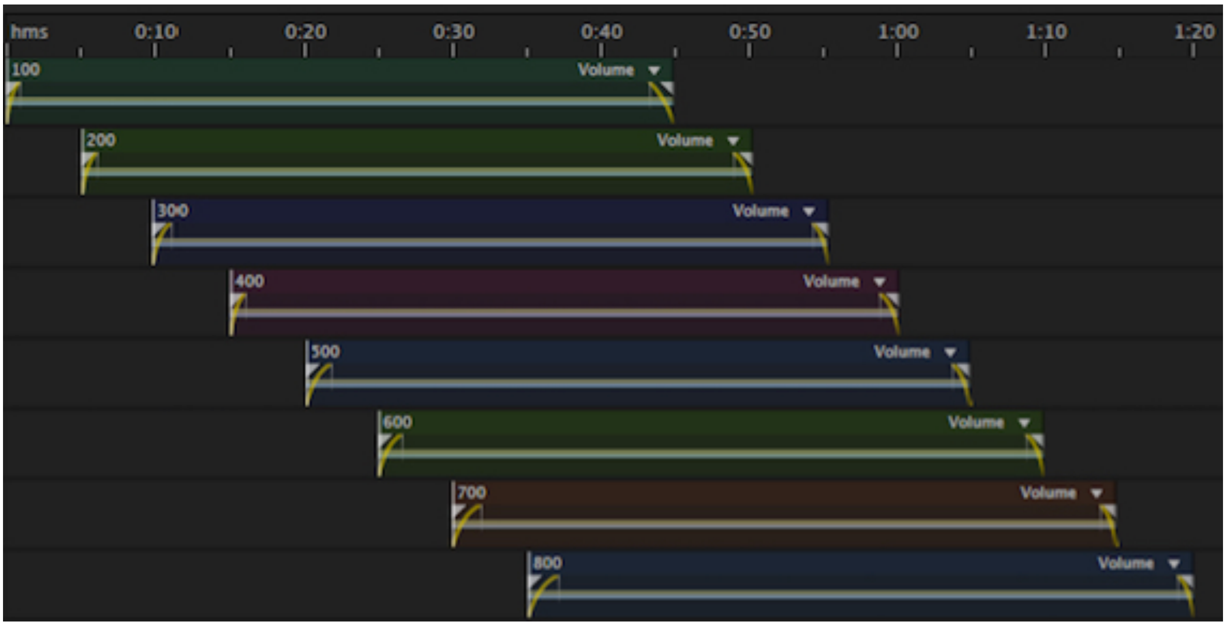
Resulting in a modulating DPOAE from 600 Hz to 100 Hz

7 Transient Evoked Otoacoustic Emissions

Short bursts of noise used as the stimulus

8 Residue Pitch

8 tones are presented in this demonstration, starting at 100 Hz and rising in integer multiples until reaching 800 Hz. This demonstration begins with just a 100 Hz tone and then each other frequency is gradually added until all are playing simultaneously. Following on from this, each frequency is gradually removed, starting with 100 Hz and rising (as outlined in the below image). The listener will notice no change in perceived 100 Hz tone, other than changes in colour, until the final 800 Hz tone remains unaccompanied.



9 Distortion Product Otoacoustic Emissions as Primary Tones for Binaural Beating

LEFT	RIGHT
1,450 Hz	2,455 Hz
1,000 Hz	2,000 Hz

RESULTING DPOAE FREQUENCY	
450 Hz	455 Hz

RESULTING BINAURAL BEAT FREQUENCY
5 Hz

10 Residue Pitch as Primary Tones for Binaural Beating

	LEFT	RIGHT
PRIMARY TONE	3,000 Hz	5,020 Hz
PRIMARY TONE	2,500 Hz	4,515 Hz
PRIMARY TONE	2,000 Hz	4,010 Hz
PRIMARY TONE	1,500 Hz	3,505 Hz
PRIMARY TONE	1,000 Hz	3,000 Hz

RESIDUE PITCH	500 Hz	505 Hz

BINAURAL BEAT FREQUENCY	CENTERED
	505 – 500 = 5 Hz

11 Distortion Product Otoacoustic Emissions as Primary Tones for Residue Pitch

BALANCED

RESIDUE PITCH PRIMARY TONE TYPE	**FREQ**
DPOAE	1,800 Hz
DPOAE	1,600 Hz
DPOAE	1,400 Hz
DPOAE	1,200 Hz
DPOAE	1,000 Hz

RESIDUE PITCH	200 Hz

In this demonstration the DPOAEs are first presented individually, starting at 1,000 Hz and rising, before all 5 DPOAEs are presented simultaneously. A low fuzz-like sound at approximately 200 Hz should be heard.

Additional Notes

Contents of DVD discs

Disc 1

1 Waves
2 Ear Walk
3 Invisibilia
4 Chase
5 Swarm

Disc 2

6 Occultum Tabulatum
7 Critical Bands
8 Maeple
9 Oscima
10 Transcape
Audio Demonstrations

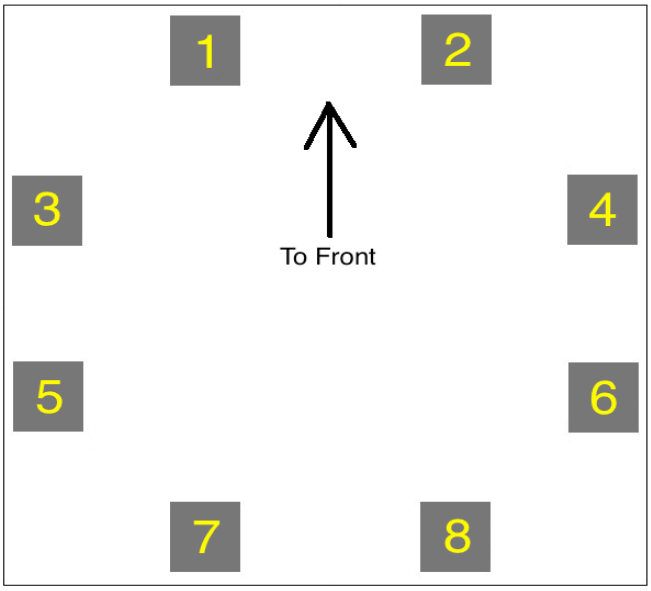
A USB flash drive has also been provided for the reader's convenience. This drive contains all of the material from Disc 1 and Disc 2.

If you wish to obtain score or audio (individual monophonic files/binaural versions, etc) content digitally, please feel free to contact Brian directly through brian@brian-connolly.com

Notes on compositions and loudspeaker setup

All audio files are labelled according to their respective loudspeakers.

The following is the correct loudspeaker setup for this portfolio.



Ear Walk

Please use a single headphone for the output of the track entitled 'Single Headphone Output.' This track will most likely be required to be played through a separate software to the one playing the 8 monophonic tracks.

Headphones with rotating ear pieces may be required for the performance of this piece. It is vital that the listener does not have any headphone placed over their right ear during this installation.

As each listening room will differ, master levels may need to be adjusted accordingly so that the loudspeaker and headphone outputs are not at independent levels. A balance must be struck between the two levels for this work. Please use the headphone volume as a starting point: the headphone output should be as loud as possible, providing that it is comfortable for the listener and does not distract from the loudspeaker output.

When this piece is installed, the audio of each of the monophonic tracks is subtly faded into a repeat of itself to avoid any noticeable clicks. Multiple hours of duplicate tracks are placed in sequence for the installation.

Oscima

The audio provided here is from a live performance (Dance Limerick venue, ISSTA 2015). Please adjust the master volume accordingly to suit the listening space in question.

Compositional Output

Chase

- ISSTA, Derry (September 2016)

Critical Bands

- TIES, Toronto (August 2015)
- NYCEMF, New York (June 2017)

Ear Walk

- Sound and Sculpture Conference, Huddersfield (May 2016)

In-Ear Performances

This is a headphone installation comprised of a stereo reduction of *Oscima*, *Critical Bands, Maeple*, *Transcape* and *Invisibilia*

- Northern Ireland Science Festival, Belfast (February 2016)

Invisibilia

- SMC, Maynooth (August 2015)
- Sonorities, Belfast (November 2016)
- Sounding Out the Space, Dublin (November 2017)

Maeple

- MUSLAB, Mexico City (December 2015)
- FEASt Fest, Miami (November 2015)
- TIES, Toronto (August 2016)

Oscima

- ISSTA, Limerick (August 2015)

Transcape

- INTIME, Coventry (October 2015)

Waves

- Music Current Festival, Dublin (April 2016)

Paper presentations

'Six Studies for Fixed Media'
- Composition as Research Symposium, Maynooth (May 2013)

'The Fetish of Technology'
- SMI Postgraduate Conference, Cork (January 2014)

'The Listening System as Performance Medium'
- ISSTA, Limerick (August 2015)

'Transient-Evoked Otoacoustic Emissions in *Transcape'*
- INTIME, Coventry (October, 2015)

'The Inner Ear as a Musical Instrument'
- ASA, Florida (November 2015)

'Did You Know Your Ears Can Sing?: The Muted Potential of the Ear'
- BEAST FEaST, Birmingham (April 2016)

Composing for Non-Linearity: Exploiting the Physicality of the Listener in 'Ear Walk'
- Sound and Sculpture Conference, Huddersfield (May 2016)

'Proposing an Application for Binaural Beating in Timbre Modulation'
- TIES, Toronto (August 2016)

‘Employing the Listener: Investigating a Psychoacoustical Approach to Sound Art Composition’
- Sounding Out the Space, Dublin (November 2017)

Publications

'The Inner Ear as a Musical Instrument'
- Proceedings of Meetings on Acoustics (Vol 25), Acoustical Society of America.

'Compositional Applications for Binaural Beating in Timbre Modulation'
- eContact! (Issue 18.4)

Waves

(violin, cello and fixed media)

Brian Connolly
2016

Additional notes to the performers:

Please refrain from the following:

- Vibrato
- Unnecessary force while changing bowing position

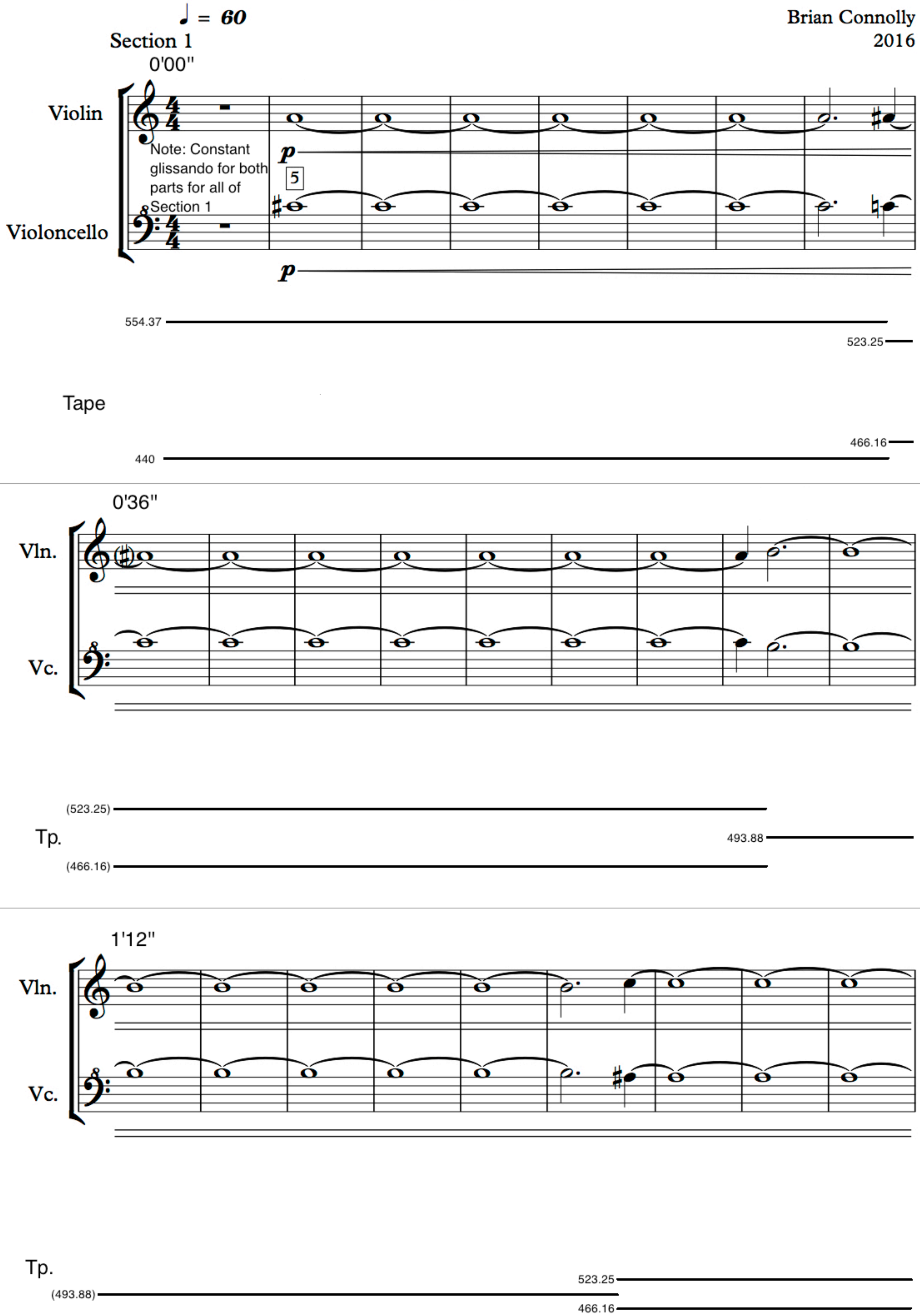
'Waves'
live electronics legend

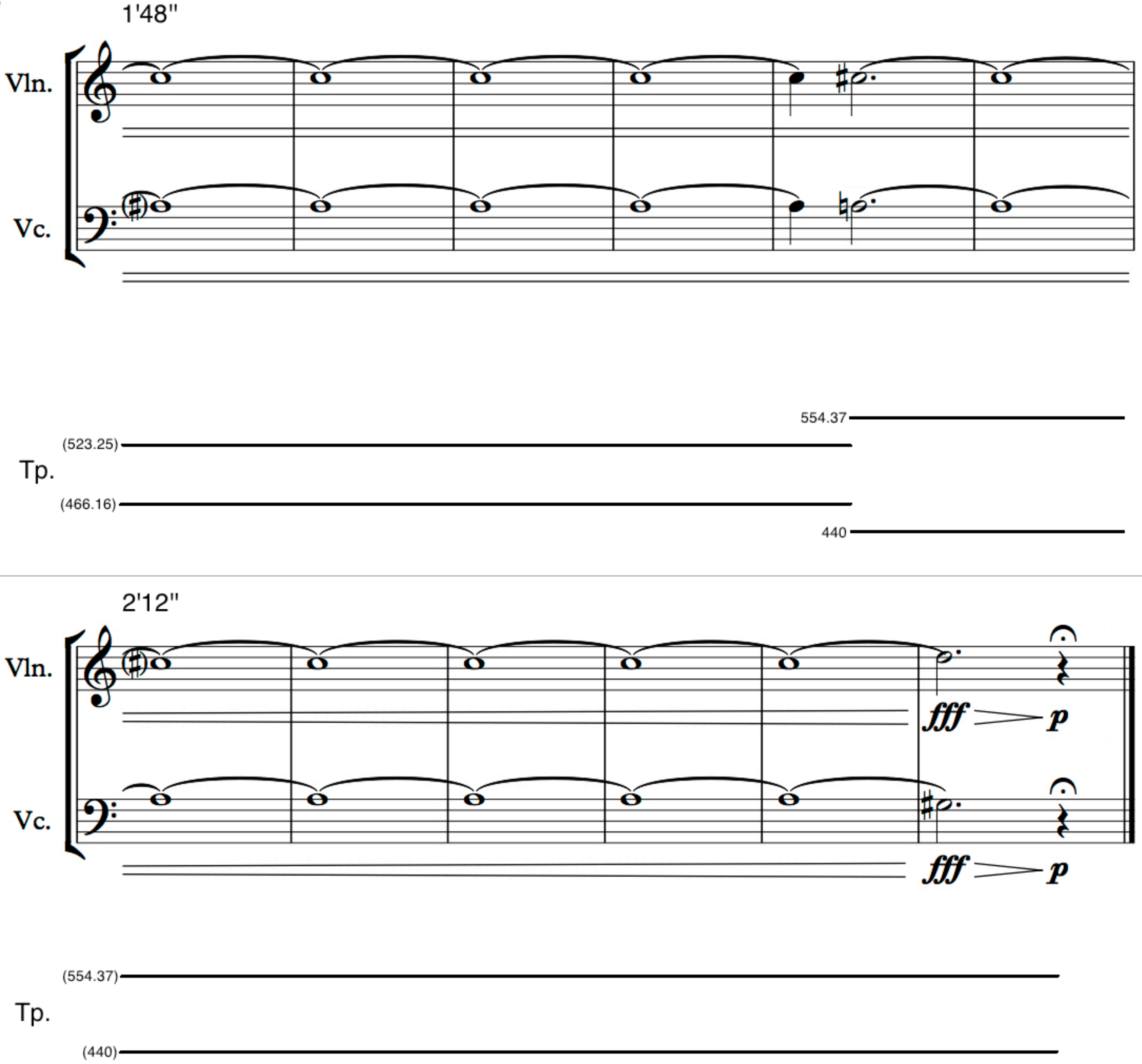
sine wave
- unless otherwise stated

filtered noise
with fixed peak
centre frequency
of A and
modulating
bandwidth

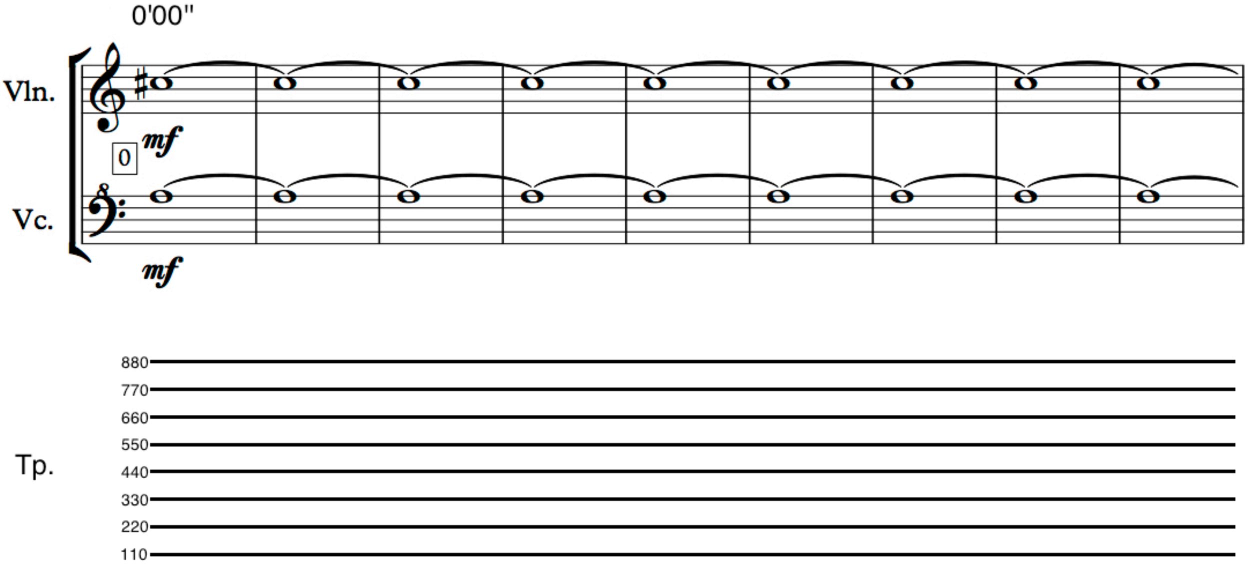
Waves

Brian Connolly
2016

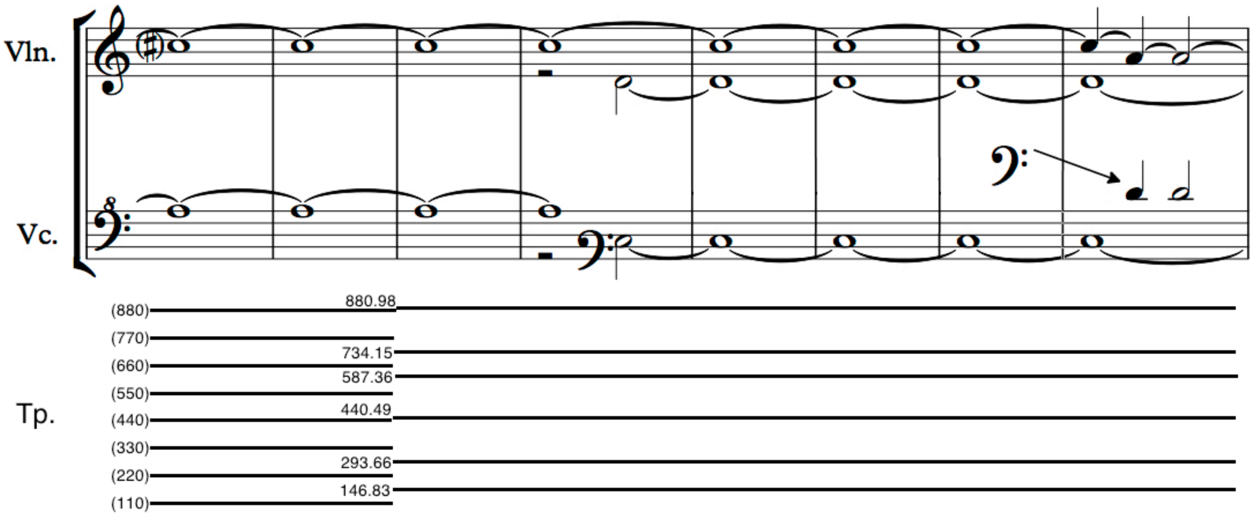



1'48"
Vln.
Vc.
554.37
(523.25)
Tp.
(466.16)
440
2'12"
Vln.
fff
p
Vc.
fff
p
(554.37)
Tp.
(440)

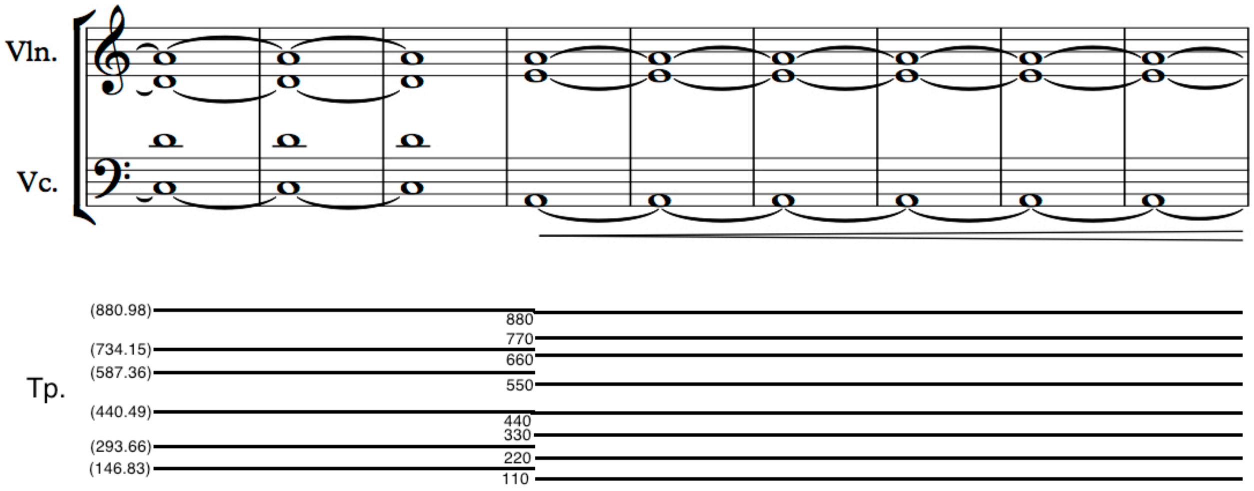
Section 2


0'00"
Vln.
0
mf
Vc.
mf
880
770
660
550
440
330
220
110
Tp.

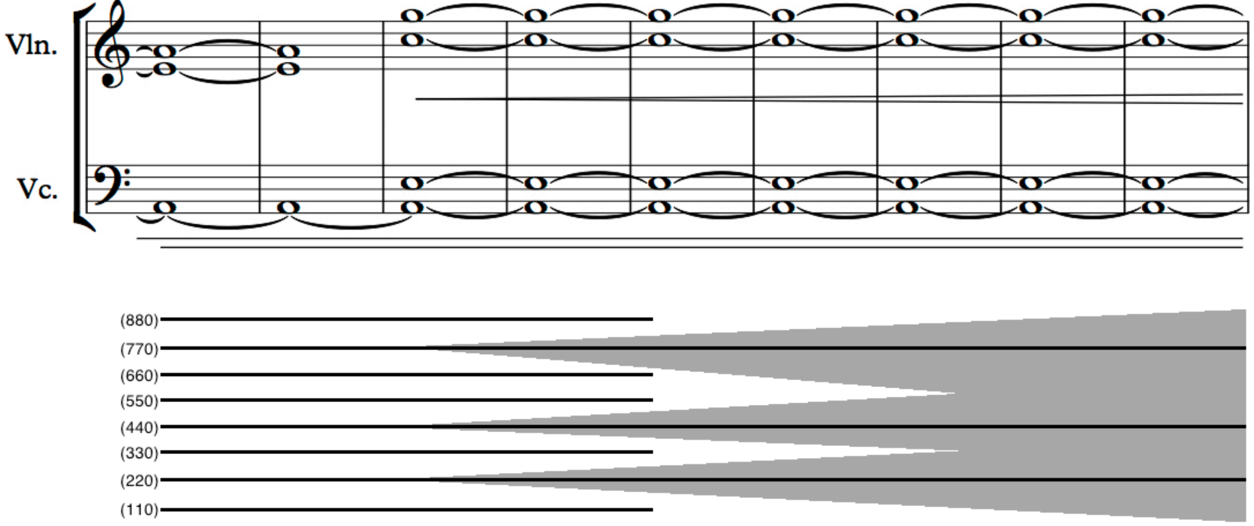
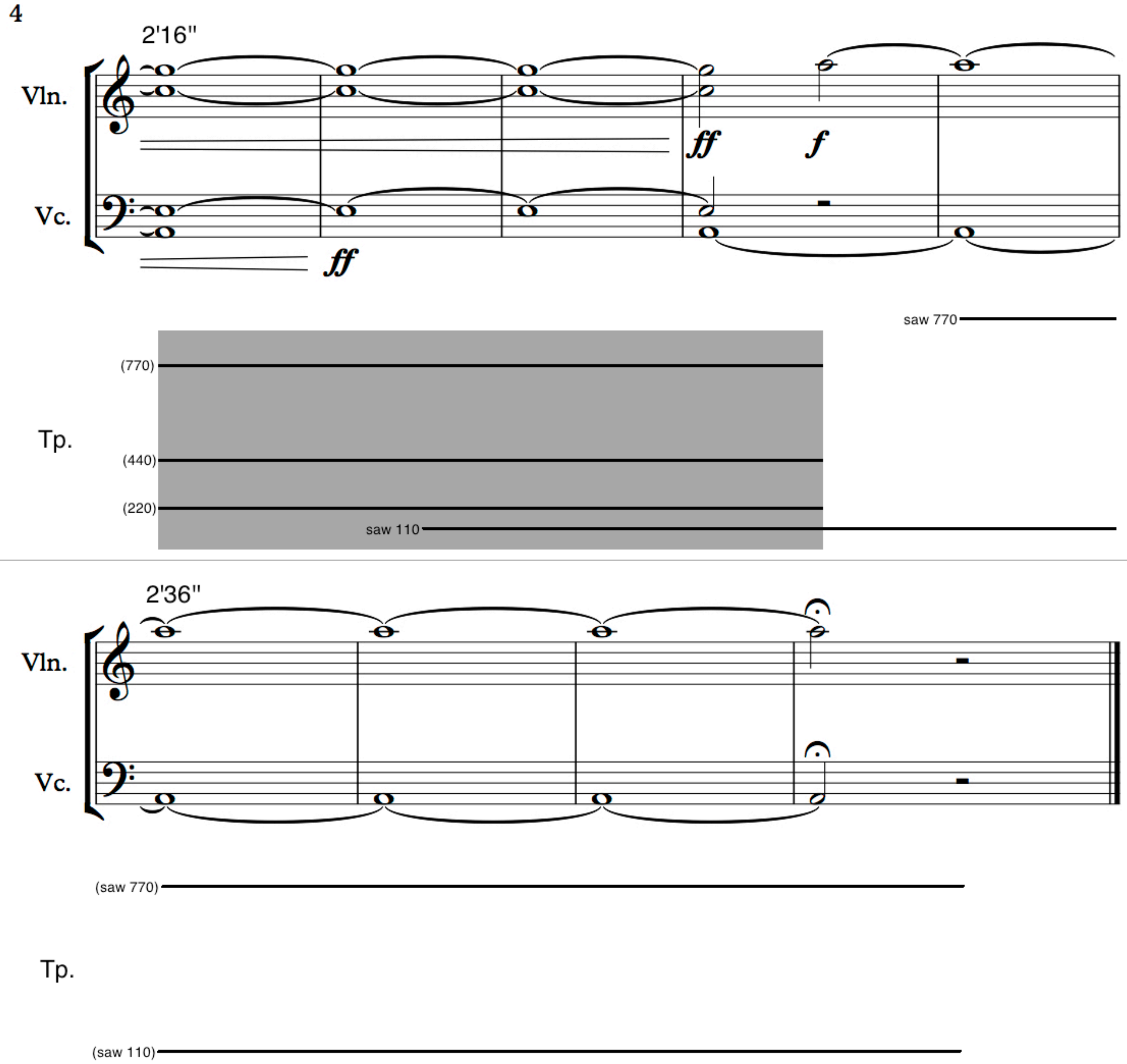
0'38"


Vln.
Vc.
Tp.
(880)
880.98
(770)
734.15
(660)
587.36
(550)
440.49
(440)
(330)
293.66
(220)
146.83
(110)

1'12"

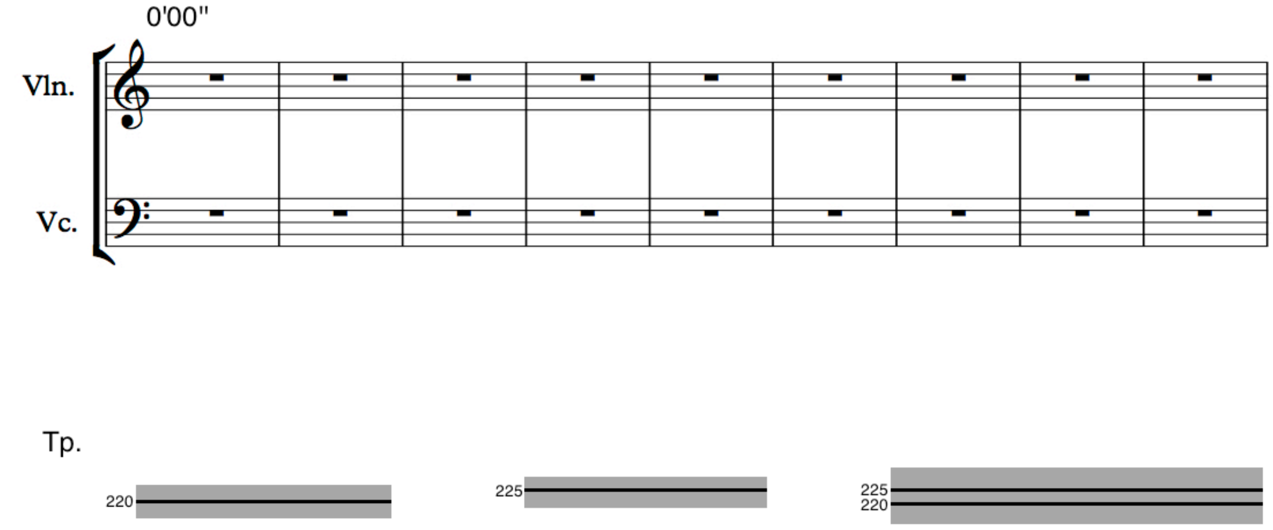

Vln.
Vc.
Tp.
(880.98)
880
770
(734.15)
660
(587.36)
550
(440.49)
440
330
(293.66)
220
(146.83)
110

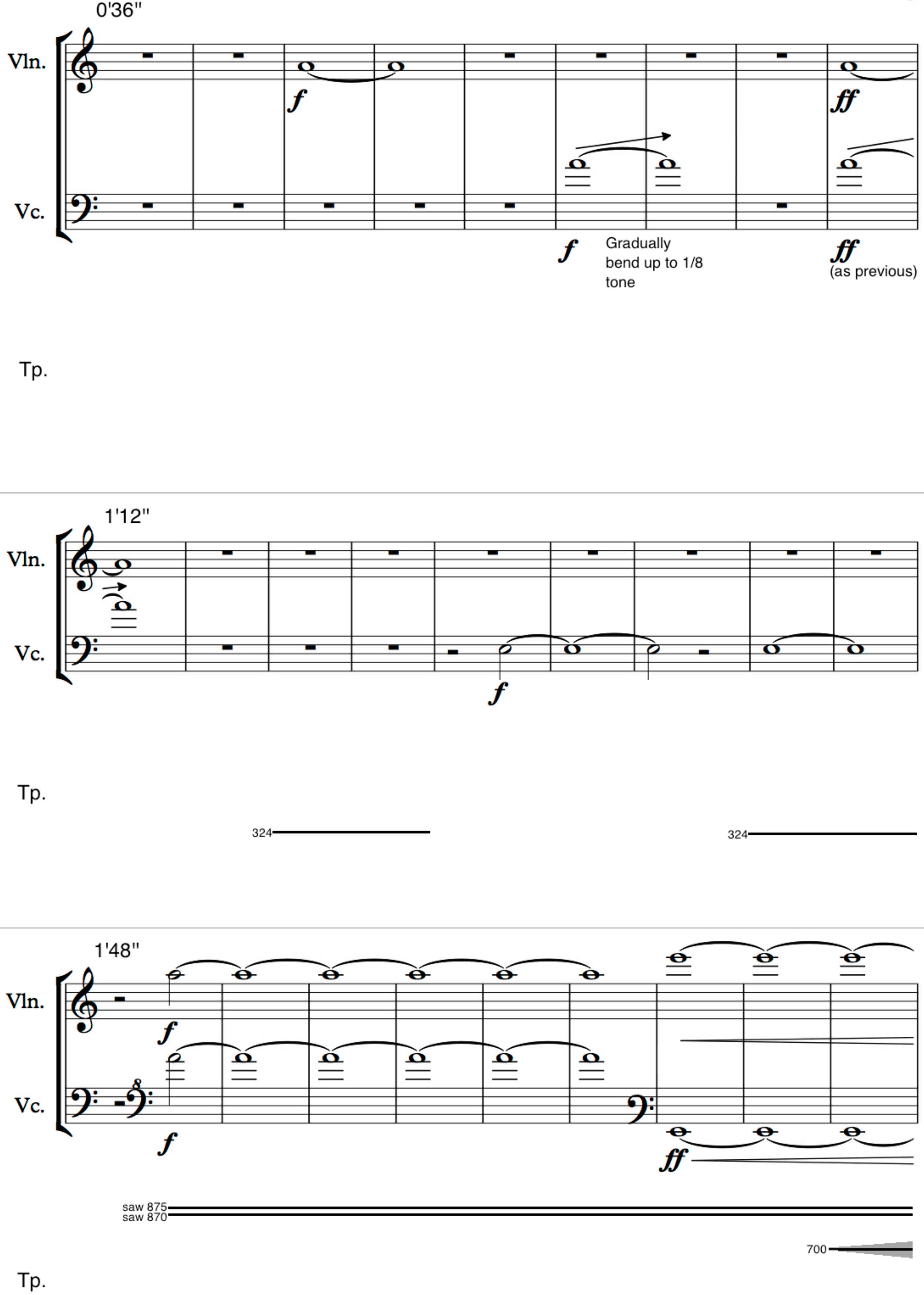
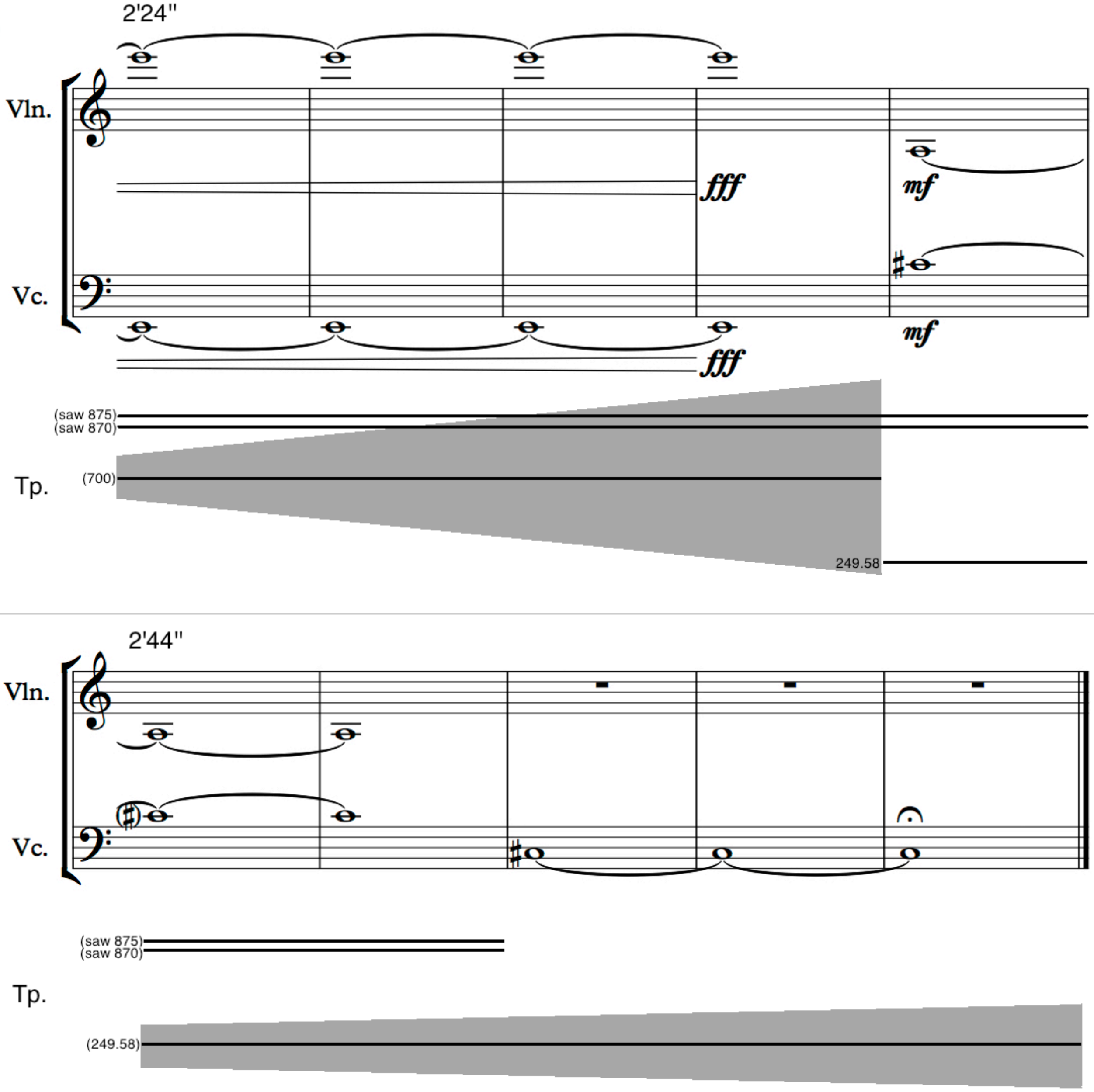
1'44"


Vln.
Vc.
(880)
(770)
(660)
(550)
(440)
(330)
(220)
(110)


2'16"
Vln.
Vc.
ff
ff
f
saw 770
(770)
Tp.
(440)
(220)
saw 110
2'36"
Vln.
Vc.
(saw 770)
Tp.
(saw 110)

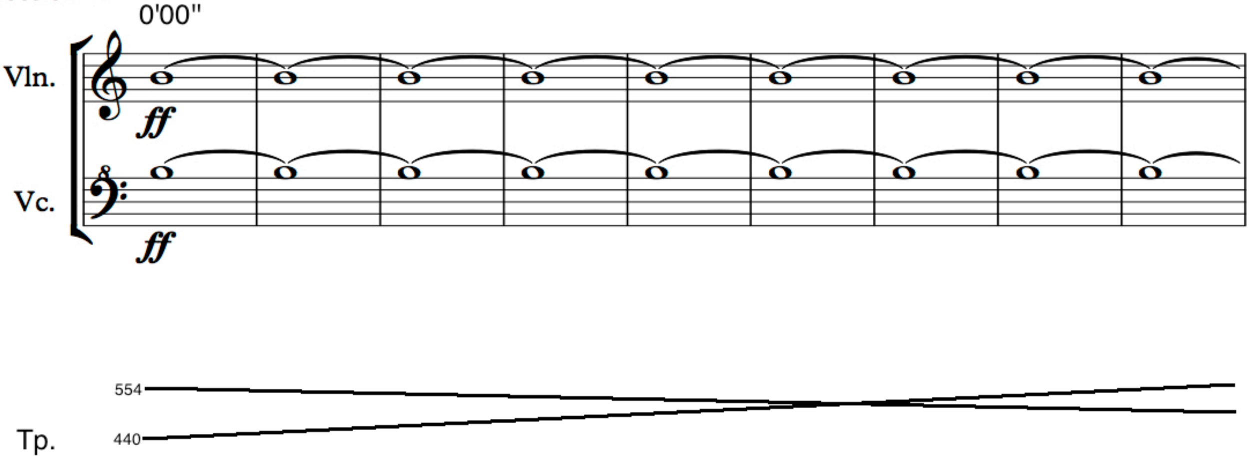
Section 3

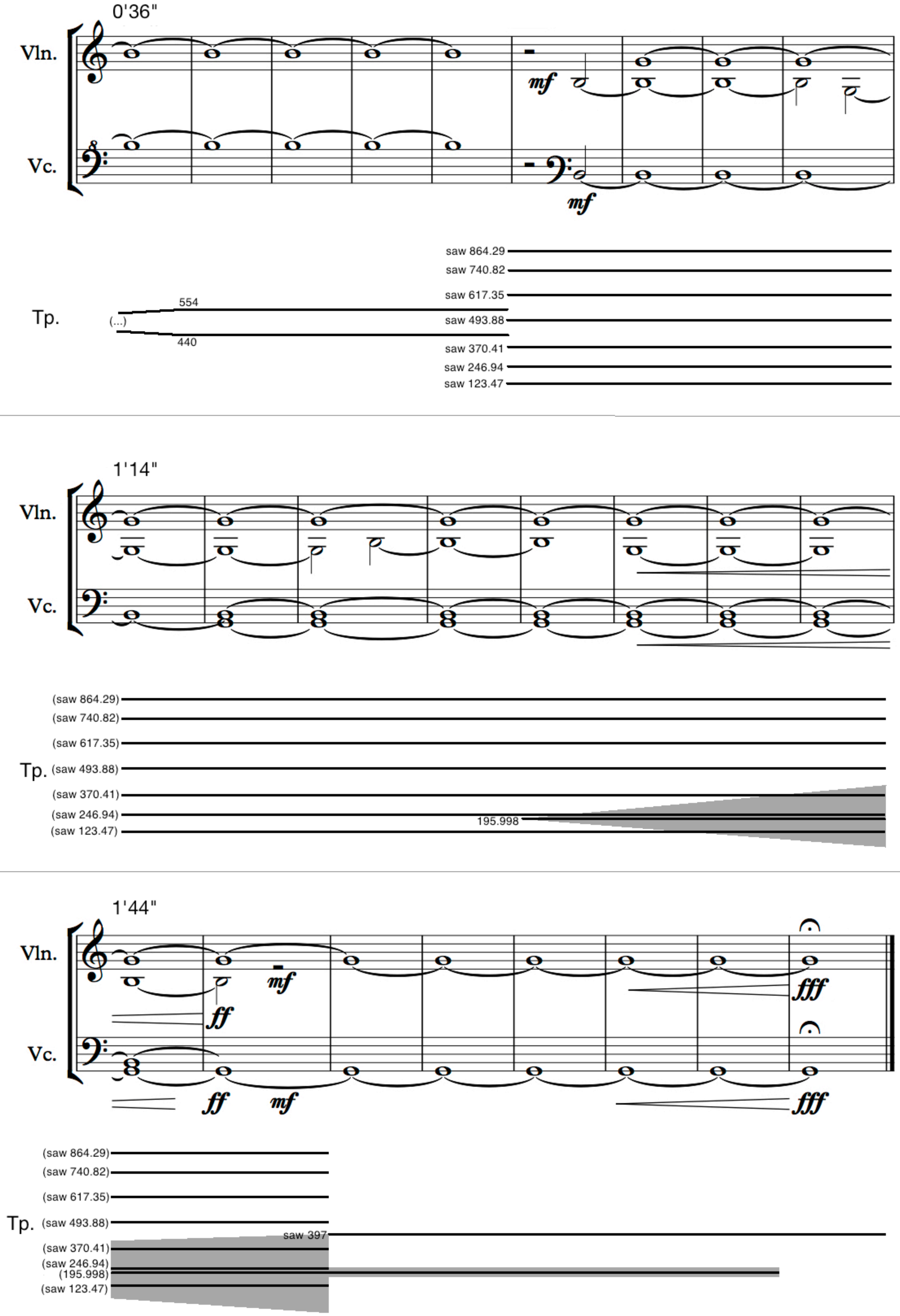

0'00"
Vln.
Vc.
Tp.
220
225
225
220


0'36"
Vln.
Vc.
f
ff
f
Gradually bend up to 1/8 tone
ff
(as previous)
Tp.
1'12"
Vln.
Vc.
f
Tp.
324
324
1'48"
Vln.
Vc.
f
f
8
ff
saw 875
saw 870
700
Tp.


2'24"
Vln.
Vc.
fff
mf
fff
mf
(saw 875)
(saw 870)
Tp.
(700)
249.58
2'44"
Vln.
Vc.
(saw 875)
(saw 870)
Tp.
(249.58)

Section 4


0'00"
Vln.
ff
Vc.
ff
554
Tp.
440


0'36"
Vln.
Vc.
mf
mf
Tp.
(...)
554
440
saw 864.29
saw 740.82
saw 617.35
saw 493.88
saw 370.41
saw 246.94
saw 123.47
1'14"
Vln.
Vc.
Tp.
(saw 864.29)
(saw 740.82)
(saw 617.35)
(saw 493.88)
(saw 370.41)
(saw 246.94)
(saw 123.47)
195.998
1'44"
Vln.
Vc.
ff
mf
ff
mf
fff
fff
Tp.
(saw 864.29)
(saw 740.82)
(saw 617.35)
(saw 493.88)
saw 397
(saw 370.41)
(saw 246.94)
(195.998)
(saw 123.47)

Chase

(piano and fixed media)

Brian Connolly
2016

Additional notes to the performer:

The performer has control over their choice of notes in this piece within the following boundaries:

- Any note appearing on the score will be the highest (treble) or lowest (bass) note that is allowed to be performed at that particular time.
- Any note in between these limitations can be played. The range will expand from F4 to C1 and C8 over the course of the work.
- No note can be played if it has not yet appeared on the score.

Please refrain from the following:

- Creating any 'thematic-like' idioms (melodic or otherwise).
- Excessive use of glissandi.
- Dramatic shifts in intensity due to sudden clusters, etc.
- Starting too energetically. This piece should gradually build in intensity throughout.
- Lifting the pedal before the sound has entirely attenuated.

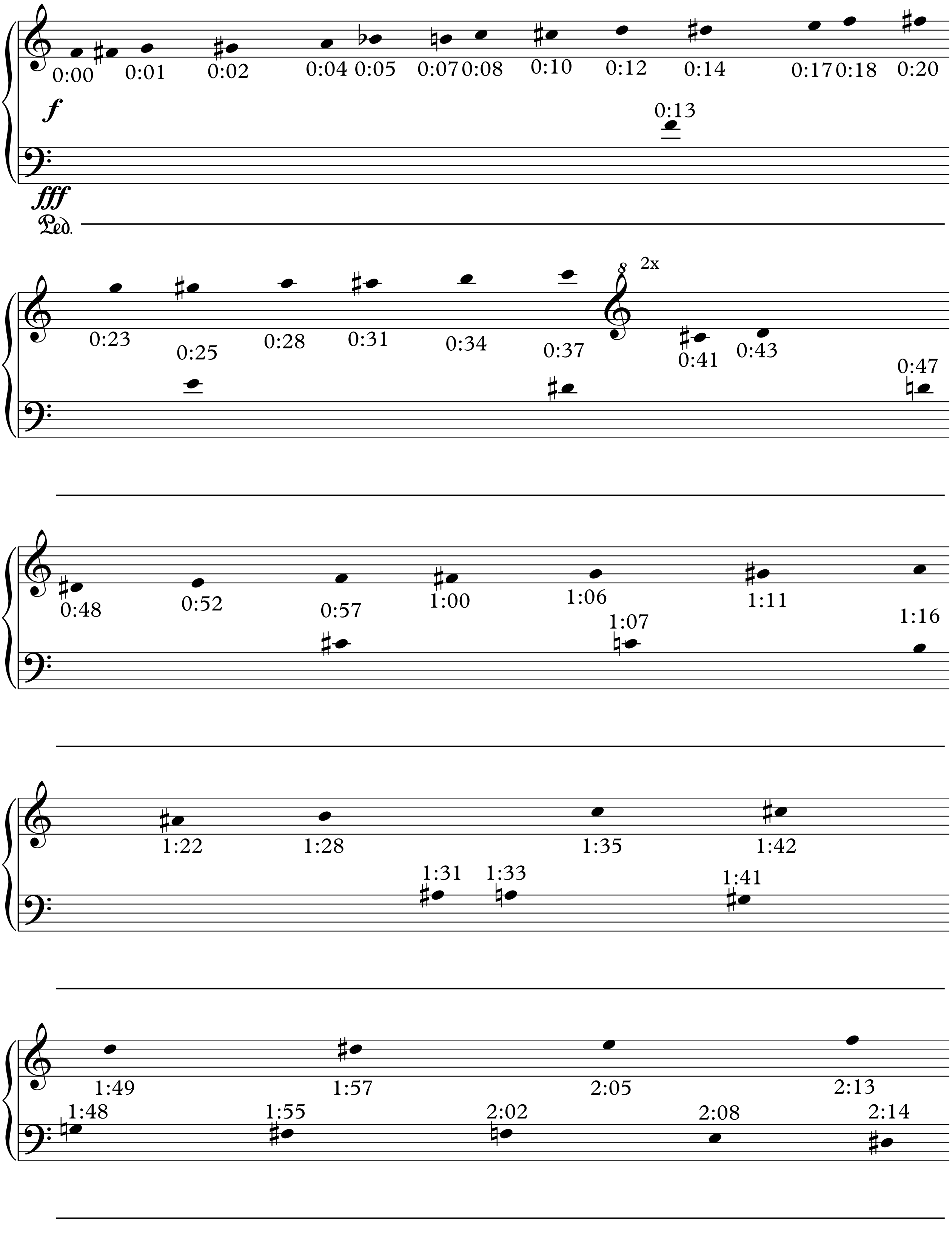
All notes indicated on the score should be struck within reasonable time (a short number of seconds) of the time that is written.

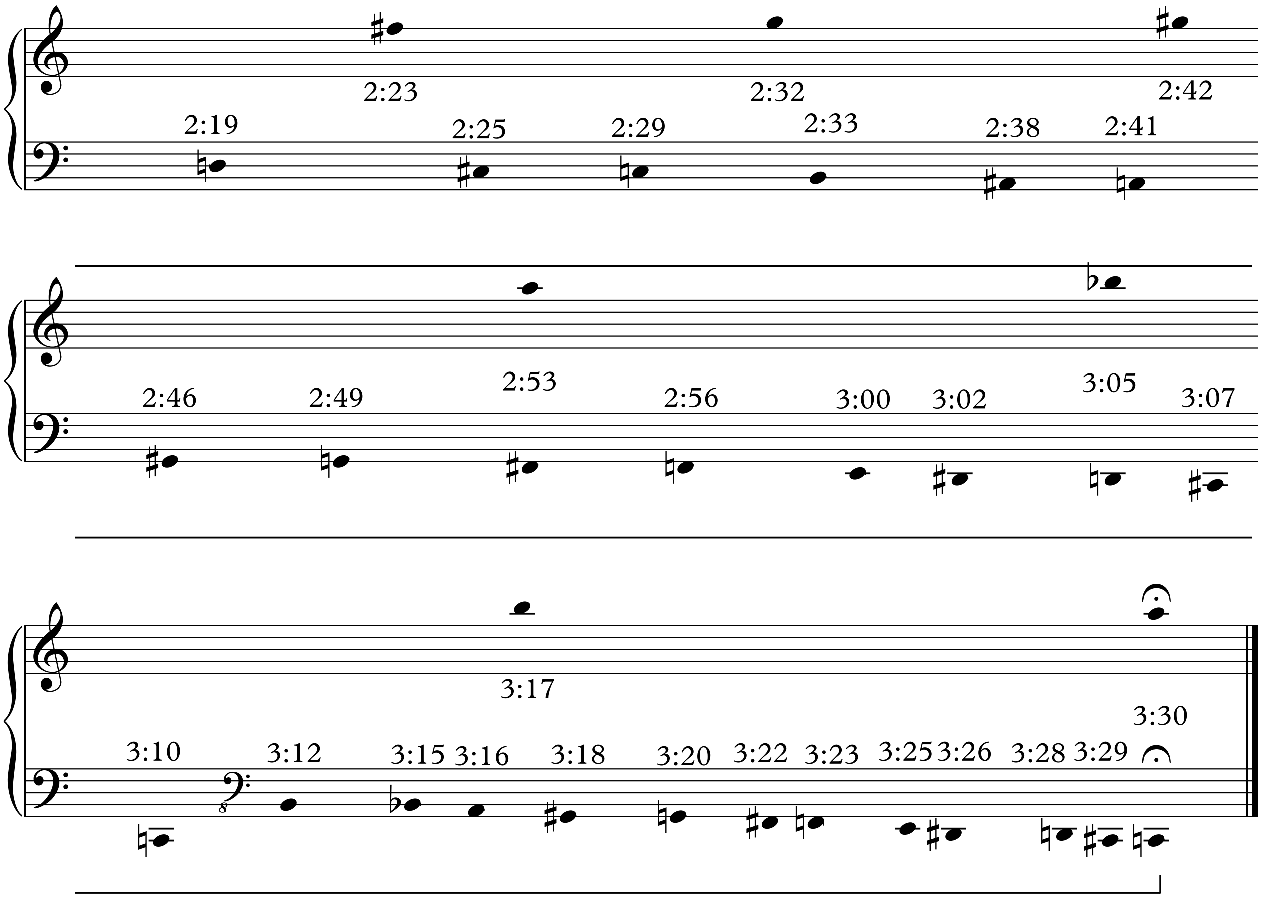
Chase

(Piano part)

Follow stopwatch timer

Brian Connolly
2016




2:19
2:23
2:25
2:29
2:32
2:33
2:38
2:41
2:42
2:46
2:49
2:53
2:56
3:00
3:02
3:05
3:07
3:10
3:12
3:15
3:16
3:17
3:18
3:20
3:22
3:23
3:25
3:26
3:28
3:29
3:30

Occultum Tabulatum

(electric cello and fixed media)

Brian Connolly
2015

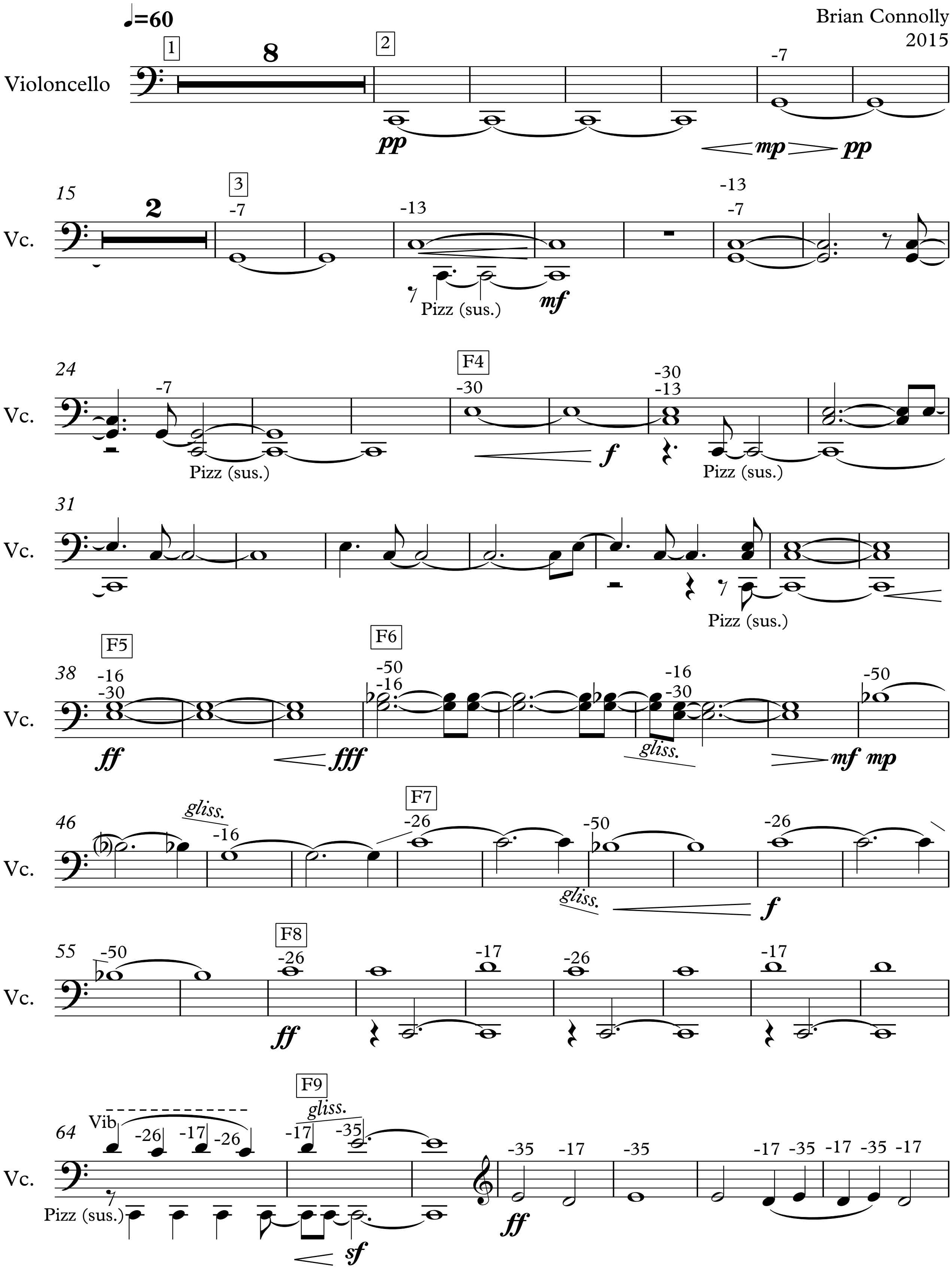
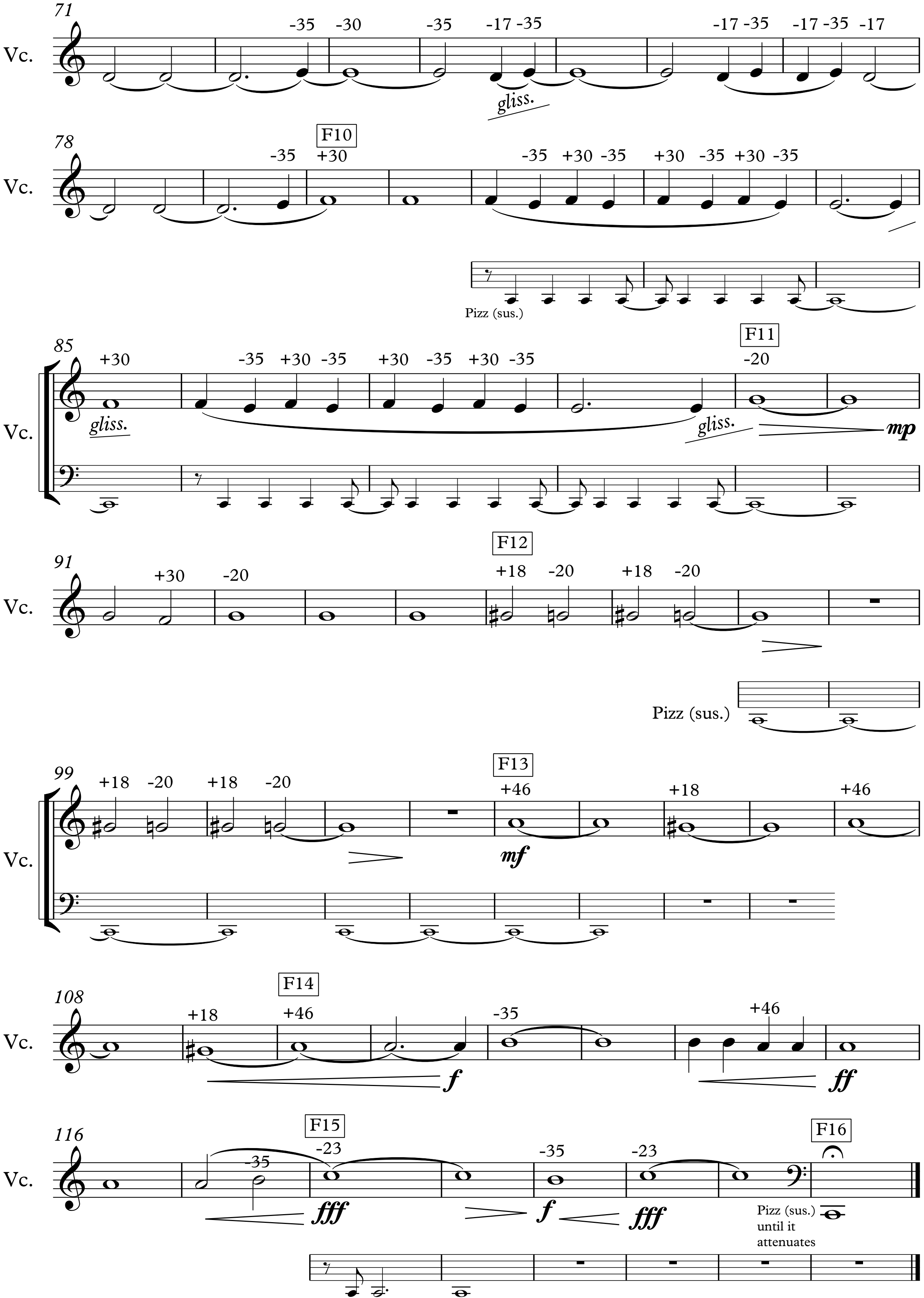
Additional notes to the performer:

The lower staff is used to accommodate the notation of notes on the open C string. All open C string notes are to be played pizzicato with sustain, while the upper voices remain arco for the duration of the piece.

All double stops are to be played non-divisi.

The performer is asked to avoid playing the written notes with perfect tuning. Microtonal markings are provided to inform the performer of the exact position of either of the lowest partials in the sine wave stack at that particular time. The performer is encouraged to explore the movement and dissonance created by the auditory beating sensations, which emerge in the performance space as a result of 'mistunings'. These microtonal markings should serve as a guide to the performer. As the tuning of the cello moves closer to the tuning as indicated by the cent markings, the beating will become slower and more intrusive on the work.

Occultum Tabulatum

Brian Connolly
2015


71
Vc.
-35
-30
-35
-17
-35
gliss.
-17
-35
-17
-35
-17
78
Vc.
F10
-35
+30
-35
+30
-35
+30
-35
+30
-35
Pizz (sus.)
85
Vc.
+30
gliss.
-35
+30
-35
+30
-35
+30
-35
F11
-20
gliss.
mp
91
Vc.
+30
-20
F12
+18
-20
+18
-20
Pizz (sus.)
99
Vc.
+18
-20
+18
-20
F13
+46
mf
+18
+46
108
Vc.
+18
F14
+46
f
-35
+46
ff
116
Vc.
F15
-35
-23
fff
-35
f
-23
fff
F16
Pizz (sus.)
until it
attenuates